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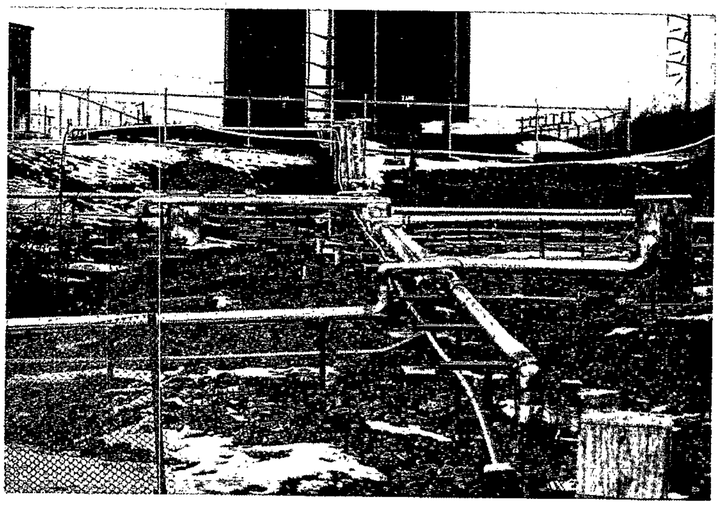
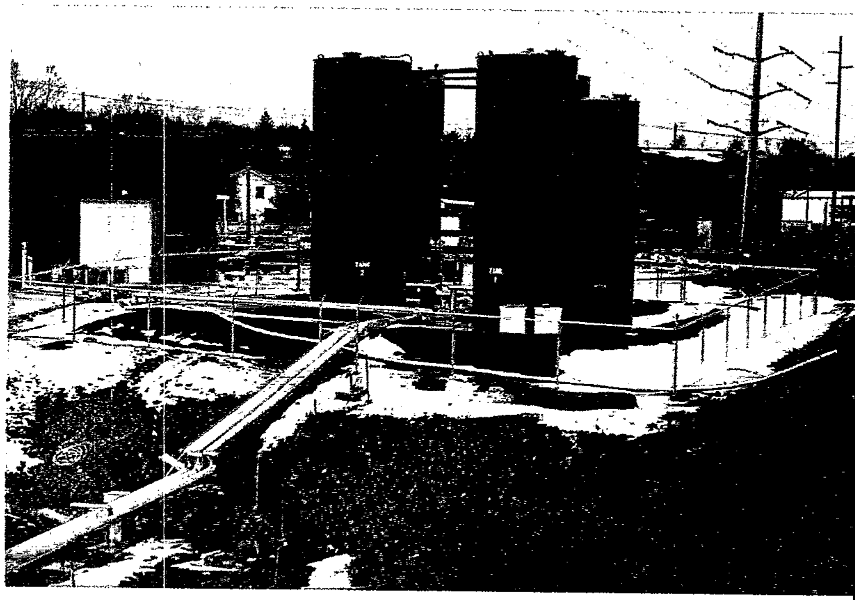
Western Research Institute Contained Recovery of Oily Wastes (CROW) Process

Innovative Technology Evaluation Report





SITE
SUPERFUND INNOVATIVE
TECHNOLOGY EVALUATION

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Western Research Institute Contained Recovery of Oily Wastes (CROW) Process

Innovative Technology Evaluation Report

National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

Notice

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Foreword

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

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

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

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

Abstract

This report presents performance and economic data from a Superfund Innovative Technology Evaluation (SITE) Program demonstration of the Contained Recovery of Oily Wastes (CROW) process. The demonstration evaluated the technology's ability to treat subsurface accumulations of oily wastes. The results of bench- and pilot-scale testing of the technology are presented as appendices to this report.

The CROW process was developed by the Western Research Institute as an in situ remediation technology to mobilize and remove oily waste accumulations from the subsurface. The technology involves the injection of heated water into the subsurface to mobilize oily wastes, which are removed from the subsurface through recovery wells. The oily waste is separated from the groundwater and is disposed of or recycled. A portion of the water is then heated and reinjected in the subsurface. The excess water is treated before being discharged. The CROW process may be modified to treat any size area by varying the number of injection and recovery wells and adjusting the capacity of the water treatment system.

The CROW process technology was demonstrated at the Brodhead Creek Superfund site in Stroudsburg, Pennsylvania. This technology demonstration was a full-scale remediation effort lasting about 20 months. The CROW process system used for the SITE demonstration included six hot water injection wells, two recovery wells, an aboveground water treatment system, and a data acquisition and control system. The injection and recovery wells targeted an accumulation of free-phase coal tar within a 40-foot by 80-foot treatment area.

Primary demonstration objectives evaluated whether the CROW process removed coal tar from the subsurface or flushed the coal tar outside of the treatment area. The CROW process was successful in removing coal tar from the subsurface; however, it was unable to reduce coal tar concentrations to residual immobile levels. Measurements of the concentration of coal tar in the soil outside of the treatment area before and after the demonstration did not show a significant change. This suggests that the CROW process did not flush large amounts of contamination outside of the treatment area. Measurements of the amount of coal tar in the layer under the treatment zone before and after the demonstration suggest that some coal tar was pushed down into the underlying confining unit.

Potential sites for applying this technology include Superfund and other hazardous waste sites where the aquifer is contaminated by oily wastes. Economic data indicate that remediation costs of using this technology are affected by site-specific factors. At the Brodhead Creek Superfund site, the cost for implementing a site cleanup using the CROW process was calculated at $85,000 per pore volume. As a comparison, the cost per pore volume at the Bell Lumber and Pole Company (Bell Pole) site in New Brighton, Minnesota was calculated at $61,900. The costs for the Bell Pole site are less due to better site conditions including less dissolved iron in the aquifer and a uniform sand aquifer. The cost per pore volume for implementing this technology at other sites is expected to fall within this range.

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Acronyms, Abbreviations, and Symbols

ACL	Alternate concentration limit
AES	Atlantic Environmental Services, Inc.
amsl	Above mean sea level
ARAR	Applicable or relevant and appropriate requirement
BaP	Benzo(a)pyrene
Bell Pole	Bell Lumber and Pole Company
BFB	Bromofluorobenzene
BOD	Biochemical oxygen demand
BS/BSD	Blank spike/Blank spike duplicate
BTEX	Benzene, toluene, ethylbenzene, and xylene
CAA	Clean Air Act
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
cm/sec	Centimeters per second
COD	Chemical oxygen demand
CROW	Contained Recovery of Oily Wastes
CWA	Clean Water Act
DFTPP	Decafluorotriphenylphosphine
DNAPL	Dense nonaqueous-phase liquids
DP	Demonstration Plan
EPA	U.S. Environmental Protection Agency
ERM	Environmental Resources Management, Inc.
ft/d	Feet per day
ft/ft	Foot per foot
GAC-FBR	Granular activated carbon-fluidized bed reactor
GC/MS	Gas chromatograph/mass spectrometer
gpm	Gallons per minute
H_0	Null hypothesis
HVAC	Heating, ventilation, and air conditioning
ITER	Innovative Technology Evaluation Report
LCS/LCSD	Laboratory control sample/laboratory control sample duplicate

Acronyms, Abbreviations, and Symbols (continued)

LDR	Land disposal restriction
LNAPL	Light nonaqueous-phase liquids
MCL	Maximum contaminant level
mg/kg	Milligram per kilogram
mg/L	Milligram per liter
MGP	Manufactured gas plant
MS/MSD	Matrix spike/Matrix spike duplicate
NAAQS	National Ambient Air Quality Standard
NAPL	Nonaqueous phase liquids
NCP	National Contingency Plan
NPDES	National Pollutant Discharge Elimination System
O&G	Oil and grease
O&M	Operation and maintenance
ORD	Office of Research and Development
OSWER	Office of Solid Waste and Emergency Response
PADER	Pennsylvania Department of Environmental Resources
PAH	Polynuclear aromatic hydrocarbon
POTW	Publicly owned treatment works
PP&L	Pennsylvania Power and Light
PPE	Personal protective equipment
PRC	PRC Environmental Management, Inc.
PSD	Prevention of significant deterioration
QAPP	Quality assurance project plan
QA/QC	Quality assurance/quality control
RCRA	Resource Conservation and Recovery Act
ReTeC	Remediation Technologies, Inc.
SARA	Superfund Amendments and Reauthorization Act
SDG	Sample data group
SDWA	Safe Drinking Water Act
SITE	Superfund Innovative Technology Evaluation
SVOC	Semivolatile organic compound
TER	Technology Evaluation Report
TOC	Total organic carbon
TRPH	Total recoverable petroleum hydrocarbon
TSDF	Treatment, storage, and disposal facility
TSS	Total suspended solid
TtEMI	Tetra Tech EM Inc.

Acronyms, Abbreviations, and Symbols (continued)

µg/L	Microgram per liter
VISITT	Vendor Information System for Innovative Treatment Technologies
VOC	Volatile organic compound
WHPA	Well head protection area
WRI	Western Research Institute
WQS	Water quality standard

Conversion Factors

	To Convert From	*To*	*Multiply By*
Length	inch	centimeter	2.54
	foot	meter	0.305
	mile	kilometer	1.61
Area:	square foot	square meter	0.0929
	acre	square meter	4,047
Volume:	gallon	liter	3.78
	cubic foot	cubic meter	0.0283
Mass:	pound	kilogram	0.454
Energy:	kilowatt-hour	megajoule	3.60
Power:	kilowatt	horsepower	1.34
Temperature:	(°Fahrenheit - 32)	°Celsius	0.556

Acknowledgments

This report was prepared for the U.S. Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) Program by Tetra Tech EM Inc. (*formerly PRC Environmental Management, Inc.*) under the direction and coordination of Mr. Richard Eilers, work assignment manager in the Land Remediation and Pollution Control Division (LRPCD) of the National Risk Management Research Laboratory (NRMRL) in Cincinnati, Ohio.

The CROW process demonstration was a cooperative effort that involved the following personnel from the EPA Site Program, EPA Region 3, Pennsylvania Power and Light (PP&L), Remediation Technologies Inc. (ReTec), and Western Research Institute (WRI).

- Annette Gatchett — EPA NRMRL, Acting LRPCD Director
- Richard Eilers — EPA SITE Work Assignment Manager
- Ann Vega — EPA LRPCD Quality Assurance Officer
- John Banks — EPA Region 3, Remedial Project Manager
- Jim Villaume — PP&L Project Manager
- Alfred Leuschner — ReTec Project Manager
- Mark Miller — ReTec Project Engineer
- Jason Gerrish — ReTec Project Engineer
- Lyle Johnson — WRI Project Manager
- L. John Fahy — WRI Project Engineer

Executive Summary

The Contained Recovery of Oily Wastes (CROW) process was developed by the Western Research Institute (WRI) as an in situ remediation technology to mobilize and remove oily waste accumulations from the subsurface. This technology was demonstrated under the U.S. Environmental Protection Agency's Superfund Innovative Technology Evaluation (SITE) Program at the Brodhead Creek Superfund site in Stroudsburg, Pennsylvania. The technology demonstration was a full-scale remediation effort lasting about 20 months.

The purpose of this Innovative Technology Evaluation Report (ITER) is to present information that will assist Superfund decision-makers in evaluating the CROW process technology for application to a particular hazardous waste site cleanup. The report introduces the SITE Program and CROW process technology (Section 1), analyzes the technology's applications (Section 2), analyzes the economics of using the CROW process system to treat subsurface accumulations of oily wastes (Section 3), provides an overview and evaluation of the CROW process demonstration (Section 4), summarizes the technology's status (Section 5), and presents a list of references used to prepare the ITER (Section 6). Vendor's claims for the CROW process technology are presented in Appendix A, and results of bench- and pilot-scale testing of the technology are presented in Appendices B and C, respectively.

The executive summary briefly describes the CROW process technology and system, provides an overview of the SITE demonstration of the technology, summarizes the SITE demonstration results, and discusses the Superfund feasibility evaluation criteria for the CROW process technology.

CROW Process Technology and System Description

The CROW process was developed by the WRI as an in situ remediation technology to mobilize and remove oily waste accumulations from the subsurface. The technology involves the injection of heated water into the subsurface to mobilize oily wastes, which are removed from the subsurface through recovery wells. The oily waste is separated from the recovered groundwater and is disposed of or recycled. A portion of the recovered water is then heated and reinjected into the subsurface. The excess water is treated before being discharged. The CROW process may be modified to treat any size area by varying the number of injection and recovery wells and adjusting the capacity of the water treatment system.

WRI claims that the CROW process reduces the volume of oily wastes and increases the permeability of the aquifer, resulting in more uniform groundwater flow within the aquifer. These more uniform and permeable conditions allow for more effective control of bacterial inoculation, nutrient addition, environmental manipulation, and oily waste removal to accelerate complete remediation of sites contaminated with oily wastes (L.A. Johnson and F.D. Guffey 1990).

The CROW process system used for the SITE demonstration included six hot-water injection wells, two recovery wells, an aboveground water treatment system, and a data acquisition and control system. The injection and recovery wells targeted an accumulation of free-phase coal tar within a 40-foot by 80-foot treatment area. The water treatment system consisted of a series of tanks to separate oil from the recovered water, a biological reactor, carbon adsorption units, and bag and sand filters. The data acquisition and control system monitored flow rates and flow pressures at each well; water temperatures at the production wells, injection wells, monitoring wells, and water treatment units; and groundwater levels in selected monitoring wells.

Overview of the CROW Process Technology SITE Demonstration

The CROW process technology was demonstrated from November 1994 through July 1996 at the Brodhead Creek Superfund site in Stroudsburg, Pennsylvania. SITE demonstrations are typically conducted over a relatively brief time frame (on the order of weeks). This SITE demonstration however, was a full-scale remediation effort lasting 20 months.

The Brodhead Creek site is the location of a former coal gasification plant. A waste product from this plant was a black tar-like liquid (coal tar) with a density greater than water and principally composed of polynuclear aromatic hydrocarbons (PAH). The coal tar was disposed of in an open pit located on the property for approximately 60 years until the mid-1940s, when the plant was abandoned (Environmental Resources Management 1990).

The SITE demonstration for the CROW process technology was designed with four primary and five secondary objectives to provide potential users of the technology with the information necessary to assess the applicability of the CROW process technology at other contaminated sites.

The primary objectives (P) of the technology demonstration were as follows:

- P-1 Measure Reduction of Coal Tar in the Aquifer
- P-2 Assess Potential Upward Migration of Contaminants
- P-3 Assess Potential Downward Migration of Coal Tar
- P-4 Assess Areal Containment of Coal Tar

The secondary objectives (S) of the technology demonstration were as follows:

- S-1 Record CROW Process Operational Parameters
- S-2 Evaluate CROW Process Cost
- S-3 Assess Potential Fractionation of Coal Tar
- S-4 Assess Water Treatment System Effectiveness
- S-5 Evaluate Hydrologic Capture Zones

SITE Demonstration Results

Key findings of the CROW process technology are listed below:

- The CROW process was successful in removing coal tar from the subsurface (1,504 gallons recovered); however, it was unable to reduce coal tar concentrations to residual immobile levels since free-phase coal tar was present after the demonstration.

- Measurements of the amount of coal tar in the lower confining layer under the treatment zone before and after the demonstration suggest that some coal tar was pushed down into the lower confining unit.

- Measurements of the concentration of coal tar in the soil outside of the treatment zone before and after the demonstration did not show a significant change. This result suggests that the CROW process did not increase soil contaminant concentrations outside the treatment zone.

- The average injection and extraction rates for the hot-water injection period were 19.6 and 24.0 gallons per minute (gpm), respectively. The groundwater extraction rate exceeded the total water injection by approximately 4 gpm throughout the test to provide hydraulic containment and recovery of the injected hot water. The pore volume of the aquifer in the treatment zone was estimated at 455,000 gallons. Over the 366-day period, 20.8 pore volumes were injected into the treatment zone and a total of 25.5 pore volumes were extracted from the treatment zone.

- Site-specific factors can affect the performance and costs of using the CROW process treatment system. At the Brodhead Creek Superfund site, site-specific factors such as a shallow groundwater table and a high concentration of dissolved iron in the groundwater directly and indirectly reduced injection rates, reduced flow rates through the treatment zone, and extended the treatment time.

- At the Brodhead Creek Superfund site, the cost for implementing a site cleanup using the CROW process was calculated at $85,000 per pore volume (approximately 455,000 gallons) flushed through the treatment zone. As a comparison, the cost per pore volume (approximately 950,000 gallons) at the Bell Lumber and Pole Company (Bell Pole) site in New Brighton, Minnesota, another site where the CROW process was deployed, was calculated at $61,900. The lower costs for the Bell Pole site are due to better site conditions, including less dissolved iron in the aquifer, and a uniform sand aquifer. The cost per pore volume for implementing this technology at other sites is expected to fall within this range.

- The results of the data analysis were inconclusive concerning coal tar fractionation that may have resulted from application of the CROW process.

- The water treatment system successfully reduced contaminant concentrations throughout most of the demonstration. Total benzene, toluene, ethylbenzene, and xylene (BTEX) concentrations were reduced by more than 98 percent by the biological reactor and by more than 99.9 percent before discharge. Total PAH concentrations were reduced by more than 96 percent by the biological reactor and by more than 98 percent before discharge.

- The CROW process was successful in recovering the injected water. However, the groundwater samples also show that during initial startup the changes in the ambient groundwater flow system resulted in spikes of contamination being released downgradient.

Technology Evaluation Summary

Table ES-1 briefly discusses the Superfund feasibility evaluation criteria for the CROW process technology to assist Superfund decision-makers considering the technology for remediation of subsurface accumulations of oily wastes at hazardous waste sites.

Table ES-1. Superfund Feasibility Study Evaluation Criteria for the CROW Process Technology

Criteria	CROW Process Assessment
Overall protection of human health and the environment	The CROW process failed to provide both short- and long-term protection of human health and the environment since it did not remove oily wastes in the subsurface to residual immobile concentrations. The process is intended to increase the mobility of the contamination to enhance removal from the subsurface. Depending on the characteristics of the lower confining unit the enhanced mobility may result in the spread of contamination. Complete removal of the mobile waste would prevent further migration, reduce the amount available for dissolution into groundwater, and increase the effectiveness of bioremediation and natural attenuation.
Compliance with federal and state applicable or relevant and appropriate requirements (ARAR)	Compliance with chemical-, location-, and action-specific ARARs should be determined on a site-specific basis. Compliance with chemical-specific ARARs depends on the ability of the CROW process to remove the oily wastes from the subsurface and the effectiveness of the water treatment system in treating water prior to discharge.
Long-term effectiveness and permanence	The CROW process failed to provide long-term remediation of non-aqueous phase liquid (NAPL) in aquifers since it did not remove oily wastes in the aquifer to residual immobile concentrations.
Reduction of toxicity, mobility, or volume through treatment	The CROW process reduces the volume of the contaminants by removing oily wastes from the subsurface. The CROW process reduces the mobility of the oily waste by removing mobile oily wastes from the aquifer. Treatment of the excess process water prior to discharge reduces the volume and toxicity of contaminants dissolved in the groundwater.
Short-term effectiveness	The CROW process starts to remove oily waste from the aquifer as soon as it starts operation. It also removes dissolved contaminants in the excess process water.
Implementability	The CROW process can be implemented at any site that can be reached by the equipment necessary to install the injection and recovery wells and construct the tank farm. Electricity is also required to operate the pumps, water heater, and process control system. All the equipment necessary to construct and operate the CROW process is commercially available throughout the industrialized world.
Cost	A complete analysis of costs to install and operate the CROW process at the Brodhead Creek site is presented in Section 3. The total cost of the Brodhead Creek site interim removal action was $2,168,000. The cost for implementing a site cleanup using the CROW process was compared to the number of pore volumes flushed through the treatment area. A total of 25.5 pore volumes were extracted from the treatment area. The total cost per pore volume was calculated at $85,000.
Community acceptance	Community acceptance is anticipated to be favorable because the CROW process has very few impacts after the initial construction. Sites that have significant accumulations of oily wastes are usually industrial and the noise and traffic impacts of site construction are not out of the ordinary.
State acceptance	State acceptance is anticipated to be favorable because the CROW process is one of the few technologies available to remove oily wastes from the subsurface. State regulatory agencies may require a National Pollutant Discharge Elimination System (NPDES) permit, permits for operation, and a permit to store hazardous waste in the recovered oil tank for greater than 90 days.

Section 1
Introduction

This section briefly describes the Superfund Innovative Technology Evaluation (SITE) program and SITE reports; states the purpose and organization of this Innovative Technology Evaluation Report (ITER); provides background information regarding the development of the Contained Recovery of Oily Wastes (CROW) process technology; describes the CROW process technology; identifies wastes to which this technology may be applied; and provides a list of key contacts who can supply information about the technology and demonstration site.

1.1 Description of SITE Program and Reports

This briefly describes the purpose, history, and goals of the SITE Program and the reports that document SITE demonstration results.

1.1.1 Purpose, History, and Goals of the SITE Program

The primary purpose of the SITE Program is to advance the development and demonstration, and thereby establish the commercial availability, of innovative treatment technologies applicable to Superfund and other hazardous waste sites. The SITE Program was established by the U.S. Environmental Protection Agency (EPA) Office of Solid Waste and Emergency Response (OSWER) and Office of Research and Development (ORD) in response to the Superfund Amendments and Reauthorization Act of 1986 (SARA), which recognized the need for an alternative or innovative treatment technology research and demonstration program. The SITE Program is administered by ORD's National Risk Management Research Laboratory (NRMRL). The overall goal of the SITE Program is to carry out a program of research, evaluation, testing, development, and demonstration of alternative or innovative treatment technologies that may be used in response actions to achieve long-term protection of human health and welfare and the environment.

The SITE Program consists of four component programs, one of which is the Demonstration Program. The objective of the Demonstration Program is to provide reliable performance and cost data on innovative technologies so that potential users can assess a given technology's suitability for specific site cleanups. Innovative technologies chosen for a SITE demonstration must be pilot- or full-scale applications and must offer some advantage over existing technologies. To produce useful and reliable data, demonstrations are conducted at actual hazardous waste sites or under conditions that closely simulate actual waste site conditions.

Data collected during the demonstration are used to assess the performance of the technology, the potential need for pretreatment and post-treatment processing of the treated waste, the types of wastes and media that can be treated by the technology, potential treatment system operating problems, and approximate capital and operating costs. Demonstration data can also provide insight into a technology's long-term operation and maintenance (O&M) costs and long-term application risks.

Under each SITE demonstration, a technology's performance in treating an individual waste at a particular site is evaluated. Successful demonstration of a technology at one site does not ensure its success at other sites. Data obtained from the demonstration may require extrapolation to estimate a range of operating conditions over which the technology performs satisfactorily. Any extrapolation of demonstration data also should be based on other information about the technology, such as case study information.

Cooperative arrangements among EPA, the site owner, and the technology developer establish responsibilities for conducting the demonstration and evaluating the technology. EPA is responsible for project planning, sampling and analysis, quality assurance and quality control (QA/QC), preparing reports, and disseminating information. The site owner is responsible for transporting and disposing of treated waste materials and site logistics. The technology developer is responsible for demonstrating the technology at the selected site and is expected to pay any costs for transport, operations, and removal of equipment.

Implementation of the SITE Program is a significant, ongoing effort involving ORD, OSWER, various EPA regions, and private business concerns, including technology developers and parties responsible for site remediation. The technology selection process and the Demonstration Program together provide a means to perform objective and carefully controlled testing of field-ready technologies. Each year, the SITE Program sponsors about 10 technology demonstrations. This ITER was prepared under the SITE Demonstration Program.

1.1.2 Documentation of SITE Demonstration Results

The results of each SITE demonstration are usually reported in four documents: (1) a Demonstration Bulletin, (2) a Technology Capsule, (3) a Technology Evaluation Report (TER), and (4) the ITER.

The Demonstration Bulletin provides a two-page description of the technology and project history, notification that the demonstration was completed, and highlights of the demonstration results. The Technology Capsule provides a brief description of the project and an overview of the demonstration results and conclusions.

The purpose of the TER is to consolidate all information and records acquired during the demonstration. The TER data tables and graphs summarize test results in terms of whether project objectives and applicable or relevant and appropriate requirements (ARAR) were met. The tables also summarize QA/QC data in comparison to data quality objectives. The TER is not formally published by EPA. Instead, a copy is retained by the EPA project manager as a reference for responding to public inquiries and for record-keeping purposes. The purpose and organization of the ITER are discussed in Section 1.2.

1.2 Purpose and Organization of the ITER

Information presented in the ITER is intended to assist decision-makers in evaluating specific technologies for a particular cleanup situation. The ITER represents a critical step in the development and commercialization of a technology demonstrated under the SITE Program. The ITER discusses the effectiveness and applicability of the technology and analyzes costs associated with its application. The technology's effectiveness is evaluated based on data collected during the SITE demonstration and from other case studies. The applicability of the technology is discussed in terms of waste and site characteristics that could affect technology performance, material handling requirements, technology limitations, and other factors.

This ITER consists of six sections, including this introduction. Sections 2 through 7 and their contents are summarized below.

- Section 2, Treatment Applications Analysis, discusses information relevant to the application of the CROW process technology, including an assessment of the technology related to the nine feasibility study evaluation criteria, potentially applicable environmental regulations, and the operability and limitations of the technology.

- Section 3, Economic Analysis, summarizes the actual costs, by cost category, associated with using the CROW process technology at the Brodhead Creek Superfund site, variables that may affect costs at other sites, and conclusions derived from the economic analysis.

- Section 4, CROW Process SITE Demonstration, presents information relevant to the design and implementation of the technology including the characteristics of the Brodhead Creek Superfund site. It also presents an overview of the SITE demonstration objectives, documents the demonstration procedures, and summarizes the results and conclusions of the demonstration.

- Section 5, Technology Status, summarizes the developmental status of the CROW process technology.

- Section 6, References, lists the references used to prepare this ITER.

In addition to these sections, this ITER has three appendices: Appendix A, Vendor's Claims for the Technology; Appendix B, Bench-scale Testing of Brodhead Creek Superfund Site Soils; and Appendix C, Pilot-scale Testing at the Bell Pole Site in New Brighton, Minnesota.

1.3 Background Information on CROW Process Technology Under the SITE Program

The CROW process technology was developed by the Western Research Institute (WRI). In 1988, this technology was accepted into the SITE Emerging Technology Program. In March 1989, WRI began bench-scale testing of the technology using contaminated material from the Brodhead Creek Superfund site. The purpose of these tests was to demonstrate the ability of the technology to treat oily wastes associated with manufactured gas facilities and to develop preliminary site-specific information for the Brodhead Creek site (Johnson and Guffey 1990). The results of these bench-scale tests are summarized in Appendix B. Based on the promising bench-scale results, the CROW process technology was accepted into the SITE Demonstration Program in 1991, and was then selected for demonstration at the Brodhead Creek site.

In September 1991, WRI field-tested a pilot-scale deployment of the CROW process technology at the Bell Lumber and Pole Company (Bell Pole) site in New Brighton, Minnesota. This pilot test of the technology was funded separately by the U.S. Department of Energy (DOE). The results of this pilot test are discussed in Appendix C.

1.4 CROW Process Technology Description

The CROW process was developed as an in situ remediation technology to mobilize and remove oily waste accumulations from the subsurface. The technology involves the injection of heated water into the subsurface to mobilize oily wastes, which are removed from the subsurface through recovery wells. The oily waste is separated from the groundwater and is disposed of or recycled. A portion of the water is heated and reinjected into the subsurface and the excess water is treated before it is discharged. The CROW process may be modified to treat any size area by varying the number of injection and recovery wells and adjusting the capacity of the water treatment system.

Subsurface accumulations of oily wastes are a persistent source of groundwater contamination. Oily waste discharges that are denser than water permeate downward through the subsurface until further penetration is blocked by impermeable barriers. Above these barriers, the oily liquid accumulates and spreads laterally, filling a large fraction of the subsurface pore space. If this spreading mass of organic liquid encounters fractures, discontinuities, or permeable sections in the barriers, the oily wastes penetrate into deeper strata (Johnson and Guffey 1990). Saturation of pore spaces with water-immiscible organic liquid in highly contaminated zones reduces the permeability of the aquifer and thereby reduces or prevents groundwater flow through oily waste accumulations. Over time, this resistance to groundwater flow may even retard extraction of water-soluble compounds (Johnson and Guffey 1990). Accumulations of immiscible organic liquids also hinder natural microbial degradation for the following reasons: (1) a limited nonaqueous-phase liquid (NAPL) surface area is exposed to the aqueous environment, (2) some components of the organic liquid may be toxic to groundwater bacteria, and (3) a low rate of groundwater flow further reduces the supply of nutrients for microbial activity. These conditions limit the rate of natural or induced microbial degradation and may even isolate large areas of oily waste accumulations as sterile environments (Johnson and Guffey 1990).

WRI claims that the CROW process reduces the volume of oily wastes and increases the permeability of the aquifer, resulting in more uniform groundwater flow within the aquifer. These more uniform and permeable conditions allow for more effective control of bacterial inoculation, nutrient addition, environmental manipulation, and oily waste removal and accelerate complete remediation of sites contaminated with oily wastes (Johnson and Guffey 1990).

WRI claims that the CROW process will recover a portion of the organic liquid phase in subsurface oily waste accumulations (Resource Technology, Inc. [ReTeC] 1993) by injecting hot water or steam into the aquifer to heat and mobilize accumulations of oily wastes. Heating the wastes reduces the density and viscosity of the organic liquid phase and increases the mobility of the oily wastes. Hot water or steam can effectively mobilize free-phase organic waste and a portion of the residual oily waste trapped by capillary forces. The hot water or steam is injected at the perimeter of the oily waste formation and is recovered near the center of the formation along with the mobilized wastes. Oily waste is separated from the water for disposal. The water is then reheated and reinjected into the aquifer. Hot-water injection and groundwater-recovery rates are controlled to sweep oily waste accumulations through the more permeable regions of the aquifer. Displacement of the oily wastes increases the organic liquid saturation in the subsurface pore space. High saturations of the organic liquid phase increase the relative permeability of the aquifer to the oily wastes, so injected hot water tends to displace the oil to the recovery wells. Some immobile residual waste remains trapped in the subsurface pore space (Johnson and Guffey 1990).

1.5 Applicable Wastes

Based on the demonstration results from the Brodhead Creek site and available information from other applications of the technology, including the Bell Pole site, the CROW process technology can be used to treat accumulations of oily wastes in an aquifer. This technology is useful for mobilizing and removing oily wastes at wood treatment facilities, manufactured gas plants (MGP), or similar industrial sites where groundwater is contaminated by creosote, pentachlorophenol, coal tar, or other oily wastes.

1.6 Key Contacts

Additional information on the CROW process technology and the SITE Program can be obtained from the following sources:

CROW Process Technology
Mr. Lyle Johnson
Western Research Institute
365 North Ninth
Laramie, Wyoming 82070
Phone: (307) 721-2281
FAX: (307) 721-2233
E-mail: *lylej@uwo.edu*

SITE Program
Mr. Richard Eilers
U.S. Environmental Protection Agency
National Risk Management Research Laboratory
26 West Martin Luther King Drive
Cincinnati, Ohio 45268
Phone: (513) 569-7809
FAX: (513) 569-7676
E-mail: *eilers.richard@epamail.epa.gov*

Information on the SITE Program is also available through the following on-line information clearinghouse: the Vendor Information System for Innovative Treatment Technologies (VISITT) Hotline: (800) 245-4505. This database contains information on 154 technologies offered by 97 developers.

Technical reports may be obtained by contacting U.S. EPA/NCEPI, P.O. Box 42419, Cincinnati, Ohio 45242-2419, or by calling (800) 490-9198.

Section 2
Treatment Applications Analysis

This section addresses the general applicability of the CROW process technology to contaminated waste sites. Information presented in this section is intended to assist decision-makers in screening specific technologies for a particular cleanup situation. This section presents the advantages, disadvantages, and limitations of the technology and discusses factors that have a major impact on the performance and cost of the technology. The analysis is based on the demonstration results for the Brodhead Creek site and available information from other applications of the technology, including pilot-scale implementation at the Bell Pole site in New Brighton, Minnesota.

2.1 Key Features of the CROW Process Technology

WRI claims that the CROW process can remove mobile NAPLs from an aquifer, leaving only residual immobile contamination behind. The technology may be used to remove accumulations of NAPL, including coal tar, pentachlorophenol, creosote, and heavy oils. Removal of the NAPL will increase the effectiveness of bioremediation and decrease the time required for treatment of groundwater using conventional pump-and-treat technologies.

The CROW process may be modified to treat any size area by varying the number of injection and recovery wells and adjusting the capacity of the water treatment system. The following information is important for proper design of the CROW process: aquifer hydraulic conductivity, hydraulic gradient, and saturated thickness; contaminant distribution and chemical and physical properties; and the groundwater iron, manganese, and calcium concentrations. Optimum performance can typically be achieved in aquifers with hydraulic conductivities greater than 10^{-3} centimeters per second (cm/sec) and iron concentrations below 2 milligrams per liter (mg/L).

The CROW process recovers more water from the treatment zone than it injects in order to maintain hydraulic containment. The excess water must be treated prior to discharge to a publicly owned treatment works (POTW). Additional treatment will be required to comply with the discharge limits set by the National Pollutant Discharge Elimination System (NPDES) or Safe Drinking Water Act (SDWA). The recovered oil must be disposed of or recycled.

2.2 Technology Applicability

The CROW technology is designed to remove semivolatile organic compounds (SVOC), like coal tar, creosote, and heavy oil, for which viscosity can be reduced and solubility increased by heating. While this technology is designed to remove oily wastes that have a specific gravity greater than water (dense nonaqueous-phase liquids [DNAPL]), it may also be used to remove oily wastes that have a specific gravity less than water (light nonaqueous-phase liquids [LNAPL]).

The types of aquifers for which the CROW process is most effective include those composed of fine sand to cobbles and with hydraulic conductivities greater than 10^{-3} cm/sec. More permeable aquifers allow greater volumes of water to be injected and recovered, resulting in shorter treatment times. Greater groundwater flow rates will increase the rate at which the aquifer can be heated through the injection of hot water and also increase the waste removal efficiency.

2.3 Technology Limitations

Several factors may limit the use of the CROW process. The CROW process will not treat inorganics and may not be applicable to volatile organic compound (VOC) wastes because the injected hot water may cause volatilization of the contaminants in the subsurface or during water storage, treatment, and reinjection. High iron concentrations in the groundwater can result in the production of iron floccules that may clog the injection wells and water treatment system. However, by adjusting the pH of the water recovered from the aquifer and adding a flocculent, the iron may be removed in the production tanks, preventing damage to the injection wells and plugging of the water treatment system.

2.4 Process Residuals

The CROW process generates residuals such as contaminated soil, groundwater, and personal protective equipment (PPE) in addition to the oily waste. Installation of the injection and recovery wells may produce contaminated soil cuttings that require disposal. To maintain hydraulic containment, the CROW process must remove more water from the aquifer than it injects. The excess water contains dissolved contaminants at elevated concentrations that must be removed prior to discharge to most POTWs or before discharge to surface water under a NPDES permit. PPE produced during the installation of the injection and recovery wells and periodically during operation will require disposal. At the Brodhead Creek site, granular activated carbon canisters were used as the final step of water treatment prior to discharge to surface water; these carbon canisters also required disposal when spent.

The recovered oily waste must be disposed of or recycled. Most recovered coal tar or creosote wastes are considered Resource Conservation and Recovery Act (RCRA) hazardous wastes and must be incinerated. The coal tar recovered from the Brodhead Creek site was incinerated. Since the Bell Pole site is an active facility, the recovered creosote was recycled through the treatment process. Heavy petroleum oils that do not contain hazardous constituents may also be recycled.

2.5 Site Support Requirements

The site must be accessible to trucks, drill rigs, and construction equipment and have a location suitable for installation of a tank farm. Access is required to deliver the equipment to the site and for the drilling rigs required to install the system wells. A flat area where the tank farm and secondary containment structure can be constructed must be available. A building for the water treatment system, process controllers, and office is recommended, as are a telephone and security fencing.

Heavy equipment is required to install the injection and recovery wells, build the secondary containment structure and install the process tanks, and to install the process piping and water treatment system. During operation, heavy equipment is required to conduct pump, well, and process system maintenance.

The CROW process requires electricity to operate the pumps and electricity or gas to heat the water. Utility costs at the Brodhead Creek site totaled $60,000, or approximately 3 percent of the overall project cost.

During installation of the injection and recovery wells, a pad and clean water are required to decontaminate the drill rig and equipment. Areas and containers for storing the soil cuttings and PPE waste also should be available.

2.6 Availability and Transportation of Equipment

All the equipment necessary to install and construct the CROW process is conventional and commercially available. Installation of the CROW process includes site grading, drilling of injection and recovery wells, well development, pump installation, construction of the tank farm, construction of the process piping, and installation of the water treatment system. Depending on the size of the system, installation may span 4 to 8 months. At the Brodhead Creek site, the CROW process was installed in 6 months.

Demobilization requires dismantling all the process piping, tanks, and wells; disconnecting the utilities; and returning the tank farm secondary containment area and well field to beneficial use. At some sites, the wells will be abandoned. At the Brodhead Creek site, all the equipment was decontaminated and scrapped and the tank farm secondary containment was removed; however, the wells were not removed.

2.7 Feasibility Study Evaluation Criteria

This section presents an assessment of the CROW process relative to the nine evaluation criteria used for conducting detailed analyses of remedial alternatives in feasibility studies under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (EPA 1988b).

2.7.1 Overall Protection of Human Health and the Environment

The CROW process failed to provide both short- and long-term protection of human health and the environment since it did not remove oily wastes from the subsurface to residual immobile concentrations. The process is intended to increase the mobility of the contamination to enhance removal from the subsurface. Depending on the characteristics of the lower confining unit, the enhanced mobility may result in the spread of contamination. The removal of the waste would prevent further migration, reduce the amount available for dissolution into groundwater, and increase the effectiveness of bioremediation and natural attenuation. The oily waste is pumped from the subsurface, separated from the groundwater, and stored in a tank prior to final disposal or recycling. The groundwater that is reinjected into the subsurface passes through separation tanks and is therefore of better quality than the groundwater. The RCRA land disposal restriction (LDR) issues are discussed in Section 2.8.2 and the SDWA injection well issues are discussed in Section 2.8.4. The excess water is treated before it is discharged.

Worker exposure to oily waste and contaminated groundwater is limited. The groundwater is contained in pipes for the entire process circuit. The oily waste is stored in a tank before it is transported off site for disposal or recycling. Workers could potentially be exposed during waste transfer.

2.7.2 Compliance with Applicable or Relevant and Appropriate Requirements

General and specific ARARS identified for the CROW process are presented in Section 2.8. Compliance with chemical-, location-, and action-specific ARARs should be determined on a site specific basis; however, location- and action-specific ARARs are generally achieved. Compliance with chemical-specific ARARs depends on (1) the ability of the CROW process to remove the specific chemical from the subsurface, and (2) effectiveness of the water treatment system in treating water prior to discharge. Chemical-specific ARARs for the storage, transportation, and disposal of the oily wastes are generally achieved.

2.7.3 Long-Term Effectiveness and Permanence

The CROW process failed to provide effective long-term remediation of NAPL in aquifers since it did not remove oily wastes in the aquifer to residual immobile concentrations. The CROW process is not designed to restore aquifer water quality and will not remediate contaminants dissolved in groundwater. However, removal of the oily waste with the CROW process will increase the subsequent effectiveness of bioremediation, pump-and-treat, and natural attenuation of the aquifer.

2.7.4 Reduction of Toxicity, Mobility, or Volume Through Treatment

The CROW process reduces the mobility and volume of waste in the treatment area. The CROW process reduces the volume of the contaminants by removing oily wastes from the subsurface. The oily waste is then recycled or destroyed. After treatment, the toxicity of the residual subsurface oily wastes to indigenous microorganisms is reduced, facilitating natural or enhanced bioremediation of the remaining contamination. The CROW process reduces the mobility of the oily waste by removing the mobile fraction of the oily wastes in the aquifer. At the Brodhead Creek site, oily wastes were measured in two wells after the process run indicating that the amount of coal tar in the aquifer had not been reduced to residual immobile levels.

Treatment of the excess process water prior to discharge reduces the volume and toxicity of contaminants dissolved in the groundwater. Within the treatment area, the CROW process prevents the downgradient migration of dissolved contamination while the process is operating. After the CROW process is complete, however, dissolved contaminants may resume downgradient migration.

2.7.5 Short-Term Effectiveness

The CROW process starts to remove oily waste from the aquifer as soon as it starts operation. It also starts to remove dissolved contaminants from the excess process water. One potential short-term impact is that groundwater flow paths in the aquifer are changed once the system begins operation. This change may result in a short-term increase in the concentration of dissolved contaminants within and adjacent to the treatment area.

2.7.6 Implementability

The CROW process can be implemented at any site that can be reached by the equipment necessary to install the injection and recovery wells and construct the tank farm. Electricity is also required to operate the pumps, water heater, and process control system. The equipment necessary to construct and operate the CROW process is commercially available throughout the industrialized world.

Personnel required to install the CROW process include drillers, plumbers, electricians, pipe fitters, and heavy equipment operators. The CROW process may be routinely operated by a trained field technician. Changes in the operational parameters like pumping rates and the temperature of the injected water should be completed under the direction of the project engineer. Services and supplies necessary to operate the CROW process include laboratory analysis to monitor system performance, transportation and disposal of oily waste, and regeneration or disposal of granular activated carbon.

2.7.7 Cost

A complete analysis of costs to install and operate the CROW process at the Brodhead Creek Superfund site is presented in Section 3. The total cost of the Brodhead Creek site interim removal action was $2,168,000. A total of 25.5 pore volumes were flushed through the treatment area during operation. The total cost per pore volume was $85,000. None of the costs have been adjusted for inflation.

Several problems were encountered with the injection wells, water heater, and water treatment system. Some of the problems were caused by site-specific factors like the shallow depth to groundwater and the high iron content of the groundwater. Other costs incurred at the Brodhead Creek site may be eliminated at other sites through system design. For example, the stability of the emulsion formed when the coal tar passed through the extraction well pump was unexpected, and extra costs were incurred to redesign the system to break down the emulsion. Another example was the problems caused by the iron flocculant. The iron floc irreparably damaged the injection wells and may be the primary reason the design pumping rates were never achieved. When necessary, an iron removal system can be incorporated into the original design, thus preventing the redesign costs and increased system maintenance costs.

2.7.8 State Acceptance

State acceptance is anticipated to be favorable because the CROW process is one of the few technologies available to remove oily wastes from the subsurface. State acceptance at the Brodhead Creek site was contingent upon meeting the discharge requirements of a NPDES permit for the water discharged to Brodhead Creek. If remediation is conducted as part of RCRA corrective actions, state regulatory agencies may require a NPDES permit, permits for operation, and a permit to store hazardous waste in the recovered oil tank for longer than 90 days.

2.7.9 Community Acceptance

Community acceptance is anticipated to be favorable because the CROW process does not impact the community after the initial construction. Sites that have significant accumulations of oily wastes are usually industrial and the noise and traffic impacts of site construction are not unusual. At the Brodhead Creek site, the community expressed few comments during the public comment period and the community reaction was favorable.

2.8 Technology Performance Versus ARARs

This section discusses specific federal regulatory requirements pertinent to the CROW process, storage of oily wastes, and disposal of excess process water. Specific regulations that apply to a particular remediation activity depend on the type of remediation site and the type of waste recovered. Table 2-1 provides a summary of regulations discussed in this section. Remedial project managers will have to address federal requirements, along with state and local regulatory requirements, which may be more stringent.

2.8.1 Comprehensive Environmental Response, Compensation, and Liability Act

CERCLA, as amended by SARA, authorizes the federal government to respond to releases or potential releases of any hazardous substances into the environment, as well as to releases of contaminants that may present an imminent or significant danger to public health and welfare or the environment. Remedial alternatives that significantly

Table 2-1. Federal and State ARARs

Process Activity	ARAR	Description	Reason CROW Process is Subject to ARAR	Requirements
Remediate contaminated groundwater	SDWA 40 CFR Parts 14 through 149 or state equivalent	Establishes drinking water quality standards for public drinking water supplies.	The groundwater may be used as a source of drinking water.	Additional treatment must occur until cleanup standards are met.
Waste characterization (untreated waste)	RCRA 40 CFR Part 261, Subparts C and D or state equivalent	Identifies whether the waste is a listed or characteristic waste.	A RCRA requirement prior to managing and handling the waste.	Chemical and physical analyses must be performed.
Waste processing	RCRA 40 CFR Parts 264 and 265 or state equivalent	Identifies standards applicable to the treatment of hazardous waste at permitted and interim status facilities.	Hazardous waste must be treated in a manner that meets certain design, operating, and monitoring requirements; the CROW treatment process may be considered a miscellaneous unit.	Equipment must be operated daily. The CROW process system must be designed, monitored, and maintained to prevent leakage or failure; the tanks and equipment must be decontaminated when processing is complete.
Waste characterization (treated waste, process water, and spent granular activated carbon)	RCRA 40 CFR Part 261 or state equivalent	Identifies whether the waste is a listed or characteristic waste.	A RCRA requirement prior to managing and handling the waste; all residual wastes generated by the system must be determined if they are RCRA hazardous.	Chemical tests must be performed on treated waste and process water prior to discharge to surface water, a POTW, or prior to off-site disposal. The spent granular activated carbon is considered a hazardous waste if it is derived from treatment of a listed hazardous waste, such as K147 and K148.
Storage after processing	RCRA 40 CFR Parts 264 and 265 or state equivalent	Standards that apply to the storage of hazardous waste in tanks or containers.	If recovered oil and process water stored in tanks is considered hazardous, requirements for storage of hazardous waste in tanks may apply. Spent granular activated carbon may be handled as hazardous if derived from the treatment of a RCRA hazardous waste.	The recovered oil, process water, and spent granular activated carbon must be stored in tanks or containers that are well maintained; the container storage area must be constructed to control runon and runoff.

Table 2-1. Federal and State ARARs (continued)

Process Activity	ARAR	Description	Reason CROW Process is Subject to ARAR	Requirements
On-site disposal	RCRA 40 CFR Part 264 or state equivalent	Standards that apply to incineration and landfilling hazardous waste.	Recovered oil will likely be handled as a RCRA hazardous waste. Spent granular activated carbon may need to be managed as a hazardous waste if it is derived from treatment of hazardous waste.	If wastes are disposed of onsite, the design, construction, and operation of those disposal units must meet applicable RCRA standards.
On-site/off-site disposal	RCRA 40 CFR Part 268 or state equivalent	Standards that restrict the placement of certain hazardous wastes in or on the ground (i.e, land disposal), unless the hazardous waste meets applicable treatment standards.	The hazardous waste to be treated by the CROW process may be subject to the LDRs.	The waste must be characterized to determine if the LDRs apply; treated wastes must be tested and the results compared to applicable treatment standards prior to land disposal.
Transportation for off-site disposal	RCRA 40 CFR Part 262 or state equivalent	Manifest requirements and packaging and labeling requirements prior to transport.	Recovered oil will likely be a hazardous waste and require a manifest for off-site shipment. This may also apply to spent granular activated carbon if it is derived from treatment of hazardous waste.	An identification number must be obtained from EPA. A hazardous waste manifest must be used.
	RCRA 40 CFR Part 263 or state equivalent	Transportation standards.	Recovered oil will likely be a hazardous waste and require a manifest off-site shipment. This may also apply to spent granular activated carbon if it is derived from treatment of hazardous waste.	A transporter licensed by EPA must be used to transport the hazardous waste according to EPA regulations.
	RCRA 40 CFR Part 268 or state equivalent	LDR tracking requirements.	Recovered oil will likely be a hazardous waste and require an LDR notice and certification (if oil meets LDR treatment standards) in addition to the manifest. This may also apply to spent granular activated carbon if it is derived from treatment of hazardous waste.	A one-time LDR notice and certification (if waste meets LDR treatment standards) must be sent to disposal facility.

Table 2-1. Federal and State ARARs (continued)

Process Activity	ARAR	Description	Reason CROW Process is Subject to ARAR	Requirements
Wastewater injection	SDWA 40 CFR Parts 144 and 145	Standards that apply to the disposal of contaminated water in underground injection wells.	Treated groundwater will be reinjected into the aquifer.	If the technology is defined as underground injection and the treated groundwater still contains hazardous constituents, a waiver from EPA or the state will likely be required.
Discharge of water	CWA 40 CFR Parts 122 through 125, Part 403	Standards that apply to the discharge of water to a surface water body or a POTW.	Treated water, purge water, and decontamination water may be discharged to a surface water body or a POTW. If treated water is discharged to an off-site surface water body, a NPDES-equivalent permit may be required and permit levels must be achieved.	An NPDES permit is not required if treated water is discharged to an on-site surface water body, which may be considered further treatment. Compliance with substantive and administrative requirements of the national pretreatment program is required when treated water is discharged off site or to a POTW.
Air emissions from the system	CAA or state equivalent; RCRA 40 CFR Parts 264 and 265, Subparts AA, BB, and CC; State Implementation Plan; OSWER Directive 9355.0-28	Regulated air emissions that may impact attainment of ambient air quality standards. RCRA air emission standards are applicable only if waste contains VOCs above specified standards.	The CROW process technology usually incorporates carbon filtration of the gases as part of the treatment system. Treated air is emitted to the atmosphere.	Treatment of the contaminated air must adequately remove contaminants so that air quality is not impacted.

reduce the volume, toxicity, or mobility of hazardous materials and provide long-term protection are preferred. Selected remedies must also be cost effective and protect human health and the environment.

Contaminated water is treated on site, while residual wastes generated during the installation, operation, and monitoring of the system may be treated either on or off site. CERCLA requires identification and consideration of environmental laws that are ARARs before implementation of a remedial technology at a Superfund site. CERCLA requires that on-site actions meet all substantive federal and state ARARs. Substantive requirements pertain directly to actions or conditions in the environment (such as groundwater effluent and air emission standards). Off-site action must comply with both legally applicable substantive and administrative ARARs. Administrative requirements, such as permitting, facilitate the implementation of substantive requirements.

ARARs are determined on a site-by-site basis and may be waived under six conditions: (1) the action is an interim measure, and the ARAR will be met at completion; (2) compliance with the ARAR would pose a greater risk to health and the environment than noncompliance; (3) it is technically impracticable to meet the ARAR; (4) the standard of performance of an ARAR can be met by an equivalent method; (5) a state ARAR has not been consistently applied elsewhere; and (6) fund balancing where ARAR compliance would entail such cost in relation to the added degree of protection or reduction of risk afforded by that ARAR that remedial action at other sites would be jeopardized. These waiver options apply only to Superfund actions taken on site, and justification for the waiver must be clearly demonstrated. Off-site remediations are not eligible for ARAR waivers, and all substantive and administrative applicable requirements must be met.

For the CROW process, soil cuttings, treated groundwater, and recovered oily waste are the primary residual wastes generated from installing and operating the treatment system. During the SITE demonstration, spent granular activated carbon was also generated from the treatment of process water prior to discharge to Brodhead Creek. Given the waste types typically generated by the CROW process the following regulations pertinent to the CROW process were identified: (1) RCRA, (2) the Clean Water Act (CWA), (3) SDWA, (4) the Clean Air Act (CAA), and (5) the Occupational Safety and Health Act (OSHA). These five regulatory authorities are discussed below. Specific ARARs under these acts that are applicable to the CROW process site demonstration are presented in Table 2-1.

2.8.2 Resource Conservation and Recovery Act

RCRA, as amended by the Hazardous and Solid Waste Amendments of 1984 (HSWA), established separate regulatory programs for the identification, management, and disposal of solid and hazardous wastes (Subtitles D and C of RCRA, respectively). Federal regulations implementing the RCRA hazardous waste management program are set forth under Title 40 of the Code of Federal Regulations (CFR) Parts 260-279. The EPA and state programs authorized under RCRA (authorized states are listed in 40 CFR Part 272) implement and enforce RCRA regulations.

In general, hazardous waste regulations under RCRA are ARARs at CERCLA response actions because the response involves the generation and management of hazardous substances that also are considered RCRA hazardous wastes. The specific applicability of RCRA regulations depends on whether wastes generated and managed at the site are identified as hazardous waste. The definition of hazardous waste is set forth under 40 CFR 261.3, and include those wastes that are listed or exhibit characteristics of hazardous waste. Listed hazardous wastes from nonspecific and specific industrial sources, off-specification products, spill cleanups, and other industrial sources are itemized in 40 CFR Part 261, Subpart D. Criteria for identifying characteristic hazardous wastes are included in 40 CFR Part 261, Subpart C. In general, wastes identified as hazardous under RCRA are subject to specific management standards unless they qualify for special exemptions.

Under CERCLA response actions, on-site activities must only meet the substantive requirements of RCRA (for example, design and performance standards for storage tanks) and not administrative requirements, such as application and receipt of a RCRA permit. For example, tank storage of oily waste or groundwater considered a hazardous waste must meet the design and operating requirements of 40 CFR Part 264, Subpart J. However, all off-site activities, such as the disposal of hazardous wastes at a commercial disposal facility, are subject to all applicable RCRA requirements. In addition, the off-site disposal of all CERCLA waste (that is, those wastes generated during responses taken under CERCLA authority) are subject to special National Contingency Plan (NCP) provisions (that is, the CERCLA "Off-site Rule" [40 CFR 300.440]).

Subtitle C of RCRA also established a corrective action program for RCRA-regulated treatment, storage, and disposal facilities (TSDF) that have releases of hazardous waste or hazardous constituents to the environment. The RCRA corrective action program is implemented through enforcement (that is, administrative or civil orders) and RCRA permitting requirements. The CROW process may be used to clean up releases that are addressed under the RCRA corrective action program. Under the RCRA corrective action program, the CROW process may qualify as a temporary unit (40 CFR 264.553).

Pertinent RCRA requirements to the design and operation of the CROW process are discussed below. Those requirements are explained in the context of ARARs for cleanups conducted under CERCLA response authorities.

Implementation of the CROW process involves extraction, treatment, and disposal of contaminated groundwater and generation of process residuals, such as drill cuttings, recovered oil, and spent carbon filters. Under RCRA, a "generator" is defined as "any person, by site, whose act or process produces hazardous waste..., or whose act first causes a hazardous waste to become subject to regulation" (40 CFR 260.10). Thus, a person who extracts contaminated groundwater for treatment and disposal or produces waste from the treatment of contaminated groundwater will be considered a "generator" under RCRA.

Under 40 CFR 262.11, a generator must determine if the waste it produces is hazardous. In general, this regulation requires the generator to determine if the waste is a listed hazardous waste or exhibits characteristics of hazardous waste (Note: contaminated groundwater and other contaminated environmental media may be determined to "contain" a listed waste under EPA's "contained-in policy" [May 26, 1998 Federal Register - 63 FR 28621]). Operation of the CROW process generates contaminated groundwater, recovered oily waste, spent granular activated carbon (if used), and possibly contaminated soil cuttings generated during the installation, operation, and monitoring of the treatment system. All wastes generated by the installation and operation of the CROW process must be evaluated to determine whether they are hazardous waste. For example, contaminated groundwater at wood preservation sites may be considered to contain the RCRA hazardous waste K001 or possibly exhibit the RCRA characteristic of toxicity under 40 CFR 261.24.

RCRA recognizes different categories of generators, and corresponding levels or regulatory requirements, depending on the amount of hazardous waste produced in a calendar month. For purposes of this section, it is assumed that application of the CROW process generates more than 1000 kilograms per month (kg/mo) of hazardous waste, and therefore the generator is considered a "large quantity generator."

The requirements for hazardous waste generators are specified under 40 CFR Part 262. For those activities that occur on site (that is, within the property or area that is contaminated), the applicable generator requirements may include standards for accumulating hazardous waste under 40 CFR 262.34. The 40 CFR 262.34 standards apply to the short-term accumulation (less than 90 days) of hazardous waste in tanks and containers. The regulations require the person to prepare a contingency plan, provide personnel training, and undertake preparedness and prevention measures. The requirements in 40 CFR 262.34 also specify that the design and operation of container storage areas or tank systems must meet the corresponding requirements under 40 CFR Part 265, Subparts I and J, respectively. For example, the CROW process uses tank systems and those systems must meet requirements for secondary containment, leak detection, and other standards for tank systems specified under 40 CFR part 265, Subpart J. In addition, if the waste managed in those tanks contains VOCs above certain concentrations, the containers and tank systems may be subject to air emission requirements under 40 CFR Part 265, Subparts BB and CC (the requirements of Subparts BB and CC are discussed in more detail later in this section).

The generator requirements under 40 CFR Part 262 also apply to certain off-site activities. For example, if the recovered oil or spent carbon adsorption filters are hazardous waste and are shipped off site to a hazardous waste disposal facility, the waste must be manifested and prepared for transport in accordance with 40 CFR 262, Subpart B. The transporter must meet the requirements under 40 CFR Part 263. Use of the manifest requires that the generator obtain an EPA identification number. If the cleanup involving the CROW process is conducted under

CERCLA authority, an EPA identification number under 40 CFR Part 262 is required. In addition, all hazardous waste transported off site is subject to applicable requirements of the land disposal restriction (LDR) program, including the LDR treatment standards and LDR-specific tracking requirements under 40 CFR Part 268.

If site conditions dictate that hazardous waste must be stored for more than 90 days when using the CROW process, the requirements for owners or operators of TSDFs become applicable to the management of hazardous waste. Those requirements are specified in 40 CFR Parts 264 and 265. In general, the standards applicable to the management of hazardous waste stored in tanks or containers for more than 90 days are similar to those under 40 CFR 262.34, with the added requirements that the generator must prepare a waste analysis plan and closure plan.

Use of the CROW process would constitute "treatment" of hazardous waste if contaminated groundwater is considered a hazardous waste (see definition of "treatment" under 40 CFR 260.10). However, the CROW system primarily consists of tank or tank-like structures, and under RCRA, the design and operation of those tanks will likely be subject to 40 CFR Parts 264 or 265, Subpart J. Under Subpart J, the design and operating standards for tank systems do not distinguish whether treatment or storage occurs in the tanks (that is, there is no appreciable difference in the design and operating standards under 40 CFR Part 264, Subpart J for tank systems used to treat or store hazardous waste). Because treatment occurs, however, additional RCRA requirements, such as the preparation of a waste analysis plan, will be required. If the waste contains VOCs, air emission regulations under RCRA will be applicable.

Although the CROW process primarily consists of tanks and wells, the process may be considered a "miscellaneous unit" under RCRA. EPA has established design, operating, and performance standards for miscellaneous units under 40 CFR Part 264, Subpart X. If the process is considered subject to Subpart X standards, site-specific standards for treatment performance and monitoring may be applied in addition to the relevant RCRA requirements for design and operation of tank systems.

Air emissions from operation of the CROW process are subject to RCRA regulations on air emissions from hazardous waste treatment, storage, or disposal operations, as addressed in 40 CFR Parts 264 and 265, Subparts BB and CC. Subpart BB regulations apply to fugitive emissions, such as equipment leaks, from hazardous waste TSDFs that treat waste containing organic concentrations of at least 10 percent by weight. These regulations address pumps, compressors, open-ended valves or lines, and flanges. Any organic air emissions from storage tanks would be subject to the RCRA organic air emission regulations in 40 CFR Parts 264 and 265, Subpart CC. These regulations address air emissions from hazardous waste TSDF tanks, surface impoundments, and containers. The Subpart CC regulations were issued in December 1994 and became effective in July 1995 for facilities regulated under RCRA. EPA is currently deferring application of the Subpart CC standards to waste management units used solely to treat or store hazardous waste generated on site from remedial activities required under RCRA corrective action or CERCLA response authorities (or similar state remediation authorities). Therefore, Subpart CC regulations would not immediately impact implementation of the CROW process. The RCRA air emission standards are applicable to treatment, storage, or disposal units subject to the RCRA permitting requirements of 40 CFR Part 270 or hazardous waste recycling units that are otherwise subject to the permitting requirements of 40 CFR Part 270. However, the most important air requirements are probably associated with the CAA and state air toxic programs (Section 2.8.5).

The CROW process uses wells to reinject treated groundwater to the aquifer. Under RCRA, use of the injection wells is considered disposal; therefore, the reinjection of contaminated groundwater may potentially be subject to the LDR program under 40 CFR Part 268. (Note: injection wells also are subject to the provisions of the SDWA discussed later in this section). However, there are statutory and regulatory provisions that waive or otherwise exempt the reinjection of contaminated groundwater from compliance with LDRs. Section 3020(b) of RCRA provides a statutory waiver, and may likely apply to most scenarios where the CROW process is used. In all the scenarios where a statutory or regulatory waiver from LDRs is sought, however, the contaminated water must be (1) withdrawn and reinjected into the same aquifer, and (2) managed as part of on-site cleanup operations (such as free phase recovery operations or remedial actions under CERCLA and RCRA cleanup authorities).

Under 40 CFR Parts 264 and 265, Subpart F, owners or operators of land disposal units (that is, TSDFs that operate landfills, surface impoundments, waste piles, and land treatment units) are subject to groundwater monitoring requirements. The requirements in 40 CFR 264.100 establish a corrective action program for releases of hazardous constituents from those land disposal units that exceed the levels specified by the Groundwater Protection Standard or set by the regulatory authority for the facility. Those requirements may be considered ARARs for the cleanup of sites under the CERCLA program. Water quality standards under the CWA and the SDWA also may be appropriate cleanup standards and apply to discharges of treated water. The applicable provisions of the CWA and SDWA are discussed below.

2.8.3 Clean Water Act

The CWA is designed to restore and maintain the chemical, physical, and biological quality of navigable surface waters by establishing federal, state, and local discharge standards. Treated water, purge water, and decontamination water generated from the system and during monitoring of the system may be regulated under the CWA if it is discharged to surface water bodies or a POTW. On-site discharges to surface water bodies must meet substantive NPDES requirements, but do not require a NPDES permit. A direct discharge of CERCLA wastewater qualifies as "on site" if the receiving water body is in the area of contamination or in very close proximity to the site, and if the discharge is necessary to implement the response action. Off-site discharges to a surface water body require a NPDES permit and must meet NPDES permit limits. Discharge to a POTW is considered an off-site activity, even if an on-site sewer is used. Therefore, compliance with the substantive and administrative requirements of the national pretreatment program is required. General pretreatment regulations are included in 40 CFR Part 403. Any local or state requirements, such as state antidegradation requirements, must also be identified and satisfied.

Any applicable local or state requirements, such as local or state pretreatment requirements or water quality standards (WQS), must also be identified and satisfied. State WQSs are designed to protect existing and attainable surface water uses (for example, recreational and public water supply). WQSs include surface water use classifications and numerical or narrative standards (including effluent toxicity standards, chemical-specific requirements, and bioassay requirements to demonstrate no observable effect level from a discharge) (EPA 1988b). These standards should be reviewed on a state- and location-specific basis before discharges are made to surface water bodies. Bioassay tests may be required if the CROW process is implemented in particular states and if it discharges treated water to surface water bodies.

2.8.4 Safe Drinking Water Act

The SDWA, as amended in 1986, requires EPA to establish regulations to protect human health from contaminants in drinking water. The legislation authorizes national drinking water standards and a joint federal-state system for ensuring compliance with these standards. The SDWA also regulates underground injection of fluids as well as sole-source aquifer and wellhead protection programs.

The National Primary Drinking Water Standards are found in 40 CFR Parts 141 through 149. SDWA primary or health-based, and secondary or aesthetic, maximum contaminant levels (MCL) will generally apply as cleanup standards for water that is, or may be, used for drinking water supply. In some cases, such as when multiple contaminants are present, more stringent maximum contaminant level goals (MCLG) may be appropriate. In other cases, alternate concentration limits (ACL) based on site-specific conditions may be used. CERCLA and RCRA standards and guidance should be used in establishing ACLs (EPA 1987). During the demonstration, CROW process discharge water was tested for compliance with SDWA MCLs.

The reinjection of treated water into an aquifer by the CROW process may be interpreted by federal or state agencies as underground injection since treated water is placed into the subsurface. If this interpretation is applied, the water reinjected by the CROW process will be regulated by the underground injection control program found in CFR 40 Parts 144 and 145. Injection wells are categorized in Classes I through V, depending on their construction and use. Reinjection of treated water involves Class IV (reinjection) or Class V (recharge) wells and should meet requirements for well construction, operation, and closure. If after treatment the groundwater is still a characteristic hazardous waste, its reinjection into the upper portion of the aquifer would be subject to 40 CFR Part 144.13, which prohibits Class IV wells. However, 40 CFR Part 144.13(c) provides an exemption to the prohibition for reinjecting treated groundwater into the same formation from where it was drawn.

Technically, groundwater pumping wells used in conjunction with the CROW process technology could be considered Class IV wells because of the following definition found in 40 CFR Part 144.6(d):

> "(d) Class IV. (1) Wells used by generators of hazardous waste or of radioactive waste, by owners or operators hazardous waste management facilities, or by owners or operators of radioactive waste disposal sites to dispose of hazardous waste or radioactive waste into a formation which within one-quarter (1/4) mile of the well contains an underground source of drinking water.
>
> (2) Wells used by generators of hazardous waste or of radioactive waste, by owners or operators of hazardous waste management facilities, or by owners or operators of radioactive waste disposal sites to dispose of hazardous waste or radioactive waste above a formation which within one-quarter (1/4) mile of the well contains an underground source of drinking water.
>
> (3) Wells used by generators of hazardous waste management facilities to dispose of hazardous waste, which cannot be classified under paragraph (a)(1) or(1) and (2) of this section (e.g., wells used to dispose of hazardous waste into or above a formation which contains an aquifer which has been exempted pursuant to 146.04)."

The sole-source aquifer protection and wellhead protection programs are designed to protect specific drinking water supply sources. If such a source is to be remediated using the CROW process, appropriate program officials should be notified, and any potential regulatory requirements should be identified. State groundwater antidegradation requirements and WQSs may also apply.

2.8.5 Clean Air Act

EPA has developed a guidance document for control of emissions from air stripper operations at CERCLA sites. This document, entitled "Control of Air Emissions from Superfund Air Strippers at Superfund Groundwater Sites" (EPA 1989a), provides information relevant to vented gases from the CROW process system. The EPA guidance suggests that the sources most in need of control are those with an actual emissions rate of total VOCs in excess of 3 pounds per hour, or 15 pounds per day, or a potential (calculated) rate of 10 tons per year (EPA 1989a). Based on air analysis from the demonstration, vapor discharges from the CROW process system would be required to pass through carbon filters to comply with EPA guidance. The 1990 amendments to the CAA establish primary and secondary ambient air quality standards for protection of public health as well as emission limitations for certain hazardous air pollutants. Permitting requirements under the CAA are administered by each state as part of State Implementation Plans developed to bring each state into compliance with National Ambient Air Quality Standards (NAAQS). The ambient air quality standards for specific pollutants apply to the operation of the CROW process system because the technology ultimately results in an emission from a point source to the ambient air. Allowable emission limits for operation of a CROW process system will be established on a site-by-site basis depending on the type of waste treatment and whether or not the site is in an attainment area of the NAAQS. Allowable emission limits may be set for specific hazardous air pollutants, particulate matter, hydrogen chloride, or other pollutants. A local or State Implementation Plan may include specific standards to control air emissions of VOCs in ozone nonattainment areas. Typically, an air abatement device such as a carbon adsorption unit will be required to remove VOCs from the CROW process system process air stream before discharge to the ambient air.

The ARARs pertaining to the CAA can only be determined on a site-by-site basis. Remedial activities involving the CROW process technology may be subject to the requirements of Part C of the CAA for the prevention of significant deterioration (PSD) of air quality in attainment (or unclassified) areas. The PSD requirements apply when the remedial activities involve a major source or modification as defined in 40 CFR 52.21. Activities subject to PSD review must ensure application of the best available control technologies and demonstrate that the activity will not adversely impact ambient air quality.

2.8.6 Occupational Safety and Health Act Requirements

CERCLA remedial actions and RCRA corrective actions must be performed in accordance with OSHA requirements detailed in 20 CFR Parts 1900 through 1926, especially

Part 1910.120, which provides for the health and safety of workers at hazardous wastes sites. On-site construction activities at Superfund or RCRA corrective action sites must be performed in accordance with Part 1926 of OSHA, which provides safety and health regulations for construction sites. For example, electric utility hookups for the CROW process system must comply with Part 1926, Subpart K, Electrical. State OSHA requirements, which may be significantly stricter than federal standards, must also be met. In addition, health and safety plans for site remediations should address chemicals of concern and include monitoring practices to ensure that worker health and safety are maintained.

All technicians operating the CROW process system are required to complete an OSHA training course and must be familiar with all OSHA requirements relevant to hazardous waste sites. For most sites, minimum PPE for technicians will include gloves, hard hats, steel-toed boots, and coveralls. Depending on the contaminant types and concentrations, and specific operational activities, additional PPE may be required. Noise levels should be monitored to ensure that workers are not exposed to noise levels above 85 decibels (dBA) average over an 8-hour day as measured on the A-weighted scale.

Section 3
Economic Analysis

This economic analysis presents the actual costs for using the CROW process technology to remove organic contaminants from the subsurface at the Brodhead Creek Superfund Site. Cost data associated with the CROW process SITE demonstration were compiled and provided in August 1998 by ReTeC (1998). ReTeC was the consultant for Pennsylvania Power and Light (PP&L) that directed site activities. ReTec provided cost data for 12 cost categories, but did not provide any additional breakdown or documentation of the costs. The basis for each cost could not be independently verified and the costs probably represent expenditures that occurred from 1991 through 1996. Therefore, the cost figures are assumed to represent 1996 dollars and have an expected accuracy range of ±10 percent of actual costs.

Costs were organized under 12 categories applicable to typical cleanup activities at Superfund and RCRA sites (G. Evans 1990). A detailed analysis of costs within each of these 12 categories could not be completed; rather a summary of these costs provided by ReTeC is presented below.

This section introduces the economic analysis (Section 3.1), and summarizes, by cost category, the actual costs associated with using the CROW process technology at the Brodhead Creek site (Section 3.2). The section also discusses the major issues involved in this analysis and the variables that may affect costs at other sites (Section 3.3), and presents conclusions derived from the economic analysis (Section 3.4).

3.1 Introduction

Information collected from the SITE demonstration forms the basis of this economic analysis. Typically, a SITE demonstration is conducted over a relatively brief time frame (on the order of weeks) and the economic analysis is used to project costs for the full-scale implementation of the technology at other sites. In this instance, however, the SITE demonstration of the CROW process technology at the Brodhead Creek site was a full-scale remediation effort lasting about 20 months. Thus, the economic analysis focuses on presenting the actual costs of the full-scale implementation of the CROW process at the Brodhead Creek site and attempts to identify those variables that may affect the cost of implementing this technology at other sites.

3.2 Cost Categories

Cost data associated with the CROW process were grouped into the following cost categories: (1) site preparation, (2) permitting and regulatory, (3) mobilization and startup, (4) equipment, (5) labor, (6) supplies, (7) utilities, (8) effluent treatment and disposal, (9) residual waste shipping and handling, (10) analytical services, (11) equipment maintenance, and (12) site demobilization. The basis of each cost category is the treatment system demonstrated at the Brodhead Creek site. Specific items presented for each cost category are based on discussions with ReTeC (1998) about the content of each cost category. Table 3-1 and Figure 3-1 present cost breakdowns under the 12 cost categories.

3.2.1 Site Preparation

Site preparation costs typically include administrative, treatment area preparation, treatability study, and system design costs. Site preparation administrative costs include project work plan development, legal searches, access right determinations, and other site planning and design activities. Treatment area preparation can include construction costs associated with site improvements necessary to support the treatment systems. These costs can include building construction, utility improvements, and equipment installation costs.

Table 3-1. Costs Associated with the CROW Process Technology at the Brodhead Creek Superfund Site

Cost Category[a]	Total
Site Preparation	$ 675,000
Permitting and Regulatory Requirements	$ 251,000
Mobilization and Startup	$ 60,000
Equipment	$ 250,000
Labor	$ 275,000
Supplies	$ 95,000
Utilities	$ 60,000
Effluent Treatment and Disposal	$ 70,000
Residual Waste Shipping and Handling	$ 45,000
Analytical Services	$ 105,000
Maintenance	$ 190,000
Site Demobilization	$ 92,000
Total Costs	$2,168,000
Remediation Unit Cost:	
Total Costs	$2,168,000
Number of Pore Volumes Flushed	25.5
Pore Volume Size	455,000 gallons
Cost per Pore Volume	$ 85,000

Notes:

[a] All costs are in July 1996 dollars and are rounded to the nearest $1000.

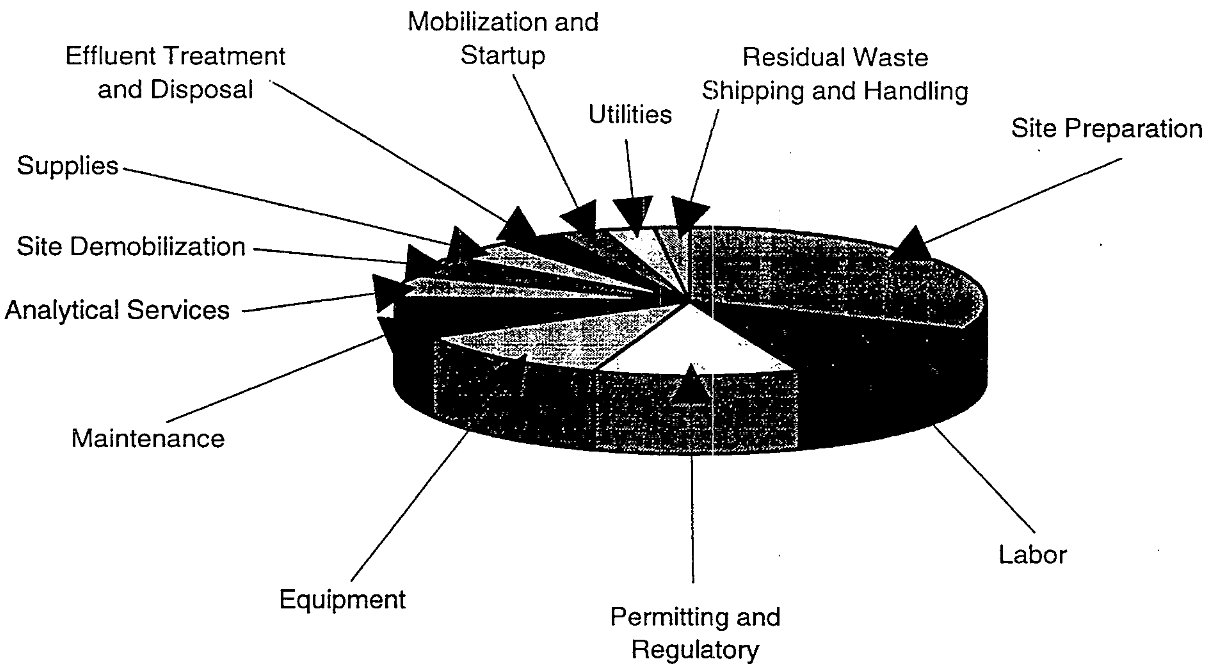


Figure 3-1. Distribution of CROW process demonstration costs for the Brodhead Creek Superfund site.

At the Brodhead Creek site, site preparation included site grading, constructing a concrete pad for the treatment building, erecting the treatment building, installing pipes, constructing the tank farm, installing electric wells, installing and connecting transformers for a water heater, installing the granular activated carbon-fluidized bed reactor (GAC-FBR), installing the water heater, installing the data acquisition system, and system testing. The cost for site preparation at the Brodhead Creek site was $675,000, or approximately 30 percent of the total project cost.

3.2.2 Permitting and Regulatory

Permitting and regulatory costs depend on whether treatment is performed at a Superfund or a RCRA corrective action site and how treated effluent and any solid wastes are disposed of. Superfund site remedial actions must be consistent with ARARs that include environmental laws, ordinances, regulations, and statutes, including federal, state, and local standards and criteria. Remediation at RCRA corrective action sites requires additional monitoring and recordkeeping, which can increase base regulatory costs by 5 percent. In general, ARARs must be determined on a site-specific basis.

Most permits that may be required for the CROW process system are based on local regulatory agency requirements and treatment goals for a particular site. At most sites, the CROW process requires more volume to be extracted than reinjected in the treatment area to provide hydraulic balance and containment. Therefore, treatment and discharge of some process water to a surface water body under a NPDES permit will typically be required. The cost of this permit is based on regulatory agency requirements and treatment goals for a particular site.

At the Brodhead Creek site, permitting and regulatory costs included obtaining a NPDES-equivalent permit for discharge to Brodhead Creek, waste disposal, and changes to the system design and operation necessitated by regulatory requirements. These changes to the system design and operation included modifications to tank sizes, piping configurations, tank farm specifications, operation time frames, and pumping rates. The cost associated with permitting and regulatory requirements at this site was $251,000, or approximately 12 percent of the total project costs.

3.2.3 Mobilization and Startup

Mobilization and startup costs typically include the costs of transporting systems to the site, mobilizing operations personnel to the site, system assembly, and performing the initial shakedown of the treatment system. Initial operator training and health and safety training may be included depending on site-specific requirements.

At the Brodhead Creek site, mobilization and startup costs included mobilization and startup labor, materials for system modifications and upgrades, chemicals, utilities, equipment rentals and services. Services also included crane service, electricians, plumbers and other crafts. Mobilization and startup costs totaled $60,000, or approximately 3 percent of the total project costs.

3.2.4 Equipment

Equipment costs typically include the costs of purchasing the treatment system components, rented support equipment, and rented auxiliary equipment.

At the Brodhead Creek site, equipment included tanks (approximately $35,000), pumps (approximately $10,000), well materials, electrical wire and components, piping, data acquisition equipment (including computer and associated wiring and electronic sensors), the treatment building, water heater, carbon adsorption system, and the chemical injection system. The cost of equipment was $250,000, or approximately 12 percent of the total project cost.

3.2.5 Labor

Labor costs include all labor necessary for operations after the shakedown period is completed through completion of the project. At the Brodhead Creek site, labor was required for 24-hour operation, year-round. Operation labor averaged 60 hours per week. The cost of labor for the Brodhead Creek project was $275,000, or approximately 13 percent of the total project cost.

3.2.6 Supplies

Supplies are those costs directly or indirectly associated with operation of the treatment system, including treatment chemicals and resins, disposal drums, filters, disposable PPE, and sampling and field analytical supplies. At the Brodhead Creek site, supply costs included costs for chemicals (for iron removal, emulsion cracking and pH adjustment), filter bags and socks, site equipment including rags and tools, and field analytical supplies including test kits for pH and Redox. Supply costs totaled $95,000, or approximately 4 percent of the total project cost.

3.2.7 Utilities

Utilities typically include electricity, natural gas, propane, water and sewer necessary for operation of the treatment system. Utility costs, including electricity costs, can vary considerably depending on the geographical location of the site and local utility rates. At the Brodhead Creek site, electricity was used to run the CROW process pumps and water heater. In addition, electricity was used for pipe heating, and for building heating, ventilation and air conditioning (HVAC). Application of the CROW process at other sites will be subject to site-specific conditions, and the consumption of electricity will vary depending on the total number of CROW process heating units, the total number of extraction and injection wells and pumps, and other electrical equipment. Utility costs at the Brodhead Creek site totaled $60,000, or approximately 3 percent of the overall project cost.

3.2.8 Effluent Treatment and Disposal

Effluent treatment and disposal costs typically include the costs for treating or disposing of treatment system discharge water. At the Brodhead Creek site, effluent treatment and disposal consisted of treating discharge water in the GAC-FBR system before discharging directly to a nearby surface water body in accordance with the discharge permit. Costs totaled $70,000, or approximately 3 percent of total project costs and were associated with carbon canisters and GAC-FBR maintenance. Depending on the treatment goals for a site, the degree of treatment and disposal and associated costs may vary considerably.

3.2.9 Residual Waste Shipping and Handling

The residuals produced during CROW process system operation include 55-gallon drums containing recovered oil, spent carbon, spent cartridge filters and filter bags, used PPE, and waste sampling and field analytical supplies. The cost for shipping, handling and disposal of these items at the Brodhead Creek site was $45,000, or approximately 2 percent of the total cost.

3.2.10 Analytical Services

Required sampling frequencies and the number of samples analyzed are highly site-specific and are based on permit and system performance requirements. Analytical costs associated with a groundwater remediation project include the costs of laboratory analyses, data reduction, and QA/QC. At the Brodhead Creek site, analytical services included weekly sampling for system performance, including multiple total organic carbon (TOC), oil and grease (O&G), and polynuclear aromatic hydrocarbons (PAH) analyses. In addition, weekly sampling and PAH analysis was conducted on discharge water in accordance with the discharge permit. Analytical services costs at the Brodhead Creek site totaled $105,000, or approximately 5 percent of the total project costs.

3.2.11 Equipment Maintenance

At the Brodhead Creek site, maintenance costs included costs for servicing various systems and components (for example, plumbers, electricians, pump repairs, and cranes). In addition, maintenance costs included materials needed during operation, including additional pipe and heat tracing. Maintenance costs included the cost for renting a compressor for jetting the injection wells. Equipment maintenance costs totaled $190,000, or approximately 9 percent of the total project costs.

3.2.12 Site Demobilization

Site demobilization activities typically include utility disconnection, treatment system shutdown, decontamination, and disassembly costs. The salvage value of the system components can be used to offset a portion of demobilization costs. At the Brodhead Creek site, demobilization included system dismantlement, site grading, topsoil, and seeding. These costs totaled $92,000, or approximately 4 percent of total project costs.

3.3 Estimating Costs at Other Sites

This section discusses the costs involved in the application of the CROW process technology at other sites based on the costs at the Brodhead Creek Superfund site. In addition, this section presents cost information for another site where pilot-scale CROW process remediation was conducted.

The major issues influencing CROW process remediation costs at the Brodhead Creek site involved site-specific factors and equipment and operating parameters. These issues and assumptions are discussed in Sections 3.3.1 and 3.3.2. In general, operating issues are based on information provided by ReTeC and observations made during the SITE demonstration.

For comparison purposes, costs for implementing a full-scale CROW process remediation project at the Bell Pole site are presented in Section 3.3.3.

3.3.1 Site-Specific Factors

Site-specific factors can affect the performance and costs of the CROW process treatment system. These factors can be divided into the following two categories: waste-related factors and site features. Waste-related factors affecting costs include waste volume, contaminant types and concentrations, treatment goals, and regulatory requirements. Waste volume affects total project costs because larger volumes take longer to remediate. The contaminant types and concentrations in the groundwater and the treatment goals for the site determine (1) the appropriate size of the CROW treatment system (number of injection wells, recovery wells, and heating units), which affects capital equipment costs; (2) the flow rate at which treatment goals can be met, which affects the time to remediate and associated operating costs; and (3) periodic sampling requirements, which affect analytical costs. Regulatory requirements affect permitting costs and effluent monitoring costs, and depend on site location and the type of disposal selected for the treated effluent.

Site features affecting site preparation and mobilization and startup costs include groundwater extraction and recharge rates, groundwater chemistry, site accessibility, availability of utilities, and the geographic site location. Groundwater extraction and recharge rates affect the time required for cleanup and the size of the CROW process system needed. The presence of metals such as iron and manganese in groundwater can decrease CROW process technology effectiveness and increase equipment and O&M costs by requiring pretreatment.

Site-specific factors at the Brodhead Creek site that influenced the cost and performance of the CROW process include the following:

- Shallow groundwater table at the site (approximately 3 feet below ground surface) resulted in water injection difficulties, reduced injection rates, reduced treatment flow rates, and an overall longer treatment time frame.
- During groundwater extraction, oxidation of dissolved iron resulted in iron precipitating out at injection wells and caused plugging problems. This problem resulted in additional maintenance (cleaning) of injection wells and significant modifications to the groundwater treatment system.

Due to these factors, even with system modifications, the overall process injection rate was reduced to 19.6 gallons per minute (gpm) from a design rate of 100 gpm (Johnson and Fahy 1997).

3.3.2 Equipment and Operating Factors

Equipment and operating factors can also influence the performance and costs of the CROW treatment system. These factors include how the treatment system itself is constructed, sizing of system components considering treatment rates, operating time frames and regimes, and health and safety requirements. The selection of system equipment and operation of the treatment system are also affected by the site-specific factors discussed in Section 3.2.1.

The construction or setup of the treatment system itself may range from a semipermanent system constructed from individual components on site to the configuration of one or more portable and modular components. The selection of the type of construction will likely be influenced by site-specific factors, including the volume of contamination, site location, and the expected treatment duration. Depending on site-specific factors, there may be a potential need for specialty subcontractors, for example, to operate or maintain specialty equipment or a portion of the treatment system, or to handle or dispose of waste streams. Other equipment and operating factors that may affect costs include the following:

- Normal treatment system operating time frame, which may range up to 24 hours per day, 7 days per week.
- Operating down-time, which includes system shutdowns for maintenance and repairs, weather-related down-time, and unscheduled shutdowns.

- The overall treatment rate, considering potential limitations on groundwater extraction, contaminant removal, secondary treatment (for example, to remove iron), groundwater injection, and treated water discharge.

- Health and safety requirements, specifically the need for PPE more stringent than Modified Level D.

- During the full-scale demonstration of the CROW process at the Brodhead Creek site, equipment and operating factors did influence overall system performance and cost. These factors included the following:

- The reduced system injection rate resulted in a loss of water temperature control. It was necessary to disconnect three of the four heater bundles and modify the control system for the fourth heater.

- Reduced extraction pumping rates caused heat buildup in the extraction pump, accelerating wear of the pump motors and impellers. Repair and replacement of the downhole pumps became more frequent as the project progressed.

- Operational and plugging problems with the biological treatment unit necessitated several months of system tuning and installation of strainers and micron-sized filters.

- Organic fouling of level indicators and particulate fouling of turbine flow meters resulted in an extraordinary amount of cleaning, repair, and replacement of the instruments.

- Software problems with the data acquisition and control system computer required installation of new software packages.

- The extraction pump system was reconfigured to remove organic material around monitoring wells RCC and RCNE (Figures 4-1 and 4-2).

- Difficulties in achieving uniform vertical heating of the aquifer required the configuration of additional monitoring wells for injection.

3.3.3 Bell Lumber and Pole Company Site Costs

In 1990 efforts were initiated to implement the CROW process technology at the Bell Pole site in New Brighton, Minnesota. At this site, the CROW process was implemented in a phased approach to remediate the contaminated area and recover NAPL. This phased approach consisted of a pilot test, and three phases of system construction and operation. The costs associated with this remediation project were provided by WRI (1998) and are shown in Table 3-2. These costs include actual costs to date (pilot test and phase 1) and estimated costs through completion of the project (phases 2 and 3).

3.4 Conclusions of the Economic Analysis

This analysis presents actual costs for treating subsurface organic contamination using the CROW process. Actual costs for full-scale treatment at the Brodhead Creek site were presented and costs for full-scale treatment at another site, the Bell Pole site, were presented for comparison.

At the Brodhead Creek site, the cost for implementing a site cleanup using the CROW process was compared to the number of pore volumes flushed through the treatment area. The total cost per pore volume flushed through the treatment area was calculated at $85,000. As a comparison, the cost per pore volume at the Bell Pole site was calculated as $61,900. The costs for the Bell Pole site are less due to better site conditions including less dissolved iron in the aquifer and a uniform sand aquifer. The cost per pore volume for implementing this technology at other sites is expected to fall within this range.

Table 3-2. Costs Associated with the CROW Process Technology at the Bell Pole Site

Cost Component[a]	Total
Permitting, Initial Engineering, and Treatability Studies	$ 80,300
Pilot Test Design, Construction, and Operation	$ 507,300
Full-Scale Design	$ 106,600
Phase 1 Drilling, Construction, and Equipment	$ 486,500
Phase 1 Startup and Modifications	$ 291,000
Phase 1 Operations	$ 306,700
System Demobilization	$ 40,000[b]
Reporting and Closure	$ 40,000[b]
Total Costs	$1,858,400
Remediation Unit Cost:	
Total Costs	$1,858,400
Number of Pore Volumes Flushed[c]	30
Pore Volume Size	950,000 gallons
Cost per Pore Volume	$ 61,900

Notes:

[a] All costs are in July 1998 dollars and are rounded to the nearest $100.
[b] Estimated costs.
[c] Estimated at completion.

Section 4
Treatment Effectiveness During the SITE Evaluation

This section addresses the effectiveness of the CROW process technology for treating subsurface accumulations of oily wastes. Because the SITE demonstration provided extensive data on the CROW process, the evaluation of the technology's effectiveness is based primarily on the demonstration results. This section specifically provides an overview of the design and implementation of the CROW process at the Brodhead Creek site; summarizes the evaluation objectives, methods, and results; and presents the conclusions of the CROW process technology demonstration.

Vendor claims regarding the treatment effectiveness of the CROW process technology are included in Appendix A. An overview of bench-scale testing of the technology using contaminated soil from the Brodhead Creek site is presented in Appendix B. Appendix C presents an overview of pilot-scale testing of the technology at the Bell Pole site in New Brighton, Minnesota.

4.1 Design and Implementation of the CROW Process at the Brodhead Creek Site

This section provides an overview of the Brodhead Creek Superfund site, including geology and hydrology, contaminant distribution, and chemical characteristics of the groundwater; summarizes the design and implementation of the CROW process technology at the site; and documents CROW process operation and modifications.

4.1.1 Brodhead Creek Superfund Site

The Brodhead Creek site is the location of a former coal gasification plant in the city of Stroudsburg, Pennsylvania. A waste product from this process was a black tar-like liquid (coal tar) with a density greater than water and principally composed of PAHs. The coal tar was disposed of in an open pit located on the property for approximately 60 years until the mid-1940s when the plant was abandoned (Environmental Resources Management [ERM] 1990). The site occupies 12 acres and is bounded on the north and northeast by Brodhead Creek; on the southeast by McMichael Creek; on the soutwest and west by the Stroudsburg municipal sewage treatment plant and a cemetery; and on the northwest by the Route 209 bridge over Brodhead Creek. Figure 4-1 provides a layout of the Brodhead Creek site.

The site is located on the 100-year flood plain of Brodhead Creek. In response to flooding in 1955 caused by Hurricane Hazel, a flood-control levee was constructed. Before construction of the levee, the site topography gently climbed from an elevation of 376 feet above mean sea level (amsl) near the creek to more than 390 feet amsl in the northwestern portion of the site. The north end of the levee connects to a concrete flood wall, which is part of the west abutment of the Route 209 bridge over Brodhead Creek. The levee runs south in a gentle arc to the north side of McMichael Creek and continues off site to the west. The levee slopes at a rate of 2.5:1 on the creek side and 2:1 on the inland side, and rises to a total elevation of 408 feet amsl, or about 25 to 30 feet above the surrounding flood plain. The levee protects against flooding in either McMichael Creek or Brodhead Creek. At the south end of the site, an older flood-control levee built to protect the sewage treatment plant extends northwest from the main levee along the northern edge of the sewage treatment plant. This levee reaches an elevation of approximately 394 feet amsl.

Coal tar was found seeping into Brodhead Creek during repair of the main flood-control levee in October 1980. A slurry wall was constructed in 1981 to contain the coal tar.

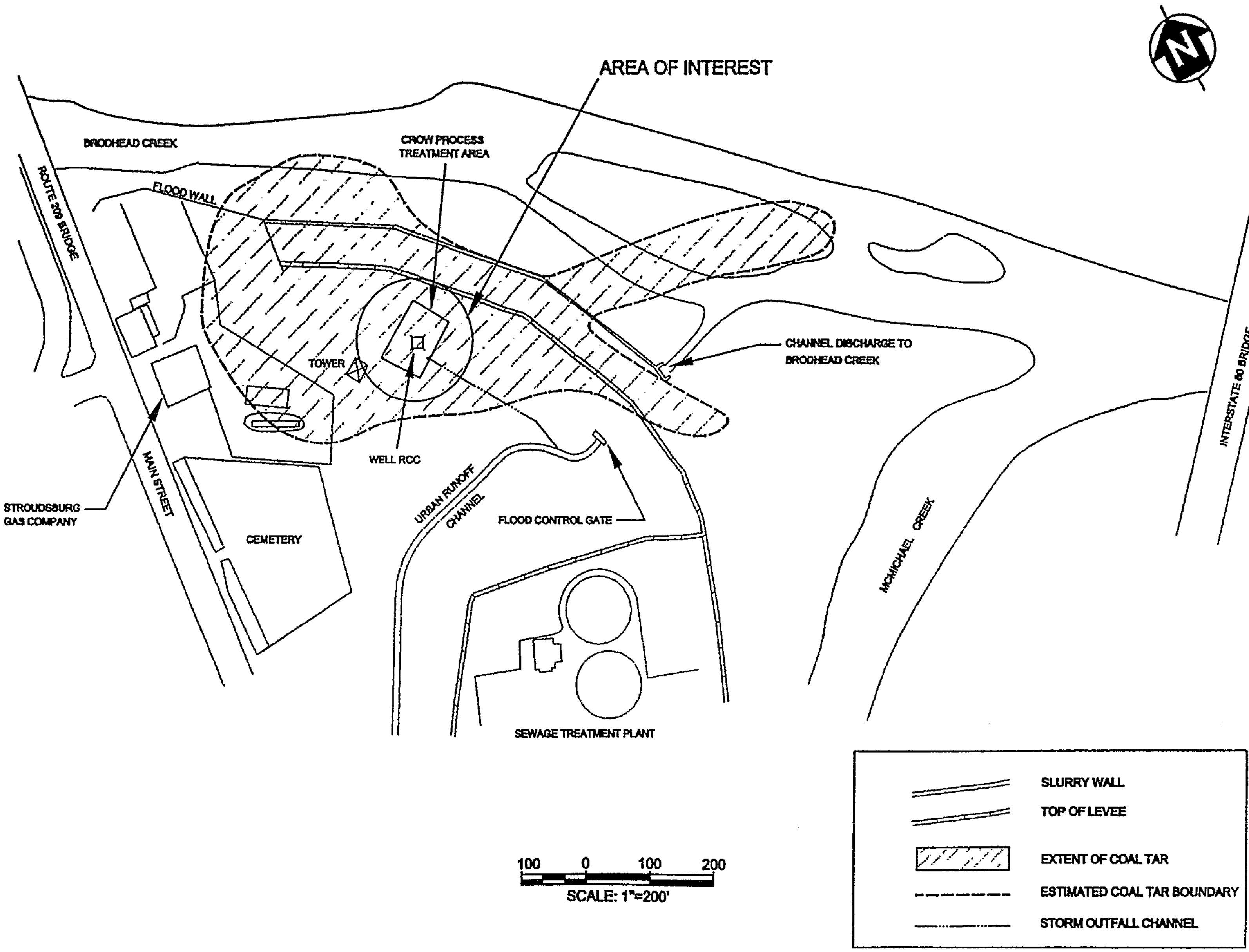


Figure 4-1. Brodhead Creek site layout.

The slurry wall is 648 feet long, 1 foot wide, and between 15 and 23.5 feet deep. The upstream end abuts the sheet piling of the Route 209 bridge, and the downstream end is connected to a 50-foot-long cement and grout curtain that joins the low-permeability levee core. The integrity of the slurry wall was considered good in 1990, since the piezometric surface elevation was lower on the downgradient side than on the upgradient side (ERM 1990).

The site contains two surface drainages. The larger surface drainage is called the urban runoff channel. It enters the site from the west, passes under the flood-control levee through a flood gate, and discharges to Brodhead Creek. The urban runoff channel is ephemeral, with an average depth of approximately 6 inches. The second surface drainage is called the storm outfall channel. It enters the site from a storm sewer outfall located near well RCC and flows south into the urban runoff channel just upstream of the floodgate. The storm outfall channel is also ephemeral.

4.1.1.1 Geology and Hydrology

The Brodhead Creek site is located in the valley and ridge physiographic province of the Appalachian Mountains. The site is in a wide northeast- to southwest-trending valley that is filled with approximately 60 feet of unconsolidated sediments and is underlain by Devonian Marcellus Shale. Marcellus Shale is a dark, fissile, carbonaceous shale and is underlain by limestone of the Devonian Buttermilk Falls Formation (Carswell and Lloyd 1979, in ERM 1990).

The unconsolidated sediments are composed of glacial deposits, stream gravels, flood plain deposits, and fill. The upper glacial unit is a gray-brown, stratified, fine sand and silt lacustrine deposit that is thought to be approximately 60 feet thick (ERM 1990). The stream gravels, located on top of and incised into the glacial unit, are loosely consolidated, stratified, well-rounded, boulders, cobbles, and coarse gravel with varying amounts of silt and sand. At the Brodhead Creek site, the stream gravel unit ranges in thickness from 0 to 25 feet. It is absent in the west-central and southern portions of the site and is thickest in a stratigraphic depression in the surface of the glacial deposits in the central portion of the site (near well RCC). The flood plain deposits overlie the stream gravel unit. The flood plain deposits are fine-grained sands and silt deposited by Brodhead and McMichael Creeks. Most of the fill material at the site is in the flood-control levee; other localized pockets of fill are present in the northern third of the site.

The unconsolidated sediments and the Buttermilk Falls Formation both contain usable water supplies. The Buttermilk Falls Formation contains the most used aquifer in the region and is separated from the water table aquifer by Marcellus Shale and glacial deposits. The water table, or upper aquifer, is located in the stream gravel lithologic unit and is 15 to 25 feet thick. Glacial deposits form the base of the upper aquifer. Upper aquifer characteristics include a hydraulic conductivity estimated to be 200 feet per day (approximately 1×10^{-2} cm/sec), a porosity of 30 percent, and a horizontal groundwater gradient of 0.005 feet per foot (ft/ft) (ERM 1990).

4.1.1.2 Contaminant Distribution

The horizontal and vertical extent of coal tar at the Brodhead Creek site were initially assessed by review of historical observations and periodic surveys of the monitoring wells for the presence of free coal tar surface (ERM 1990). Supplemental investigations were conducted by Atlantic Environmental Services, Inc. (AES), in 1992 and 1993 to better define the areal and vertical distribution of coal tar (AES 1993). Figure 4-1 shows the probable areal extent of coal tar.

Coal tar was found to exist in three different states: (1) as a mobile free phase, (2) as an immobile residual phase, and (3) dissolved in the groundwater. Free-phase coal tar exists at 100 percent pore volume saturation at the base of the upper aquifer. Free-phase coal tar is thought to exist in randomly distributed layers perched on beds with a higher proportion of finer-grained aquifer materials (AES 1993). The coal tar has only been found as a liquid; no solid or semisolid tar balls have been observed.

ERM observed a free coal tar surface near well RCC (Figure 4-1). ERM data suggested that a pool of coal tar between 3.17 and 5.53 feet thick surrounded well RCC. AES detected measurable free-phase coal tar in several on-site wells, including well RCC. During the supplemental investigation, AES also detected pockets of coal tar stained soil distributed throughout the lithologic column in all wells drilled near well RCC. Differences in elevation of the free coal tar surface in the various wells prompted AES to conclude that free-phase coal tar measured in the wells does not represent a single pool. Rather, coal tar was thought to be draining into the wells from different perched layers. The measured thickness of coal tar in the monitoring wells is an apparent thickness and may not reflect thickness in the aquifer (AES 1993).

Residual coal tar is present as coatings on the aquifer media and as agglomerations trapped in pores due to capillary pressure. Under natural conditions, residual coal tar is immobile. If site conditions are altered to reduce coal tar viscosity, some of this material may become mobile. Dissolved contaminant concentrations measured at the site are due to dissolution of residual and free phase coal tar. The areal extent of dissolved-phase contamination approximates the extent of residual coal tar (Figure 4-1) and extends beyond the CROW process demonstration area of interest.

4.1.1.3 Groundwater Chemical Characteristics

Analytical results for groundwater samples collected by ERM indicated the presence of a number of VOCs, SVOCs, and inorganic compounds. Total organic compound concentrations in the range of 50 mg/L were observed in samples from well RCC (ERM 1990). AES detected total PAH concentrations of up to 2.86 mg/L in the samples of groundwater collected near well RCC. Groundwater samples collected by ERM contained dissolved iron and manganese concentrations of up to 27.7 mg/L and 16.8 mg/L, respectively. Groundwater pH ranged from 5.85 to 11.60 standard units; however, the majority of the groundwater samples were in the range of 6.00 to 8.15 standard units (ERM 1990).

4.1.2 CROW Process Design

The CROW process system designed for the demonstration at the Brodhead Creek Superfund site targeted the zone of free-phase coal tar accumulation in the stream gravel unit near well RCC (Figure 4-1). A schematic of the CROW process demonstration design is presented in Figure 4-2. The design included six hot water injection wells, two recovery wells, and an aboveground water treatment system.

The injection and recovery wells were designed in a modified five-spot pattern within a 40-foot by 80-foot treatment area. Wells were designed to be screened across the entire upper aquifer. The design called for a pattern-wide water injection rate of 100 gpm and recovery rate of 120 gpm, with 20 gpm to be treated and discharged to Brodhead Creek.

The water treatment system design included routing recovered water through a series of tanks where mechanical processes separated oil from the recovered water. The design provided for the majority of the processed water to then be heated and reinjected into the aquifer with a portion of the processed water being treated and discharged off site. The heater was designed to heat 75 to 100 gpm of water from 50°F to 200°F. The design included treatment of discharge water using a GAC-FBR unit. The GAC-FBR is a biological treatment process where organic-degrading microorganisms were grown on granular activated carbon (Gruber 1996, in Johnson and Fahy 1997). Before discharge to Brodhead Creek, the water was also treated with activated carbon adsorption units to comply with Pennsylvania Department of Environmental Resources (PADER) effluent limitations. A data acquisition and control system was included in the design to continuously monitor flow rates and flow pressures at each well; water temperatures at the production wells, injection wells, monitoring wells, and water treatment units; and groundwater levels in selected monitoring wells.

4.1.3 CROW Process Implementation

In March 1994, the final CROW process design for the Brodhead Creek Superfund site was approved and construction commenced in May. Construction was completed by October 1994, and the first water was pumped from the aquifer on November 9, 1994. Table 4-1 lists a chronology of events associated with the shakedown and operation of the CROW process at the Brodhead Creek site.

As built the CROW process consisted of six injection wells surrounding two recovery wells in a modified five-spot pattern (Figure 4-2). Each well was screened from the top of the glacial silty sand unit to the top of the water table. The recovery wells were equipped with two pumps, one at the bottom to recover water and DNAPL and one at the top of the well to recover LNAPL. The extraction wells were designed to remove a total of 120 gpm from the aquifer. At the start of the demonstration, the extracted water was routed equally to two tanks (tanks 1 and 2) to allow the DNAPL to settle. The water was then routed to a third tank (tank 3), which was equipped with a skimmer pump to remove LNAPL. The DNAPL and LNAPL were pumped into a storage tank (tank 4). The water was then pumped into the recycled water tank (tank 5). From tank 5, the water was either heated and injected or treated and discharged. The six injections wells were expected to

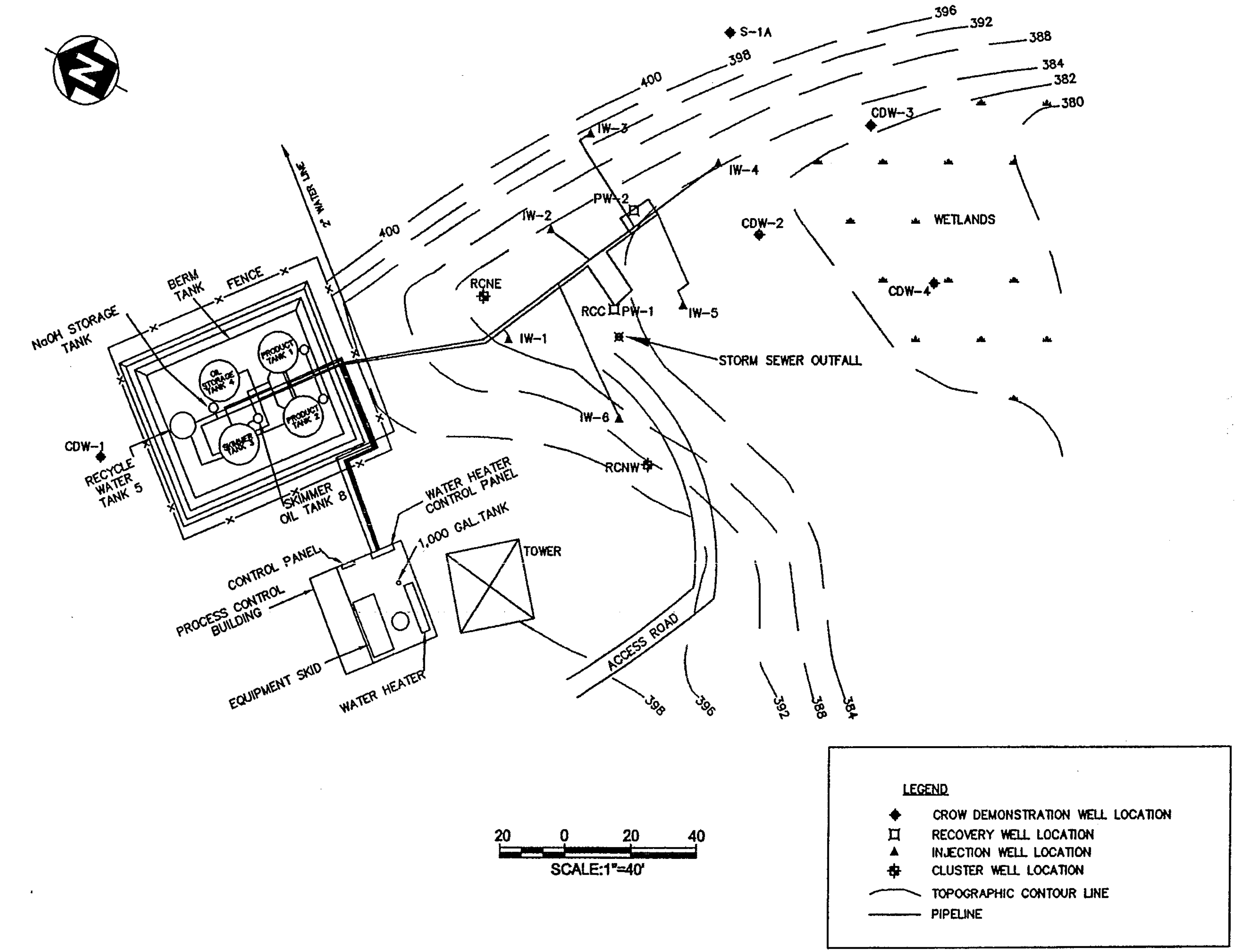


Figure 4-2. CROW process technology demonstration schematic.

Table 4-1. Chronology of Events

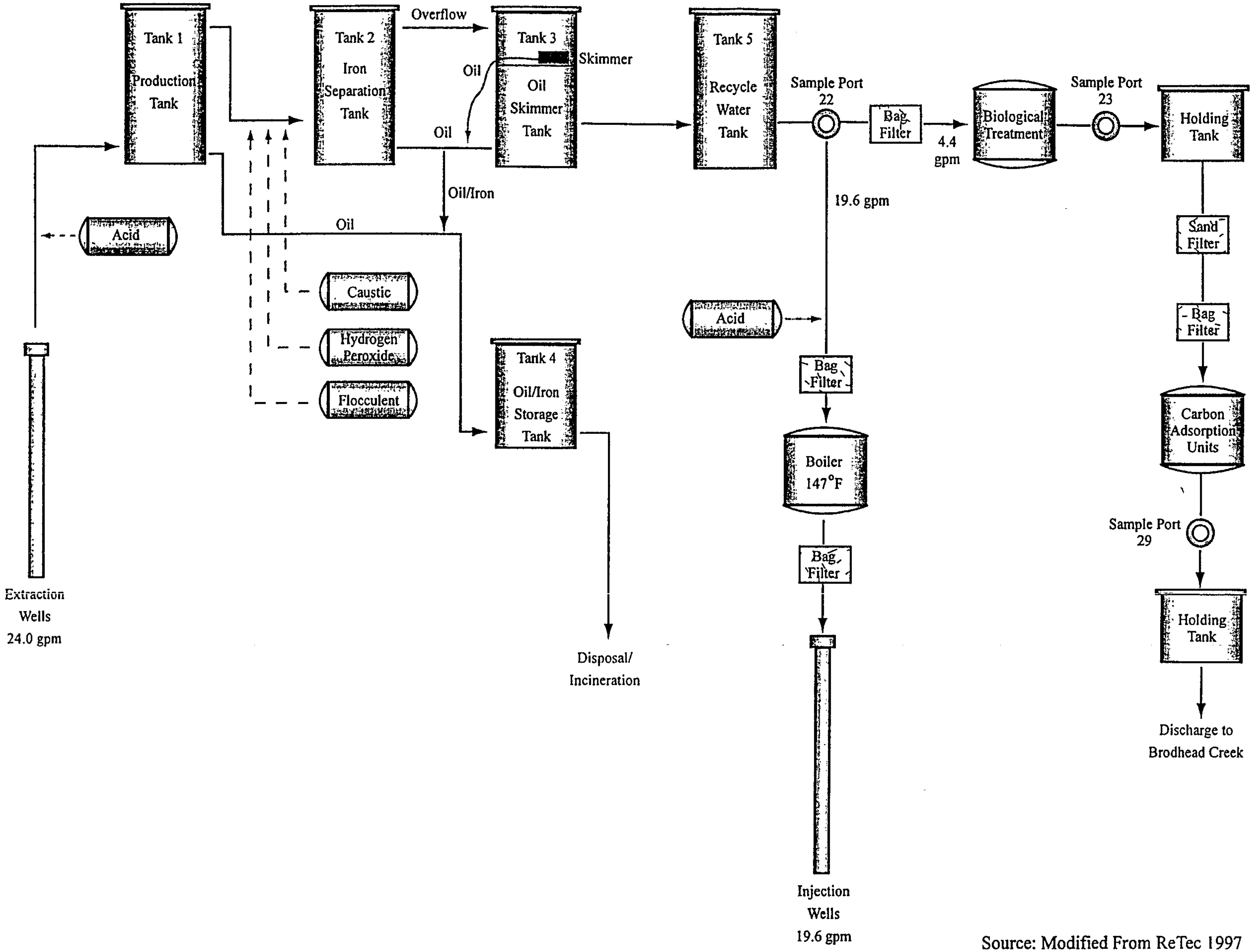
Date	Event
September 2, 1992	Consent decree signed between EPA and the parties responsible for the site (PP&L and Union Gas)
July 14, 1994	Explanation of Significant Differences issued by EPA to revise CROW process performance standards
March 1994	Remedial design completed
April 12 through 28, 1994	SITE Program predemonstration soil sampling and monitoring well installation
May 31, 1994	Construction began
July 1994	All production and injection wells completed
August 22 and 23, 1994	SITE Program predemonstration groundwater and soil gas sampling
October 1994	Construction completed
November 9, 1994	System starts operation and shakedown period (cold water injection)
November 10, 1994	First SITE Program demonstration samples collected
Late February through Late March 1995	CROW process is shut down to replumb the tank farm, redevelop the injection wells, and clean the process piping
July 1995	CROW process begins continuous steady-state operation (hot water injection)
December 6, 1995	Last SITE Program demonstration samples collected
June 7, 1996	CROW process shut off
August 12 through 15, 1997	SITE Program postdemonstration samples collected

pump approximately 15 to 17 gpm into the aquifer for a total of 100 gpm. The remaining 20 gpm of recovered water was to be treated using GAC-FBR and carbon adsorption units prior to discharge to Brodhead Creek.

Early attempts to reach the design injection rates for injection wells IW-3, IW-4, and IW-5 failed. At injection wells IW-4 and IW-5, the ground surface was within 3 feet of the top of the well screen and the bentonite seals installed in each well were unable to contain the injected water. To correct this problem, wells IW-4 and IW-5 were redeveloped and packers were installed to limit injection to the bottom 10 feet of each well. These corrective actions were not effective and the injection rates for wells IW-4 and IW-5 did not exceed 2 gpm. Injection well IW-3 was installed close to or in the bentonite core of the flood-control levee. The proximity to the impermeable levee core prevented the injection of water even after the well was redeveloped. For these reasons almost all water was injected through wells IW-1, IW-2, and IW-6.

The injection rates for injection wells IW-1, IW-2, and IW-6 steadily decreased during operation as the wells became plugged with iron flocculent. Iron in the recovered aquifer water oxidized and formed small floccules during aboveground treatment. When the water was reinjected, the iron plugged the injection wells. The inability to reach the design injection rates caused the water heater to overheat. To mitigate these problems, the injection wells were cleaned and the aboveground water production and treatment system was modified (see Figure 4-3).

Several modifications were incorporated to mitigate the iron problems. The first consisted of re-plumbing and chemical additions. The water production system was repiped to route all recovered water into tank 1. Before entering tank 1, the pH of the water was lowered to 5 using sulfuric acid. Lowering the pH facilitated the separation of organic constituents from the recovered water. The water was then piped from the top of tank 1 to the lower third of tank 2. Before entering tank 2, the pH was increased to 7 or 8 with sodium hydroxide. To facilitate oxidation and flocculation of the iron, hydrogen peroxide and polyacrylic acid were also added before tank 2. The overflow from tank 2 was routed to tank 3 and then to tank 5 for reinjection or treatment and discharge. To prevent iron clogging, the pH of the reinjected water was lowered to 6 and filters were installed before and after the hot water heater. Second, three of the four heater bundles in the



Source: Modified From ReTec 1997

Figure 4-3. CROW process water treatment system schematic.

heater were disconnected. The fourth heater bundle was connected to a proportional controller to provide the required amount of heating.

Before the CROW process system was restarted, the piping and wells were cleaned by flushing the piping and redeveloping the wells. An air jet attached to a lance was inserted in each well and compressed air was injected through the air jet to clean the screen and displace particulates. While the system was operating, acid or chlorine was added to the well to enhance cleaning by the air jet.

The CROW process demonstration at the Brodhead Creek site was initially designed to operate for 16 weeks; however, the CROW process actually operated for nearly 20 months, including the shakedown period. CROW process performance was influenced by the inability to achieve optimal pumping rates. Site-specific factors such as a shallow groundwater table and a high concentration of dissolved iron in the groundwater directly and indirectly reduced injection rates, reduced flow rates through the treatment zone, and extended the treatment time. Even after the CROW process system was modified, the overall process injection rate was reduced from a design rate of 100 gpm to 19.6 gpm.

4.2 Evaluation Objectives, Methods, and Results

The original regulatory performance goal for the CROW process demonstration was to reduce the amount of free coal tar around well RCC by 60 to 70 percent (EPA 1991a). A new regulatory performance goal was proposed after unsuccessful attempts by ReTeC and AES to quantify the amount of free coal tar in the treatment zone. The proposed regulatory goal was to remove free coal tar from the treatment zone until coal tar removal would no longer be practical. With EPA Region III concurrence, therefore, no regulatory performance standard was set for the CROW process demonstration.

Primary objectives were considered critical for evaluating the CROW process technology. The primary objectives (P) of the SITE demonstration were to validate WRI's performance claims for the technology. These objectives focused on the ability of the CROW process to remove coal tar from the aquifer and to determine if the process moved contaminants outside the treatment zone. The change in the regulatory performance standard did not change the SITE demonstration objectives. Four primary objectives were selected for the SITE demonstration.

- P-1 Measure Reduction of Coal Tar in the Aquifer
- P-2 Assess Potential Upward Migration of Contaminants
- P-3 Assess Potential Downward Migration of Coal Tar
- P-4 Assess Areal Containment of Coal Tar

Secondary objectives (S) provided additional information that was useful, but not critical, for the evaluation of the CROW process technology. The secondary objectives of the demonstration were to collect and evaluate data that are useful in assessing system performance, cost, and applicability to other sites. Five secondary objectives were selected for the SITE demonstration.

- S-1 Record CROW Process Operational Parameters
- S-2 Evaluate CROW Process Cost
- S-3 Assess Potential Fractionation of Coal Tar
- S-4 Assess Water Treatment System Effectiveness
- S-5 Evaluate Hydrologic Capture Zones

The methods and results associated with each of these objectives are presented in the following sections. The field and analytical methods and procedures used to collect and analyze samples were described in the CROW Process Demonstration Plan (DP) and Quality Assurance Project Plan (QAPP) (PRC Environmental Management, Inc. [PRC] 1994). A detailed description of the demonstration procedures is also provided in the final CROW Process TER (Tetra Tech EM Inc. [TtEMI] 1997).

4.2.1 Objective P-1: Measure Reduction of Coal Tar in the Aquifer

The goal of this objective was to determine whether the CROW process reduced coal tar concentrations in the treatment zone to residual immobile levels. The following sections discuss the objective, methods for evaluating the objective, and the results.

4.2.1.1 Discussion of Objective

The reduction in the amount of coal tar in the aquifer was evaluated in three ways: (1) measuring the reduction in the amount of free-phase coal tar in on-site wells, (2) measuring the change in the concentration of coal tar in the soil, and (3) measuring the amount of coal tar removed.

None of the three evaluation techniques could independently demonstrate the effectiveness of the CROW process. Only by combining the results from all three tests could the effectiveness of the CROW process be determined. Measuring the amount of coal tar recovered establishes that the CROW process removed coal tar from the subsurface. However, since no reliable estimate of the initial amount of coal tar in the aquifer was available, this measurement could not by itself determine removal efficiencies. Removal efficiencies were evaluated by measuring the concentration of organic compounds in the soil before and after the demonstration. These measurements were used to evaluate the change in the amount of contamination at different levels in the aquifer. The reduction in the amount of free-phase coal tar in monitoring wells was used to evaluate the claim that the coal tar is removed to residual immobile concentrations. Measurements of soil organic compound concentrations and the presence of free-phase coal tar could not by themselves establish that the CROW process removes coal tar from the subsurface. Reduction in these concentrations could indicate that the CROW process flushed contaminants outside the treatment zone.

First, the amount of free-phase coal tar was measured with an interface probe in all monitoring and recovery wells within the treatment area before and after the demonstration. The coal tar thickness was measured before the demonstration to establish the presence of free-phase coal tar and to identify wells that contained free-phase coal tar. The coal tar thickness was measured after the demonstration to evaluate the claim that the CROW process could reduce the concentration of coal tar to residual immobile levels. If free-phase coal tar was still present in one or more of the wells within the treatment area, it would logically be concluded that the CROW process was not able to remove coal tar to residual levels.

Second, total recoverable petroleum hydrocarbon (TRPH) concentrations were measured in soil samples collected from below the water table in nine soil borings inside the treatment area drilled before the demonstration and in nine soil borings drilled after the demonstration. The soil borings drilled after the demonstration were within 3 feet of the soil borings drilled before the demonstration. The samples from soil borings drilled after the demonstration were collected at the same depth as samples collected prior to the demonstration. Samples were collected at 5-foot intervals starting 1 foot below the water table and continuing until the boring intersected the silty sand glacial unit. Since the aquifer is 15 to 25 feet thick in the treatment area, three to five samples were collected from each boring. The locations of the nine soil borings (CB1, CB2, CB3, CB4, CB5, CB6, CB7, CB8, and CB9) are presented in Figure 4-4. The TRPH concentration in samples collected before the demonstration was compared to the TRPH concentration in the adjacent sample collected after the demonstration. A paired sample Wilcoxon signed rank test was used to determine reductions in soil TRPH concentrations.

Third, the amount of coal tar recovered by the CROW process was measured. To determine the amount of coal tar recovered, the volume of product recovered by the oil-water separator was measured. The mass of dissolved coal tar was to be added to the pure-phase coal tar. To determine the mass of dissolved contaminants removed from the system, the total flow volume for the time period was calculated using data from the data acquisition and control system and multiplied by the concentration of TRPH; benzene, toluene, ethylbenzene, and xylene (BTEX); and PAHs in the water samples collected from the oil-water separator outflow. However, no BTEX or PAH data were collected for the final 7 months of operation; therefore, a reliable estimate of the mass of dissolved constituents could not be calculated.

4.2.1.2 Methods

Predemonstration

Soil samples were collected to measure the amount of coal tar present in the aquifer before the CROW process was implemented. A hollow-stem auger drill rig was used to install the boreholes. Soil samples were collected between April 12 and 28, 1994 using a 3-inch-diameter split-spoon sampler. Soil from the sampler was logged and transferred to the sample container. Nine soil borings were drilled within the treatment area. A total of 38 samples and four duplicate samples were collected from the stream gravel unit within the treatment area and analyzed for TRPH. The split-spoon sampler did not collect samples representative of the stream gravel unit due to the abundance of large diameter materials. The split-spoon sampler collected the fine-grained portion of the unit and the analytical results are expected to overestimate the amount of coal tar present in the stream gravel unit. The presence or absence of free phase coal tar was not evaluated using the soil samples.

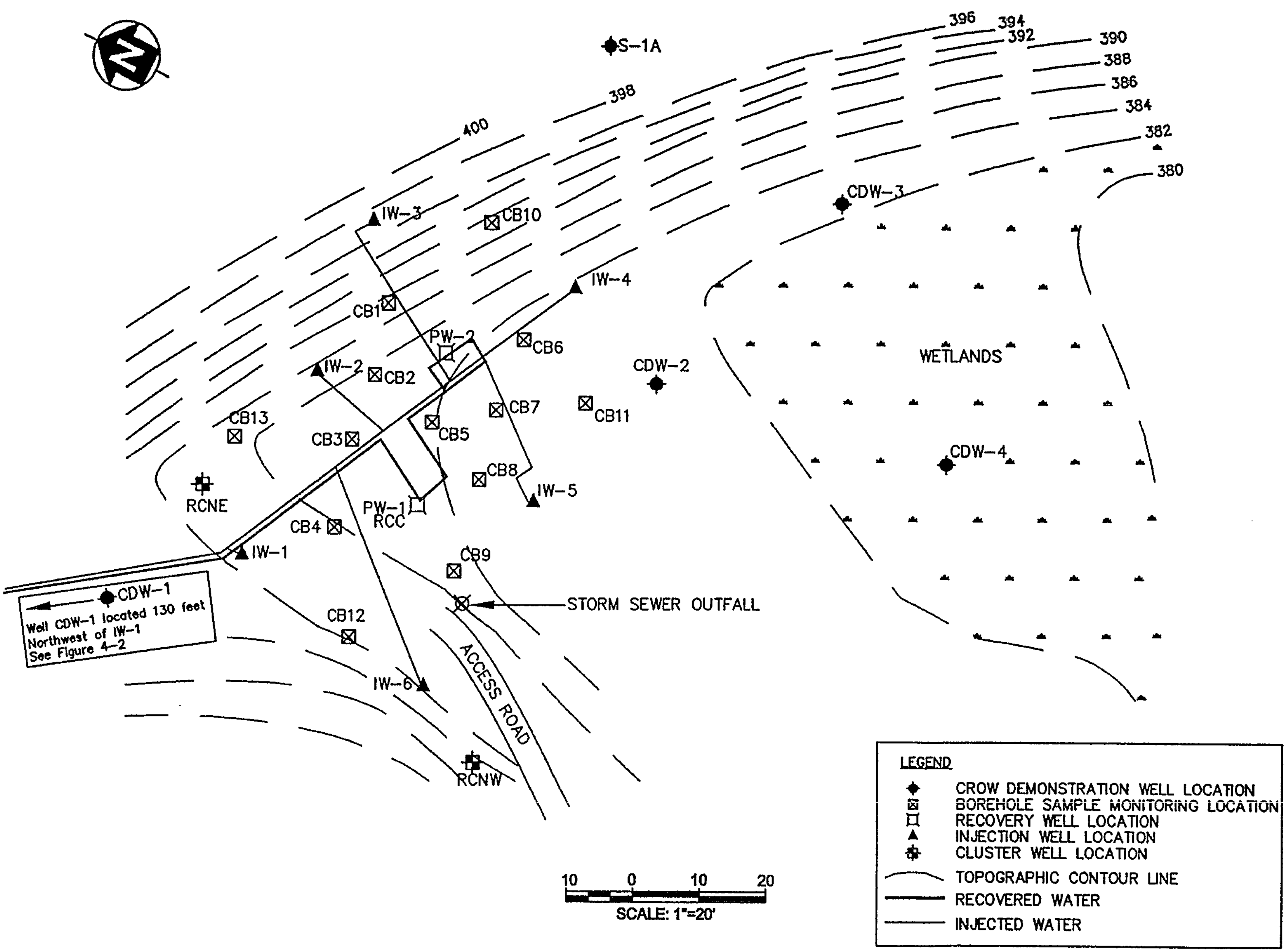


Figure 4-4. Soil boring locations.

The depth and thickness of free-phase coal tar were measured in every available well on November 11, 1994. Free product was detected only in monitoring wells RCC and RCNE. The free product thickness measured in monitoring wells RCC and RCNE is presented in Table 4-2.

Table 4-2. Free Product Thickness Measurements

Well	November 11, 1994 (feet)	August 13, 1997 (feet)	September 22, 1998 (feet)
RCC	6.0	0	0.93
RCNE	1.5	0	0.41
RCNW	0	0	<0.01

Postdemonstration

Soil samples were collected to measure the amount of coal tar present in the aquifer after the CROW process demonstration was complete. A hollow-stem auger drill rig was used to install the boreholes. Soil samples were collected between August 12 and 15, 1997 using a 3-inch-diameter split-spoon sampler. Soil from the sampler was logged and transferred to the sample container. Nine soil borings were drilled within the treatment area. A total of 33 samples and four duplicates samples were collected from the stream gravel unit within the treatment zone and analyzed for TRPH. Because insufficient sample was present at particular depth intervals, fewer postdemonstration samples were collected. Five of the samples were also analyzed for BTEX and PAHs.

Postdemonstration sampling was designed to collect soil samples as near as possible to the locations where predemonstration soil samples were collected. The areal positions of the postdemonstration boreholes were established by measurement from monitoring wells present both before and after the demonstration. The addition of fill during construction of the CROW process made the collection of samples relative to ground surface inappropriate. To determine the correct depth interval, the soil samples were therefore collected relative to the water table and the top of the silty sand unit. Measurement of the depth to water in the monitoring wells installed during the predemonstration indicated that the water table elevation changed less than 0.5 foot from the predemonstration to the postdemonstration soil sampling activities.

The depth and thickness of free-phase coal tar were measured in every available well on August 13, 1997. No free product was detected at any monitoring well during this monitoring event.

4.2.1.3 Results

Reduction in Coal Tar Thickness

Free-phase coal tar was detected only in wells RCC and RCNE prior to the demonstration. On August 13, 1997 (61 weeks after the demonstration) free-phase coal tar was not detected in any wells. However, during a site visit by PP&L on September 22, 1998, free-phase coal tar was detected in wells RCC, RCNE, and RCNW. The free product thickness measured in monitoring wells RCC, RCNE, and RCNW is presented in Table 4-2. These results suggest that free-phase product migrated into a number of on-site wells in the treatment area after the conclusion of the demonstration.

Reduction in Coal Tar Concentrations

The DP proposed that a paired sample t-test be used to compare the predemonstration TRPH sample data to the postdemonstration TRPH sample data and determine if there was a significant reduction in the TRPH concentration. The paired sample t-test requires that the data be normally or log-normally distributed (Gilbert 1987) and that the differences between the paired data must be normally distributed. Unfortunately, the Shapiro-Wilk w-test (Gilbert 1987) indicated that the data sets for the postdemonstration samples and for the difference between the paired data were not normally distributed and that the t-test is not appropriate.

A statistical test that does not require that the difference data set be normally distributed is the Wilcoxon matched-pairs signed rank test (Gilbert 1987). The Wilcoxon signed rank test was applied to the TRPH data using a significance level of 0.1. The Wilcoxon test statistic calculations are summarized in Table 4-3. The data used for the statistical analysis are the average of all acceptable quality data for each sampling point. The analytical results for predemonstration samples CB-6 (12.5-13) and CB-7 (16.5-17) were qualified estimated nondetect due to method blank contamination and were not included in the calculations. The analytical data were evaluated and conclusions regarding the validity of sample results are presented in Section 4.2.10. When all the data with

Table 4-3. Statistical Tests for the Stream Gravel Unit Within the Treatment Area

Soil Boring	Depth (feet)	TRPH Concentration: Predemonstration (mg/kg)	Postdemonstration (mg/kg)
CB1	(9.5-10)	3710.0	1680.0
CB1	(14.5-15)	2690.0	6680.0
CB1	(21-21.5)	1480.0	4420.0
CB1	(28.5-29)	2124.5	410.0
CB2	(8.5-9)	1185.0	3220.0
CB2	(13.5-14)	3705.0	4820.0
CB2	(17.5-18)	1335.0	1130.0
CB2	(22.5-23)	1155.0	1170.0
CB3	(9.5-10)	1435.0	6700.0
CB3	(14.5-15)	1735.0	278.0
CB3	(19.5-20)	4125.0	350.0
CB3	(24.5-25)	3635.0	575.0
CB4	(11.5-12)	1051.0	3630.0
CB4	(16.5-17)	2285.0	2540.0
CB4	(22.5-23)	1244.6	1470.0
CB5	(7.5-8)	11022.5	2575.0
CB5	(12.5-13)	2371.0	1910.0
CB5	(17.5-18)	1302.7	353.0
CB5	(22.5-23)	484.0	485.0
CB5	(27.5-28)	557.7	512.0
CB6	(7.5-8)	758.0	449.0
CB6	(16-16.5)	1040.0	891.0
CB6	(25.5-26)	237.9	319.0
CB7	(7.5-8)	666.0	412.0
CB7	(11-11.5)	925.0	404.0
CB7	(20.5-21)	887.0	316.0
CB7	(26-26.5)	792.0	757.0
CB8	(5.5-6)	2230.0	ND
CB8	(15.5-16)	60.8	233.0
CB8	(20-20.5)	316.0	463.0
CB9	(21.5-22)	174.5	950.0
Mean		1829.7	1670.1
Samples, n		31	30
Distribution [(a)]		log normal	non-parametric
Difference Distribution [(a)]		non-parametric	
Significance threshold, a		0.10	
Wilcoxon signed rank test statistic [(b)]		256	
One-tailed probability		0.3144	
Conclusion [(c)]		Accept H_o	

Notes:

([a]) Normality testing performed using Shapiro-Wilk w-test.
([b]) Paired sample t-test performed if difference is normally distributed; otherwise, Wilcoxon signed ranks test performed.
([c]) H_o, Null hypothesis: there is no difference between the means of the postdemonstration and predemonstration concentrations. H_A, Alternative hypothesis: the mean of the predemonstration concentrations is greater than the mean of the postdemonstration concentrations.

acceptable quality are used, the calculated Wilcoxon one-tailed probability is 0.314. This number is well above the significance threshold of 0.1. Therefore, the null hypothesis (H_0) is not rejected and there is no tendency for the predemonstration data set to contain larger or smaller values than the postdemonstration data set.

Coal Tar Recovery

Based on the measured recovery of free-phase coal tar, 1,504 gallons of coal tar was removed from the aquifer during the demonstration (Johnson and Fahy 1997). This result indicates that the CROW process is capable of removing coal tar from the aquifer; however, since no reliable estimate of the initial amount of coal tar present in the aquifer is available, there is no way to determine removal efficiency of the technology using this evaluation test.

Summary

The results of the three evaluation techniques for primary objective P-1 demonstrate that the CROW process is capable of removing oily wastes from the subsurface. However, the recovery efficiency may be low. The presence of free-phase coal tar in wells after the demonstration indicates that the CROW process did not reduce the concentration of coal tar to residual immobile levels. Furthermore, no measurable change in TRPH concentration was recorded before and after the demonstration, suggesting that the CROW process did not significantly reduce the concentration of coal tar in the treatment zone.

4.2.2 Objective P-2: Assess Potential Upward Migration of Contaminants

The goal of this objective was to determine whether the injection of hot water would increase the migration of volatile contaminants into the vadose zone. The following sections discuss the objective, methods for evaluating the objective, and the results.

4.2.2.1 Discussion of Objective

The upward migration of contaminants was to be evaluated by measuring the concentration of BTEX in soil gas before, during, and after the demonstration. Soil gas samples were to be collected 2 days before system startup, at 30-day intervals during the demonstration, and within 10 days of system shutdown. In addition, one soil gas sample was to be collected approximately 3 weeks prior to the demonstration to test the applicability of the analytical method. The resulting data were to be plotted as a function of time to assess the change in BTEX concentrations. However, construction activities during replumbing and sealing of the injection wells destroyed all the soil gas sampling probes. Only the predemonstration samples and one round of demonstration samples were collected before the probes were destroyed.

4.2.2.2 Methods

This section describes the methods and procedures used to collect and analyze samples for the SITE demonstration of the CROW process technology. The field and analytical methods and procedures used to collect and analyze samples were in accordance with the CROW Process DP/QAPP (PRC 1994). A detailed description of the demonstration procedures is also provided in the final CROW Process TER (TtEMI 1997).

Predemonstration

Between April 12 and 28, 1994, soil gas probes were installed 4 feet above the water table in eight (CB1, CB2, CB3, CB4, CB5, CB6, CB7, and CB9) of the nine soil borings drilled inside the treatment area. No probe was installed in soil boring CB8 because the water table was within 2 feet of ground surface and the soil gas probe would have been too close to the surface to ensure collection of representative samples. The soil boring locations are presented in Figure 4-4. A test sample was collected from boring CB1 on August 1, 1994. This sample was analyzed to assess whether the proposed analytical methodology for the investigation was applicable to site conditions. No analytical problems were noted. The soil gas probe in boring CB2 was destroyed before predemonstration samples were collected. Predemonstration samples were collected from the remaining soil gas probes using Summa canisters on August 23, 1994. The Summa canisters for CB6 and CB7 malfunctioned and the soil gas probes were resampled on September 9, 1994. All soil gas samples were analyzed for BTEX.

Demonstration

Soil gas within the treatment area was sampled on November 23, 1994 to evaluate whether the CROW process was causing volatile contaminants to migrate from groundwater into the vadose zone. During November 1994, the water heater operated intermittently. By early December, it became clear that the water heater would not be operational for an extended period of time. Soil gas sampling was suspended until the CROW process started to inject hot water. Unfortunately, site construction activities related to problems with the injection wells destroyed all the soil gas sampling stations before the CROW process started steady-state operation. Reinstallation of the soil gas probes was not possible due to access restrictions, and no additional soil gas samples were collected.

4.2.2.3 Results

The only injection wells capable of injecting water in November 1994 were IW-1, IW-2 and IW-6. The soil gas probes in close proximity to active injection wells were CB1, CB3, CB4, and CB9. The total BTEX concentrations in soil gas for the demonstration were an order of magnitude larger than predemonstration concentrations in samples from probes CB1 and CB3. The concentration of total BTEX in samples from probes CB4 and CB9 increased slightly. Soil gas probes CB6 and CB7 were located in an area where no water was injected. The total BTEX concentrations in samples from probes CB6 and CB7 were lower in the demonstration samples than in predemonstration samples. These data suggest that total BTEX concentrations were higher in the area influenced by active injection, while BTEX concentrations were lower in the area with no active injection. The destruction of the sampling probes prevented the collection of additional data and evaluation of long-term contaminant concentrations in the vadose zone. The limited availability of data prevents the complete evaluation of this demonstration objective and no definitive conclusions about the upward migration of contaminants can be made.

4.2.3 Objective P-3: Assess Potential Downward Migration of Coal Tar

The goal of this objective was to determine whether the injection of hot water would decrease the viscosity of the coal tar and allow it to infiltrate into the lower fine grained confining unit. The following sections discuss the objective, methods for evaluating the objective, and the results.

4.2.3.1 Discussion of Objective

The downward migration of coal tar was evaluated by measuring the TRPH concentration in soil samples collected from the silty sand lithologic unit directly below the treatment zone in nine soil borings drilled before the demonstration and in nine soil borings drilled after the demonstration. The soil borings drilled after the demonstration were within 3 feet of the soil borings drilled before the demonstration. One sample was collected from each borehole at a depth of approximately 1 foot into the silty sand unit. These borings were also used to collect samples from the overlying stream gravel unit (P-1). The locations of the nine soil borings (CB1, CB2, CB3, CB4, CB5, CB6, CB7, CB8, and CB9) are presented in Figure 4-4. The TRPH concentration in samples collected before the demonstration was compared to the TRPH concentration in the adjacent sample collected after the demonstration. A paired sample t-test was used to determine if there was a significant increase in the concentration of TRPH over the course of the demonstration.

4.2.3.2 Methods

Predemonstration

Soil samples were collected to measure the amount of coal tar present in the aquifer before the CROW process was implemented. A hollow-stem auger drill rig was used to install the boreholes. Soil samples were collected between April 12 and 28, 1994 using a 3-inch-diameter split-spoon sampler. Soil from the sampler was logged and transferred to the sample container. Nine soil borings were drilled within the treatment area. Nine samples were collected from the silty sand unit below the treatment area and analyzed for TRPH. The presence or absence of free-phase coal tar was not evaluated using the soil samples.

Postdemonstration

Soil samples were collected to measure the amount of coal tar present in the aquifer after the CROW demonstration was complete. A hollow-stem auger drill rig was used to install the boreholes. Soil samples were collected between August 12 and 15, 1997 using a 3-inch-diameter split-spoon sampler. Soil from the sampler was logged and transferred to the sample container. Nine soil borings were drilled within the treatment area. Nine samples were collected from the silty sand unit below the treatment area and analyzed for TRPH.

Postdemonstration sampling was designed to collect soil samples as near as possible to the locations where predemonstration soil samples were collected. The areal positions of the postdemonstration boreholes were established by measurement from monitoring wells present both before and after the demonstration. The postdemonstration samples were also collected from the top of the silty sand unit.

4.2.3.3 Results

The demonstration plan proposed that a paired sample t-test be used to compare the predemonstration TRPH sample data to the postdemonstration TRPH sample data and determine if there was a significant increase in the TRPH concentration. The paired sample t-test requires that the data be normally or log-normally distributed (Gilbert 1987) and that the differences between the paired data must be normally distributed. The Shapiro-Wilk w-test (Gilbert 1987) indicated that the data sets for the predemonstration and postdemonstration samples were log normally distributed and that the difference between the paired data were normally distributed. Therefore, the t-test is appropriate (Gilbert 1987).

The paired sample t-test was applied to the TRPH data using a significance level of 0.1. The t-test statistic calculations are summarized in Table 4-4. The data used for the statistical analysis are the average of all acceptable

Table 4-4. Statistical Tests for the Silty Sand Unit Below the Treatment Area

Soil Boring	Depth (feet)	TRPH Concentration: Predemonstration (mg/kg)	TRPH Concentration: Postdemonstration (mg/kg)
CB1	(31.5-32)	1450	33[d]
CB2	(25.5-26)	99	625
CB3	(31.5-32)	26	93
CB4	(25.5-26)	13	132
CB5	(30-30.5)	26	51
CB6	(27.5-28)	52	1710
CB7	(30-30.5)	64.4	33[d]
CB8	(22.5-23)	75.3	163
CB9	(24.5-25)	315	2420
Mean		235.5	584.4
Samples, n		9	9
Distribution [(a)]		log normal	log normal
Difference Distribution [(a)]		normal	
Significance threshold, a		0.10	
Paired sample t-test statistic [(b)]		-1.02	
One-tailed probability		0.8315	
Conclusion [(c)]		Accept H_o	

Notes:

([a]) Normality testing performed using Shapiro-Wilk w-test.
([b]) Paired sample t-test performed if difference is normally distributed. Otherwise, Wilcoxon signed ranks test performed.
([c]) H_o, Null hypothesis: there is no difference between the means of the postdemonstration and predemonstration concentrations. H_A, Alternative hypothesis: the mean of the predemonstration concentrations is greater than the mean of the postdemonstration concentrations.
([d]) Nondetect (ND) values replaced with the reporting limit (33 mg/kg).

quality data for each sampling point. The analytical results for predemonstration samples CB-6 (27.5-28), CB-7 (30-30.5), and CB-8 (22.5-23) were qualified estimated nondetect due to method blank contamination. These results were included in the calculation because even though the results are biased high two of the three were lower than the postdemonstration samples. A thorough evaluation of analytical data was conducted and conclusions regarding the validity of sample results are presented in Section 4.2.10. When all the data with acceptable quality are used, the calculated t-test one-tailed probability is 0.832. This is well above the significance threshold of 0.1. Therefore, the null hypothesis (H_0) is not rejected and there is no tendency for the predemonstration data set to contain larger or smaller values than the postdemonstration data set.

Qualitative evaluation of the predemonstration and postdemonstration data suggests that postdemonstration TRPH concentrations are higher than predemonstration TRPH concentrations. The mean of the postdemonstration TRPH results (584 milligrams per kilogram [mg/kg]) is approximately twice the mean of the predemonstration results (236 mg/kg). At seven out of nine sampling locations, the postdemonstration results are higher than the predemonstration results. These results suggest that the CROW process caused contamination to migrate from the stream gravel unit into the underlying silty sand unit.

4.2.4 Objective P-4: Assess Areal Containment of Coal Tar

The goal of this objective was to determine whether the CROW process allowed contamination to migrate outside of the treatment area. The following sections discuss of the objective, methods for evaluating the objective, and the results.

4.2.4.1 Discussion of Objective

The areal containment of coal tar was evaluated in two ways. The first way was to measure the TRPH, BETX, and PAH concentration in groundwater samples collected from five monitoring wells located outside of the treatment area (Figure 4-2). One well was located upgradient (CDW-1) and four wells were located downgradient (CDW-2, CDW-3, CDW-4, and S-1A). Monitoring well S-1A was installed by AES during a supplemental investigation, and monitoring wells CDW-1, CDW-2, CDW-3, and CDW-4 were installed prior to the demonstration. The wells were screened completely through the upper aquifer. Samples collected from the upgradient well were used to determine if upgradient contaminants migrated into the treatment area. Samples collected from the downgradient wells were used to determine if the CROW process flushed contaminants downgradient. The resulting data were plotted as a function of time to determine the change in TRPH, BTEX, and PAH concentrations.

The areal containment was also evaluated by measuring the concentration of TRPH in soil samples collected from below the water table in four soil borings drilled outside the treatment area before the demonstration and four soil borings drilled after the demonstration. The soil borings drilled after the demonstration were within 3 feet of the soil borings drilled before the demonstration. The samples from soil borings drilled after the demonstration were collected at the same depth as samples collected prior to the demonstration. Samples were collected at 5-foot intervals starting 1 foot below the water table. Since the aquifer is 15 to 25 feet thick outside the treatment area, three to five samples were collected from each boring. The locations of the four soil borings (CB10, CB11, CB12, and CB13) are presented in Figure 4-4. TRPH concentration in samples collected before the demonstration was compared to the TRPH concentration in the adjacent sample collected after the demonstration. A paired sample t-test was used to determine if there was a significant change in the TRPH concentrations.

4.2.4.2 Methods

Predemonstration

Soil samples were collected to measure the amount of coal tar present in the aquifer before the CROW demonstration began. A hollow-stem auger drill rig was used to install the boreholes. Soil samples were collected between April 12 and 28, 1994 using a 3-inch-diameter split-spoon sampler. Soil from the sampler was logged and transferred to the sample container. Four soil borings were drilled outside the treatment area and 11 soil samples and four duplicates were collected from the stream gravel unit and analyzed for TRPH. The split-spoon sampler did not collect samples representative of the stream gravel unit due to the abundance of large diameter materials. The split-spoon sampler collected the fine-grained portion of the unit; the analytical results are therefore expected to overestimate the amount of coal tar present in the stream gravel unit. The presence or absence of free-phase coal tar was not evaluated using the soil samples.

Groundwater samples were collected to measure the distribution of contaminants before the CROW demonstration began. Groundwater samples were collected from monitoring wells CDW-1, CDW-2, CDW-3, CDW-4, and S-1A on August 23, 1994. All samples were analyzed for TRPH, BTEX, and PAHs. Monitoring well CDW-1 was located upgradient of the treatment area, monitoring well CDW-2 was located 15 feet downgradient of the treatment area, and monitoring wells CDW-3, CDW-4, and S-1A were located in an arc approximately 100 feet downgradient of the treatment area. Monitoring wells CDW-1 through CDW-4 were installed in April 1994.

Demonstration

Groundwater samples were collected to measure the distribution of contaminants during implementation of the CROW process. Groundwater samples were collected from monitoring wells CDW-1, CDW-2, CDW-3, CDW-4, and S-1A. Monitoring well CDW-1 was sampled to establish the concentration of contaminants flowing into the treatment zone. Monitoring wells CDW-2, CDW-3, CDW-4, and S-1A were sampled to evaluate whether the CROW process was flushing contaminants downgradient.

All monitoring wells were sampled once every 2 weeks from November 21, 1994 to January 30, 1995. One set of groundwater samples was collected on March 2, 1995 while the CROW process was shut down to provide baseline information when the system resumed operation. Once the CROW process was operated at steady state, the monitoring wells were sampled on July 12, August 16, October 4, and November 21, 1995. All samples were analyzed for TRPH, BTEX, and PAHs. Groundwater was not sampled again until postdemonstration sampling in August 1997.

Postdemonstration

Soil samples were collected to measure the amount of coal tar present in the aquifer after the CROW demonstration was complete. A hollow-stem auger drill rig was used to install the boreholes. Soil samples were collected between August 12 and 15, 1997 using a 3-inch-diameter split-spoon sampler. Soil from the sampler was logged and transferred to the sample container. Four soil borings were drilled outside the treatment area. Eleven samples and four duplicates were collected from the stream gravel unit outside the treatment area and analyzed for TRPH.

Postdemonstration sampling was designed to collect soil samples as near as possible to the locations where predemonstration soil samples were collected. The areal positions of the postdemonstration boreholes were established by measurement from monitoring wells present both before and after the demonstration. The addition of fill during construction of the CROW process made the collection of samples relative to ground surface inappropriate. To determine the correct depth interval, the soil samples were therefore collected relative to the water table and the top of the silty sand unit. Measurement of the depth to water in the monitoring wells installed during the predemonstration indicated that the water table elevation was within 0.5 foot during the predemonstration and postdemonstration soil sampling activities.

Groundwater samples were collected to measure the distribution of contaminants after the CROW demonstration was complete. Groundwater samples were collected from monitoring wells CDW-1, CDW-2, CDW-3, CDW-4, and S-1A on August 13, 1997. All samples were analyzed for TRPH, BTEX, and PAHs.

4.2.4.3 Results

Coal Tar Concentrations in Soil

The demonstration plan proposed that a paired sample t-test be used to compare the predemonstration TRPH sample data to the postdemonstration TRPH sample data and determine if there was a significant increase in the TRPH concentration. The paired sample t-test requires that the data be normally or log-normally distributed (Gilbert 1987) and that the differences between the paired data must be normally distributed. The Shapiro-Wilk w-test (Gilbert 1987) indicated that the data sets for the predemonstration and postdemonstration samples were log normally distributed and that the differences between the paired data were normally distributed. Therefore, the t-test is appropriate (Gilbert 1987).

The paired sample t-test was applied to the TRPH data using a significance level of 0.1. The t-test statistic calculations are summarized in Table 4-5. The data used for the statistical analysis are the average of all acceptable quality data for each sampling point. Analytical data were

Table 4-5. Statistical Tests for the Stream Gravel Unit Outside the Treatment Area

Location	Depth (feet)	TRPH Concentration Predemonstration (mg/kg)	TRPH Concentration Postdemonstration (mg/kg)
CB10	(6.5-7)	2905.0	678.0
CB10	(11.5-12)	1410.0	713.0
CB11	(8-8.5)	3939.0	2075.0
CB11	(13.5-14)	949.0	942.0
CB12	(11.5-12)	4920.0	4855.0
CB12	(18.5-19)	983.0	1340.0
CB12	(20.5-21)	471.0	384.0
CB13	(13.5-14)	5410.0	6680.0
CB13	(15.5-16)	1056.0	4870.0
CB13	(20.5-21)	1870.0	4970.0
CB13	(24.5-25)	1866.7	1040.0
Mean		2343.6	2595.2
Samples, n		11	11
Distribution [a]		log normal	log normal
Difference Distribution [a]		normal	
Significance threshold, a		0.10	
Paired sample t-test statistic [b]		-0.45	
One-tailed probability		0.6679	
Conclusion [c]		Accept H_o	

Notes:

([a]) Normality testing performed using Shapiro-Wilk w-test.
([b]) Paired sample t-test performed if difference is normally distributed. Otherwise, Wilcoxon signed ranks test performed.
([c]) H_o, Null hypothesis: there is no difference between the means of the postdemonstration and predemonstration concentrations. H_A, Alternative hypothesis: the mean of the predemonstration concentrations is greater than the mean of the postdemonstration concentrations.

evaluated and conclusions regarding the validity of sample results are presented in Section 4.2.10. When all the data with acceptable quality are used, the calculated t-test one-tailed probability is 0.668. This figure is well above the significance threshold of 0.1. Therefore, the null hypothesis (H_O) is not rejected and there is no tendency for the predemonstration data set to contain larger or smaller values than the postdemonstration data set.

Qualitative evaluation of the predemonstration and postdemonstration soil data does not reveal any trends that may be used to characterize the change in the distribution of contaminants before and after the demonstration. Qualitative evaluation of the trends in TRPH, BTEX, and PAH concentrations in groundwater suggest that the concentration of contaminants in groundwater increased downgradient of the treatment area when the system first started operation in November 1994, and then again when hot water was continuously injected in July 1995. For example, the highest TRPH concentrations were measured in samples collected in December 1994 and August 1995 at monitoring well S-1A. These sampling events are approximately 1 month after system startup and beginning of continuous hot water injection. This same trend is observed in the TRPH results for monitoring wells CDW-3 and CDW-4.

Postdemonstration concentrations of TRPH, BTEX, and PAHs in groundwater from monitoring wells S-1A, CDW-3, and CDW-4 were all substantially lower than predemonstration concentrations. The exception is monitoring well CDW-2, where postdemonstration samples had higher concentrations of BTEX and PAH and a lower concentration of TRPH than the predemonstration samples.

These groundwater data indicate that the CROW process may cause short-term increases in contaminant concentrations downgradient of the treatment area.

4.2.5 Objective S-1: Record CROW Process Operational Parameters

The goal of this objective was to obtain data on CROW process performance. The following sections discuss the objective, methods for evaluating the objective, and the results.

4.2.5.1 Discussion of Objective

The data documenting the operational parameters were collected by the data acquisition and control system. The operational parameters that were measured consisted of temperature of injected water and recovered groundwater; injection pressure; recovery well pressure; and the water flow rate for recovery wells, injection wells, recycled water, and treated water. These data were used to evaluate the pore volume flushing rates and the thermal equilibration rate in the aquifer.

4.2.5.2 Results

Beginning in July 1995, hot water injection was established and was nearly continuous until shutdown in June 1996. During this period, 9.5 x 10^6 gallons of water at an average heater outlet temperature of 147°F was injected. Figure 4-5 shows the hot water injection and extraction rates and the cumulative pore volumes injected and extracted over the 366-day-test. The average injection and extraction rates for the hot-water injection period were 19.6 and 24.0 gpm, respectively. The groundwater extraction rate exceeded the total water injection by approximately 4 gpm throughout the test to provide hydraulic containment and recovery of the injected hot water. The affected pore volume was considered the area heated to 150°F, with a thickness of 20 feet and a porosity of 35 percent. The pore volume was estimated at 455,000 gallons. Over the 366-day period, 20.8 pore volumes were injected into the treatment area and a total of 25.5 pore volumes were extracted from the treatment area.

Initial thermal equilibration in the aquifer was reached approximately 30 days after continuous hot water injection was established. Profiles of total water injection rate, average injected water temperature, and average extracted water temperature are shown in Figure 4-5. Aquifer temperatures in extraction well water reached 120°F after 30 days and 130°F after about 50 days. Normal extraction water temperatures ranged from 130 to 140°F during the remainder of the test (see Figure 4-6).

4.2.6 Objective S-2: Evaluate CROW Process Cost

The goal of this objective was to determine the costs incurred while installing, operating, and decommissioning the CROW system. The following sections discuss the objective, methods for evaluating the objective, and the results.

4.2.6.1 Discussion of Objective

The cost to implement the CROW process at the Brodhead Creek Superfund site was determined by assessing the following 12 cost categories.

1. Site preparation
2. Permitting and regulatory requirements
3. Mobilization and startup
4. Equipment
5. Labor
6. Supplies
7. Utilities
8. Effluent treatment and disposal
9. Residual waste shipping and handling
10. Analytical services
11. Maintenance
12. Site demobilization

4.2.6.2 Results

The actual costs associated with the implementation of the CROW Process SITE demonstration at the Brodhead Creek Superfund site are presented and analyzed in Section 3. The demonstration costs are grouped into 12 cost categories, and a breakdown of these costs under the 12 cost categories is presented in Table 3-1 and Figure 3-1.

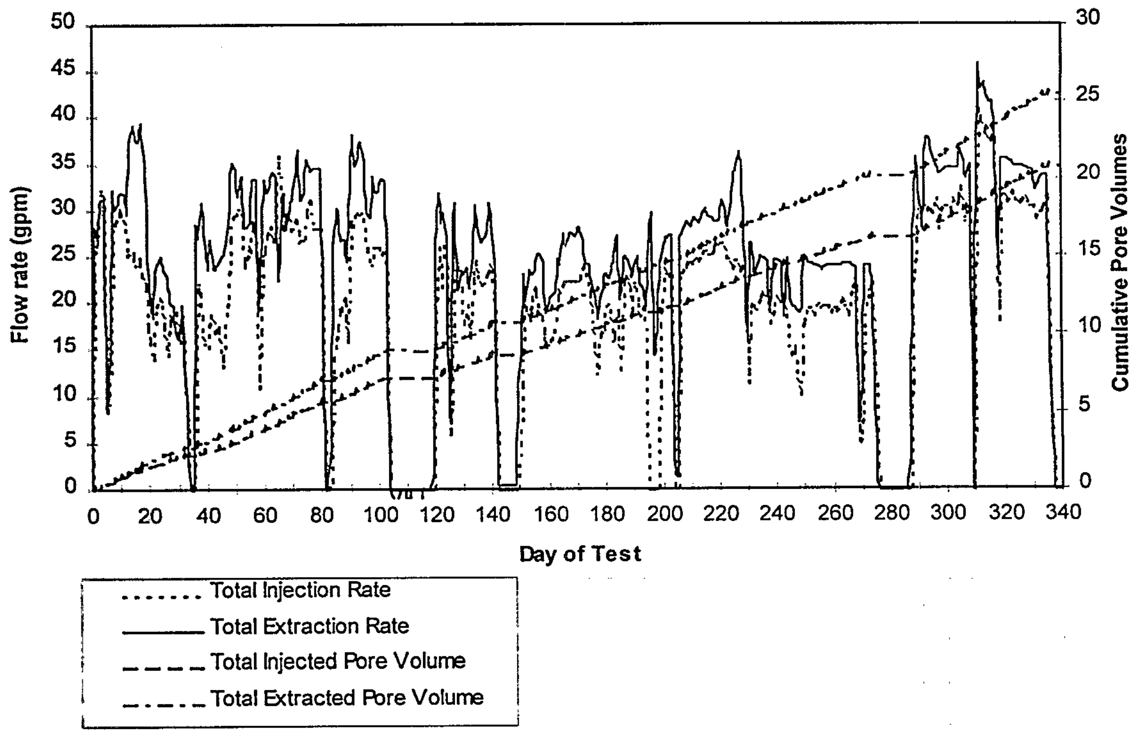


Figure 4-5. Pore volume flushing rates.

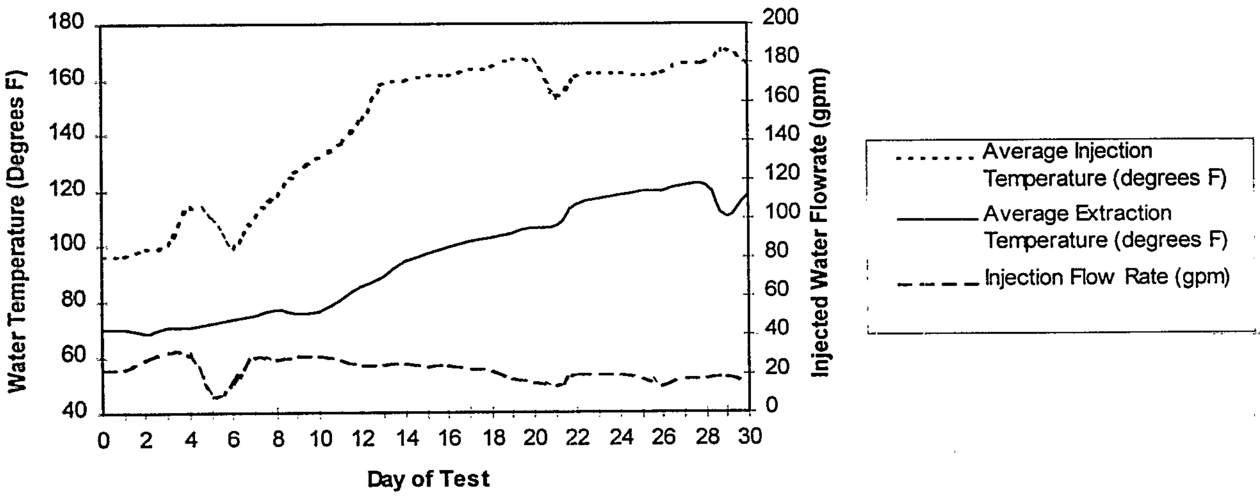


Figure 4-6. Thermal response at hot water flushing startup.

4.2.7 *Objective S-3: Assess Potential Fractionation of Coal Tar*

The goal of this objective was to determine whether the CROW process preferentially removed more mobile contaminants. The following sections discuss of the objective, methods for evaluating the objective, and the results.

4.2.7.1 Discussion of Objective

The soil samples required to evaluate coal tar fractionation were collected and analyzed with the soil samples required to assess the primary objectives. Five soil samples were collected from below the water table before the demonstration and four adjacent soil samples were collected after the demonstration. A fifth postdemonstration sample was mistakenly collected at the wrong depth interval. Before the demonstration, the soil samples were collected from the nine soil borings (Figure 4-4) installed to evaluate the primary objectives. The exact location was determined by the site geologist after a sufficient volume of sample was collected. After the demonstration, samples were collected adjacent to the samples collected before the demonstration.

The analytical suite for these samples was limited to BTEX and PAHs. To evaluate whether fractionation occurred, the ratio of total BTEX to total PAHs was calculated. In addition, the ratio of the total concentration of two- and three-ring PAHs to the total concentration of four- and five-ring PAHs was calculated. It was presumed that heating of contaminated soil areas as a result of the CROW process might cause lower density contaminants (BTEX and 2- and 3-ring PAHs) to physically separate or fractionate from heavier constituents. Physical separation of these lower viscosity fluids might allow them to more freely move to groundwater extraction points. The expected analytical variability from adjacent samples was estimated at approximately 20 percent, and it was assumed that changes in mean ratios greater than 30 percent would indicate that the CROW process fractionates the coal tar.

4.2.7.2 Results

The results of the soil boring analyses are shown in Table 4-6 and indicate no consistent pattern of changes in contaminant ratios. Large changes in the ratios of total BTEX to total PAHs concentrations were indicated, ranging from a 90 percent decrease to a 1,348 percent increase; however, it is not clear what phenomenon is responsible for the changes. Increases in ratios at soil borings CB3 and CB6 were primarily the result of increases in BTEX concentrations. Decreases in ratios at CB7 and CB9 were the result of both increases in PAH concentrations and decreases in BTEX concentrations. In addition, large changes were indicated at CB7 and CB9, where little or no effective hot water injection occurred. Although ratios of total 2- and 3-ring PAHs to total 4- and 5-ring PAHs at the four sampling locations were more comparable to each other than the total BTEX to total PAH ratios, percent changes at CB6, CB7, and CB9 were within the 20 percent variability considered expected. The 30 percent decrease in ratios of total 2- and 3-ring PAHs to total 4- and 5-ring PAHs at CB3 may indicate fractionation; however, these results are not corroborated by the results at the other sampling locations. The results

Table 4-6. Predemonstration and Postdemonstration Contaminant Ratios

	Ratio of Total BTEX to Total PAHs			Ratio of 2- and 3-Ring PAHs to 4- and 5-Ring PAHs		
Soil Boring	Pre-demonstration	Post-demonstration	Percent Change	Pre-demonstration	Post-demonstration	Percent Change
CB3	0.02299	0.33538	+1,359%	3.5872	2.5146	-30%
CB6	0.02392	0.13194	+452%	2.6273	2.6497	+1%
CB7	0.01062	0.00018	-98%	1.9400	1.7284	-11%
CB9	0.05764	0.00550	-90%	1.3376	1.1452	-14%

of the data analysis are inconclusive regarding coal tar fractionation due to the CROW process.

4.2.8 Objective S-4: Assess Water Treatment System Effectiveness

The goal of this objective was to determine whether the water treatment system effectively removed the contamination prior to discharge. The following sections discuss the objective, methods for evaluating the objective, and the results.

4.2.8.1 Discussion of Objective

Effluent water samples were collected at the treatment system discharge and were chemically analyzed to determine compliance with PADER discharge requirements. These monitored parameters included BTEX, PAHs, pH, biochemical oxygen demand (BOD), chemical oxygen demand (COD), oil and grease (O&G), total suspended solids (TSS), total phenols, and TOC. Process water was sampled at three locations. Figure 4-3 provides a schematic diagram of the water treatment system. The first sampling location, SP22, was located downstream of the oil separator tank and represented pretreatment conditions. The second sampling location, SP23, was located downstream of the GAC-FBR treatment unit and upstream of the carbon adsorption units. The third sampling location, SP29, was located after the carbon adsorption treatment unit and represented discharge water quality. These three sampling locations, but specifically SP23 and SP29, were used to monitor the ability of the water treatment system to conform to PADER discharge requirements. When the system started operation, samples were collected once per week. Samples were collected once per 2 weeks after the system started steady-state operation in July 1995.

4.2.8.2 Methods

Process water samples were collected from three locations: SP22, SP23, and SP29. SP22 was located after tank 5 and before the water was heated and reinjected. SP23 was located after the GAC-FBR unit and before the carbon adsorption units. SP29 was located just before the treated water was discharged to Brodhead Creek.

Samples were collected from SP22 to measure the concentrations of TRPH, BTEX, and PAHs that were being reinjected into the treatment area. The CROW process started operation on November 9, 1994. From November 10, 1994 through February 16, 1995, samples were collected from SP22 once or twice per week. In late February through mid-March 1995, the CROW process was shut down to replumb the tank farm, redevelop the injection wells, and clean the process piping. The system again started to pump water in late March 1995. Samples were collected from SP22 once every 2 weeks until early July 1995, when the heater was turned on. Samples were collected from SP22 once per week or once every other week from July 12 through August 16, 1995. Samples were collected once every 2 to 3 weeks from October 4 through December 6, 1995. No demonstration samples were collected after December 6, 1995.

Samples were collected from SP23 and SP29 to assess the performance of the water treatment system. Samples were collected at both locations once per week from November 9, 1994 through February 16, 1995. Samples were not collected again until after the CROW process had started steady-state operation in early July 1995. Samples were collected on July 27 and August 16, 1995 and once every 2 weeks from October 4 through December 6, 1995. No samples were collected from SP23 and SP29 after December 6, 1995.

4.2.8.3 Results

Figures 4-7 and 4-8 present comparisons of total BTEX and total PAH sampling analytical results, respectively, at the three sampling locations. As illustrated by these figures, the water treatment system was successful at reducing contaminant concentrations throughout most of the demonstration. On average, total BTEX concentrations were reduced by more than 98 percent by the GAC-FBR system and by more than 99.9 percent before discharge. Total PAH concentrations were reduced by an average of more than 96 percent by the GAC-FBR system and by more than 98 percent before discharge. Some elevated concentrations of PAHs were detected in the treated water discharge during system startup and in the later part of the test.

Throughout the demonstration, measured BTEX and PAH concentrations at SP29 were compared with the federal MCLs. All BTEX concentrations were below the MCL. The only PAH with a promulgated MCL is benzo(a)pyrene (BaP). As shown in Figure 4-9, detectable concentrations of BaP above the MCL of 0.2 microgram per liter (mg/L) were measured during the demonstration in 10 of 22

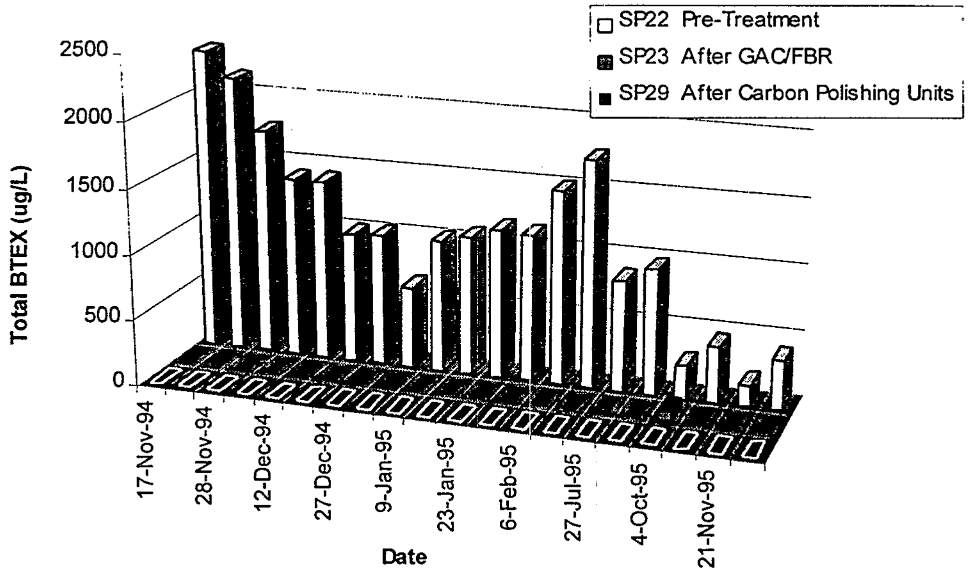


Figure 4-7. Water treatment system BTEX sampling results.

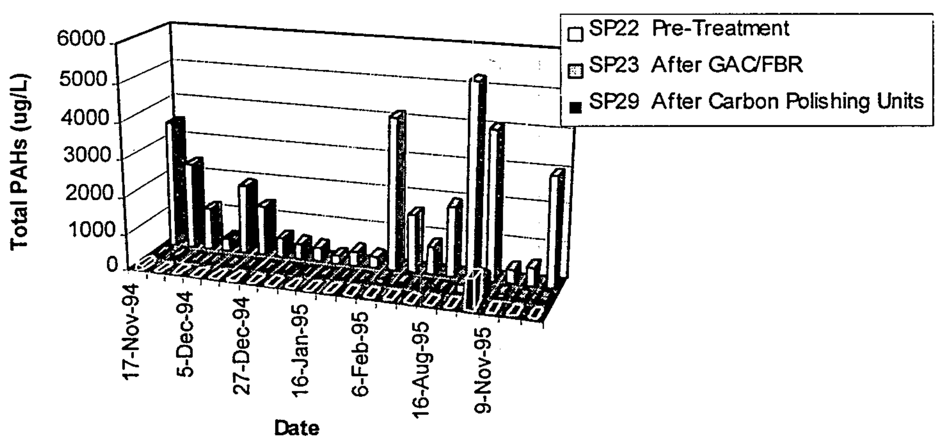


Figure 4-8. Water treatment system PAH sampling results.

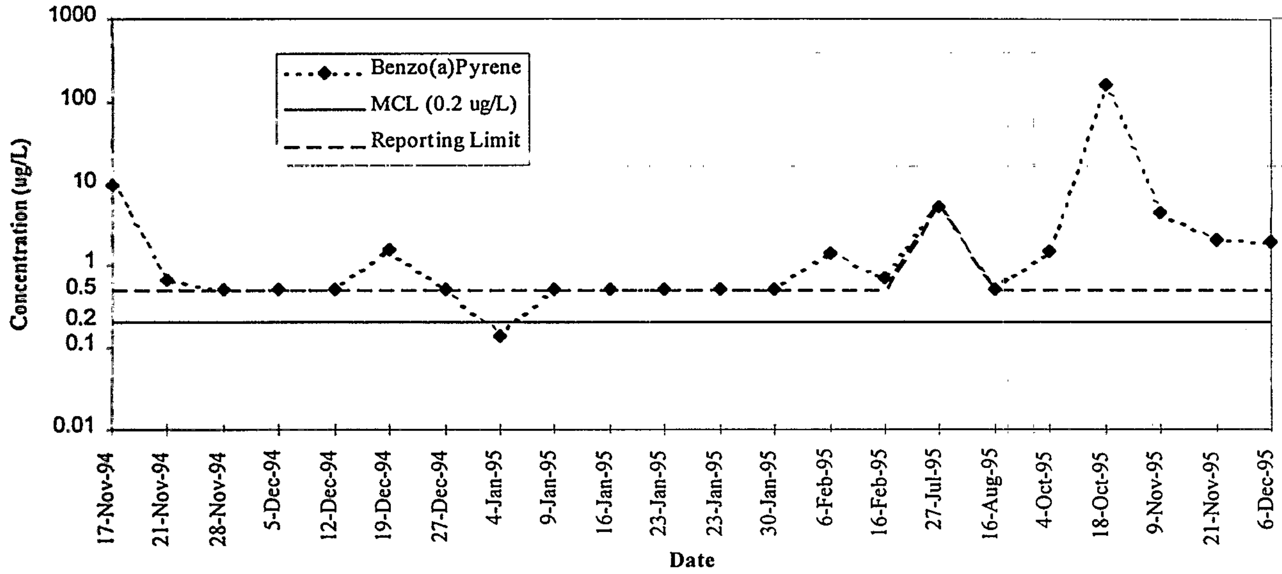


Figure 4-9. Water treatment system benzo(a)pyrene discharge concentrations.

sampling events. During the demonstration, the analytical detection limit for BaP of 0.5 mg/L or greater was also above the MCL. Therefore, BaP concentrations could have been above the MCL when analytical results were reported as not detected.

Throughout the demonstration, measured concentrations of PAH, BTEX, pH, BOD, COD, TSS, and total phenols at SP29 were compared with the PADER effluent limits established for the discharge of process water to Brodhead Creek. The PADER daily maximum effluent limits and analytical results for two sampling events with elevated PAH concentrations are presented in Table 4-7.

Detectable concentrations of PAHs above the effluent limits were measured throughout the demonstration. Limits for the following PAHs were exceeded the greatest number of times: benzo(g,h,i)perylene (10 of 22 sampling events), BaP (at least 10 of 22 sampling events), and pyrene (8 of 22 sampling events). During the demonstration, the analytical detection limit of 0.5 mg/L or greater was above the effluent limits for benzo(g,h,i)perylene and BaP. This makes it impossible to determine if concentrations of benzo(g,h,i)perylene and BaP exceeded the discharge standards at other times or if the water treatment system was able to reduce these concentrations to conform with the effluent limits prior to discharge. In addition, the analytical detection limit was above the discharge standard for anthracene, fluoranthene, indeno(1,2,3-cd)pyrene, phenanthrene, and pyrene on two occasions. The analytical detection limit was below the effluent limits for these parameters during the rest of the demonstration. The sample with the highest measured PAH concentration (823.6 mg/L) was collected on October 18, 1995, approximately 13 weeks after the start of hot water injection.

All BTEX concentrations were below the discharge standards. All pH measurements during the demonstration were within the effluent limit. All TSS and total phenols concentrations were below the discharge limits except those samples collected on October 18, 1995. The combined BOD/COD effluent limit was exceeded on August 16, 1995; October 18, 1995; and November 9, 1995. All three exceedances occurred after the injection of hot water started.

4.2.9 Evaluate Hydrologic Capture Zones

The goal of this objective was to evaluate whether the CROW process recovery wells were able to recover the

Table 4-7. PADER Effluent Limits for the CROW Process Demonstration

Parameter	Daily Maximum (µg/L)	SP29 - November 17, 1994 (µg/L)	SP29 - October 18, 1995 (µg/L)
Benzene	10.0	5.0 (U)	3.5
Toluene	20.0	5.0 (U)	0.5 (U)
Ethylbenzene	10.0	5.0 (U)	0.5 (U)
Acenaphthene	20.0	9.3 (J)	7.8
Acenaphthylene	20.0	10.0	130 (E)
Anthracene	2.00	5.0	47.0
Benzo(a)anthracene	20.0	9.2	18.0
Benzo(a)pyrene	0.24	10.0	160 (E)
Benzo(g,h,l)perylene	0.18	2.3 (J)	35.0
Chrysene	20.0	8.6	60.0
Dibenzo(a,h)anthracene	20.0	5.0 (U)	13.0
Fluoranthene	2.20	9.1	5.5
Fluorene	20.0	6.5	18.0
Indeno(1,2,3-cd)pyrene	2.00	2.8 (J)	34.0
Naphthalene	6.00	6.1	0.5 (U)
Phenanthrene	2.80	13.0	13.0
Pyrene	1.96	13.0	150 (E)
Total Phenol	20.0	5.0 (U)	64.6
BOD/COD	50,000	5.0 (U)	148,800
TSS	16,000	5.0 (U)	95,800
pH	6-9 at all times	7.55	6.37

Notes:

U Compound not detected at concentration shown.
J Estimated concentration.
E Concentration exceeded calibration range.

injected water. The following sections discuss the objective, methods for evaluating the objective, and the results.

4.2.9.1 Discussion of Objective

The objectives of groundwater modeling at the Brodhead Creek Superfund site were to determine (1) the extent of capture by the on-site extraction wells (PW-1 and PW-2), and (2) whether water that is reinjected using on-site injection wells (IW-1, IW-2, IW-3, IW-4, IW-5, and IW-6) is completely captured by the on-site extraction wells.

4.2.9.2 Methods

A conceptual model of the site hydrogeology was formulated before a computer code was selected to simulate capture zones and reinjection water flow paths. A conceptual model describes the components of the groundwater flow system and is developed from regional, local, and site-specific data. Flow system components include parameters such as groundwater flow direction and gradient, aquifer thickness, and water transmitting properties. Development of a conceptual model was necessary before constructing a computerized groundwater flow model.

The conceptual model was formulated to organize existing field data so that the groundwater flow system could be analyzed more readily. The conceptual model was simplified as much as possible; however, enough complexity was retained to simulate groundwater system behavior adequately for the intended purposes of modeling (Anderson and Woessner 1992). The conceptual model for the site was developed using all existing data and information. Model assumptions that were applied are listed below.

Assumptions Required for Use in Analytical Models:

- The aquifer is homogeneous and isotropic
- Groundwater flow is horizontal, unidirectional, and at a steady state

Assumptions Based on Available Field Data:

- The hydraulic conductivity is equal to 129.6 feet per day (ft/d)
- The saturated thickness of the aquifer is equal to 10 feet
- The transmissivity equals 1296 square feet per day (ft^2/d)
- The magnitude of the hydraulic gradient is equal to 0.0036 ft/ft
- The levee core to the east of the site treatment area can be modeled as a no-flow boundary condition
- The hydraulic gradient direction is primarily to the south, and parallel to the levee core
- The aquifer porosity is equal to 0.30 (unitless)
- The groundwater seepage velocity is 1.56 ft/d, or about 569 feet per year. This estimate is based on an average hydraulic conductivity of 129.6 ft/d, a hydraulic gradient of 0.0036 ft/ft, and an effective porosity of 0.30, using a variation of Darcy's Law (Fetter 1980).

The calculation used to determine these parameters is as follows:

$$Q = (K \times I) / n_e$$

where:

Q = seepage velocity, or pore water velocity (ft/d)
K = hydraulic conductivity (ft/d)
I = hydraulic gradient (ft/ft)
n_e = effective porosity (unitless)

The Well Head Protection Area (WHPA) model (Blandford and Huyakorn 1991) was selected to simulate capture zones and reinjection water flow paths associated with site activities. The WHPA model is a semianalytical program based on superposition of mathematical solutions for groundwater movement that would result from pumping extraction or injection wells in the presence of a regional hydraulic gradient. The WHPA model delineates capture zones associated with discharging extraction wells and flow paths associated with reinjection water using a particle tracking technique. A particle is viewed as an individual molecule of water or molecule of a conservative tracer that moves through the aquifer coincident with the bulk movement of groundwater flow. Time-related capture zones are obtained by tracing the pathlines formed by a series of particles placed around the well bore of the pumping well. These particles are either forward- or reverse-tracked with time. The WHPA model is EPA-approved and is widely used in the public domain. It is distributed and supported by the International Groundwater Modeling Center (IGWMC) in Golden, Colorado.

4.2.9.3 Results

Capture zones and reinjection water flow paths were analyzed for this pumping and reinjection scenario using the WHPA model code. The flow rate data from the data acquisition system was evaluated and average flow rates for the extraction and injection wells were calculated. For this scenario, extraction wells PW-1 and PW-2 discharge at 5.9 gpm and 24.3 gpm, respectively. Water is reinjected into the aquifer at the following rates: IW-1 (8.7 gpm); IW-2 (6.4 gpm); IW-3 (0.0 gpm); IW-4 (0.0 gpm); IW-5 (0.0 gpm); and IW-6 (6.0 gpm). Simulated capture zones for the two discharging wells and flowpaths for the reinjected water from the three active reinjection wells are provided in Figure 4-10. This figure indicates that all reinjected water is captured by the two on-site extraction wells.

4.2.10 Quality Control Results

A data quality assessment was conducted to evaluate the field and laboratory QC results, evaluate the impact of all QC measures on the overall data quality, and remove all unusable values from the investigation data set. The results of this assessment were used to produce the known, defensible information employed to define the investigation findings and to draw conclusions. The QC data were evaluated with respect to the QA objectives defined in the CROW Process DP/QAPP (PRC 1994).

The analytical data for groundwater, process water, and soil samples collected during the CROW Process demonstration were reviewed to ensure that all laboratory data generated and processed are scientifically valid, defensible, and comparable. Data verification was conducted using both field QC samples and laboratory QC samples. The field QC samples included equipment blanks, field blanks, trip blanks, matrix spike/matrix spike duplicates (MS/MSD), and sample duplicates. Laboratory QC samples included blank spike/blank spike duplicates (BS/BSD), and laboratory control sample/laboratory control sample duplicates (LCS/LCSD). Initial and continuing calibration results were also analyzed to assure the quality of the data and that proper procedures were used. The results of these samples were used to calculate the precision, accuracy, completeness, representativeness, and comparability of the data.

The following items were evaluated during the data review:

- Sample chain-of-custody condition and holding times
- Instrument performance check (gas chromatograph/ matrix spike [GC/MS] volatile and semivolatile analysis)
- Initial and continuing calibrations
- Surrogate spike recoveries (GC/MS volatile and semivolatile analysis)
- Blanks (trip, field, and laboratory)
- BS/BSD recoveries and precision
- MS/MSD recoveries and precision
- LCS/LCSD recoveries and precision
- Sample/sample duplicate precision

The following subsections summarize the limitations of analytical data based on the evaluation of QA/QC samples and discuss whether data quality objectives were met. For the critical parameters of interest, analytical data was investigated and conclusions regarding the validity of sample results are presented below. Review of the overall data packages indicates that the data are useful for the purpose of evaluating the technology. Table 4-8 presents the percentage of useable data based on a review of the QC results. Although there were QC issues in the analytical results for the predemonstration soils, enough data were of acceptable quality to allow comparison with the postdemonstration soils results and to evaluate changes in contaminant concentrations.

Soil Samples

Soil samples were analyzed for TRPH to evaluate primary objectives P-1, P-3, and P-4. A select number were also analyzed for SVOCs and VOCs to evaluate secondary

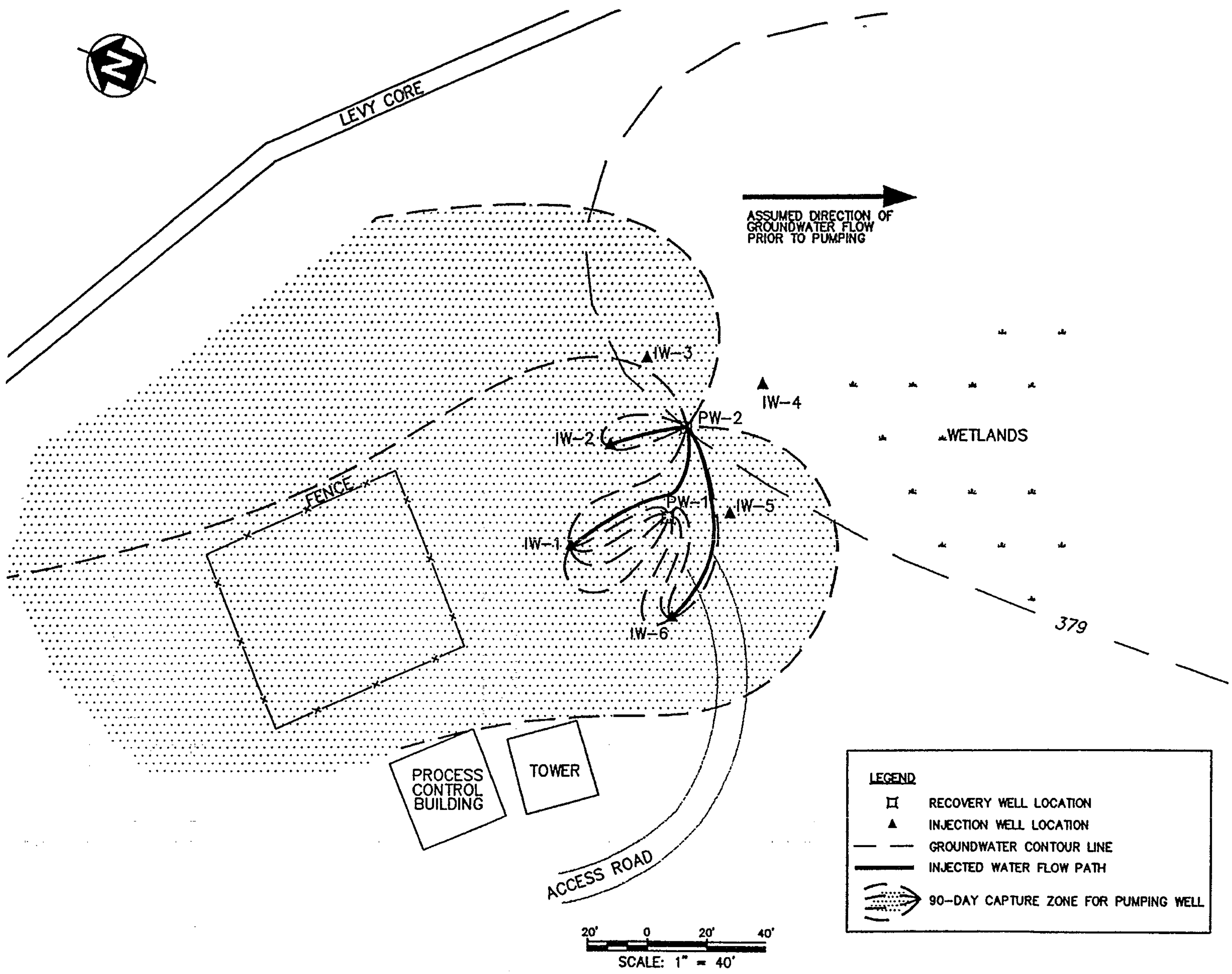


Figure 4-10. Capture zone and flow line analyses.

Table 4-8. Percentage of Useable Data

Matrix	Critical Parameters	Predemonstration [a]	Demonstration [a]	Postdemonstration [a]
Soil	TRPH	91% [b]	Not Conducted	100%
Groundwater	TRPH	100%	100%	100%
	BTEX	100%	100%	100%
	PAHs	100%	100%	100%
Process water	TRPH	Not Conducted	100%	Not Conducted
	BTEX	Not Conducted	100%	Not Conducted
	PAHs	Not Conducted	100%	Not Conducted

Notes:

[a] The completeness goal for the demonstration was 90 percent.
[b] Data were rejected (9%) due to method blank contamination - rejected data were less than five times the method blank concentration.

objective S-3. The predemonstration soil samples were analyzed by Versar Laboratories in Springfield, Virginia and Radian Analytical Services in Austin, Texas. The samples were analyzed for the critical parameter TRPH by EPA method 418.1. Versar analyzed the samples in five sample data groups (SDG). Radian analyzed the samples in one SDG. Table 4-9 presents a summary of the Versar and Radian data quality information. There are no apparent QA/QC problems with the Radian data. All blank, calibration, LCS, duplicate, and MS data are within acceptable limits.

Some data quality issues were associated with the Versar data. SDG 15 was extracted on April 20, 1994, and analyzed on May 10, 1994. SDG 15 includes the samples collected from borings CB2, CB3, CB4, CB5, CB9, CB12, and CB13. The data from borings CB2, CB3, CB4, CB5, and CB9 were used to evaluate objectives P-1 and P-3. The data from borings CB12 and CB13 were used to evaluate objective P-4. Due to low recoveries for the initial calibration verification standard and MS samples, the instrument was recalibrated and the SDG was reanalyzed. The reanalysis also exhibited low MS recoveries. Since the calibration, LCS, and BS recoveries were acceptable, the low MS recoveries were likely due to matrix effects. The low MS recoveries suggest that the data from these sample runs are biased low. Splits of 10 samples were analyzed in SDG 15 and by Radian. For seven of the 10 samples, the TRPH concentration reported by Radian was lower than the concentration reported by Versar. Comparison to the Radian data suggests that the SDG 15 data are not biased low.

SDG 16 was extracted on April 22, 1994, and analyzed on May 16, 1994. SDG 16 includes the samples collected from boring CB8, and the data were used to evaluate objectives P-1 and P-3. The method blank contained TRPH ata concentration of 58.9 mg/kg and MS recoveries were relatively low (59 to 62.2 percent). Since the calibration, LCS, and BS recoveries were acceptable, the low MS recoveries are likely due to matrix effects. The low MS recoveries suggest that the data from these sample runs are biased low. However, the contamination in the method blank suggest that the data could be biased high.

The sample and duplicate results for sample CB815516 were qualified estimated nondetect since the reported concentrations were less than 5 times the amount of blank contamination. Splits of three samples were analyzed in SDG 16 by Radian. All three TRPH concentration reported by Radian were lower than the concentration reported by Versar. Comparison to the Radian data suggests that the SDG 16 data are not biased low.

Table 4-9. TRPH Analytical Quality Assurance Data

Laboratory	Sample Data Group	Holding Times	ICV and CCV Recovery (percent)	Method Blank TRPH Concentration (mg/kg)	LCS Recovery (percent)	Duplicate RPDs (percent)	MS Recovery (percent)	BS Recovery (percent)
Versar	15	Met	87 to 101	<5	105	Laboratory duplicate 9.9 to 35.5; MSD 7.9 to 23.2; BSD 50	-48 to -0.6	106 to 176
	15 Reanalysis	Met	110 to 112	<5	90	Laboratory duplicate 4.2 to 29.7; MSD 5.3 to 23.1; BSD 50	-47 to 2.8	122 to 127
	15 Reextraction reanalysis	Exceeded by >15 days	105 to 109	25.3 to 28.3	113	Laboratory duplicate 0.2 to 1.7; MSD 0.9 to 61.7	-209 to 374	NA
	16	Met	109 to 112	59.8	119	Laboratory Duplicate 18.2; MSD 3.1; BSD 16.7	59 to 62	95 to 113
	16[a] Reextraction reanalysis	Exceeded by >14 days	105 to 106	99 to 103	160	Laboratory Duplicate 34.4; MSD 15	88.7 to 112	NA
	17	Met	104 to 105	37.4	102	Laboratory Duplicate 5.1; MSD 5.2; BSD 1.4	1.5 to 1.7	111 to 113
	17[a] Reextraction reanalysis	Exceeded by >14 days	104 to 106	99 to 103	160	Laboratory Duplicate 37.9; MSD 1.1	83 to 90	NA
	18	Met	99 to 99	39.8	101	Laboratory Duplicate 12.4; MSD 1.7; BSD 5.6	1.3 to 2.2	99 to 104
	18[a] Reextraction reanalysis	Exceeded by >14 days	103 to 106	99 to 103	160	Laboratory Duplicate 3.4; MSD 15.4	131 to 260	NA
	21	Met	94 to 95	<5	133	Laboratory Duplicate 16.8; MSD 24.4 BSD 0.3	-1.3 to 2.5	112 to 112
	21 Reextraction reanalysis	Exceeded by >15 days	100 to 106	10.8	99	Laboratory Duplicate 23.3; MSD 3.2	535 to 618	NA
Radian	NR	Met	NA[b]	<5	110 to 127	Laboratory Duplicates 1.4 to 2.0	105 to 112	NA
Columbia	9708000220	Met	NA	<33	NA	Laboratory Duplicate 12	55	96 to 104
	9709000100	5 samples - 4 days out	NA	<33	NA	Laboratory Duplicates 7 to 15	112 to 293	105 to 112

Notes:

[a] The reextraction and reanalysis of sample data groups 16, 17, and 18 were completed at the same time.
[b] Calibration data for standards were acceptable.

SDG 17 was extracted on April 28, 1994, and analyzed on May 17, 1994. SDG 17 includes the samples collected from borings CB6 and CB7. The data from these borings were used to evaluate objectives P-1 and P-3. The method blank contained 37.4 mg/kg and MS recoveries were low (1.5 to 1.7 percent). Since the calibration, LCS, and BS recoveries were acceptable, the low MS recoveries are likely due to matrix effects. The low MS recoveries suggest that the data from these sample runs are biased low. However, the contamination in the method blanks suggests that the data could be biased high. The results for samples CB612513, CB627528, CB716517, and CB730305 were qualified estimated nondetect since the reported concentrations were less than 5 times the amount of blank contamination. Splits of two samples were analyzed in SDG 17 and by Radian. In one sample, the TRPH concentration reported by Radian was lower than the concentration reported by Versar. Comparison to the Radian data suggests that the SDG 17 data are not biased low.

SDG 18 was extracted on April 30, 1994 and analyzed on May 18, 1994. SDG 18 includes the samples collected from borings CB1, CB10, and CB11. The data from boring CB1 were used to evaluate objectives P-1 and P-3. The data from borings CB10 and CB11 were used to evaluate objective P-4. The method blank contained 39.8 mg/kg and MS recoveries were low (1.3 to 2.2 percent). Since the calibration, LCS, and BS recoveries were acceptable, the low MS recoveries are likely due to matrix effects. The low MS recoveries suggest that the data from these sample runs are biased low. However, the contamination in the method blanks suggests that the data are biased high. No sample data were qualified due to the method blank contamination. Splits of four samples were analyzed in SDG 18 and by Radian. In three samples, the TRPH concentrations reported by Radian were lower than the concentrations reported by Versar. Comparison to the Radian data suggests that the SDG 18 data are not biased low.

SDG 21 was extracted on May 17, 1994, and analyzed on May 20, 1994. SDG 21 includes one sample collected from boring CB11 and the data were used to evaluate objective P-4. The MS recoveries were low (-1.3 to 2.5 percent). Since the calibration, LCS, and BS recoveries were acceptable, the low MS recoveries are likely due to matrix effects. The low MS recoveries suggest that the data from these sample runs are biased low. A split of one sample was analyzed in SDG 21 and by Radian. The TRPH concentration reported by Radian was lower than the concentration reported by Versar. Comparison to the Radian data suggests that the SDG 21 data are not biased low.

The postdemonstration soil samples were analyzed by Columbia Analytical Services in two SDGs. The samples were analyzed for TRPH by EPA method 418.1. The sample cooler contents for both SDGs were received above the acceptable temperature range by the laboratory. All samples were analyzed within the specified holding time with the exception of five samples in one SDG that were analyzed 4 days past holding time. Elevated cooler temperatures and exceedance of the holding time may indicate a potential bias low. The laboratory blanks were nondetect for each SDG and the duplicate relative percent differences (RPD) were acceptable. The BS recoveries were also acceptable however, for SDG 9708000220 the MS recoveries were acceptable (112 percent) to high (293 percent) and for SDG 9709000100 the MS recovery was low (55 percent). The results for SDG 9708000220 may be biased high. The results for samples in SDG 9709000100 are likely biased low.

Five predemonstration soil samples and five postdemonstration soil samples were analyzed for BTEX and SVOCs to evaluate secondary objective S-3. The predemonstration samples were analyzed by Versar in SDGs 15 and 17. For SDG 15, all QA parameters were within acceptable levels, except that the BS recoveries were generally high while the MS recoveries for fluoranthene were low. The original analysis of SDG 17 did not include a BS/BSD and the surrogates were diluted out of all the samples. SDG 17 was reanalyzed to include a BS/BSD and surrogates at higher concentrations. All QA parameters were within acceptable levels except that the recovery of benzo(g,h,i)perylene in the MS/MSD and BS/BSD were low. The relatively low MS recoveries for SDGs 15 and 17 suggest that the SVOC data are biased low. There is no apparent bias for the VOC data.

The postdemonstration SVOC and VOC samples were analyzed by Columbia Analytical Services. The samples were analyzed in two SDGs. The temperatures inside the coolers when they arrived at the laboratory were elevated for both SDGs. Elevated cooler temperatures may indicate a potential bias low. All other QA parameters were acceptable for SDG 9708000220. There is no apparent bias for the SVOC or VOC data. For SDG 9709000100, two VOC and SVOC samples were analyzed outside of holding time (between 11 and 17 days). The VOC data may be biased low due to analysis after the holding time. The 2-fluorobiphenyl surrogate recovery and the acenaphthalene, fluoranthene, and pyrene MS were high. The SVOC data are therefore likely biased high.

Groundwater Samples

Groundwater samples were collected to evaluate demonstration objective P-4. The predemonstration and demonstration groundwater samples were analyzed by Columbia Analytical Services. The postdemonstration groundwater samples were also analyzed by Columbia Analytical Services. One predemonstration SDG and 13 demonstration SDGs were analyzed by GTC. Columbia Analytical Services analyzed one postdemonstration SDG.

All predemonstration groundwater samples were analyzed for the critical parameters TRPH by EPA method 418.1, BTEX by SW-846 method 8260, and PAHs by SW-846 method 8270A. The sample cooler contents were received within the acceptable temperature range by the laboratory. All samples were extracted and analyzed within the specified holding times. The initial and continuing calibrations were acceptable for all samples, and all tuning criteria for bromofluorobenzene (BFB) and decafluorotriphenylphosphine (DFTPP) were within limits. All field and laboratory blanks for the predemonstration groundwater samples were acceptable. Accuracy was evaluated by calculating the percent recovery of the BS, MS, LCS, and surrogates. Precision was determined through the use of BS/BSD pairs, MS/MSD pairs, and sample/sample duplicate pairs. Accuracy and precision were within QC limits with the exception of low terphenyl-d14 (20 to 30 percent) and high nitrobenzene-d5 (131 to 167 percent) semivolatile surrogate recoveries. The outliers, however did not significantly affect data quality, and all of the data are considered adequate for the intended use and without significant bias.

All demonstration groundwater samples were analyzed for TRPH by EPA method 418.1, BTEX by SW-846 method 8260, and PAHs by SW-846 method 8270A. Two SDGs were not analyzed for BTEX. The sample cooler contents for all SDGs were received within the acceptable temperature range by the laboratory. All samples were extracted and analyzed within the specified holding times, except one PAH sample from well CDW-2, collected on November 21, 1994, and the BETX samples from wells S-1A and CDW-1, collected on January 16, 1995, were analyzed 1 day past holding time. Missing the holding time by 1 day should not significantly bias the data. The initial and continuing calibrations were acceptable for all samples, and all tuning criteria for BFB and DFTPP were within limits. All laboratory blanks for the demonstration groundwater samples were acceptable. The trip blanks for two SDGs were contaminated with traces of toluene and xylene, but there was no significant effect on data quality. Terphenol-d14 surrogate recovery was low (31 to 32 percent) for the sample from well CDW-1 collected on December 5, 1994 and for the sample collected from well CDW-3 collected on December 19, 1994. Nitrobenzene-d5 surrogate recovery was high (123 to 150 percent) for the sample from well CDW-4 collected on July 12, 1995 and for the sample collected from well CDW-3 collected on August 16, 1995. The SVOC MS/MSD recoveries for several compounds were high for the samples collected on December 5, 1994 and July 12, 1995. The SVOC MS/MSD recoveries for several compounds were low for the samples collected on December 5, 1994; January 4, 1995; January 16, 1995; and July 12, 1995. The VOC MS/MSD recoveries for benzene was low (40 to 60 percent) for the samples collected on January 4, 1995 and January 16, 1995. Although there were QA data outliers, data quality was not significantly affected, and all of the data are considered adequate for the intended use and without significant bias.

All postdemonstration groundwater samples were analyzed for TRPH by EPA method 418.1, BTEX by SW-846 method 8260, and PAHs by SW-846 method 8270B. The sample cooler contents were received within the acceptable temperature range by the laboratory. All samples were extracted and analyzed within the specified holding times. The initial and continuing calibrations were acceptable for all samples, and all tuning criteria for BFB and DFTPP were within limits. All field and laboratory blanks for the postdemonstration groundwater samples were acceptable. All QA data were within QC limits with the exception of acenaphthene MS recovery (8 percent). The low MS recovery is likely the result of a matrix effect. The data from the SDG with the low MS recovery are comparable to the results from other data groups. The outlier however, did not significantly affect data quality, and all of the data are adequate for the intended use and without significant bias.

Untreated Process Water Samples

Samples of the process water were collected after tank 5, prior to biological treatment (Figure 4-3) to evaluate objective P-1. They were to be used for calculating the amount of dissolved coal tar removed from and reinjected into the aquifer. Unfortunately, the major gaps in data collection prevent a meaningful utilization of these data. The untreated process water samples (SP22) were collected only during the demonstration phase of the project and were analyzed by Columbia Analytical Services. Forty-five SDGs containing results from the analysis of untreated process water samples were submitted. All samples were analyzed for the critical parameters TRPH by EPA method 418.1, BTEX by SW-846 method 8260, and PAHs by SW-846 method 8270A.

With only one exception (sample collected on April 19, 1995), the sample cooler contents for all SDGs were received within the acceptable temperature range by the laboratory. The temperature of the cooler did not result in the disqualification of any data. The only sample not extracted and analyzed within the specified holding times was for the BTEX analysis of the sample collected on January 16, 1995. The initial and continuing calibrations were acceptable for all samples, and all tuning criteria for BFB and DFTPP were within limits. All laboratory blanks for the untreated process water samples were acceptable. The trip blanks for seven SDGs were contaminated with traces of toluene and xylene, but with no significant effect on data quality. The recovery of surrogate nitrobenzene-d5 was high for the samples collected on November 10, 1994; November 17, 1994; June 14, 1995; and July 12, 1995. The recovery of surrogate terphenyl-d14 was low for the samples collected on November 21, 1994; January 6, 1995; and July 27, 1995. The SVOC MS/MSD recoveries for several compounds were high for the samples collected on November 17, 1994 and July 18, 1995. The SVOC MS/MSD recoveries for several compounds were low for the samples collected on November 17, 1994; December 22, 1994; July 18, 1995; and October 18, 1995. The VOC MS/MSD recovery for benzene was low (40 to 60 percent) for the sample collected on November 17, 1994. Although there were accuracy and precision outliers, data quality was not significantly affected, and all of the data were considered useable and without significant bias.

Treated Process Water Samples

A portion of the process water that was not heated and reinjected into the subsurface was treated using a GAC-FBR and with carbon adsorption units before discharge to Brodhead Creek. The treated process water was sampled at two locations in the treatment process to ensure conformance with PADER effluent limitations (demonstration objective S-4). The process water was sampled after the GAC-FBR (SP23 on Figure 4-3) and after the carbon adsorption units (SP29). The treated process water samples were collected only during the demonstration phase of the project and were analyzed by Columbia Analytical Services.

The treated process water samples (SP23 and SP29) were generally collected at the same time as the untreated process water sample (SP22). These samples were analyzed together with the analytical results being submitted in the same SDGs. The treated process water however, was not sampled as frequently as the untreated process water.

Twenty-three SDGs containing results from the analysis of treated process water samples were submitted. All samples were analyzed for BTEX by EPA method 524.2 and PAHs by EPA method 525. The exceptions include two SDGs (November 17, 1994 and July 27, 1995) where the samples were analyzed for BTEX by SW-846 method 8260 and PAHs by SW-846 method 8270A. All of the treated process water samples, except those in one SDG, were also analyzed for the following noncritical parameters: (1) pH by SW-846 method 1110A or EPA method 150.1, (2) BOD by EPA method 405.1, (3) COD by EPA method 410.4, (4) O&G by EPA method 413.1, (5) TSS by EPA method 160.2, (6) total phenols by EPA method 420.2, and (7) TOC by EPA method 9060A.

The sample cooler contents for all SDGs were received within the acceptable temperature range by the laboratory. The majority of the samples were extracted and analyzed within the specified holding times. Both BOD samples in one SDG, both TSS samples in a separate SDG, and both pH samples in three separate SDGs were analyzed outside of the holding time. Additionally, both PAH samples in one SDG were extracted outside of the holding time. The initial and continuing calibrations were acceptable for all samples, and all tuning criteria for BFB and DFTPP were within limits.

All laboratory blanks for the treated process water samples were acceptable. The trip blanks for five SDGs were contaminated with traces of toluene and xylene, but with no significant effect on data quality. Accuracy was evaluated by calculating the percent recovery of the BS, MS, LCS, and surrogates. Precision was determined through the use of BS/BSD pairs, MS/MSD pairs, LCS/LCSD pairs, and sample/sample duplicate pairs. Although there were accuracy and precision outliers, data quality was not significantly affected, and 100 percent of the data were considered useable.

Audit Findings

As a vital part of the QA program, two field audits and three laboratory audits were conducted by EPA to ensure that measurements associated with sampling and analysis were in conformance with the CROW Process DP/QAPP (PRC 1994). The field audit of the soil sampling was conducted on April 13, 1994 and the audit of groundwater and soil gas sampling was completed on August 23, 1994. No concerns were found during either review. The audit of the Versar Laboratory was completed on April 28, 1994. Although the auditors noted some concerns during the audit of Versar Laboratories that could affect data quality, the impact was minimized by the laboratory taking immediate and proper corrective actions. The auditors' concerns did not result in the disqualification of any data. The audit of the Radian Laboratory was completed on September 8, 1994. Four minor concerns on the TO-14 analysis of the soil gas samples were noted. The concerns were not anticipated to affect data quality. The audit of the GTC laboratory was completed on August 31, 1994. Several minor concerns that were not anticipated to affect data quality were noted.

4.3 Evaluation Conclusions

The primary demonstration objectives were to determine whether the CROW process removed coal tar from the subsurface or flushed the coal tar outside of the treatment area. The CROW process was successful in removing coal tar from the subsurface (1,504 gallons recovered), but it was unable to reduce coal tar concentrations to residual immobile levels since free-phase coal tar was present after the demonstration. Site characterization activities demonstrated that the stream gravel unit contained interlayered lenses of fine- and coarse-grained material. The water injected by the CROW process probably preferentially flowed through the coarse-grained layers, leaving the fine-grained intervals relatively untreated. Since the free-phase coal tar is perched on or in the finer grained layers, much of the coal tar was not hydraulically available for removal by the CROW process.

Groundwater samples collected downgradient of the site, and the groundwater flow and capture zone model, both suggest that the CROW process was able to recover the injected water during steady-state operation. However, the groundwater samples also show that during initial startup the changes in the ambient groundwater flow system resulted in spikes of contamination being released downgradient. Measurements of the concentration of coal tar in the soil outside of the treatment area before and after the demonstration did not show a significant change. This result suggests that the CROW process did not flush large amounts of contamination outside of the treatment area. Measurements of the amount of coal tar in the lower confining layer under the treatment area before and after the demonstration suggest that some coal tar was pushed down into the lower confining unit. This result is likely due to the increase in temperature in the treatment area that reduced the viscosity of the coal tar and allowed the coal tar to migrate into the finer grained sediments of the lower confining unit.

Section 5
Technology Status

The CROW process may be used to remove NAPL from the subsurface. At the demonstration site the CROW process failed to remove NAPL to residual, immobile levels. Waste types that may be recovered with the CROW process include coal tar, creosote, fuel oils, or other SVOCs. The CROW process has been installed at the Brodhead Creek Superfund site in Stroudsburg, Pennsylvania and the Bell Pole site in New Brighton, Minnesota. At the Brodhead Creek site, the CROW process was used to recover coal tar at an abandoned MGP. At the Bell Pole site, the CROW process was used to remove creosote and pentachlorophenol in a fuel oil carrier at a wood treating facility.

The equipment and materials necessary to install the CROW process are readily available. Prior to installation, the subsurface lithology, waste distribution, waste characteristics, and groundwater chemistry must be characterized. To complete the design, a treatability test should be conducted to optimize the extraction temperature, pumping rates, and water treatment system. Treatability testing can be completed within 2 months. Once the treatment design is completed, installation of the treatment system can take from 1 to 6 months depending on regulatory requirements, the number of injection and recovery wells, and the complexity of the water treatment system.

Section 6
References

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Appendix A
Vendor's Claims for the Technology

Nonaqueous-phase liquids have contaminated groundwater at a variety of locations in the United States. Dense organic liquids represent a special waste management problem. When these liquids are denser than water and immiscible with water, waste discharges onto the ground surface result in downward permeation through the saturated groundwater environment. This downward permeation continues until the waste penetration is blocked by an impermeable barrier. At these locations, high waste accumulations remain as long-term sources of contamination to local aquifers. For this reason, the Western Research Institute (WRI) has developed a new in situ process to contain and recover organic wastes.

A.1 Introduction

WRI's Contained Recovery of Oily Waste (CROW™) process is designed to address both lighter-than-water nonaqueous-phase liquids (LNAPL) and denser-than-water nonaqueous-phase liquids (DNAPL). The CROW process is an in situ remediation process for light and dense organic liquids such as coal tars, chlorinated hydrocarbons, and petroleum products that have contaminated groundwater at numerous industrial sites.

Lateral containment of organic waste accumulations does not stop the contamination of aquifers. Containments such as slurry walls can temporarily isolate organic wastes from lateral groundwater transport into adjacent surface waters. High waste concentrations also inhibit microbial degradation and extend the threat of lateral transport beyond the effective lifetime of the containment. During the period of containment, the organic wastes can also penetrate deeper through fractures or discontinuities in natural impermeable barriers. These deeper penetrations of organic wastes can contaminate underlying aquifers and can result in lateral transport of organic wastes underneath the surface containment.

Excavation can only remove organic waste accumulations above natural barriers. Any deeper penetrations of high waste concentrations remain as long-term sources of groundwater contamination. During excavation, workers and adjacent residents are exposed to vapor emissions from the saturated organic wastes. Exposing the bedrock may also result in long-term vapor emissions from deeper waste accumulation. In this case, removal of the natural cover can actually hinder subsequent recovery of the deeper waste accumulations.

In situ recovery and treatment of organic wastes restores both the subsurface soils and bedrock to the original condition before contamination. In this two-step process, organic wastes are first immobilized by reducing waste concentrations to residual saturation, and then the immobile wastes are degraded microbially. During the initial recovery of organic wastes, lateral containment of the site prevents contamination of adjacent surface waters. However, long-term maintenance of the lateral containment is avoided by immobilizing the organic wastes in the first step of the restoration. WRI has developed the CROW process to accomplish this crucial first step in the restoration of organic waste sites.

The initial developmental work for the CROW process was completed under the U.S. Environmental Protection Agency (EPA) Superfund Emerging Technology Program. The development consisted of several one- and three-dimensional physical simulations of the process. Based on the laboratory performance of the process, the EPA advanced the process to the Superfund Innovative Technology Evaluation (SITE) Demonstration Program, and a field-scale demonstration was conducted (the subject of this report). Further development of the process has been funded by the U.S. Department of Energy (DOE) as two separate projects. The first project was a study to determine the enhancement of the process performance by the addition of a small volume of biodegradable chemical to the injected hot water. The second project is the application of the process to LNAPL and chlorinated hydrocarbon contamination.

A.2 Technology Description

The general technical description describes the process as it applies to denser-than-water organic liquid, which will be the hardest to handle. However, the CROW process is applicable to a wider range of organic liquid densities as covered in the patent for the process.

CROW uses hot-water or steam displacement with or without chemical addition to reduce concentrations of organic wastes in subsurface soils and underlying bedrock. In the CROW process, downward penetration of dense organic liquids is reversed by controlled heating of the subsurface to suspend organic wastes in the water. The buoyant wastes are displaced to extraction wells by sweeping the subsurface with hot water. Waste flotation and vapor emissions are controlled by maintaining both temperature and concentration gradients near the ground surface. Reducing waste concentrations to residual saturation immobilizes the organic wastes and promotes complete restoration of the site using microbial degradation.

Wastewater treatment is minimized in the CROW process by reinjecting water that is recovered with the organic wastes. The hot-water or steam displacement produces a mixture of organic waste and water. After separation, the recovered water is heated and reinjected into the subsurface above any aquifers. This reinjected water is contained laterally, and cannot permeate downward when there is a rising flow of hot water from steam injection beneath the recovery operation. During the recovery operation, the net wastewater production corresponds only to steam condensation and groundwater influx. Only this net production of wastewater is treated for discharge or boiler feed.

Vapor emissions are controlled in the CROW process by maintaining both temperature and concentration gradients in the injected water near the ground surface. At some waste sites, subsurface heating may result in appreciable vapor pressures of phenols or other volatile components in the organic wastes. The concentrations of water-soluble volatiles can also increase when recovered water is reinjected without treatment. If the cooler water temperatures near the ground surface do not lower vapor pressures sufficiently, steam-stripping can reduce the concentration of volatiles in the water that is reinjected at the top level of the recovery process. In this case, the water barrier to oil flotation also serves as an absorber to reduce vapor emissions during recovery operations.

A.3 Advantages of the CROW Process Technology

The CROW process has many benefits over other technologies that remediate contaminated aquifers. The benefits of the CROW process are listed below.

- Organic recovery reduces waste management costs in comparison with either conventional containment or excavation. In some cases, the recovered organic is reusable and offsets a portion of the processing costs.
- By lowering waste concentrations in the subsurface, the process promotes natural restoration and reduces the duration of long-term containment. The injection and production wells may also be used to inject air or oxygen and nutrients for accelerating microbial degradation of residual organic wastes. During this restoration, groundwater contamination is avoided because the residual wastes have been leached and are no longer mobile.
- Controls groundwater contamination and vapor emissions by thermal gradients and well placement.
- Not limited by depth, deep contaminations even in the bedrock can be treated as well as shallow contaminations.
- Because it is an in situ process, there is minimization of the exposure of contaminated material at the surface or to personnel.
- Should be considerably faster for remediation of a site than most other processes.
- The process can also remediate an area where buildings or active facilities exist without disrupting the on going work or removing the buildings.
- No specialized equipment is required.

A.4 Treatment Systems

The treatment systems for the CROW process are designed as modular units. Each unit of the system is a commercially available unit. By using commercially available units, lower equipment costs can be realized over noncommercial units.

A.5 System Considerations and Applications

General considerations for the CROW process are (1) the contaminating organic should be free-phase in the aquifer or liquid saturated zone, (2) the hydraulic conductivity of the zone must be sufficient to allow sustained injection and production from multiple wells, and (3) the physical characteristics and depth of the contaminate area. For the best performance, the organic phase should be a continuous, free-fluid phase over the treatment area. If the contaminate is in dispersed pockets throughout the area, the CROW process would remove some of the organics, but may spread the remaining organics over the swept area. The spreading of the organics may not be a drawback because the organic will be immobile and at the lower saturation it will be more amenable to natural or induced bioremediation.

Chlorinated hydrocarbons, coal tars, and heavy petroleum products are common examples of dense organic liquids. Coal tars have been produced as byproducts in the manufacture of town gas and in coking operations by the steel industry. Creosote derived from coal tar and pentachlorophenol mixed with diesel oils have been used as wood treating preservatives. The petroleum refining, storage, and transportation industries have produced assorted petroleum based contaminants. At a variety of sites throughout the United States, these complex mixtures of dense organic liquids have leaked from tanks, ponds, ditches or other impoundments and have accumulated as organic wastes in the saturated groundwater environment.

If further remediation of a site is required, the use of bioremediation following the CROW process has been evaluated by Remediation Technologies Inc., now ThermoRetec (ReTeC). ReTeC was successful in evaluating in situ bioremediation processes for treatment of CROW conditioned soils. In addition, biological treatment of CROW process product water was demonstrated. Biological treatment of the CROW product water was incorporated into the Stroudsburg, Pennsylvania project.

A.6 Cost Considerations

The cost for application of the CROW technology is highly dependent upon the site characteristics and size, and the extent of the process monitoring required. Generally, the larger the site, the lower the treatment cost per cubic yard of contaminated soil. To give an idea of the cost range, two sites have projected costs of $34 and $350 per cubic yard of contaminated soil for a 2.6 and 0.2 acre areas, respectively. Both sites have a 20- to 30-foot-thick contaminated zone within a highly permeable aquifer. The use of the CROW process for a given site should be highly competitive with other processes, if not more cost effective.

A.7 Case Studies

Full-scale remediations of a wood treatment site is presently being conducted with the remediation of two manufactured gas plant (MGP) sites completed. One of the MGP sites is the Superfund Site located in Stroudsburg, Pennsylvania and is the subject of this report. The other MGP site is located in Columbia, Pennsylvania and consisted of the remediation of a cement capped, 60-foot-diameter by 27-foot-deep former gas relief holder. The project objective was the removal of a portion of the coal tars from the debris filled holder followed by the stabilization of the holder with grout. Closure of the site is presently in front of the EPA.

The wood treatment project is located at the Bell Lumber and Pole facilities in New Brighton, Minnesota. Construction and operation of the facility is being done by the site owner. WRI designed the treatment scheme, and monitors and evaluates the operations. The full-scale remediation is being carried out as a staged remediation using three five-spot patterns with each pattern flushed in a sequential order. Prior to implementing the full-scale project, a pilot test was operated to demonstrate the containment and organic removal features of the CROW process. The pilot test was a success in both areas. As of November 1998, over 55,000 gallons of creosote, pentachlorophenol (PCP), and a petroleum carrier fluid have been extracted from the first pattern. Half of the recovered organics have been reused in the ongoing wood treatment operations.

Also, WRI has conducted treatability studies for wood treatment, MGP, Brownfield, and chemical waste sites in several states. Included in the laboratory studies have been preliminary testing of chlorinated hydrocarbon remediation with excellent results. Laboratory tests of the process conducted for the U.S. EPA and private clients using materials from MGP and wood treatment sites indicated that 60 to 70 percent of the MGP contaminant and 84 to 94 percent of the wood treatment contaminant can be recovered at the optimum water flushing temperature. Additionally, removals of 90 percent or greater can be achieved for MGP materials if surfactants, at 1 percent or less by volume, are incorporated into the flush water.

Appendix B
Bench-Scale Testing of Brodhead Creek Superfund Site Soils

Western Research Institute (WRI) tested the CROW process effectiveness in the laboratory using one-dimensional and three-dimensional displacement tests. The reactor system used for the one-dimensional displacement tests was the tube reactor shown in Figure B1-1. The disposable chlorinated polyvinyl chloride reactor tube was uniformly packed with contaminated soil from the Brodhead Creek site and was vertically oriented within a series of insulated shield heaters. Auxiliary equipment included inlet water injection and metering devices, a water heater, product collection equipment, and a gas chromatograph. The entire system was connected to a data acquisition computer that recorded temperatures, pressures, and flow rates (WRI 1990).

Water was metered into the bottom of the reactor by a positive displacement pump. The injected water passed through a heater to generate steam or hot water. Product water samples were collected from the automatic sampling valve system. Product gas was collected from the sample vessels, and gas composition was analyzed as needed by an on-line gas chromatograph. After each test, the treated sample was extruded from the tube for sampling (WRI 990). The experimental apparatus used for the three-dimensional tests was a large, thick-walled vessel into which an encapsulated sample was placed (Figure B1-2). The vessel was sealed using screw-on domed ends. The fluid-handling system consisted of an injection system, a product-collection and sampling system, and a product gas-collection and analyzing system. The reactor instrumentation and control system consisted of flow controllers and meters; pressure regulators and transmitters; microprocessors; recorders; thermocouples; gas-analysis equipment; and a minicomputer for data collection, storage, and analysis. The injection array for the sample consisted of multiple injection points to simulate the entire CROW concept. Process-water samples were routinely collected to provide information on organic production.

The samples for the three-dimensional tests were placed in the reactor from bottom to top in the following order: (1) a base of grout to simulate an impermeable barrier, (2) a layer of resaturated site material to represent an oily waste accumulation, (3) a layer of material from the Brodhead Creek site, and (4) clean, dry sand to represent the vadose zone. Three wells were inserted in the sample, a production well in the center of the sample and an injection well at each end of the sample. The injection wells were equipped for cold-water injection in the upper 4 inches and hot-water injection in the bottom 8 inches. The cold-water layer was intended to prevent the heated contaminants from rising to the vadose region (WRI 1990).

The results of the one-dimensional tests indicated that the percent reduction in oily saturation measured in the treated soil increased up to 61.8 percent as the temperature increased to approximately 156 °F. Results of the one-dimensional tests with additions of surfactants indicated oily saturation reduction of 87 percent at 156 °F. The three-dimensional test without addition of surfactants produced a 60 percent reduction in the oily saturation at 140°F (WRI 1990).

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Western Research Institute, 1990. Contained Recovery of Oily Wastes (CROW) Final Report. August.

SOURCE: Modified from WRI 1990

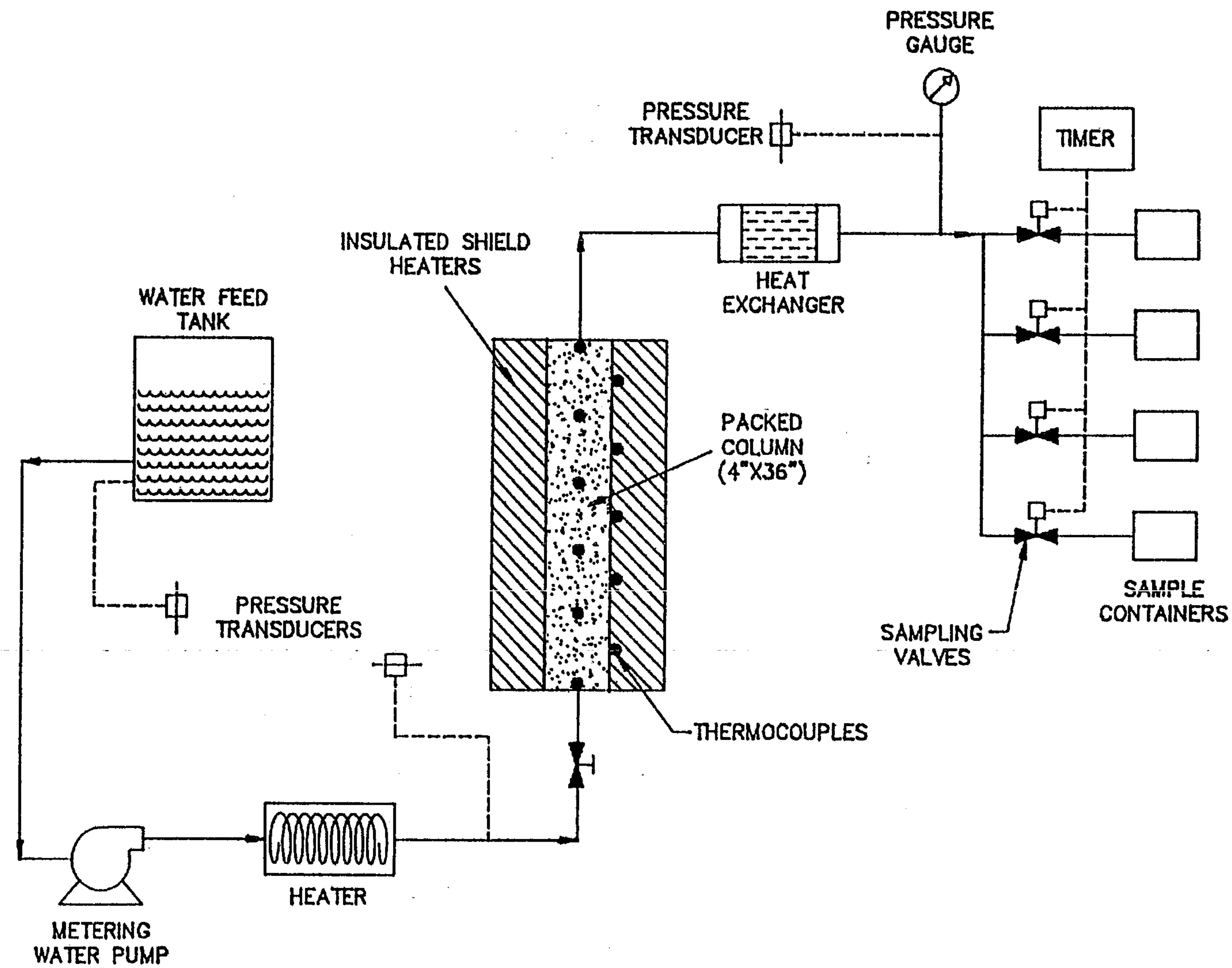

Figure B1-1. Bench-scale tube reactor.

SOURCE: Modified from WRI 1990

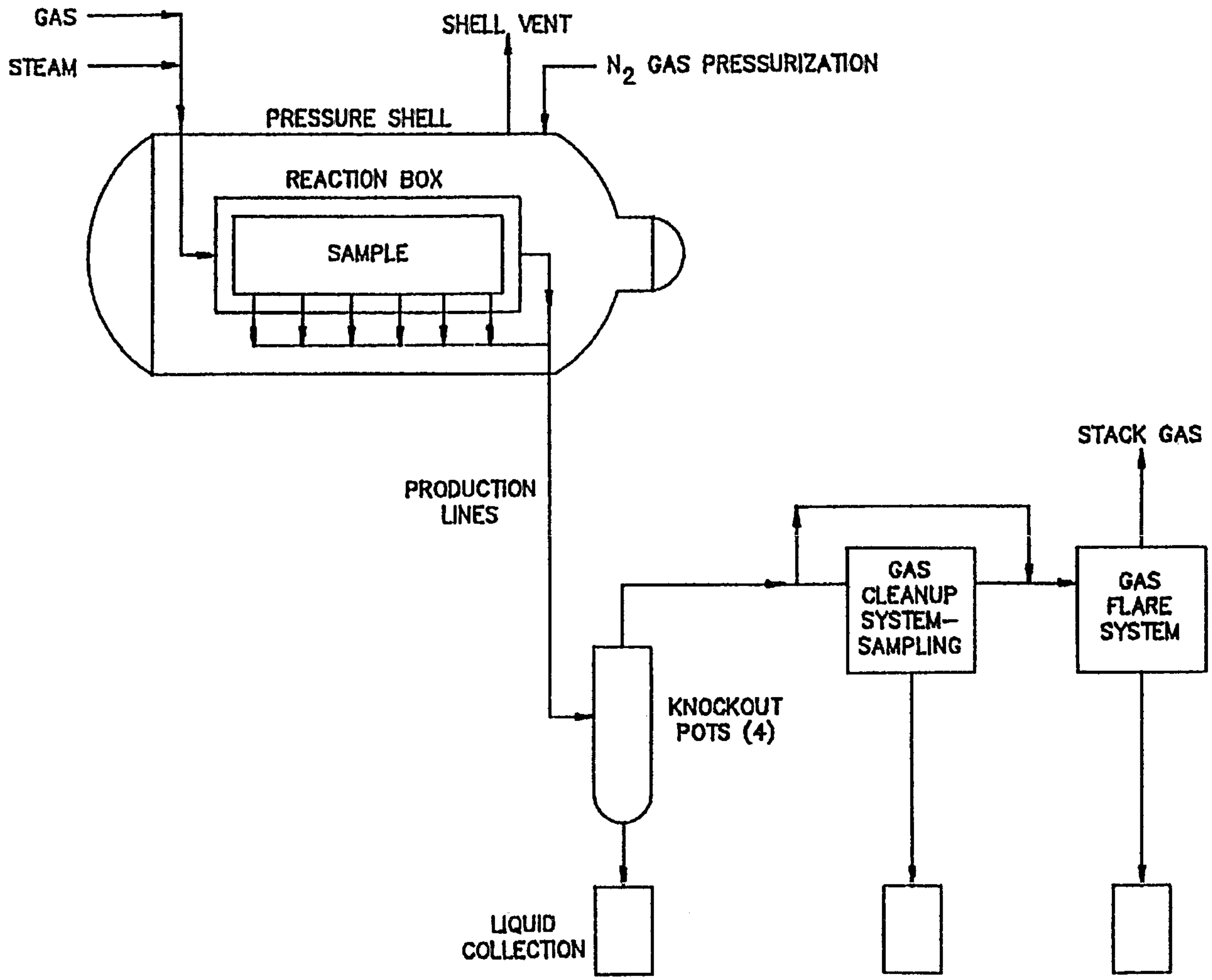

Figure B1-2. Bench-scale experimental unit.

Appendix C
Pilot-Scale Testing at the Bell Pole Site in New Brighton, Minnesota

WRI-97-R010

CROW™ FIELD DEMONSTRATION WITH BELL LUMBER AND POLE

Topical Report

By
L. John Fahy
Lyle A. Johnson Jr.

April 1997

Work Performed as Jointly Sponsored Research
Under Cooperative Agreement
DE-FC21-93MC30127 Task 13

For
Bell Lumber and Pole
New Brighton, Minnesota

and
U.S. Department of Energy
Office of Fossil Energy
Federal Energy Technology Center
Morgantown, West Virginia

By
Western Research Institute
Laramie, Wyoming

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EXECUTIVE SUMMARY

In 1990 efforts were initiated to implement an in situ remediation project for the contaminated aquifer at the Bell Lumber and Pole Company (Bell Pole) Site in New Brighton, Minnesota. The remediation project involves the application of the Contained Recovery of Oily Waste (CROW^{TM}) process, which consists of hot-water injection to displace and recover the nonaqueous phase liquids (NAPL).

While reviewing the site evaluation information, it became apparent that better site characterization would enhance the outcome of the project. Additional coring indicated that the areal extent of the contaminated soils was approximately eight times greater than initially believed. Because of these uncertainties, a pilot test was conducted, which provided containment and organic recovery information that assisted in the design of the full-scale CROW process demonstration.

Based on the results from the pilot test the following conclusions were made:

1. The pilot test provided sufficient hydraulic information to design the full-scale CROW remediation system. The pumping test portion of the pilot test indicated uniform aquifer properties. The entire thickness of the aquifer reached the target temperature range, and containment of the injected hot water was achieved.

2. Pre-test injection and extraction rate predictions were achieved.

3. The post-test soil boring data indicated hot-water injection displaced more than 80% of the NAPL near the injection well. The data indicates that a NAPL saturation of approximately 19% (pore volume basis) and a 500-fold decrease in pentachlorophenol (PCP) concentration can be achieved with 20 pore volumes of flushing.

4. The produced water treatment system used during the pilot test was effective in reducing PCP and polynuclear aromatic hydrocarbon (PAH) compounds to concentrations acceptable for sanitary sewer discharge.

5. The microbial assay of the post-test samples found an encouraging increase in microbial population compared to data collected before the pilot test.

Based on the results from the pilot test, conditions and procedures were developed for implementing a full-scale CROW process demonstration to remediate the remaining contaminated soil at the Bell Pole site.

After reviewing the cost ramifications of implementing the full-scale CROW field demonstration, Bell Pole approached Western Research Institute (WRI) with a request for a staged, sequential site remediation. Bell Pole's request for the change in the project scope was prompted by budgetary constraints. Bell Pole felt that even though a longer project might be more costly, by extending the length of the project, the yearly cost burden would be more manageable.

After considering several options, WRI recommended implementing a phased approach to remediate the contaminated area. Phase 1 involves a CROW process demonstration to remediate the upgradient one-third of the contaminated area, which is believed to contain the largest amount of free organic material.

The Bell Pole Phase 1 CROW demonstration is operating satisfactorily. However, due to equipment problems, the system is operating at less than the design conditions and is unable to operate continuously for extended periods of time. Only two pore volumes of hot water and two pore volumes of cold water were injected during 1996. By the end of 1996, over 20,000 gallons of oil had been transferred to the oil storage tank. Bell Pole has also used about 6000 gallons of the produced oil in its pole treating operation.

INTRODUCTION

Beginning in 1990, efforts were initiated for Western Research Institute (WRI) to implement an in situ remediation project for the contaminated aquifer at the Bell Lumber and Pole Company (Bell Pole) Site in New Brighton, Minnesota. The remediation project involves the application of the Contained Recovery of Oily Waste (CROW™) process, which consists of hot-water injection to displace and recover the non-aqueous phase liquids (NAPL) (Johnson and Sudduth 1989).

Wood treating activities began at the Bell Pole Site in 1923 and have included the use of creosote and pentachlorophenol (PCP) in a fuel oil carrier. Creosote was used as a wood preservative from 1923 to 1958. Provalene 4-A, a non-sludging fuel-oil-type carrier for PCP, was used from 1952 until it was no longer commercially available in 1968. A 5–6% mixture of PCP in fuel oil has been used as a wood preservative since 1952, and a fuel-oil-type carrier, P-9, has been used since 1968.

While reviewing the site evaluation information, it became apparent that better site characterization would enhance the outcome of the project. Additional coring indicated that the areal extent of the contaminated soils was approximately eight times greater than initially believed. Because of these uncertainties, a pilot test was conducted, which provided containment and organic recovery information that assisted in the design of the full-scale CROW process demonstration.

BELL POLE PROJECT CHRONOLOGY

1979	Five monitoring wells were installed by Bell Pole and MacGillis-Gibbs Company.
1983	The Bell Pole New Brighton site was placed on the EPA National Priorities List. Bell Pole signed a consent order and agreed to voluntary site remediation and began site cleanup and removal of disposal areas.
September 1985	The groundwater purge well, PW-1 was installed and pumping tests were conducted. Bell Pole subsequently pumped approximately 2000 gallons of free organic product over the next few years.
April 1986	Conestoga-Rovers & Associates Limited (CRA) completed the "Remedial Investigation Phase One Report" for Bell Pole.
February 1989	Bell Pole constructed a rotary kiln incinerator and completed soil incineration operations at the Bell Pole site east yard.

December 1989	Western Research Institute and Bell Pole submitted a proposal to the Department of Energy (DOE) and was awarded funding for a Jointly Sponsored Research (JSR) project to apply CROW process technology to remediate the Bell Pole New Brighton site.
March 1990	CRA completed a site soil boring study indicating the contaminated area was about two acres.
August 1990	CRA and WRI completed for Bell Pole an Interim Response Action Work Plan which was submitted to the Minnesota Pollution Control Agency (MPCA) and the Minnesota Department of Health (MDH). This document proposed conducting a 30-day, two-well pilot test to demonstrate the feasibility of using the CROW process to remediate the Bell Pole site.
February 1991	CRA submitted for Bell Pole an Interim Response Action Work Plan for process area soil removal.
April 1991	Bell Pole began operations in its new process plant.
April 1991	At the request of the MPCA, CRA and Bell Pole submitted an Application for Variance Interim Response Action for the CROW process source remediation.
June 1991	Approval to conduct the two-well pilot test of the CROW process was granted by the MPCA and MDH.
September 1991	The two-well pilot test was initiated.
November 1991	The two-well pilot test was completed and the system equipment dismantled.
June 1992	CRA and WRI submitted the Bell Pole CROW 30-Day Pilot Test Report to the MPCA.
July 1992	The Bell Pole CROW 30-Day Pilot Test Report was found acceptable by the MPCA staff.
August 1992	WRI submitted the Bell Pole Pilot Test Evaluation report to DOE.
August 1992	Bell Pole completed the incineration of the process area contaminated soil located above the water table.
June 1993	CRA submitted for Bell Pole a draft of the final design report of CROW and a plan for a phased implementation of the CROW process.
July 1993	CRA and WRI submitted for Bell Pole the final design report of CROW to the MPCA.

August 1993	Bell Pole submitted a permit application to construct the CROW/maintenance building.
November 1993	WRI and CRA completed the drilling and installation of six injection and three monitoring wells at the Bell Pole site.
February 1994	CRA and Bell Pole submitted an application for a variance interim response action to extend the previous variance.
August 1994	WRI completed fabrication of a data acquisition and control system for use by Bell Pole during the CROW field demonstration.
March 1995	Construction for the CROW process system was completed, and groundwater extraction was initiated on a limited basis.
May 1995	Hot-water injection was initiated.
July 1995	Continuous injection/extraction was terminated because sewer discharge criteria were not being met.
February 1996	A hydrogen peroxide injection system was added to the water cleanup system, which resulted in meeting discharge criteria. Groundwater extraction was restarted.
March 1996	Hot-water injection was restarted.
July 1996	Heat exchanger failure occurred. Cold-water injection and extraction continued.
November 1996	Injection and extraction were terminated because of emulsion problems in the oil/water treatment system.

SITE CHARACTERIZATION

Site characterization of the contaminated area at the Bell Pole site has been conducted for several years by Conestoga-Rovers & Associates Limited (CRA) and other consultants. The contaminated soil is contained in the New Brighton Formation (Stone 1966). It has been described as a relatively uniform silty fine-medium grain sand, 23 to 47 feet thick (CRA 1986). The contaminated soil is underlain by the Twin Cities Formation, which is a silty to sandy clay till. The New Brighton Formation is highly permeable, with hydraulic conductivities in the range of 3.1×10^{-3} to 9.5×10^{-3} cm/sec. Conversely, the underlying Twin Cities Formation has low permeability, with a conductivity on the order of 1.0×10^{-7} cm/sec (CRA 1986). The underlying clay till has provided an effective lower boundary to fluid migration and has been responsible for limiting the downward migration of the organic material.

A continuous aquifer lies at a depth of 10 to 20 feet below ground surface (BGS). Groundwater flows radially from a pond, located to the northeast, at a velocity of 0.1 to 0.6 ft/day. Across the Bell Pole site the groundwater gradient is 0.004 ft/ft toward the southwest, where the water appears to discharge into a drainage ditch.

In early 1990, 22 boreholes were drilled to define the extent of the contamination. Later, in preparation for the two-well pilot test, one new injection well and three monitor wells were also drilled and cored. Based on the evaluation of the coring data, it appears that the contaminated or saturated interval has an elongated teardrop shape which dips toward the northeast (Figure 1). The maximum thickness in the center of the zone is approximately 25 feet, while the edge of the contaminated zone is only a foot or two thick.

TREATABILITY TESTS

While the coring operations were being conducted, two large samples of contaminated soil were collected. These samples were used to conduct laboratory treatability tests. These flushing tests were necessary to appraise the effectiveness of the CROW process at this site and to determine operating conditions.

For each flushing test, approximately 30 lb of the contaminated site material was packed into a 3.75-in. diameter by 36-in. long reactor tube. The reactor tube was then placed vertically within the reactor shell. During the packing of each reactor tube, a composite sample of the packed material was prepared for organic loading determination. Each test was conducted by establishing water flow at the desired flow rate through the bottom of the tube with the flush water produced from the top of the tube.

Two tests were conducted, one each at a nominal 120°F and 140°F. The operating conditions and results for the two flushing tests are listed in Table 1. The reduction in the organic saturation was essentially the same, 0.53 and 0.54 wt %, even with the variance in the weight percent oil for the pre-test samples ranges, 2.87 to 7.44%.

The initial and post-test samples submitted for PCP analyses show that the decrease in PCP concentration during the flushing tests was higher than the decrease in the total oil phase concentration.

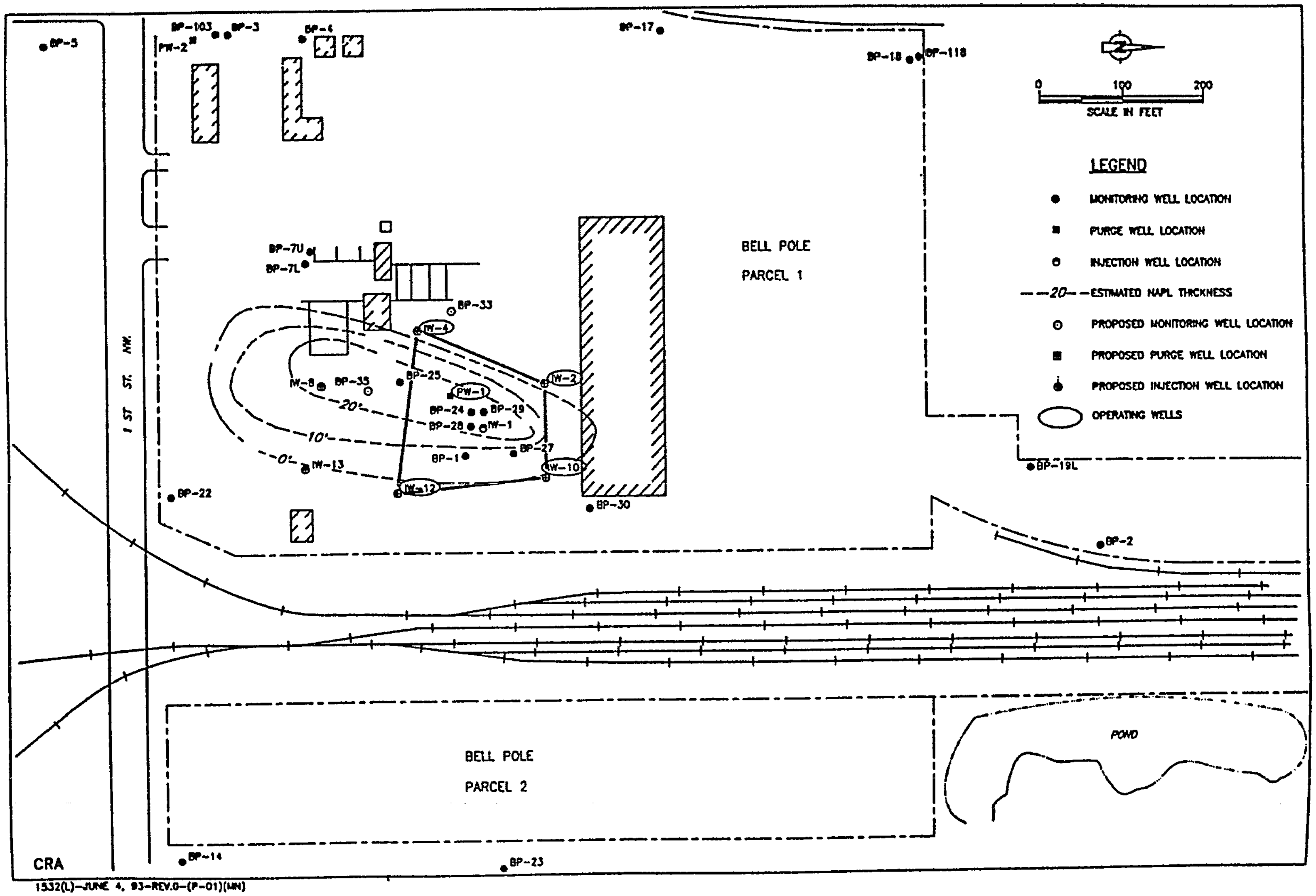

Figure 1. Phase I Well Pattern

Table 1. Process Simulations for Bell Pole

Test Number	103	104
Water Injection		
Temperature, °F	140	120
Flux, cm^3/min	107	118
Velocity, cm/min	2.5×10^{-2}	2.8×10^{-2}
Porosity, %	35.5	33.6
Initial Oil Saturation of Mobile Oil Zone		
% Pore Volume	42.2	16.2
wt %	7.44	2.87
Residual Oil Saturation		
% Pore Volume	10.0	10.0
wt %	0.54	0.53
Removal of Oil, wt %	93.5	84.3
PCP Concentration, ppm		
Initial Material	3200	1500
Flushed Material	2.3	BDL[a]
% Reduction	99.9	99.8[b]

a BDL = Below detection limit

b Value based on the flushed material for test 103

PILOT TEST OBJECTIVES

An Interim Response Action (IRA) work plan was prepared in 1990 by CRA and WRI. The IRA detailed how the CROW process would be implemented at the Bell Pole Site (CRA and WRI 1990). Based on the IRA and after the granting of variances by the Minnesota Pollution Control Agency and the Minnesota Department of Health, a two-well pilot test of the CROW process was conducted. The test consisted of injecting hot, potable water into the NAPL-saturated area of the aquifer, producing groundwater (and NAPL) from an existing extraction well, PW1, and treating the produced water for sanitary sewer discharge.

The objectives of the pilot test were to:

1. Compare predicted injection and extraction rates with actual field data;

2. Demonstrate the ability to heat the aquifer to the 120°F to 140°F range;

3. Demonstrate the ability to hydraulically control the injected water to prevent spreading contamination;

4. Confirm treatment system effectiveness in reducing PCP and polynuclear aromatic hydrocarbons (PAHs) prior to sanitary sewer discharge; and

5. Predict anticipated operating conditions for full-scale CROW application.

PILOT TEST DESCRIPTION

The pilot-test location was selected from the site characterization mapping and the location of the existing extraction well, PW1. One new injection well, IW1, was drilled 50 feet upgradient to the northeast from well PW1. Both the injection and extraction wells were located in an area that contained high organic accumulations (Figure 1).

The pilot test began on September 24, 1991. The first step of the test involved pumping the extraction well, PW1. Treatment of water began on September 26, day 3 of the test. Hot-water injection started on day 7 at an initial injection temperature of 147°F. On day 9, the injection temperature was increased to 203°F. Injection was terminated on October 31, day 37 of the pilot test. Pumping continued at PW1 until day 41 when the test ended. Water treatment continued until day 45, and the treatment system was subsequently dismantled.

PILOT TEST RESULTS

Flow rates and injection pressures were recorded by the data acquisition system. The pumping rate at PW1 was started at 5 gpm and stepped up to 9 gpm during the seven days prior to injection startup. During the remainder of the test, PW1 averaged 6.5 gpm (Table 2).

Table 2. Pilot Test Operating Conditions and Results

Total Hot-Water Injection Time	30 days
Average Hot-Water Injection Rate	4.5 gpm
Steady-State Hot-Water Injection Wellhead Temperature	200°F
Total Water Injected	193,000 gallons
Total Water and NAPL Production Time	41 days
Average Fluid Production Rate During Hot-Water Injection Phase	6.5 gpm
First Pumping Test Production Rate	5.0 gpm
Second Pumping Test Production Rate	9.0 gpm
Total Fluids Produced	390,000 gallons
Total NAPL Production	2000 gallons
Areal Extent of Injected Water	3285 ft^2
Time to NAPL Production Response From Start Of Injection	14 days
Time to Breakthrough from Start of Hot-Water Injection	20 days
Average Hot-Water Injection Front Velocity, ft/day	2.5 ft/day

3. The post-test soil boring data indicated hot-water injection displaced more than 80% of the NAPL near the injection well. The data indicates that a NAPL saturation of approximately 19% (pore volume basis) and a 500-fold decrease in PCP concentration can be achieved with 20 pore volumes of flushing.

4. The produced water treatment system used during the pilot test was effective in reducing PCP and PAH compounds to concentrations acceptable for sanitary sewer discharge.

5. The microbial assay of the post-test samples found an encouraging increase in microbial population compared to earlier data collected before the pilot test.

CROW TEST PROCEDURE AND DESIGN

Based on the results from the pilot test, conditions and procedures were developed for implementing a full-scale CROW process demonstration to remediate the remaining contaminated soil at the Bell Pole site.

After reviewing the cost ramifications of implementing the full-scale CROW field demonstration, Bell Pole approached WRI and the MPCA with a request for a staged, sequential site remediation. Bell Pole's request for the change in the project scope was prompted by budgetary constraints. Bell Pole felt that even though a longer project might be more costly, by extending the length of the project, the yearly cost burden would be more manageable.

After considering several options, WRI recommended implementing a phased approach to remediate the contaminated area. Phase 1 involves a CROW process demonstration to remediate the upgradient one-third of the contaminated area, which is believed to contain the largest amount of free organic material. The phased approach to remediating the site is not expected to cause any adverse effects except for extending the time required to complete the entire project.

WELL NETWORK DESIGN

During 1993, WRI drilled four, Phase 1 injection wells and three monitoring wells, plus two Phase 2 injection wells, which are being used as downgradient monitoring wells during the first phase.

By using the existing extraction well, PW1, and the new injection wells, an inverted five-spot pattern was installed (Figure 1). Due to its pre-existing location, PW1 is closer to the downgradient injection wells than to the upgradient injection wells, which is anticipated to enhance the overall capture efficiency of the system. Injection-to-extraction well spacings are approximately 100 feet, which is about twice the spacing utilized during the pilot test.

SURFACE TREATMENT SYSTEM DESIGN

Based on results from the pilot test, plus bench-scale tests conducted by Bell Pole and various vendors, a produced fluid treatment system was designed and installed.

During the pilot test it was observed that a significant amount of oil/water separation was occurring in the 40,000-gallon tank into which all produced oil and water was being pumped. To capitalize on this occurrence, all produced water and oil is pumped into a 40,000 gallon process tank after sulfuric acid has been added to lower the pH to approximately 3.5. Oil is skimmed from the top of the tank and pumped off of the bottom of the tank and then routed to an oil storage tank. This is a batch operation that is performed daily.

Water is continuously pumped from the 40,000 gallon process tank to an air flotation unit where the oily water is aerated and most of the remaining oil and grease, PCP, and organic carbon are removed and recycled back to the 40,000 gallon process tank.

The treated water leaving the air flotation unit is treated with sodium hydroxide, then pumped to a 10,000-gallon equalization tank. From this tank, part of the water, 5 to 10 gpm, is pumped to an ozonation unit, which removes the PCP. The water is then treated with hydrogen peroxide to break down the remaining PAH compounds and is disposed of in the sewer. The water that is not pumped to the ozonation unit is recycled through a boiler/heat exchanger system where it is heated and reinjected. The conceptual design of the water treatment system is shown in Figure 2.

Prior to installing the CROW process system, Bell Pole installed a two-well pump and treat system. The water produced from the pump and treat wells enters the 10,000-gallon equalization tank and is either treated for disposal or reinjected.

CONTROL AND DATA ACQUISITION SYSTEM

For the Bell Pole Phase 1 CROW demonstration, WRI developed and installed a control and data acquisition system (CDAS). This system collects all temperature, pressure, flow, and pH data generated by the process. From this data, the CDAS determines what type of control should be exerted on the process. If required, the CDAS will turn a pump, valve, or alarm on or off as specified by the control logic.

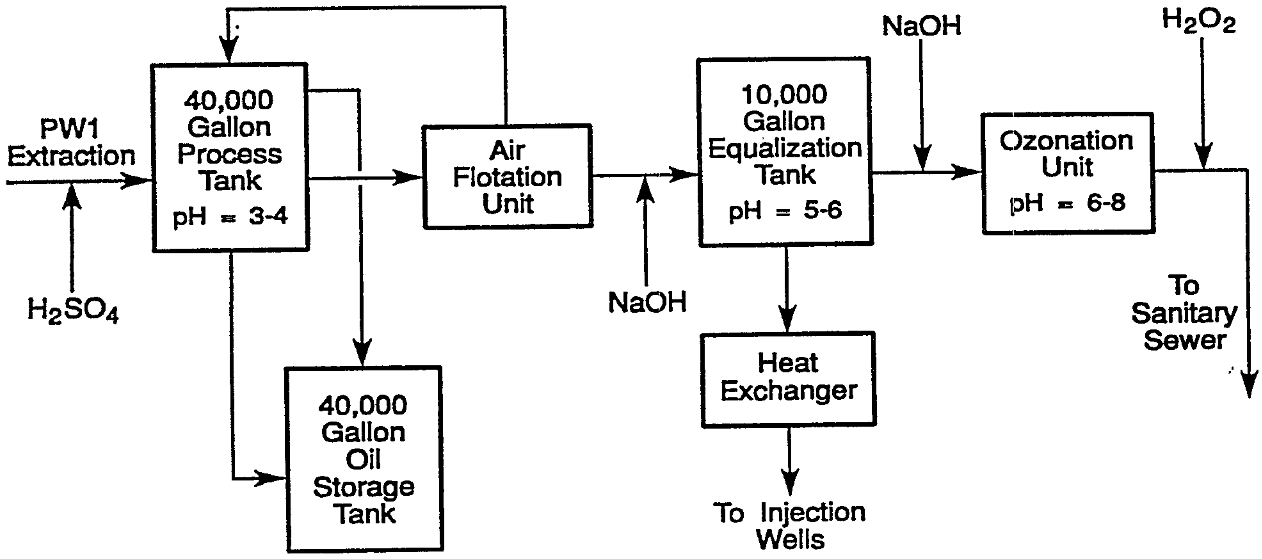

Figure 2. Treatment System Conceptual Design

In addition to controlling the physical process, the CDAS also displays the status of the various parameters on the computer monitor through the use of several computer screens. The system also records the status of these parameters to computer files, which are routinely downloaded via the modem system for analyses and archiving.

From the beginning, the CDAS system operated basically as designed. However, the computer had a tendency to "hang up" occasionally. In October, 1995, an upgrade of the control system and Windows 95.0 were installed. These upgrades have eliminated the previous problems, and the system has been operating trouble free.

PROJECT OPERATION

By early 1995, all of the equipment, except for the hydrogen peroxide system, had been installed. Water extraction began March 1995, and the system was operated intermittently through April 1995. On May 16, 1995, continuous operation of the CROW system began. Continuous hot-water injection was terminated on June 29, and continuous extraction and disposal of excess water was terminated July 12, 1995, because of failure to meet the sewer discharge criteria.

The ozonation unit was originally designed for removal of PCP and has functioned satisfactorily. However, high concentrations of PAHs, particularly naphthalene and phenanthrene, exceeding the discharge criteria were occurring. After several attempts to reduce the PAH concentration in the discharge water, the hydrogen peroxide injection system was installed downstream of the ozonation unit. Hydrogen peroxide injection brought the PAH concentrations down to acceptable discharge limits (Table 3).

Table 3. Water Disposal PAH Concentration, mg/L

PAH Compound	Before Hydrogen Peroxide Injection	After Hydrogen Peroxide Injection	Discharge Limits
Naphthalene	3900	630	3000
Acenaphthene	530	40	3000
Fluorene	[1]BDL	340	3000
Pentachlorophenol	BDL	280	3000
Phenanthrene	5200	780	3000
Anthracene	340	37	3000
Fluoranthene	1100	360	3000
Pyrene 1400	370	3000	
Benzo-a-anthracene	260	57	3000
Chrysene	340	110	3000
Benzo-b-fluoranthene	BDL	23	3000
Benzo-k-fluoranthene	BDL	60	3000
Benzo-a-pyrene	BDL	14	3000
2-Methylnapthalene	1400	290	3000
Total PAH Concentration	14470	3391	10000

[1]Below Detection Limits

Once it was demonstrated that the discharge criteria could routinely be met, the water contained in the water treatment system was treated and disposed of, and extraction from PW1 was restarted. Continuous groundwater extraction was established February 26, 1996, and continuous hot-water injection began a week later on March 4, 1996.

On March 12, 1996, the entire water treatment system was analyzed for oil and grease concentration and partially analyzed for PCP and total PAH concentration (Table 4). The extraction well, PW1, oil and grease concentration was uncharacteristically low, suggesting groundwater pumping prior to hot-water response has lowered the oil concentration in the immediate area. PW1 oil and grease concentrations had typically been in the 1000 to 3000 mg/L range when sampled. The oil and grease concentration after the air flotation unit was reduced significantly compared to earlier results and this is attributed to operating at a lower pH.

Table 4. Process Train Hydrocarbon Sampling
March 13, 1996

PW1 Effluent		
Oil and Grease Concentration, mg/L		300
After Air Flotation Unit		
Oil and Grease Concentration, mg/L		71
Injection Water		
Oil and Grease Concentration, mg/L		96
PCP Concentration, mg/L	10	
Discharge Water		
PCP Concentration, mg/L	<1	
Total PAH Concentration, mg/L		<4

Continuous hot-water injection was terminated on July 15, 1996, following a heat exchanger failure. At that time, aquifer temperatures were approaching 120°F, and 70°F water was being produced at the extraction well. Cold-water injection and groundwater extraction continued while efforts were made to replace the heat exchanger. The entire system was shut down November 8, 1996, because of problems caused by oil/water emulsion in the water treatment system.

During this shutdown period, the 40,000-gallon process tank is being heated, and the oil/water emulsion is slowly being broken. The oil is being transferred to the oil storage tank and the produced water treated and sent to the sewer. A new heat exchanger is being procured and should be available soon, at which time the CROW system will be restarted.

DISCUSSION

The Bell Pole Phase 1 CROW demonstration is operating satisfactorily. However, due to equipment problems, the system is operating at less than the design conditions and is unable to operate continuously for extended periods. When the replacement heat exchanger is brought online, efforts will be made to increase the injection temperature to the 195-200°F range, which will improve the aquifer temperature response.

Only two pore volumes of hot water and two pore volumes of cold water were injected during 1996. Actual injection and extraction fluid rates have been 11 and 14 gpm, respectively. These conditions are about half the original designed operating conditions. At the current rates, it will take another 30 months to complete 20 pore volumes of injection. The Bell Pole CROW test summaries are shown in Tables 5 and 6.

Table 5. Bell Pole CROW Test Summary
January 3, 1995 through February 25, 1996

Total Water Injected, gal	222,811
Total Fluid Extracted, gal	642,138
Total Water Disposed, gal (Includes Off Pattern Pump and Treat Production)	543,315
Total Water Inventory in Tanks, gal	25,890

Table 6. Bell Pole CROW Test Summary
February 26, 1996 through December 31, 1996

Continuous Extraction Time, days	257
Hot-Water Injection Time, days	134
Cold-Water Injection Time, days	116
Average Hot-Water Injection Temperatures	
Heater Temperature, °F	172
Injection Manifold Temp, °F	171
IW4 Injection Line Temp, °F	165
Maximum PW1 Aquifer Temp, °F	78
Injection Well Aquifer Temp Range (measured 7/11/96), °F	166-175
Total Hot-Water Injected, gallons	4,103,856
Total Fluid Extracted, gallons	5,288,544
Total Water Disposed, gallons (Including Off-Pattern Pump and Treat Production)	1,670,883
Average Pattern Water Injection Rate, gpm	11.2
Average Pattern Water Extraction Rate, gpm	14.1
Average Water Disposal Rate, gpm (Including Off Pattern Pump and Treat Production)	4.3
Individual Injection Well Flow Rates (Normalized Values), gpm	
IW2	2.8
IW4	1.9
IW10	3.7
IW12	2.8
Cumulative Product Recovery Estimate, gal (excluding oil in Process Tank)	20,000

Based on the aquifer temperature measurements, an areal temperature contour map was prepared (Figure 3). The high temperature front was arbitrarily defined by the 75°F temperature contour. While there are a number of monitoring wells within the pattern area, the data are limited, making the contours somewhat interpretive.

However, the data does suggest some important trends. First, the hot-water injection period has not progressed long enough to establish an interconnected hot-water front or fronts. Second, the majority of the high temperature measurements in the pattern appear to be influenced by injection into IW10. However, the relatively low temperature response at PW1 indicates the extraction well was mainly influenced by the injection at IW2. Third, the more downgradient wells, IW4 and IW12, will require a longer time and more injected pore volumes before they noticeably affect the extraction well, PW1. Fourth, the aquifer temperature data confirms that the injected water is contained within the pattern area.

Monitor well BP27, which is located on a line between wells IW10 and PW1, experienced the greatest temperature response. Figure 4 shows the aquifer temperature profile at different times before and after termination of hot-water injection. As expected, the aquifer is returning to ambient temperature without the injection of hot water.

Oil production has been estimated daily from the transfer of oil from the process tank to the oil storage tank. An actual daily rate has been difficult to determine because the oil remaining in the production tank after oil transfer can only be estimated. By the end of 1996, more than 20,000 gallons of oil had been transferred to the oil storage tank. Bell Pole has used about 6000 gallons of the produced oil in its pole treating operation.

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