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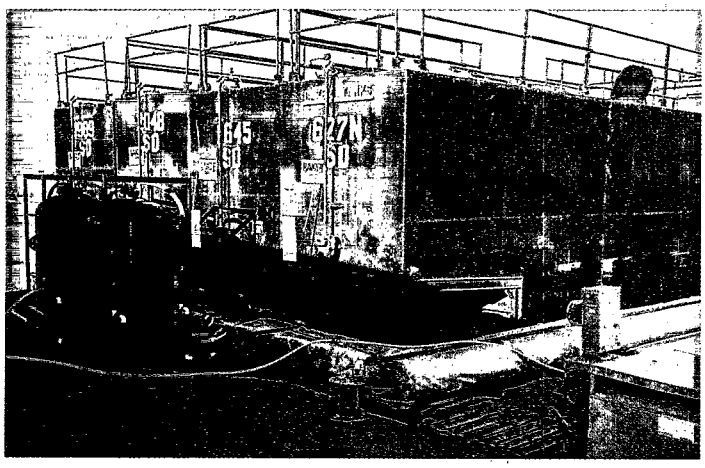
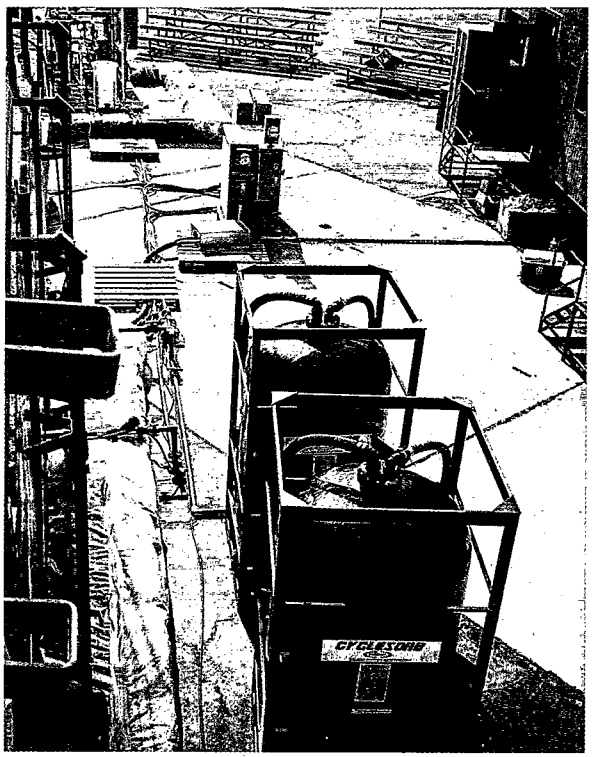
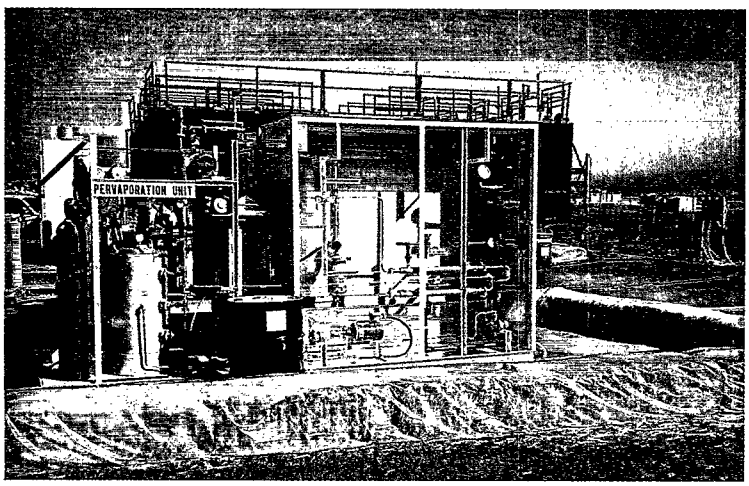
ZENON Environmental, Inc.

Cross-Flow Pervaporation Technology

Innovative Technology Evaluation Report







SITE
SUPERFUND INNOVATIVE
TECHNOLOGY EVALUATION

EPA/540/R-95/511
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ZENON Environmental, Inc.

Cross-Flow Pervaporation Technology

Innovative Technology Evaluation Report

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

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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

The U.S. Environmental Protection Agency (EPA) has focused on policy, technical, and informational issues related to exploring and applying new technologies to Superfund site remediation. One EPA initiative to accelerate the development, demonstration, and use of innovative technologies for site remediation is the Superfund Innovative Technology Evaluation (SITE) Program.

The SITE Program evaluated the ZENON Environmental, Inc. (ZENON), Cross-Flow Pervaporation technology, a membrane-based process that removes volatile organic compounds (VOC) from aqueous matrices. The ZENON technology provides an alternative approach to treating organic-contaminated water at sites where conventional treatment technologies are used, such as air stripping or carbon adsorption. A full-scale demonstration of the technology was performed during February 1995 at a former waste disposal area (Site 9) at Naval Air Station, North Island (NASNI), in Coronado, California. Groundwater at the site contains a variety of contaminants, mainly trichloroethene (TCE).

The primary objectives of this demonstration were to (1) determine if the technology could remove TCE in groundwater to below the federal maximum contaminant levels (MCL) at varying flow rates, and (2) to determine the removal efficiency for TCE. A number of secondary objectives were also included in the demonstration, including the amount of TCE released from the technology to the outside air, the amount of concentrated waste (permeate) generated by the technology, and the costs associated with its use. To achieve the demonstration objectives, samples of untreated influent, treated effluent, and vapor were taken from the technology. Sampling and analytical procedures and quality assurance (QA) objectives for the demonstration were specified in an EPA-approved quality assurance project plan (QAPP).

Lowering TCE concentrations to below MCLs may require multiple passes through the pervaporation module, which can prove impractical when compared to other technologies. The SITE evaluation demonstrated that the ZENON technology is best suited for reducing high concentrations of VOCs to levels that can be reduced further and more economically by conventional treatment technologies.

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Acronyms, Abbreviations, and Symbols

ARAR	Applicable or Relevant and Appropriate Requirements
BACT	Best Available Control Technologies
bgs	Below ground surface
CAA	Clean Air Act
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CERI	Center for Environmental Research Information
CFR	Code of Federal Regulations
CWA	Clean Water Act
DNAPL	Dense Nonaqueous-Phase Liquid
EPA	U.S. Environmental Protection Agency
gpm	Gallons Per Minute
GC	Gas Chromatograph
ITER	Innovative Technology Evaluation Report
kWh	Kilowatt-Hour
LDR	Land Disposal Restrictions
LNAPL	Light Nonaqueous-Phase Liquid
MCL	Maximum Contaminant Level
MDL	Method Detection Limit
mg/L	Milligrams Per Liter
MS	Matrix Spike
MSD	Matrix Spike Duplicate
NELP	Naval Environmental Leadership Program
NPDES	National Pollutant Discharge Elimination System
ORD	Office of Research and Development
OSHA	Occupational Safety and Health Administration
PPE	Personal Protective Equipment
PVC	Polyvinyl Chloride
ppm	Parts Per Million
psi	Pounds Per Square Inch
psia	Pounds Per Square Inch-Absolute
POTW	Publicly Owned Treatment Works

Acronyms, Abbreviations, and Symbols (continued)

QA	Quality Assurance
QAPP	Quality Assurance Project Plan
QC	Quality Control
RCRA	Resource Conservation and Recovery Act
SARA	Superfund Amendments and Reauthorization Act (of 1986)
SDWA	Safe Drinking Water Act
SITE	Superfund Innovative Technology Evaluation
SWDIV	Southwest Division
SVOC	Semivolatile Organic Compound
TCE	Trichloroethene
TER	Technical Evaluation Report
TRPH	Total Recoverable Petroleum Hydrocarbons
TSS	Total Suspended Solids
µg/L	Micrograms Per Liter
ULC	Upper Confidence Limit
VISITT	Vendor Information System for Innovative Treatment Technologies
VOC	Volatile Organic Compounds
"Hg	Inches of Mercury

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

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Executive Summary

This report summarizes the findings of an evaluation of the cross-flow pervaporation technology developed by ZENON Environmental, Inc. (ZENON). This evaluation was conducted under the U.S. Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) Program. The ZENON pervaporation technology was demonstrated over a 5-day period in February 1995 at Naval Air Station North Island (NASNI) in Coronado, California.

The purpose of this Innovative Technology Evaluation Report (ITER) is to provide information from the SITE demonstration of the pervaporation technology that is useful for remedial managers, environmental consultants, and other potential technology users implementing the technology at Superfund and Resource Conservation and Recovery Act (RCRA) hazardous waste sites. Section 1.0 of the ITER presents an overview of the SITE Program, describes the ZENON technology, and lists key contacts. Section 2.0 discusses information relevant to the technology's application, including an assessment of the technology related to the nine feasibility study evaluation criteria, potential applicable environmental regulations, and operability and limitations of the technology. Section 3.0 summarizes the costs associated with implementing the technology. Section 4.0 presents the site characterization, demonstration approach, demonstration procedures, and the results and conclusions of the demonstration. Section 5.0 summarizes the technology status, and Section 6.0 contains a references list. Appendix A presents the analytical data tables.

The Cross-Flow Pervaporation Technology

According to ZENON, the pervaporation technology is a membrane-based process that removes volatile organic compounds (VOC) from aqueous matrices. The ZENON cross-flow pervaporation technology uses an organophilic membrane made of nonporous silicone rubber, which is permeable to organic compounds but highly resistant to degradation. The composition of the membrane causes organics in solution to adsorb to it; the organics then diffuse through the membrane by a vacuum and condense into a highly concentrated liquid called permeate. The permeate separates into aqueous and organic phases. The organic phase can either be disposed of or sent off site for further processing to recover the organics. The aqueous phase is sent back to the pervaporation unit for retreatment, where remaining VOCs are removed along with those in untreated water.

The ZENON pervaporation technology effectively removes most VOC contamination from groundwater and other aqueous waste streams. It is best suited for reducing high concentrations of VOCs to levels that can be reduced further and more economically by conventional treatment technologies, such as carbon adsorption. The technology is not practical for reducing VOC concentrations to most regulatory limits, notably drinking water standards. According to the developer, once the ZENON technology is installed and equilibrated, it requires minimal support from on-site personnel.

Demonstration Objectives and Approach

The SITE demonstration for the ZENON technology was designed with two primary and eight secondary objectives to provide potential users of the technology with the necessary information to assess the applicability of the pervaporation technology at other contaminated sites. The following primary and secondary objectives were selected to evaluate the technology:

Primary Objectives:

P1) Determine if the system can remove trichloroethene (TCE) in groundwater to below federal maximum contaminant levels (MCL) at varying flow rates, at the 95 percent confidence level

P2) Determine the removal efficiency of the system for TCE

Secondary Objectives:

S1) Assess the pervaporation system's ability to remove nontarget VOCs, semivolatile organic compounds (SVOC), and total recoverable petroleum hydrocarbons (TRPH) from contaminated groundwater

S2) Determine the volume of recovered liquid permeate generated during each run

S3) Measure VOC emissions from the pervaporation system

S4) Determine requirements for anti-scaling additions, and monitor the potential scaling of the system by identifying reductions in total suspended solids (TSS) and concentrations of carbonate, fluoride, sulfate, silica, strontium, calcium, barium, magnesium, and iron in treated and untreated water

S5) Determine if the technology's efficiency in removing VOCs, SVOCs, and TRPH is reduced, and if scaling due to the precipitation of the analytes listed under secondary objective S4 occurs after a 3-week period

S6) Determine the physical effects the ZENON system has on treated groundwater

S7) Document the operating conditions of the ZENON system

S8) Estimate the capital and operating costs of treating contaminated groundwater at NASNI Site 9 with full-scale ZENON pervaporation systems

The demonstration program objectives were achieved through the collection of untreated and treated groundwater samples, as well as air samples from a vacuum vent of the system, over four 8-hour sampling runs, and one 4-hour run. The fifth day run was shortened because a seal on the pervaporation module failed and could not be replaced in the field. To meet the objectives, samples were collected at set times throughout each run. Each day, the flow rate of the system and TCE influent concentrations were changed to present a variety of operating conditions.

Demonstration Results

Based on the ZENON SITE demonstration, the following conclusions may be drawn about the applicability of the ZENON technology:

- The system significantly reduced TCE concentrations in the groundwater from an average of 125 milligrams per liter (mg/L) to an average of 1.49 mg/L (1,490 micrograms per liter [µg/L]); however, the federal MCL of 5 µg/L was not achieved. From the limited number of sampling runs, the technology appeared most efficient when operating at lower flow rates (2.1 gallons per minute [gpm] to 5 gpm).

- Removal efficiencies for TCE averaged about 97.3 percent. Sixteen of 18 comparisons of treated water samples to untreated samples showed average TCE removal efficiencies of 99.3 percent. Generally, the technology presented higher reduction percentages as the concentration of TCE in the untreated groundwater increased.

- For other VOCs present in the groundwater at Site 9, the removal efficiency for the technology ranged from an overall average for the demonstration of 96.5 percent for 1,1-dichloroethene to 16.0 percent for 2-butanone. Because of data quality flaws, namely VOC presence in trip blanks and SVOC MS/MSD results outside of QA objectives, the usefulness of the VOC and SVOC results is considered limited.

- Because of the failure of a condensate pump, the amount of permeate generated by a typical ZENON system could only be estimated. At NASNI, the system generated an average of about 2.9 gallons per hour (gph), totaling 23 gallons per 8-hour run. The average amount of untreated groundwater passed through the system was 441 gph.

- VOC releases from the vacuum vent of the system, which allows the discharge of volatilized organic compounds from the pervaporation module, increased

with higher VOC concentrations in the untreated water. The average concentration of TCE in vapor vented from the module was 53,889 milligrams per cubic meter. As a percentage of total TCE contaminant load, TCE in vapor discharged from the module averaged 21.9 percent.

- No notable reductions of inorganic parameters occurred during the treatment process. TSS appeared to deposit onto the pervaporation membranes. Scaling of the membranes proved to be a continual problem during the demonstration. The addition of antiscaling chemicals appeared effective in reducing this; however, no long-term effects of scaling of the membranes or long-term success of antiscalents could be determined.

- The system's VOC removal efficiency, and the effects of scaling on treatment efficiency, were to be monitored after allowing the technology to operate continuously for a 3-week period; however, because the technology failed during the fifth run, these factors could not be evaluated.

- The average change in temperature between untreated groundwater (before entering the system) and treated groundwater (discharged groundwater) was 4.0 °C. The pH of the groundwater increased 0.56 by passing through the system.

- Estimated cost for operating a ZENON system at NASNI Site 9 at 8 gallons per minute for a period of 15 years, treating 63 million gallons of groundwater, is $1,961,000. The total cost per 1,000 gallons of treated groundwater is $31, or roughly 3 cents per gallon. If operational problems experienced during the demonstration are not addressed by ZENON, these costs could rise dramatically.

Technology Evaluation Summary

The technology was analyzed to assess its advantages, disadvantages, and limitations, and was then evaluated based on the nine criteria used for decision-making in the Superfund feasibility study process (see Table ES-1). This evaluation is presented in Section 2.0 of the ITER. The technology as demonstrated is limited to treatment of VOCs in the saturated zone. During the demonstration sampling runs at NASNI, the pervaporation technology proved to be effective in removing VOCs from contaminated groundwater. The demonstration results indicate that the overall effectiveness of the system depends on a number of factors, including the influent flow rate through the system, the contaminant concentrations, the volatility of the organics present in the water, and the potential for scaling and fouling of the system based on the water characteristics. The technology mainly employs readily available equipment and materials. Material handling requirements and site support requirements are minimal.

Although the technology was able to remove VOCs at a high rate during the sampling runs, continual failures of various components of the system occurred throughout the demonstration, eventually causing an early termination of sampling. Modifications of equipment used in conjunction with the pervaporation modules, including seals, filters, pumps, and various valves is necessary before the technology can be readily applied at other remote groundwater sites. The remote location of Site 9, along with occasional severe weather, also caused logistical problems during the demonstration.

Table ES-1. Feasibility Study Evaluation Criteria for the ZENON Technology

Criteria	ZENON Technology Assessment
Overall Protection of Human Health and the Environment	The technology reduces contaminants in the groundwater and prevents further migration of those contaminants with minimal exposure to on-site workers and the community.
Compliance with Federal and State ARARs	Compliance with chemical-, location-, and action-specific ARARs must be determined on a site-specific basis. The technology is not suited for removing contaminants to maximum contaminant level (MCL) and may require additional treatment to meet National Pollutant Discharge Elimination System (NPDES) standards depending on (1) influent contaminant concentrations, and (2) treatment efficiency of the ZENON technology.
Long-Term Effectiveness and Permanence	Contaminants are permanently removed from the groundwater. Treatment residuals (concentrated permeate) require proper off-site recycling, treatment or disposal.
Reduction of Toxicity, Mobility, or Volume Through Treatment	Contaminants are removed from the groundwater, thus reducing its toxicity. The radius of influence of wells used to pump influent to the system, the pumping rate, and the time-frame of pumping will determine the mobility of contaminants in the groundwater over the treatment period. Treatment followed by discharge to publicly owned treatment works (POTW) or surface water prevents further migration of contaminants and reduces the volume of contaminated media.
Short-Term Effectiveness	During site preparation and installation of the treatment system, no adverse impacts to the community, workers, or the environment are anticipated. Risks to workers involve the movement of containerized permeate and possible venting of contaminants from the system. The time requirements for treatment using the ZENON system is dependent on site conditions and may require several years.

Table ES-1. Feasibility Study Evaluation Criteria for the ZENON Technology (continued)

Criteria	ZENON Technology Assessment
Implementability	The site requires a hard surface such as concrete or packed soil to support the system and associated tanks, which require about 120 square feet. A large capacity bulk tank is recommended for the equalization of contaminated water before it is pumped into the system. Services and supplies required include laboratory analyses and electrical utilities.
Cost	For use of the technology at NASNI Site 9 for a 15-year period treating a total of 63 million gallons of groundwater, total fixed costs are $189,500. Equipment costs comprise 79 percent of the total fixed costs. Total annual variable costs are $118,000. Total cost for treatment is $1,961,000.
Community Acceptance	The small risks to the community and permanent removal of the contaminants make public acceptance of this technology likely.
State Acceptance	State acceptance is anticipated to be favorable because the ZENON system generates a low volume of waste in relation to treated groundwater, and air emissions are negligible. State regulatory agencies may require permits to operate the treatment system, for air emissions, and to store concentrated permeate for greater than 90 days.

Section 1
Introduction

This section provides background information about the U.S. Environmental Protection Agency's (EPA) Superfund Innovative Technology Evaluation (SITE) program, discusses the purpose of this Innovative Technology Evaluation Report (ITER) and describes the ZENON cross-flow pervaporation technology. Additional information about the SITE program, the ZENON technology, and the demonstration is available from the key individuals listed at the end of this section.

1.1 The Site Program

The SITE program is a formal program established by EPA's Office of Solid Waste and Emergency Response and Office of Research and Development (ORD) in response to the Superfund Amendments and Reauthorization Act of 1986 (SARA). The SITE program's primary purpose is to maximize the use of alternatives in cleaning up hazardous waste sites by encouraging the development, demonstration, and use of new or innovative treatment and monitoring technologies. It has four major goals:

- Identify and remove obstacles to the development and commercial use of alternate technologies
- Structurea development program that nurtures emerging technologies
- Demonstrate promising innovative technologies to establish reliable performance and cost information for site characterization and cleanup decision-making
- Develop procedures and policies that encourage the selection of available alternative treatment remedies at Superfund sites, as well as other waste sites and commercial facilities

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

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

The results of the demonstration are published in two documents: the Technology Capsule and the ITER. The Technology Capsule provides relevant information on the technology, emphasizing key features of the results of the SITE demonstration. Both the Technology Capsule and the ITER are intended for use by remedial managers making a detailed evaluation of the technology for a specific site and waste.

1.2 Innovative Technology Evaluation Report

The ITER provides information on the ZENON technology and includes a comprehensive description of the demonstration and its results. The ITER is intended for use by EPA remedial project managers, EPA on-scene coordinators, contractors, and other decision-makers for

implementing specific remedial actions. The ITER is designed to aid decision-makers in evaluating specific technologies for further consideration as an applicable option in a particular cleanup operation.

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

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

1.3 ZENON Cross-Flow Pervaporation Technology

The ZENON pervaporation technology is a membrane-based process that removes VOCs from aqueous matrices. The ZENON cross-flow pervaporation technology uses an organophilic membrane made of nonporous silicone rubber, which is permeable to organic compounds but highly resistant to degradation. The composition of the membrane causes organics in solution to adsorb to it; the organics then diffuse through the membrane by a vacuum and condense into a highly concentrated liquid called permeate. The permeate separates into aqueous and organic phases. The organic phase can either be disposed of or sent off site for further processing to recover the organics. The water phase is sent back to the pervaporation unit for retreatment.

The ZENON technology removes organic contamination from groundwater and other aqueous waste streams. The technology is not practical for reducing VOC concentrations to regulatory limits, most notably drinking water standards. It is best suited for reducing high concentrations of VOCs to levels that can be reduced further and more economically by conventional treatment technologies, such as carbon adsorption. According to the developer, once the ZENON technology is installed and equilibrated, it requires minimal support from on-site personnel.

The ZENON pervaporation technology involves modules containing dense polymeric membranes. Each membrane consists of a nonporous organophilic polymer, similar to silicone rubber, formed into capillary fibers measuring less than 1 millimeter in diameter. Silicone rubber exhibits high selectivity toward organic compounds and is highly resistant to degradation. The capillary fibers are aligned in parallel on a plane and spaced slightly apart. This arrangement of capillary fibers forms a membrane layer.

Separate membrane layers are aligned in series, as shown in Figure 1-1, with the interior of the capillary fibers exposed to a vacuum (about 1 pound per square inch absolute). The number of membranes used in a particular system depends on expected flow rates, contaminant concentrations in the untreated water, and target concentrations for contaminants in the treated water. Process temperatures are elevated to improve treatment; however, temperatures are kept at or below 75 °C (165 °F).

The organophilic composition of the membrane causes organics to adsorb into the capillary fibers. The organics migrate to the interior of the capillary fibers and are then extracted from the membrane by the vacuum.

Figure 1-2 displays a schematic diagram of the ZENON cross-flow pervaporation system in a typical field application (sampling locations for the system are designated S1, S2, S3, and S4). Contaminated water is pumped from an equalization tank through a 200-micron prefilter to remove debris and silt particles, and then into a heat exchanger that raises the water temperature. The heated contaminated water then flows into the pervaporation module. Organics and small amounts of water are extracted from the contaminated water, and treated water exits the pervaporation module and is discharged from the system after further treatment.

The extracted organics and small amount of water is called permeate. The permeate from the membranes is drawn into a condenser by the vacuum, where the organics and any water vapor are condensed. Because the vacuum is vented from the downstream side of the condenser, most organics are kept in solution, thus minimizing air releases.

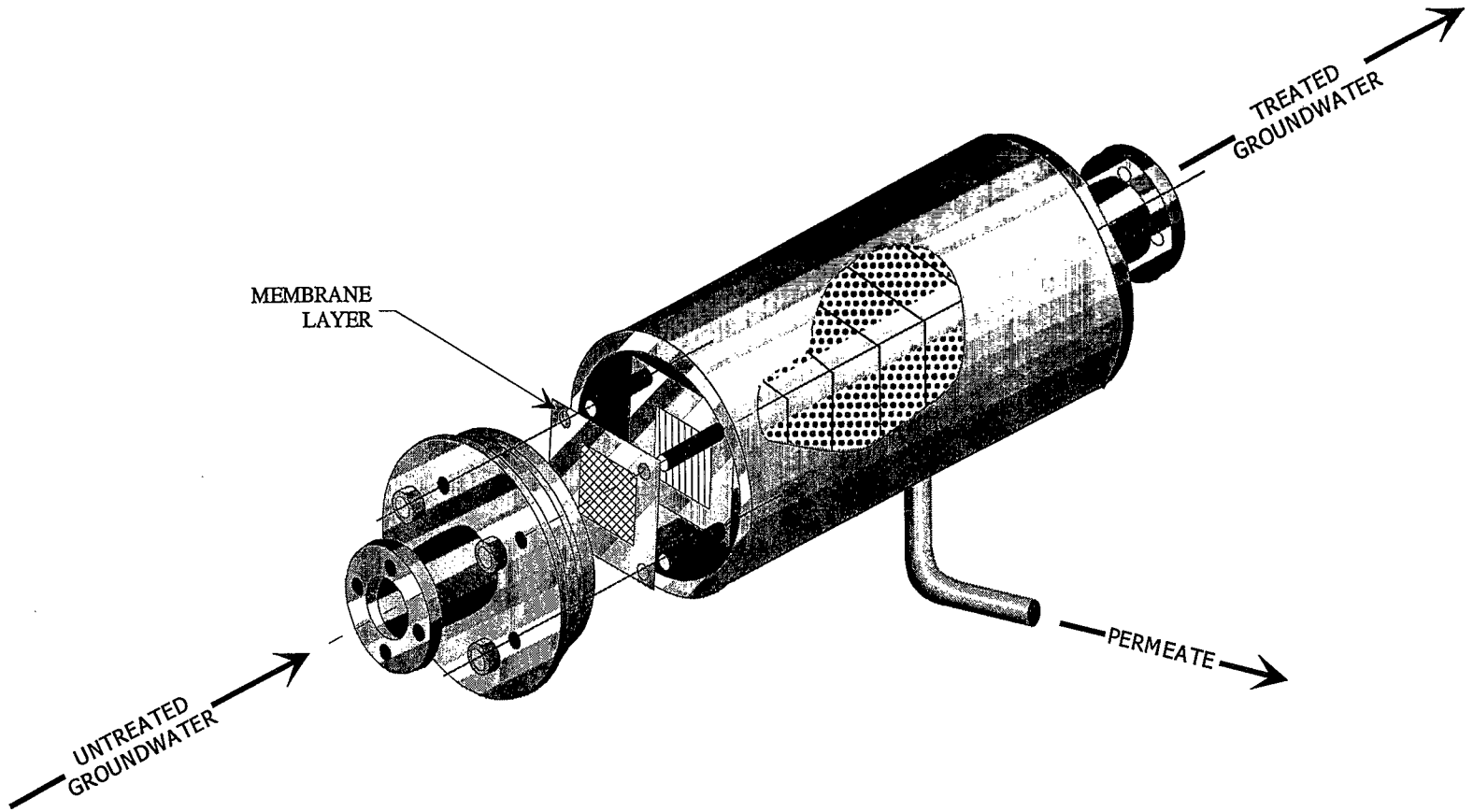

Figure 1-1. ZENON cross-flow pervaporation module.

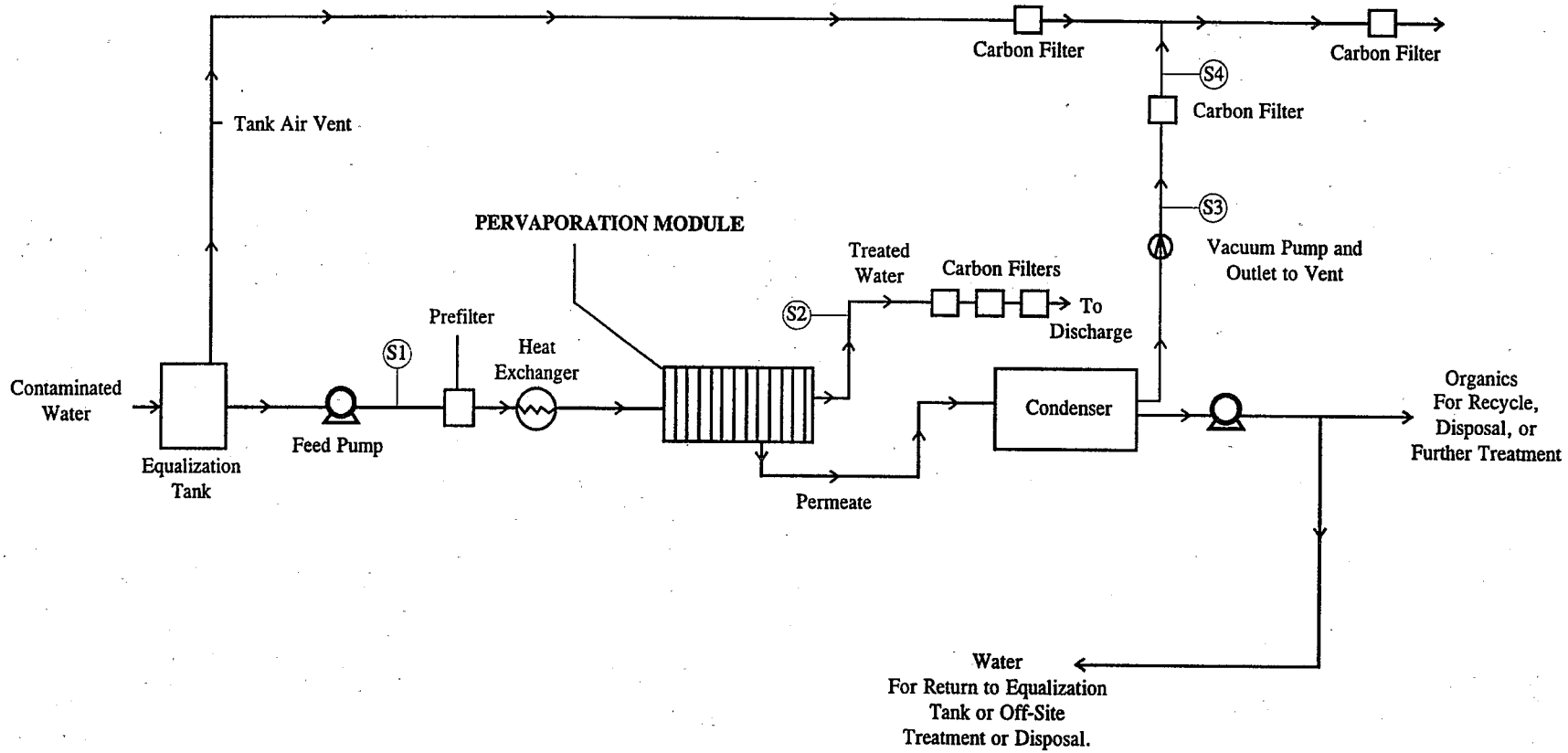

Figure 1-2. ZENON cross-flow pervaporation system.

Because condensed permeate contains highly concentrated organic compounds, the liquid permeate generally separates into aqueous and organic phases, rendering the organic fraction potentially recoverable. The organic phase permeate is pumped from the condenser to storage, while aqueous phase permeate, which contains lower concentrations of organics, can either be returned to the pervaporation module for further treatment or removed for disposal.

Water containing exceedingly high concentrations of contaminants require multiple passes through the module. Although the system can treat light nonaqueous phase liquids (LNAPL) and dense nonaqueous-phase liquids (DNAPL), they should be removed from water before it enters the system to decrease the number of passes.

1.4 Pilot-Scale Demonstration

A pilot-scale study of the ZENON pervaporation technology was performed in October 1993 at a former petroleum pumping station in Waterdown, Ontario, Canada. Samples of treated groundwater showed that benzene, toluene, ethylbenzene, and xylene (BTEX) concentrations were significantly reduced in treated groundwater samples compared to untreated samples. The removal efficiencies of BTEXs for the system ranged from 96.8 to 99.3 percent. The average removal efficiency for benzene was 98.0 percent; for toluene, ethylbenzene, and xylenes, the average removal efficiency was 98.4 percent.

1.5 Full-Scale Demonstration

This report summarizes the findings of an evaluation of the ZENON cross-flow pervaporation technology by EPA's SITE Program. The demonstration was conducted at Naval Air Station North Island (NASNI), in Coronado, California, as a cooperative effort between EPA and the Naval Environmental Leadership Program (NELP). Operations involving the technology were conducted from September 1994 through February 1995 at a former waste disposal site (Site 9) at NASNI. The site was selected for the demonstration following a bench-scale test of contaminated groundwater that was conducted by ZENON in December 1993. SITE demonstration sampling from the technology occurred over a period 5 days in February 1995, with trichloroethene the primary contaminant of concern.

1.6 Key Contacts

Additional information on the ZENON pervaporation technology and the SITE program are available from the following sources:

ZENON Pervaporation Technology
Chris Lipski
Process Engineering
Zenon Environmental, Inc.
45 Harrington Court
Burlington, Ontario, Canada L7N 3P3
905-639-6320
FAX: 905-639-1812

SITE Program
Annette Gatchett
National Risk Management Research Laboratory
U.S. Environmental Protection Agency
26 West Martin Luther King Drive
Cincinnati, OH 45268
513-569-7697

Information on the SITE program is available through the following on-line information clearinghouse: the Vendor Information System for Innovative Treatment Technologies (VISITT) (Hotline: 800-245-4505) 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
Technology Applications Analysis

This section addresses the general applicability of the ZENON pervaporation 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 and available information from other applications of the technology.

2.1 Key Features of the Zenon Treatment Technology

ZENON claims that cross-flow pervaporation provides an alternative approach to treating organic-contaminated water at hazardous waste sites and industrial facilities where conventional air stripping or carbon adsorption are currently used. Pervaporation releases less volatile organic compounds (VOC) to the outside air than air stripping. Because contaminants pass through the pervaporation membranes, the membranes can be used for years before degradation requires replacement. Organic contaminants removed from untreated water are concentrated in recovered permeate, thus greatly reducing waste volume.

A full-scale pervaporation unit measures about 8 feet by 12 feet at its base, allowing transportation in a semitrailer or a flat-bed truck. ZENON also claims that shakedown time for a pervaporation unit averages about 2 weeks, and manual operation and monitoring requirements are limited. It is a stand- alone technology, but can be used in series with other conventional technologies such as soil washing, carbon adsorption, or flocculation with solids removal. Contaminated aqueous media can be pumped directly to the pervaporation module; however, it is recommended that water be equalized in a bulk tank before entering the system. Depending on local pretreatment standards, treated water exiting the ZENON system may be discharged to a publicly owned treatment works (POTW). To comply with limitations imposed by the National Pollutant Discharge Elimination System (NPDES) or the Safe Drinking Water Amendment (SDWA), further treatment with a separate technology is usually required.

2.2 Technology Applicability

The ZENON cross-flow pervaporation technology removes VOCs from aqueous matrices, such as groundwater, wastewaters, and leachate. The technology can treat a variety of concentrations; however, it is best suited for reducing high concentrations of VOCs to levels that can be reduced further and more economically by conventional treatment technologies, such as carbon adsorption. The technology can also remove a limited number of semivolatile organic compounds (SVOC) and petroleum hydrocarbons. Both the pilot- and full-scale demonstrations have evaluated the ZENON technology's treatment of contaminated groundwater.

2.3 Technology Limitations

A number of factors must be considered before using pervaporation. The prefilter prevents solids from reaching the pervaporation module and inhibiting the movement of organics through the membrane. Solids can clog the prefilter, requiring frequent cleaning. Influent with a high alkalinity or high amounts of calcium or iron can cause the system to scale. In these cases, anti-scalents can be added to the untreated water as a preventive measure.

The ZENON technology does not remove inorganic contamination and can only remove only a limited number of SVOCs and petroleum hydrocarbons. Heavy metals

dissolved in groundwater have not adversely affected the treatment ability of the technology.

VOCs with water solubilities of less than 2 percent weight (20,000 mg/L) are generally suited for removal by pervaporation. Highly soluble organics such as alcohols are not effectively removed by a single-stage pervaporation process. Also, low-boiling VOCs such as vinyl chloride tend to remain in the vapor phase after moving through the condenser, and can escape to the surrounding air through the vacuum vent. For elevated concentrations of most low-boiling VOCs, a carbon filter placed on the vacuum vent ensures that contaminants are not released to the outside air.

The system has proven effective in reducing certain VOC concentrations in groundwater to near federal maximum concentration limits (MCL). However, lowering concentrations to below MCLs may require multiple passes through the pervaporation module, which can prove impractical when compared to other technologies, such as carbon adsorption. Water containing high concentrations of contaminants, including LNAPLs and DNAPLs, also require multiple passes through the module. To decrease the number of passes, LNAPLs and DNAPLs should be removed from water before it enters the system.

Water quality standards normally will not allow water exiting the ZENON system to be discharged directly into surface water bodies. Depending on local standards, treated water may be acceptable for discharge to a local POTW. During the SITE demonstration at NASNI, water discharged from the ZENON system required additional treatment through a series of two 1,000-pound carbon filters for polishing. VOC concentrations in the water were then monitored with an on-site gas chromatograph (GC). The water was discharged to the sanitary sewer.

The ZENON system tested at NASNI could achieve a maximum flow rate of about 11 gallons per minute (gpm), which is the highest flow rate for the technology to date. Sites requiring treatment at higher flow rates will require multiple systems or additional pervaporation modules.

2.4 Process Residuals

The ZENON system generates two waste streams: treated water and concentrated permeate. During the SITE demonstration at NASNI, granular activated carbon used to remove VOCs from emissions released from the vacuum vent of the system also required disposal. Treated water may require further treatment to meet local or site-specific discharge requirements.

Permeate usually separates into an organic and an aqueous phase. The organic phase permeate is pumped from the condenser to storage and eventual recycling or disposal. Because of the high VOC concentrations expected with permeate, it must normally be handled as a RCRA hazardous waste, and storage regulations must be followed. Aqueous phase permeate can either be returned to the pervaporation module for further treatment or removed for disposal.

Depending on the application and local regulations, personal protective clothing and equipment, along with field laboratory waste, may require disposal at a licensed disposal facility. If monitoring and pumping wells will be installed as part of a remediation effort, contaminated soil cuttings may need to be stored in permitted areas and disposed of in accordance with applicable regulations.

2.5 Site Support Requirements

The ZENON system is a self-supporting treatment unit, and as such, requires other basic site support elements. If wells are used as the groundwater source, pumps must be used to extract groundwater and direct it to the ZENON system. The pumping capacity of the system may limit the amount of groundwater it can pull from a series of monitoring wells.

Access roads at treatment sites are necessary because a full-scale pervaporation system is shipped to sites in a semi trailer or on flat-bed trucks. The ZENON system is mounted in a steel enclosure measuring about 12 feet by 8 feet by 7 feet. The enclosure is designed to be moved with a large forklift or a small crane. The enclosure must be placed on a hard surface, preferably an asphalt or concrete pad, although packed soil will support it.

The ZENON system requires utility hookups for electricity and water. A full-scale ZENON system capable of 11 gpm requires 460-volt, 3-phase, 15-ampere service. During shakedown, clean water is necessary to verify that all components are operating correctly before contaminated water enters the system.

Clean water is also needed to decontaminate process equipment and for health and safety. Permeate must be

stored in drums or bulk tanks, which under Resource Conservation and Recovery Act (RCRA) regulations requires secondary containment and possibly permits. To move drums of permeate at the site, a two-wheel drum mover or forklift is advised. A receptacle for treated water, such as bulk tanks or sewer lines, is also necessary. A small office trailer, a telephone, and security fencing are recommended for moderate- to long-term operations.

2.6 Availability And Transportation of Equipment

The ZENON technology employs conventional, commercially available equipment and materials that are easily transported in a semi trailer or on a flat-bed truck. On-site assembly and maintenance requirements are minimal. ZENON claims that the treatment system can begin operating within 2 weeks of startup if all necessary facilities, utilities, and supplies are available.

Demobilization activities include decontaminating on-site equipment, disconnecting utilities, disassembling equipment, and transporting equipment off site. In a groundwater treatment scenario, wells used for the extraction of groundwater may require plugging and abandonment after project completion.

2.7 Feasibility Study Evaluation Criteria

This section presents an assessment of the ZENON pervaporation technology 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). Table 2-1 presents a summary of the pervaporation technology's relation to the nine evaluation criteria.

2.7.1 Overall Protection of Human Health and the Environment

The ZENON technology provides both short- and long-term protection of human health and the environment by removing contaminants from groundwater and by preventing further migration of contaminants in the groundwater. VOCs are removed from the groundwater in the pervaporation module, condensed, and placed in storage. VOC releases to the surrounding air are controlled by carbon filters. Although worker protection is required when moving and handling the highly concentrated permeate, contaminants are removed from the groundwater with minimal exposures to on-site workers and the community. Heavy equipment is necessary to unload and place the unit in a designated location. Once in place and operating, heavy equipment usage would be limited to the occasional movement of drums of permeate with a forklift.

2.7.2 Compliance with Applicable or Relevant and Appropriate Requirements

General and specific applicable or relevant and appropriate requirements (ARAR) identified for the ZENON pervaporation technology 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 generally are achieved. Compliance with chemical-specific ARARs depends on (1) the efficiency of the ZENON system in removing contaminants from the groundwater,(2) influent contaminant concentrations, (3) the amount of treated water recirculated in the system, and (4) postpervaporation treatment. To meet chemical-specific ARARs, contaminated groundwater may require multiple passes through the treatment system, along with posttreatment (such as carbon adsorption).

2.7.3 Long-Term Effectiveness and Permanence

The ZENON pervaporation technology provides an effective long-term solution to aquifer remediation by removing contaminants from the groundwater. Depending on treatment requirements, some residual risk may exist at a given site after treatment. The magnitude of residual risk can be controlled by extending the length of time that the system operates, or by allowing groundwater to recirculate through the treatment system in multiple passes.

2.7.4 Reduction of Toxicity, Mobility, or Volume Through Treatment

The ZENON system reduces the toxicity of contaminated groundwater by actively removing organic contaminants through the membrane-based process. The membrane-based process reduces the volume of contaminated media

Table 2-1. Feasibility Study Evaluation Criteria for the ZENON Technology

Criteria	ZENON Technology Assessment
Overall Protection of Human Health and the Environment	The technology reduces contaminants in the groundwater and prevents further migration of those contaminants with minimal exposure to on-site workers and the community.
Compliance with Federal and State ARARs	Compliance with chemical-, location-, and action-specific ARARs must be determined on a site-specific basis. The technology is not suited for removing contaminants to maximum concentration limits (MCL) and may require additional treatment to meet National Pollutant Discharge Elimination System (NPDES) standards depending on (1) influent contaminant concentrations, and (2) treatment efficiency of the ZENON technology.
Long-Term Effectiveness and Permanence	Contaminants are permanently removed from the groundwater. Treatment residuals (concentrated permeate) require proper off-site recycling, treatment or disposal.
Reduction of Toxicity, Mobility, or Volume Through Treatment	Contaminants are removed from the groundwater, thus reducing its toxicity. The radius of influence of wells used to pump influent to the system, the pumping rate, and the time-frame of pumping will determine the mobility of contaminants in the groundwater over the treatment period. Treatment followed by discharge to publicly owned treatment works (POTW) or surface water prevents further migration of contaminants and reduces the volume of contaminated media.
Short-Term Effectiveness	During site preparation and installation of the treatment system, no adverse impacts to the community, workers, or the environment are anticipated. Risks to workers involve the movement of containerized permeate and possible venting of contaminants from the system. The time requirements for treatment using the ZENON system is dependent on site conditions and may require several years.

Table 2-1. Feasibility Study Evaluation Criteria for the ZENON Technology (continued)

Criteria	ZENON Technology Assessment
Implementability	The site requires a hard surface such as concrete or packed soil to support the system and associated tanks, which require about 120 square feet. A large capacity bulk tank is recommended for the equalization of contaminated water before it is pumped into the system. Services and supplies required include laboratory analyses and electrical utilities.
Cost	For use of the technology at NASNI Site 9 for a 15-year period treating a total of 63 million gallons of groundwater, total fixed costs are $189,500. Equipment costs comprise 79 percent of the total fixed costs. Total annual variable costs are $118,100. Utilities costs comprise 47 percent of the variable costs, and residual waste handling services comprise 28 percent.
Community Acceptance	The small risks to the community and permanent removal of the contaminants make public acceptance of this technology likely.
State Acceptance	State acceptance is anticipated to be favorable because the ZENON system generates a low volume of waste in relation to treated groundwater, and air emissions are negligible. State regulatory agencies may require permits to operate the treatment system, for air emissions, and to store concentrated permeate for greater than 90 days.

by separating the organic contaminants from the groundwater and concentrating them into a highly concentrated liquid permeate. This treatment results in a significant volume reduction compared to the untreated water. The radius of influence of wells used to pump influent to the system, the time frame of pumping, and the aquifer characteristics will determine the volume of material treated.

Treatment of the organic contaminants followed by discharge of the treated water to a POTW or surface water prevents further migration of contaminants and reduces the volume of contaminated media. Water quality standards normally will not allow water exiting the ZENON system to be discharged directly into surface water bodies, and further treatment is required. Results of the ZENON demonstration at NASNI, displaying contaminant reductions, are presented in Section 4.3.

2.7.5 Short-Term Effectiveness

The pervaporation technology provides a long-term solution to removing VOCs from contaminated groundwater or wastewaters. VOCs in untreated water are reduced immediately as the water passes through the system. Further treatment may be required depending on the regulations applicable to individual sites.

2.7.6 Implementability

Site preparation and access requirements for the technology are minimal. As noted in Section 2.6, a given site requires access roads large enough to allow passage of a semi truck. The entire system occupies an area of about 200 square meters. Installation and operation of the ZENON system is anticipated to involve few administrative difficulties. Operation and monitoring can be performed by a trained field technician and does not require a specialist. However, system maintenance should be provided by personnel familiar with operation of the system. Routine activities include monitoring target compound concentrations in the system influent and effluent wells. Services and supplies required to implement the ZENON system include bulk tanks for equalization and treated water storage, laboratory analyses to monitor the system performance, electrical and water utilities, and carbon adsorption regeneration or disposal.

2.7.7 Cost

A complete analysis of costs to operate the ZENON pervaporation system is presented in Section 3.0. The analysis presents cost estimates for treating groundwater at NASNI contaminated with TCE. In short, operating conditions include treating the groundwater at 8 gpm for a period of 15 years. Total fixed costs are $189,500. Equipment costs comprise 79 percent of the total fixed costs. Total annual variable costs are $118,100. Utilities costs comprise 47 percent of the variable costs, and residual waste handling services comprise 28 percent. After operating for 15 years, the total cost of the groundwater remediation scenario presented in this analysis is $1,961,000. Annual costs were not adjusted for inflation. A total of 63 million gallons of groundwater would be treated over this time period. The total cost per 1,000 gallons treated is $31, or roughly 3 cents per gallon. During the demonstration, numerous equipment failures occurred, which caused extensive downtime. It is assumed that the pervaporation system will be perfected by ZENON thereby decreasing maintenance requirements. If technical needs are not addressed by ZENON, the costs associated with applying this system could be substantially higher than those presented in this analysis.

2.7.8 State Acceptance

State acceptance is anticipated to be favorable because the ZENON system is an advanced technology that generates low relative residual waste. Also, the ZENON system is small and relatively easy to transport, operate, and manage. If remediation is conducted as part of RCRA corrective actions, state regulatory agencies may require that permits be obtained before implementing the system, such as a permit to operate, an air emissions permit, and a permit to store permeate for greater than 90 days if these items are considered hazardous wastes.

2.7.9 Community Acceptance

The ZENON system has limited space requirements, minimal maintenance and monitoring, and a low noise level. Emissions are limited when the system is used in conjunction with carbon filters. Because an operating ZENON system requires only minor maintenance, traffic in and out of a particular site will be limited. Short-term risks to the community are minimal, which include delivery vehicle traffic to and from the site electrical concerns during installation. Long-term benefits include

the permanent removal of organic contaminants from groundwater. These factors make this technology favorable to the public.

2.8 Technology Performance Versus ARARs

This section discusses specific federal regulatory requirements pertinent to the treatment, storage, and disposal of water and permeate, along with other materials generated during the operation of the technology. Regulatory requirements that apply to a particular remediation activity will depend on the type of remediation site and the type of waste being treated. Contaminated groundwater is usually not considered a hazardous waste unless it is withdrawn from the aquifer and placed in stand-alone containers or tanks. Contaminated leachates and other waste streams considered hazardous may be RCRA regulated. Table 2-2 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 the Superfund Amendments and Reauthorization Act (SARA) of 1986, authorizes the federal government to respond to releases or potential releases of any hazardous substances into the environment, as well as to releases of pollutants or contaminants that may present an imminent or significant danger to public health and welfare or the environment. Remedial alternatives that significantly 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 that on-site actions meet all substantive state and federal ARARs. Substantive requirements pertain directly to actions or conditions in the environment (such as, groundwater effluent and air emission standards). Off-site actions 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 ZENON technology, treated groundwater and concentrated permeate are the primary residual wastes generated from the treatment system. During the SITE demonstration, spent granular activated carbon was also generated from treatment of air emissions. CERCLA requires identification and consideration of environmental laws that are ARARs for site remediation before implementation of a remedial technology at a Superfund site. Given these wastes (typical of operation of a ZENON system), the following additional regulations pertinent to use of a ZENON system 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 Administration (OSHA). These five regulatory authorities are discussed below. Specific ARARs under these acts that were applicable to the SITE demonstration are presented in Table 1.

2.8.2 Resource Conservation and Recovery Act

RCRA, as amended by the Hazardous and Solid Waste Disposal Amendments of 1984, regulates management and disposal of municipal and industrial solid wastes. The EPA and RCRA-authorized states [listed in Title 40 of the Code of Federal Regulations (CFR) Part 272] implement and enforce RCRA and state regulations. Some of the RCRA requirements under 40 CFR Part 264 apply at

Table 2-2. Federal and State ARARs

Process Activity	ARAR	Description	Why ZENON is Subject to ARAR	Requirements
Remediate contaminated groundwater (cleanup standards)	SDWA 40 CFR Parts 141 through 149 or state equivalent TCE - 0.005 mg/L	Establishes drinking water quality standards for public 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 hazardous 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 the operating and monitoring requirements; the treatment process may be considered a miscellaneous unit.	Equipment must be operated and maintained daily. The ZENON system must be monitored and maintained to prevent leakage or failure; the tanks and equipment must be decontaminated when processing is complete.
Waste characterization (treated waste, permeate, and spent carbon)	RCRA 40 CFR Part 261 or state equivalent	Identifies whether the waste is a listed or characteristic hazardous waste	A RCRA requirement prior to managing and handling the waste; it must be determined if treated waste is still a RCRA hazardous waste.	Chemical tests must be performed on treated waste and permeate prior to discharge to surface water, a POTW, or off site disposal. The spent carbon is considered a hazardous waste if it is derived from treatment of hazardous waste.
Storage after processing	RCRA 40 CFR Part 264 and 265 or state equivalent	Standards that apply to the storage of hazardous waste in tanks or containers	If treated water stored in tanks is considered hazardous, requirements for storage of hazardous waste in tanks may apply. Spent carbon in the containers may be handled as hazardous if derived from the treatment of a RCRA hazardous waste.	The spent 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 2-2. Federal and State ARARs (continued)

Process Activity	ARAR	Description	Why ZENON is Subject to ARAR	Requirements
On-site/off-site disposal	RCRA 40 CFR Part 264 or state equivalent	Standards that apply to incineration and landfilling hazardous waste	Organic permeate will likely be handled as a RCRA hazardous waste. Spent carbon may need to be managed as a hazardous waste if it is derived from treatment of hazardous waste.	Wastes must be incinerated or disposed of at a RCRA-permitted hazardous waste facility, or EPA approval must be obtained EPA to dispose of wastes on site.
	RCRA 40 CFR Part 268 or state equivalent	Standards that restrict the placement of certain hazardous wastes in or on the ground	The hazardous waste may be subject to the LDRs.	The waste must be characterized to determine if the LDRs apply; treated wastes must be tested and results compared.
Transportation for off-site disposal	RCRA 40 CFR Part 262 or state equivalent	Manifest requirements and packaging and labeling requirements prior to transport	Organic permeate will likely need to be manifested and managed as a hazardous waste. This may also apply to spent carbon if it is derived from treatment of hazardous waste.	An identification number must be obtained from EPA.
	RCRA 40 CFR Part 263 or state equivalent	Transportation standards	Organic permeate will likely need to be manifested and managed as a hazardous waste. This may also apply to spent 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.
Wastewater injection	SDWA 40 CFR Parts 144 and 145	Standards that apply to the disposal of contaminated water in underground injection wells	Treated groundwater may be reinjected into the aquifer.	If the technology is defined as underground injection and the treated groundwater still contains hazardous constituents then a waiver from EPA or the state will likely be required.

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

Process Activity	ARAR	Description	Why ZENON is Subject to ARAR	Requirements
Discharge of water	CWA 40 CFR Parts 122 to 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, an NPDES permit is 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 treated water is discharged off-site to a POTW.
Air emissions from the system	CAA or state equivalent; RCRA 40 CFR Part 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	The ZENON 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.

Notes:

ARAR	Applicable or Relevant and Appropriate Requirements
SDWA	Safe Drinking Water Act
40 CFR	Title 40 of the Code of Federal Regulations
NPDES	National Pollutant Discharge Elimination System
CWA	Clean Water Act
CAA	Clean Air Act
TCE	Trichloroethene

CERCLA sites that contain RCRA hazardous waste because remedial actions generally involve treatment, storage, or disposal of hazardous waste.

Contaminated water treated by the ZENON system will most likely be hazardous or sufficiently similar to hazardous waste so that RCRA standards will apply. Tank storage of contaminated water considered a hazardous waste must meet the requirements of 40 CFR Part 264 or 265, Subpart J. Pertinent RCRA requirements are discussed below.

The presence of RCRA-defined hazardous waste determines whether RCRA regulations apply to the ZENON technology. If wastes generated during the installation, monitoring, or operation of the technology are determined to be hazardous according to RCRA, all RCRA requirements regarding the management and disposal of hazardous wastes will need to be addressed. RCRA regulations define hazardous wastes and regulate their transport, treatment, storage, and disposal. Wastes defined as hazardous under RCRA include characteristic and listed wastes. Criteria for identifying characteristic hazardous wastes are included in 40 CFR Part 261, Subpart C. Listed 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.

If contaminated groundwater is determined to be a hazardous waste, and is extracted for treatment, storage, or disposal, the requirements for a hazardous waste generator will be applicable. Requirements for hazardous waste generators are specified in 40 CFR Part 262. These requirements include obtaining an EPA identification number, meeting waste accumulation standards, labeling wastes, and keeping appropriate records. These requirements also allow generators to store wastes up to 90 days without a permit and without having interim status as a treatment, storage, or disposal facility. If the untreated influent is a "listed waste," or the treated effluent is a "characteristic waste," and treatment residues are stored on site for 90 days or more, requirements in 40 CFR Part 265 apply. If hazardous wastes are treated by the ZENON system, the owner or operator of the treatment or disposal facility must obtain an EPA identification number and a RCRA permit from the EPA- or RCRA-authorized state. RCRA requirements for permits are specified in 40 CFR Part 270. In addition, to the permitting requirements, owners and operators of facilities that treat hazardous waste must comply with 40 CFR Part 264.

Use of the ZENON system would constitute treatment as defined by RCRA. Therefore, treatment requirements may apply if the ZENON system is found to belong to a treatment category classification regulated under RCRA, and if it is used to treat a RCRA listed or characteristic waste. Treatment requirements in 40 CFR Part 264, Subpart X, which regulate hazardous waste, treatment, and disposal in miscellaneous units, may be relevant to the ZENON system. Subpart X requires that treatment in miscellaneous units protect human health and the environment. Treatment requirements in 40 CFR Part 265, Subpart Q (Chemical, Physical, and Biological Treatment), could also apply. Subpart Q includes requirements for automatic influent shutoff, waste analysis, and trial tests. RCRA also contains special standards for ignitable or reactive wastes, incompatible wastes, and special categories of waste (40 CFR Parts 264 and 265, Subpart B). These standards may apply to the ZENON system, depending on the waste to be treated.

Requirements for corrective action at RCRA-regulated facilities are provided in 40 CFR Part 264, Subparts F and S. These subparts also apply to remediation at Superfund (CERCLA) sites. Subparts F and S include requirements for initiating and conducting RCRA corrective actions, remediating groundwater, and ensuring that corrective actions comply with other environmental regulations. Subpart S also details conditions under which particular RCRA requirements may be waived for temporary treatment units operating at corrective action sites. Thus, RCRA mandates requirements similar to CERCLA, and as proposed, allows treatment units such as the ZENON treatment system to operate without full permits.

Air emissions from operation of the ZENON are subject to RCRA regulations on air emissions from hazardous waste treatment, storage, or disposal operations and are addressed in 40 CFR Parts 264 and 265, Subparts AA, BB, and CC. Subpart AA regulations apply to process vents associated with specific treatment operations for wastes contaminated with organic constituents, which would apply to the ZENON system due to the vacuum vent. Subpart BB regulations apply to fugitive emissions, such as equipment leaks, from hazardous waste treatment, storage, or disposal facilities 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. Subpart BB regulations would normally not impact the ZENON system because of lower contaminant concentrations usually found in affected aquifers. 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 treatment, storage, or disposal facility 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. Presently, EPA is 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 ZENON system. The 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. The most important air requirements are probably associated with the Clean Air Act (CAA) and state air toxic programs (see Section 2.8.5).

Concentrated permeate, spent granular activated carbon (if used), and possibly, contaminated soil cuttings generated during the installation, operation, and monitoring of the treatment system must be stored and disposed of properly. If the untreated water is a listed hazardous waste, treatment residues will be considered a hazardous waste (unless RCRA delisting requirements are met). If the untreated water is a characteristic hazardous waste, treatment residues should be tested to determine if they are a RCRA characteristic hazardous waste. If activated carbon and soil cutting residues are not hazardous and do not contain free liquids, they can be disposed of at a nonhazardous waste landfill.

If the organic phase of the permeate, spent carbon, or soil cuttings is hazardous, RCRA standards may apply. For most applications involving the removal of VOCs from water, concentrated permeate will normally be classified as a hazardous waste, requiring recycling or disposal at a designated treatment facility. Any facility (on-site or off-site) designated for permanent disposal of hazardous wastes must comply with RCRA. Disposal facilities must fulfill permitting, storage, maintenance, and closure requirements contained in 40 CFR Parts 264 through 270. In addition, any authorized state RCRA requirements must be fulfilled. If treatment residues are disposed off site, transportation standards apply.

Water quality standards included in RCRA (such as groundwater monitoring and protection standards), the CWA, and the SDWA are appropriate cleanup standards and apply to discharges of treated water. 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 an NPDES permit. A direct discharge of CERCLA wastewater would qualify 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 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 ZENON

system 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 and 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 level (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, ZENON system performance was tested for compliance with SDWA MCLs for TCE. Removal of TCE to below the MCL was not met and is discussed in Section 4.3.

If the treated water is reinjected into an aquifer, the ZENON system may be interpreted by federal or state agencies as underground injection since treated water is placed into the subsurface. If this interpretation is applied, water discharged from the ZENON system 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 still contains 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. Technically, groundwater pumping wells used in conjunction with the ZENON 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 of 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 (¼) 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 (¼) mile of the well contains an underground source of drinking water.

(3) Wells used by generators of hazardous waste or owners or operators of hazardous waste management facilities to dispose of hazardous waste, which cannot be classified under paragraph (a)(1) or (d) (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 ZENON system, 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 ZENON system. The EPA guidance suggests that the sources most in need of controls 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 1989b). Based on air analysis from the demonstration, vapor discharges from the ZENON system would be required to pass through carbon filters to comply with the EPA guidance.

The CAA and the 1990 amendments 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 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 ZENON system because the technology ultimately results in an emission from a point source to the ambient air. Allowable emission limits for operation of a ZENON system will be established on a site-by-site basis depending on the type of waste treated 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 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 ZENON system's 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 ZENON technology may be subject to the requirements of Part C of the CAA for the prevention of significant deterioration of air quality in attainment (or unclassified) areas. The PSD requirements will 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 best available control technologies and demonstrate that the activity will not adversely impact ambient air quality.

2.8.6 Occupational Safety and Health Administration 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 waste 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 constructions sites. For example, electric utility hookups for the ZENON 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 is maintained.

All technicians operating the ZENON treatment system are required to have completed an OSHA training course and must be familiar with all OSHA requirements relevant to hazardous waste sites. For most sites, minimum personal protective equipment (PPE) for technicians will include gloves, hard hats, steel-toed boots, and coveralls. Depending on 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 a time-weighted average of 85 decibels over an 8-hour day on the A-weighted scale.

Section 3
Economic Analysis

This economic analysis presents cost estimates for using the ZENON cross-flow pervaporation technology to treat groundwater contaminated with VOCs. Cost data were compiled during the SITE demonstration at NASNI Site 9 and from information obtained from independent vendors, R.S. Means Inc. (Means 1995), and ZENON. Costs have been placed in 12 categories applicable to typical cleanup activities at Superfund and RCRA sites (Evans 1990). Costs, which are presented in 1995 dollars, are rounded to the nearest 100 dollars, and are considered to be estimates with an expected accuracy within 50 percent above and 30 percent below the actual costs.

This economic analysis presents the costs associated with using the ZENON pervaporation treatment system at NASNI Site 9 operating at 8 gpm continuously for 15 years. Section 3.1 describes the issues and assumptions that form the basis of the economic analysis. Section 3.2 discusses costs associated with using the ZENON technology to treat groundwater contaminated with VOCs, and Section 3.3 presents conclusions of the economic analysis.

3.1 Issues And Assumptions

This section summarizes major issues and assumptions regarding site-specific factors, equipment, and operating parameters used in this economic analysis. Issues and assumptions are presented in Subsections 3.2.1 through 3.2.3. Assumptions are summarized in bullets following each section. Certain assumptions were made to account for variable site and waste parameters. Other assumptions were made to simplify cost estimating for situations that actually would require complex engineering or financial functions. In general, most ZENON system operating issues and assumptions are based on information provided by ZENON and observations made during the SITE demonstration.

3.1.1 Site-Specific Factors

Site-specific factors can affect the costs of using the ZENON pervaporation treatment system. These factors can be grouped into waste-related factors or site features.

Waste-related factors affecting costs include waste volume, contaminant types and concentrations, and treatment goals designated by regulatory agencies. Waste volume affects total project costs because a larger volume takes longer to remediate. However, economies of scale can be realized with a larger-volume project because the fixed costs, such as equipment costs, are distributed over the larger volume. The contaminant types and levels in the groundwater and the treatment goals for the site determine (1) the appropriate number of ZENON pervaporation modules, which affects capital equipment costs; (2) the flow rate at which treatment goals can be met, which affects the duration of the remediation; and (3) periodic sampling requirements, which affect analytical costs.

Site features affecting costs include geology, aquifer permeability, groundwater chemistry (such as naturally occurring minerals in solution), and site geographic location. Site geology and soil characteristics such as total organic content and permeability also affect the groundwater extraction rate and the required treatment period. Overall, annual variable costs are relatively low with this technology. As a result, factors that affect the duration of remediation do not significantly impact total treatment costs.

Groundwater chemistry can affect the pervaporation system in several ways. Solids can clog the prefilter, requiring frequent cleaning. Influent with a high alkalinity or high amounts of calcium or iron can cause scaling of the system. Anti-scalents can be added to the untreated water as a preventative measure. These factors would increase

the duration of remediation, affecting consumable and time-related variable costs, or may impact maintenance costs.

Geographic location will impact site preparation, mobilization, and demobilization costs. Mobilization and demobilization costs are affected by the relative distances that system materials must be transported to the site. Site preparation costs are influenced by the availability of access roads and utility lines.

Site-specific assumptions used for the economic analysis include the following:

- The groundwater is contaminated with TCE in concentrations ranging from 30 to 250 milligrams per liter (mg/L) and is a hazardous waste
- Treated water will be discharged to a POTW
- Utilities, including electricity and water, along with other infrastructure features (for example, access roads to the site) are readily available
- The groundwater remediation project involves a total of 63 million gallons of contaminated water. This groundwater volume corresponds to the volume that the system can treat operating continuously for 15 years at an average flow rate of 8 gpm. Some down-time is expected for system maintenance and repair, and is not considered in this cost estimate

3.1.2 Equipment and Operating Parameters

ZENON will provide the appropriate system configuration, which includes pervaporation modules, condensers, and piping. The configuration is based on site-specific conditions such as aquifer permeability and groundwater contaminant types.

Depreciation of equipment is not considered in this analysis in order to simplify presenting the costs of this analysis. An additional assumption is that the pervaporation system will be perfected by ZENON thereby decreasing maintenance requirements. During the demonstration, numerous equipment failures occurred, which caused extensive downtime and eventually required demonstration sampling to be shortened to 5 days (see Section 4.2.3). If technical needs are not addressed by ZENON, the costs associated with applying this system could be substantially higher than those presented in this analysis.

The equipment and operating parameter assumptions include the following:

- A 100-square-foot concrete pad is needed for the pervaporation system
- The individual components of the treatment system are mobilized to the site and assembled by ZENON
- Groundwater will be extracted from the contaminated aquifer using existing wells
- The treatment system is operated 24 hours per day, 7 days per week, 52 weeks per year for 15 years. Routine maintenance results in a down-time of about 2 percent of this time and is not considered in the calculations.
- The treatment system operates automatically without the constant attention of an operator, with the exception of maintenance-related labor
- The treatment system is effective enough to allow treated groundwater to be discharged to a POTW. To comply with NPDES or SDWA limitations, further treatment with a separate technology, such as carbon adsorption, may be required; however, postpervaporation carbon filters for water are not considered as part of this analysis.
- Air emissions monitoring is not needed based on the use of a carbon filter

3.1.3 Miscellaneous Factors

For this analysis, annual costs are not adjusted for inflation, and no net present value is calculated. Most groundwater remediation projects are long-term in nature, and usually a net present worth analysis is performed for cost comparisons. The variable costs for this technology are relatively low. In addition, no other system configurations or technologies are presented in this analysis for comparison.

Additional premises used for this economic analysis are the following:

- The ZENON system is mobilized to the remediation site from within 500 miles of the site
- Labor costs for operation, maintenance, and sampling are incurred by the client. ZENON performs maintenance and modification activities that are paid for by the client.
- Initial operator training is provided by ZENON a part of installation and startup services

3.2 Cost Categories

Table 3-1 presents cost breakdowns addressing the 12 cost categories. Cost data associated with the ZENON technology have been presented for the following 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. Each of these cost categories is discussed in the following sections.

3.2.1 Site Preparation

Site preparation costs include performing a treatability study, conducting engineering design activities, and preparing the treatment area. A treatability study will take about 1 month to complete and cost between $1,000 and $3,000. After the study and a preliminary site assessment, ZENON will design the optimal system configuration for a particular site. System design costs are included in the equipment costs in Subsection 3.2.4.

Preparation of the treatment area includes installing a 100-square-foot concrete pad, fencing, and piping and pumps to connect the wells to the system. Groundwater wells with sufficient pumping and recovery rates are assumed to be available, but piping will need to be installed to connect the wells to the ZENON system and will cost about $10 per linear foot to construct. For this analysis, it is assumed that 500 feet of piping will be necessary to connect the groundwater wells to the ZENON system. Total piping costs, including labor, are $5,000.

A concrete pad is preferred to support the ZENON system, although it is also possible to use packed soil. The concrete pad should be bermed, epoxy-coated, reinforced, and 6 inches thick. This pad can be constructed for $25 per square foot for a total of $2,500. A 6-foot-high security fence and one gate is needed to limit access to the treatment system. Fencing costs about $21 per foot, which includes labor and supplies. This analysis assumes the fence will secure a 20-foot-by-20-foot area. Total fencing costs, including labor and supplies, are $1,700.

Secondary containment for bulk storage of untreated and treated water was required during the SITE demonstration and may be required in other applications of the technology. Secondary containment for a 15-year treatment operation would probably require a sealed concrete dike. An average of $5,000 has been used for secondary containment.

Total site preparation costs are estimated to be $17,200.

3.2.2 Permitting and Regulatory Costs

Permitting and regulatory costs depend on whether treatment is performed at a Superfund or a RCRA corrective action site and on how disposal of treated effluent and any generated solid wastes occurs. Remedial actions at Superfund sites must be consistent with ARARs of 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 the regulatory costs. In general, ARARs must be determined on a site-specific basis. This analysis assumes remediation at a Superfund site.

For this analysis, permitting and regulatory costs are associated with discharging treated groundwater to a POTW. The cost of all permits are based on the characteristics of the effluent and related receiving water requirements. An air permit is also necessary for the release of VOCs that escape from the pervaporation system's vacuum vent.

Total permitting and regulatory costs for this analysis are estimated to be $3,000.

Table 3-1. Costs Associated with the ZENON Treatment Process

Cost Categories	Itemized Cost (b)	Total Cost (b)
Site Preparation Costs (c)		$17,200
Treatability study	$3,000	
Piping from wells	5,000	
Concrete pad	2,500	
Security fence	1,700	
Secondary containment	5,000	
Permitting and Regulatory Costs (c)		3,000
Mobilization and Startup (c)		19,300
Transporation	1,500	
Assembly	4,000	
Forklift rental	600	
Electric hookup	4,000	
GC rental (two months)	8,000	
Trailer	1,200	
Equipment (c)		150,000
Pervaporation system	140,000	
Bulk tanks	10,000	
Labor (d)		7,000
Technician labor	7,000	
Supplies (d)		2,900
Carbon Canisters	2,000	
Personal protective equipment	200	
Disposal drums	700	
Utilities (d)		55,200
Electricity	55,200	
Effluent Treatment and Disposal Costs (d)		7,000
Publicly owned treatment works charges	7,000	
Residual Waste Shipping and Handling (d)		33,600
Carbon Canister Disposal	2,400	
Drum disposal	28,800	
Transportation charges	2,400	
Analytical Services (d)		8,400
Equipment Maintenance (d)		4,000
Replacement parts	1,500	
Anti-scaling and acidic chemicals	2,500	
Site Demobilization (e)	0	
Total One-Time Costs		$189,500
Total Annual Variable Costs		118,100
Total Groundwater Treatment Project Costs (f)		$1,961,000
Costs per 1,000 gallons treated (g)		31

Notes:

(a) Based on conditions similar to SITE demonstration at NASNI Site 9

(b) Costs are in May 1996 dollars

(c) Fixed costs

(d) Annual variable costs

(e) Equipment may require disposal or have salvage value, therefore assume no cost

(f) Total of 63 million gallons treated

(g) Total over a 15-year period; costs not adjusted for inflation

3.2.3 Mobilization and Startup

Mobilization and startup costs include the costs of delivering the ZENON system components to the site from the suppliers, assembling the system, and performing the initial shakedown of the treatment system. ZENON provides trained personnel to assemble and shake down the ZENON system. ZENON personnel are assumed to be trained in appropriate health and safety procedures, so health and safety training costs are not included as a direct startup cost. Initial operator training is needed to ensure safe, economical, and efficient operation of the system. ZENON includes initial operator training to its customers in the cost of the capital equipment.

Transportation costs vary depending on the location of the site in relation to the ZENON offices in Burlington, Ontario. The pervaporation system is mounted in a steel enclosure measuring about 12 feet by 8 feet by 7 feet, that can be shipped to sites in a semi trailer. The ZENON offices are assumed to be located within 500 miles of the site. Transportation costs are estimated to be $1,500 or about $3 per mile.

Assembly costs include the costs of unloading delivered equipment, assembling the ZENON system, piping connections, and electrical connections. A two-person crew will work 10 8-hour days to unload and assemble the system and perform the initial shakedown. Working at a wage rate of $25 per hour, which includes per diem, personnel costs for assembly are about $4,000. The only heavy equipment requirement is a forklift to move the pervaporation system from the semi-trailer to the treatment location. A forklift would be necessary for this work for about 1 week. Forklift costs are estimated to be $600 for a weekly rental. Electricity connection costs will vary based on the site location and are estimated to be $4,000. Total assembly costs are estimated to be $8,600.

Clean water is used during the shakedown process to verify that all components are operating correctly before the contaminated water enters the system. Clean water is also needed for decontaminating process equipment and for site personnel. However, as the water requirements are minimal, no costs have been estimated.

Once the ZENON system is assembled and operational, a GC is needed to monitor the effectiveness of contaminant removal from the effluent. The GC is necessary for about 2 months for ZENON to ensure that the system is operating at its optimum. Rental costs for the GC are estimated to be $4,000 per month, for a total cost of $8,000.

A trailer will be needed during mobilization to house equipment, the GC, and as a meeting area. A 2-month trailer rental is about $1,200.

Total mobilization and startup costs are estimated to be $19,300.

3.2.4 Equipment Costs

Equipment costs consists of the costs of purchasing the ZENON treatment system. ZENON configures the complete ZENON treatment system based on site-specific conditions. The components for this analysis and their respective costs include: the pervaporation system ($140,000) and two 10,000-gallon steel bulk tanks ($10,000 or $5,000 each) for equalization of the groundwater. System design costs are included with these costs.

The equipment will be used for the duration of the groundwater remediation project, which for this analysis is 15 years. The pervaporation modules have a potential salvage value of 25 percent of their original cost; however, because of the uncertainty of economic circumstances and market conditions, no salvage value was assumed for this analysis.

The total equipment costs of this treatment system are $150,000.

3.2.5 Labor

Once the system is functioning, it is assumed to operate unattended and continuously except during routine equipment monitoring. One operator, trained by ZENON, performs routine equipment monitoring and sampling activities. Under normal operating conditions, an operator is required to monitor the system about 4 hours per week. This labor could be contracted at about $45 per hour.

Total annual labor costs are estimated to be $7,000.

3.2.6 Supplies

Supplies that will be needed include carbon filters, disposable Level D PPE, waste drums, and sampling and field analytical supplies.

To comply with air regulations, carbon filters for capturing VOC releases from the vacuum vent of the system are a requirement in most applications of this technology. Two 55-gallon carbon canisters were used during the demonstration – one initial filter was as a primary capturing measure, while the second was used as a precautionary measure, in the event VOCs escaped from the first filter. Carbon canisters cost about $250 each. Analytical results from the demonstration showed no breakthrough to the second carbon filter over about four months of off and on activity. It is estimated that eight filters would be required each year initially, changed out quarterly. This number could change based on analysis results and site conditions. Total cost for carbon canisters are about $2,000 per year.

Disposable PPE typically consists of latex inner gloves, nitrile outer gloves, and safety glasses. This PPE is needed during monthly sampling activities that are assumed to be conducted by the contracted operator. Disposable PPE is assumed to cost about $200 per year for the operator.

Disposable PPE and concentrated permeate are assumed to be hazardous and need to be disposed of in a 55-gallon steel drum. About four drums are assumed to be filled every month, and each drum costs about $15. Total annual drum costs are about $700.

Sampling supplies are usually provided free of charge by laboratories and consist of sample bottles and containers, labels, shipping containers, and laboratory forms for off-site analyses. Costs for laboratory analyses and sampling collection labor are presented in Subsection 3.2.10.

Total annual supply costs are estimated to be $2,900.

3.2.7 Utilities

Electricity and water are the utilities used by the ZENON system. Less than 2,000 gallons of water would be necessary during mobilization, so water costs are considered negligible. Based on observations made during the SITE demonstration, the system operating for 24 hours draws about 1,680 kilowatt hours (kWh) of electricity per day. The total annual electrical energy consumption is estimated to be about 613,200 kWh. Electricity is assumed to cost $0.09 per kWh, including demand and usage charges. The total annual electricity costs are about $55,200.

3.2.8 Effluent Treatment and Disposal Costs

This analysis assumes that no further treatment is needed prior to releasing the treated effluent into the POTW. Permitting costs were presented under permitting and regulatory costs in Subsection 3.2.2. Actual disposal costs depend on the concentrations of VOCs in the effluent and on the rates charged by a local POTW. Based on 1996 industrial sewer rates for medium-sized cities, total annual effluent treatment costs are $7,000 (PRC Environmental Management, Inc. [PRC] 1996a and 1996b).

3.2.9 Residual Waste Shipping and Handling

The residuals produced during operation of the ZENON system are spent carbon canisters, used PPE, and concentrated permeate, all of which would be contained in steel drums. For purposes of this analysis, this waste is considered hazardous and requires disposal at a permitted facility. It is also assumed that the drums will be removed every 90 days in accordance with RCRA generator accumulation requirements. Carbon canister removal is calculated separately from PPE and permeate.

The disposal of carbon canisters during the demonstration equaled about $300 per drum. Transportation costs are estimated at $300 per shipment. Estimating the removal of eight canisters per year over four trips, annual cost of disposing of the carbon canisters is $3,600.

PPE generation is estimated at two drums per year and could be removed with the concentrated permeate. Because of mechanical problems with the ZENON technology during the demonstration, the amount of permeate generated could only be estimated. This analysis assumes that about 48 drums of concentrated permeate would be generated annually. As a result, transportation costs will be incurred four times a year. The cost of handling and transporting the drums is $300 per load, and disposing of them at a hazardous waste disposal facility by incineration costs about $600 per drum. Annual drum disposal costs will be about $30,000.

Total annual costs for the removal and disposal of residuals is about $33,600.

3.2.10 Analytical Services

Required sampling frequencies and number of samples are site-specific and based on treatment goals and contaminant concentrations. Analytical costs associated with a groundwater remediation project include the costs of laboratory analyses, data reduction, and quality assurance/quality control (QA/QC). This analysis assumes that one sample of treated water, and an associated QC sample (trip blank) will be collected and analyzed monthly for the following two series of parameters: VOCs ($195) and SVOCs ($370). Monthly analytical costs for these parameters are about $600. Also, to indicate evaluate contaminant breakthrough, one air sample should collected each quarter from the vacuum vent line, between the two carbon canisters. This could be done with a SUMMA™ canister and analyzed for about $300 each. There is no charge for labor associated with sample collection because the operator who performs the routine monitoring will also perform the sampling activities. The total annual analytical costs are estimated to be $8,400.

3.2.11 Equipment Maintenance

Maintenance labor is needed to check the pervaporation module prefilter for debris or biological build-up. If debris or bacteria is found, it is manually scraped off of the prefilter membranes. Occasional acid washings are necessary to clean scaled materials from the membranes. A neutralization chemical, such as sodium hydroxide would have to be added to the acid solution before discharge to a POTW. Depending on the chemistry of water to be treated, an anti-scaling chemical may need to be added to the influent. Costs for acid and anti-scalents are determined on a site-by-site basis and can vary widely. ZENON considered the groundwater chemistry conditions during the demonstration to be atypical, presenting a worst-case scenario. It is estimated that $2,500 would be spent on anti-scalent chemicals per year. No additional charges for labor associated with equipment maintenance are added because the operator performing the sampling and routine monitoring labor will also perform equipment maintenance.

Although the groundwater remediation is long-term, equipment replacement is expected to be minimal. The only replacement parts identified by ZENON that would require replacement are seals for the piping. However, other costs should be expected, and replacement part costs are estimated at an average of $1,500 per year.

Total annual equipment maintenance costs are estimated to be $4,000.

3.2.12 Site Demobilization

Site demobilization includes treatment system shutdown, disassembly, and decontamination; site cleanup and restoration; utility disconnection; and transportation of the ZENON equipment off site. This analysis assumes that all equipment will be transported off site for overhaul or disposal.

For this analysis, demobilization costs are assumed to occur 15 years from the date of startup. Because of the uncertainty of economic circumstances and market conditions, this analysis does not estimate the cost of demobilization or if the equipment has salvage value.

3.3 Conclusions of Economic Analysis

This analysis presents cost estimates for treating groundwater contaminated with TCE. Operating conditions include treating the groundwater at 8 gpm for a period of 15 years. Table 3-1 shows the costs associated with the 12 cost categories presented in this analysis.

Total fixed costs are $189,500. Treatment equipment costs comprise 79 percent of the total fixed costs. Figure 3-1 shows the distribution of fixed costs. Total annual variable costs are $118,100. Utilities costs comprise nearly 50 percent of the variable costs, and residual waste handling services comprise about 28 percent. Figure 3-2 shows the distribution of variable costs.

After operating for 15 years, the total cost of the groundwater remediation scenario presented in this analysis is $1,961,000. Annual costs were not adjusted for inflation. A total of 63 million gallons of groundwater would be treated over this time period. The total cost per 1,000 gallons treated is $31, or roughly 3 cents per gallon.

As noted, it is assumed that the pervaporation system will be perfected by ZENON thereby decreasing maintenance requirements. During the demonstration, numerous equipment failures occurred, which caused extensive downtime. If technical needs are not addressed by ZENON, the costs associated with applying this system could be substantially higher than those presented in this analysis.

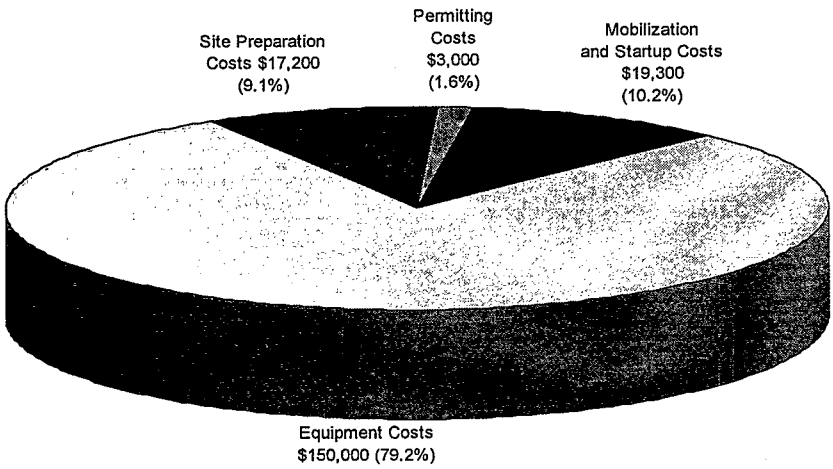

Figure 3-1. Fixed costs.

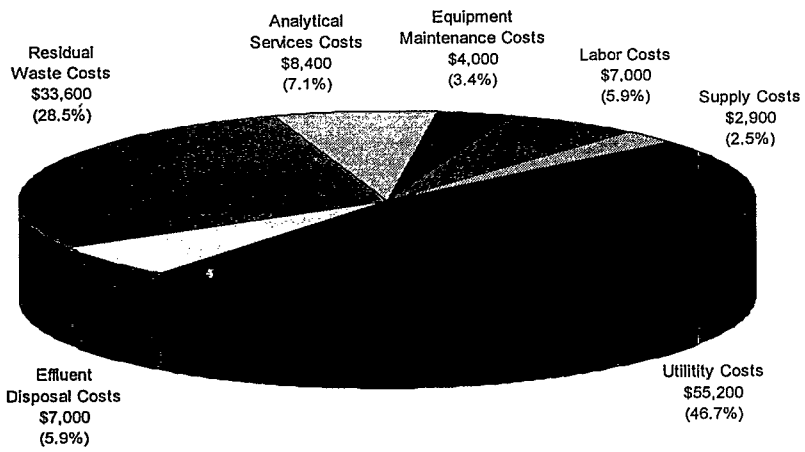

Figure 3-2. Annual variable costs.

Section 4
Treatment Effectiveness

This section documents the background, field and analytical procedures, results, and conclusions used to assesses the ability of the ZENON cross-flow pervaporation technology to remove VOCs from contaminated groundwater. This assessment is based on the activities conducted during the SITE demonstration at NASNI. Because the results of the SITE demonstration are of known quality, conclusions in this section are drawn only from the demonstration results.

4.1 Background

EPA conducted a SITE demonstration of the ZENON system at Site 9 at NASNI, which is located in Coronado, California (see Figure 4-1). A description of the environmental setting at NASNI and Site 9 are presented in Subsections 4.1.1 and 4.1.2. An overview of the demonstration objectives and approach is presented in Subsection 4.1.3.

4.1.1 Naval Air Station North Island

NASNI is located at the north end of the peninsula that forms San Diego Bay and adjoins the city of Coronado. NASNI is accessible by land through Coronado by way of the San Diego - Coronado Bay Bridge or through Imperial Beach by way of the Silver Strand Highway, State Route 75. Commissioned in November 1917, NASNI is an active, 2,520-acre naval complex that supports naval aviation activities and units.

NASNI is currently conducting environmental investigations under the Installation Restoration Program at 12 sites, one of which is Site 9. The Navy is expediting cleanup of these sites through the Naval Environmental Leadership Program (NELP). The main objective of NELP is to demonstrate innovative technologies and focus management to expedite compliance and remediation at contaminated NASNI sites. Successful technologies may be applied to contaminated sites at other naval facilities.

During mid-1993, the SITE program and NELP began to discuss the potential for demonstrating innovative technologies at NASNI. The SITE program informed NELP of the treatment methodology of the ZENON technology and site requirements for a demonstration. NELP provided the SITE program with groundwater data for Site 9, along with information regarding site access and available utilities. In March 1994, after verifying that it was a suitable candidate for treatment with the ZENON technology, SITE 9 was selected for the demonstration. The demonstration of the technology at NASNI was performed under a cooperative agreement between NELP and the SITE Program, and was financed in part by EPA, the U.S. Navy, and ZENON.

4.1.2 Site 9 Features

Site 9 is a 4.7-acre area located on the western end of NASNI. It is bordered to the north by an aircraft taxiway, a number of maintenance buildings, an open area; to the east by small buildings and runways; to the south by an ammunition storage area; and to the west by an ammunition pier and a channel of San Diego Bay. The demonstration area at Site 9 and surrounding features are shown in Figure 4-2. Site 9 is relatively flat; however, just south of 3rd Street West, there is an immediate 7-foot rise of the land surface to a terrace.

Geology and Hydrogeology

Borings performed during previous investigations indicate that formations underlying Site 9 consist of varying, unconsolidated layers of sand, silt, and clay, with a few lenses of shell beds. The Bay Point formation underlies all of Site 9 at an average depth of about 25 to 30

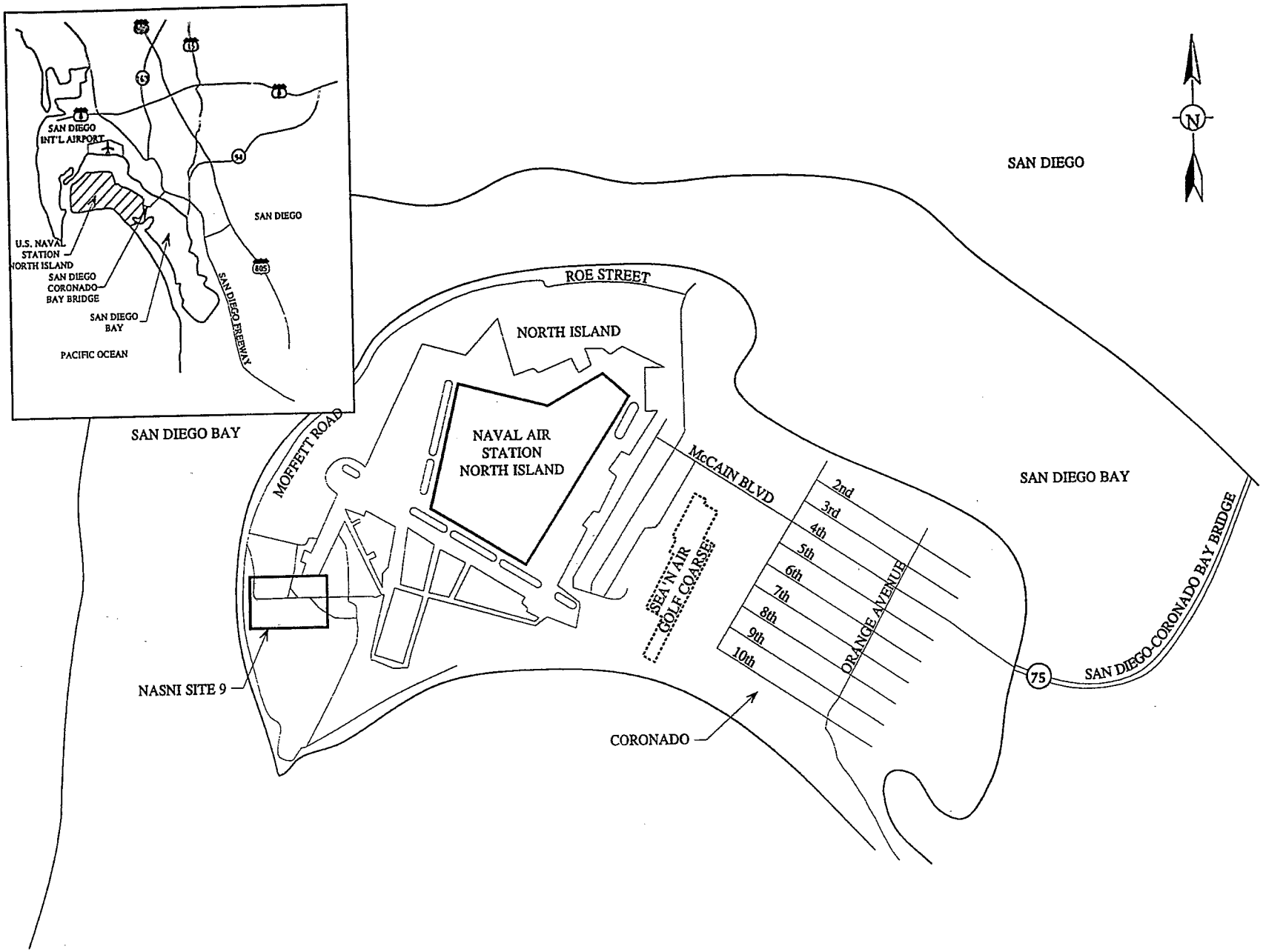

Figure 4-1. NASNI and Site 9 location map.

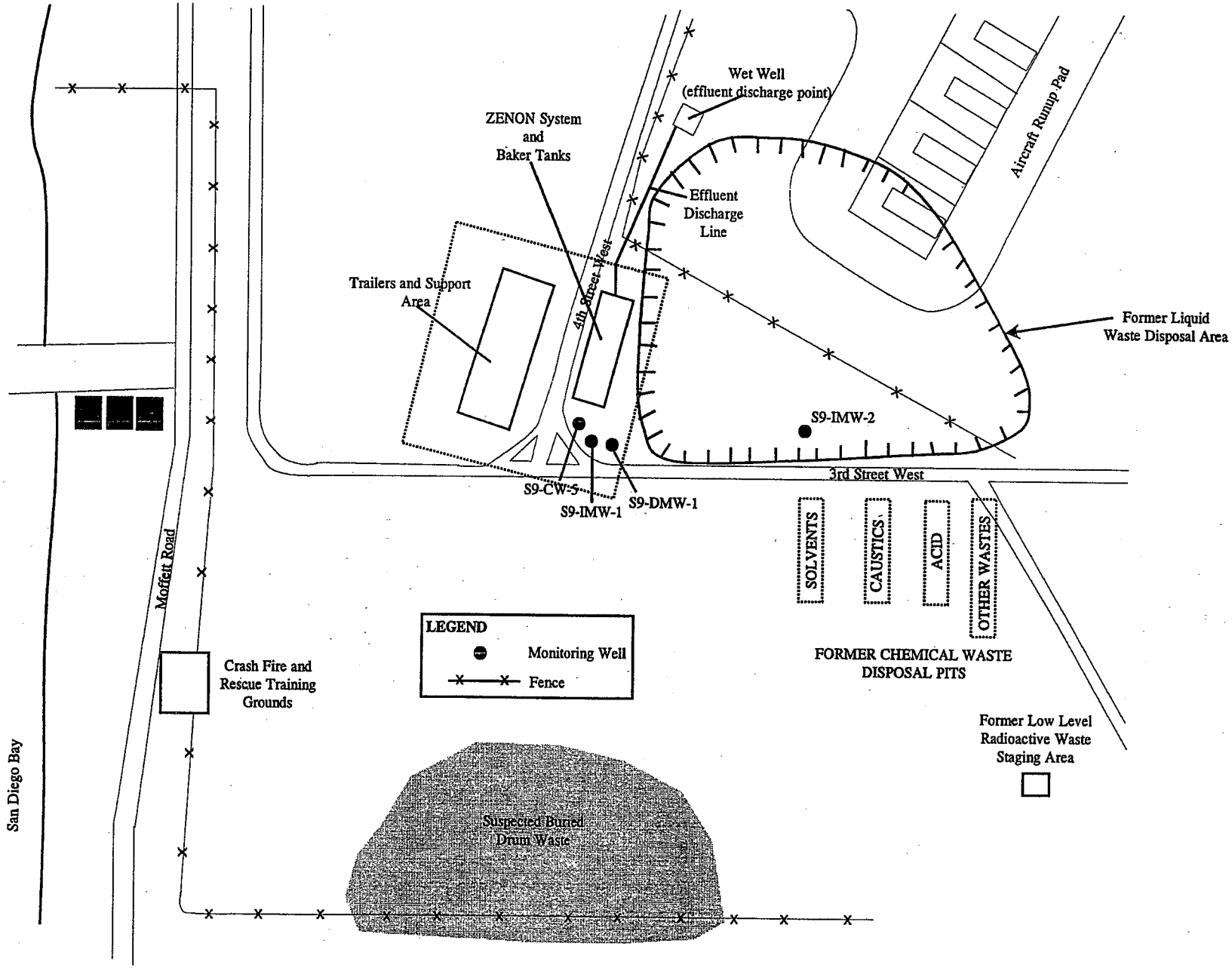

Figure 4-2. Site 9 demonstration area.

feet below ground surface (bgs). It is exposed east of the site near the central portion of North Island and dips sharply at an undetermined gradient towards the west. The Bay Point formation is highly unconsolidated and consists of micaceous, clayey, fossiliferous, very fine- to medium-grained, silty sand.

Overlying the Bay Point formation is a series of three artificial fill layers. The fill was placed in 1936, 1976, and 1978 from various island extension projects and dredging. Borings indicate that the fill consists of micaceous, fossiliferous, fine- to medium-grained sand and silty sand, with some areas containing gravel, wood chips, concrete, and asphalt debris. The layers are considered poorly graded and unconsolidated (Southwest Division Naval Facilities [SWDIV] 1993).

The water table at Site 9 averages about 8 feet bgs, and groundwater flow direction is west toward the shoreline. The saltwater-freshwater interface is about 60 feet bgs (SWDIV 1993). The Bay Point formation's porosity ranges from 33 to 47 percent; the hydraulic conductivity ranges from 70 to 92 feet per day. Porosities of the fill layers range from 45 to 56 percent; hydraulic conductivities range from 8 to 16 feet per day.

Waste Disposal Practices

Waste disposal records from the mid-1970s indicate that about 300,000 to 800,000 gallons of liquid wastes were disposed of annually at Site 9 (SWDIV 1993). These wastes included waste acids, waste solvents, waste paint materials, electroplating wastes, and various petroleum hydrocarbons.

Site 9 consists of three former waste disposal areas. The first area is located just north of 3rd Street West. From the 1940s or 1950s until 1968, various liquid wastes were drained into a large, shallow pit. Waste materials have since migrated through the groundwater to various portions of the surrounding area. The second area is located just south of 3rd Street West and consisted of four parallel disposal pits oriented north to south. From an undetermined date to the mid-1970s, liquid wastes, including caustics, acids, and other hazardous materials, were segregated and disposed of in these separate trenches. Contamination has migrated from the trenches and entered the underlying groundwater. The third former waste disposal area is located south of 3rd Street West near the center of Site 9 extending to its southern boundary. It was used periodically from the 1950s until 1978 for the burial of unidentified drummed chemical wastes. Groundwater contamination has been confirmed near this location (SWDIV 1993). Site 9 also contains a former low-level radioactive materials staging area. A 1977 land development map displays an area just south of the waste disposal trenches as a radioactive materials disposal area; however, radioactive waste disposal has not been documented near this area.

No development of the Site 9 area has occurred since waste disposal operations ended, and none is planned in the near future. Under NASNI's federal RCRA permit, Site 9 is required to undergo a RCRA facility investigation. Monitoring well installation; sampling and analysis of soils, sediments, and groundwater; and geophysical surveys have been performed as part of this investigation.

Demonstration Monitoring Wells

Monitoring wells installed as part of the RCRA Facility Investigation at Site 9 provided groundwater for the ZENON demonstration. EPA's SITE team and ZENON reviewed Site 9 monitoring well data, including the most recent analytical results, screened depths, and well construction criteria. Because of logistical concerns, including pump capacity limitations, only monitoring wells within 500 feet of the proposed demonstration area were considered for use during the demonstration.

The following four wells were selected as potential sources of groundwater because of elevated concentrations of TCE, as well as other VOC concentrations: 9-IMW-1, 9-IMW-2, 9-DMW-1, and 9-CW-5. The well locations are shown on Figure 4-2; selected analytical results for these four wells from samples collected during the Spring of 1994 are shown in Table 4-1.

4.1.3 Bench-Scale Study

In December 1993, ZENON performed a bench-scale study of the pervaporation technology using groundwater sampled from monitoring well 9-IMW-1 at NASNI Site 9. The study was mainly performed to determine if high salinity and the presence of nontarget compounds in groundwater at Site 9 would be detrimental to the performance of a pervaporation system. The results of the bench-scale study indicated that salinity or other characteristics of the local groundwater did not affect the system's ability to remove VOCs (ZENON 1994).

Table 4-1. Analytical Results for Site 9 Groundwater

Well ID	9-IMW-1	9-IMW-2	9-DMW-1	9-CW-5
Screened Interval	17 - 38 feet	17 - 38 feet	43 - 64 feet	5 - 20 feet
Volatile Organic Compounds (mg/L)				
Trichlorethene	61.0	420	5.30	0.77
Vinyl chloride	3.30 J	25.0 U	0.17	4.3 J
Methylene chloride	0.38	15	0.01 U	0.10 U
Acetone	7.70 J	25.0 U	0.01 U	720
2-Butanone	170	130	0.01 U	140
Toluene	2.50 J	8.00 J	0.13 J	3.10 J
4-Methyl-2-pentanone	10.0 J	25.0 U	1.40 J	70.0
2-Hexanone	0.10 U	25.0 U	.012	0.01 U
Carbon disulfide	0.10 U	25.0 U	0.12	0.01 U
cis-1,2-Dichloroethene	54.0	25.0 U	8.10	0.68
Semivolatile organic compounds (mg/L)				
Phenol	24.4	2.41	0.17	3.53 J
2-Methylphenol	3.17	0.17	0.08 J	1.21 J
4-Methylphenol	46.6	1.72	0.42	355
2,4-Dinitrophenol	0.25 U	0.25 U	0.03 U	0.25 U
4-Nitrophenol	0.25 U	0.25 U	0.03 U	0.25 U
4,6-Dinitro-2-methylphenol	0.25 U	0.25 U	0.03 U	0.25 U
Pentachlorophenol	0.25 U	0.25 U	0.03 U	0.25 U
Total metals (mg/L)				
Barium	0.22	0.03 J	0.03 J	0.13 J
Calcium	163	111	355	7.79
Chromium	0.96	0.34	0.01 U	0.77
Cyanide	0.20	1.57	0.01	0.15
Iron	604	0.67	0.12 J	5.21
Magnesium	360	679	800	491
Manganese	0.42	0.86	0.86	0.08
Potassium	182	301	419	31.0
Sodium	4,510	2,500	8,950	1,800

Table 4-1. Analytical Results for Site 9 Groundwater (continued)

Well ID	9-IMW-1	9-IMW-2	9-DMW-1	9-CW-5
Screened interval	17 - 38 feet	17 - 38 feet	43 - 64 feet	5 - 20 feet
Total Suspended Solids	NA	NA	28	NA
Alkalinity	NA	NA	1,041	NA
Sulfate	NA	NA	521	NA
Petroleum Hydrocarbons	NA	NA	NA	NA

Notes:

1	Source: Southwest Division Naval Facilities 1994
mg/L	milligrams per liter
J	Indicates an estimated concentration value. The result is considered qualitatively acceptable, but quantitatively unreliable.
U	Indicates that the data are acceptable both qualitatively and quantitatively.

4.1.4 Demonstration Objectives and Approach

The SITE demonstration was designed to address primary and secondary objectives selected for evaluation of the ZENON pervaporation technology. These objectives were selected to provide the U.S. Navy and other potential users of the technology with the necessary technical information to assess its applicability to NASNI Site 9 and other contaminated sites. For the SITE demonstration of the ZENON technology, two primary and eight secondary objectives were formulated and are summarized below:

Primary Objectives:

P1) Determine if the system can remove trichloroethene (TCE) in groundwater to below federal maximum contaminant levels (MCL) at varying flow rates, at the 95 percent confidence level

P2) Determine the removal efficiency of the system for TCE

Secondary Objectives:

S1) Assess the pervaporation system's ability to remove nontarget VOCs, semivolatile organic compounds (SVOC), and total recoverable petroleum hydrocarbons (TRPH) from contaminated groundwater

S2) Determine the volume of recovered liquid permeate generated during each run

S3) Measure VOC emissions from the pervaporation system

S4) Determine requirements for anti-scaling additions, and monitor the potential scaling of the system by identifying reductions in total suspended solids (TSS) and concentrations of carbonate, fluoride, sulfate, silica, strontium, calcium, barium, magnesium, and iron in treated and untreated water

S5) Determine if the technology's efficiency in removing VOCs, SVOCs, and TRPH is reduced, and if scaling due to the precipitation of the analytes listed under secondary objective S4 occurs after a 3-week period

S6) Determine the physical effects the ZENON system has on treated groundwater

S7) Document the operating conditions of the ZENON system

S8) Estimate the capital and operating costs of treating contaminated groundwater at NASNI Site 9 with full-scale ZENON pervaporation systems

The demonstration objectives were achieved by collecting data from analysis of untreated and treated groundwater samples, along with vapor samples. To meet the demonstration objectives, data were collected and analyzed using the methods and procedures summarized in Section 4.2. A more detailed description of the demonstration procedures is provided in the final ZENON quality assurance project plan (QAPP) (PRC 1994c) and the ZENON Technology Evaluation Report (PRC 1996c).

4.2 Demonstration Procedures

This section describes the methods and procedures used to collect and analyze samples for the SITE demonstration of the ZENON technology. The field and analytical methods and procedures used to collect and analyze samples were conducted in accordance with the ZENON demonstration QAPP. The activities associated with the SITE demonstration included (1) demonstration preparation, (2) demonstration design, (3) groundwater sample collection and analysis, (4) vapor sample collection, and (4) field and laboratory QA/QC.

4.2.1 Demonstration Preparation

Predemonstration activities included preparing of the demonstration QAPP, site specific health and safety plan (PRC 1994b), demonstration work plan (PRC 1994a), the acquisition of permits, and site preparation. The QAPP, site specific health and safety plan, and the demonstration work plan were submitted in May 1994 to various agencies for review. Final versions of these documents were prepared in August and September 1994.

Three permits were required for the SITE demonstration at NASNI. The California EPA Division of Toxic Substance Control required a Hazardous Waste Research Development and Demonstration Permit Variance for the demonstration. This allowed the extraction, treatment, and discharge of contaminated groundwater, along with the storage of hazardous waste at Site 9, to be performed under NASNI's RCRA permit. A permit was required by the City of San Diego for the discharge of treated water to a sewer line at NASNI running to a POTW. The permit required analyses of the treated groundwater for various organic contaminants. A permit was also required by the San Diego County Air Pollution Control District for the release of vapors from the pervaporation system. No sampling was required under this permit. Inspections at Site 9 by the above-mentioned agencies were required before the demonstration could proceed. Because of delays in performing the demonstration, extensions of all three permits were required (see Subsection 4.2.3).

Preparation activities conducted at Site 9 included the following: (1) connecting of electrical power and fresh water to the site; (2) testing dedicated groundwater pumps for the monitoring wells identified for use during the demonstration; (3) placing four 21,000-gallon steel bulk tanks at the site; (4) constructing secondary containment units surrounding the bulk tanks and the pervaporation unit; (5) installing various groundwater pumping lines; (6) installing a GC unit for field sample analysis; and (7) installing carbon filters. Other requirements included temporary fencing, storage drums, an on-site trailer, sanitary facilities, sample containers, PPE, and laboratory supplies (PRC 1994a).

4.2.2 ZENON System Configuration

A detailed description of the ZENON cross-flow pervaporation technology is provided in Section 1.3. The following explains the system configuration during the SITE demonstration at NASNI Site 9.

During the demonstration, previously installed monitoring wells were used to obtain all groundwater necessary for testing and sampling. The monitoring wells were equipped with dedicated pumps, usually capable of about 8 gpm, depending on the depth of the pump. Control boxes for regulating the pumps were supplied by EPA and plugged into the well head. Power for the wells was provided by direct electrical hookups installed for the demonstration. Groundwater was pumped from the wells to a manifold equipped with flow meters displaying the flow rate of groundwater pumped from each well (three maximum), and a sampling port. The manifold served to combine the flows and allowed the demonstration team to regulate the flow from each well, and in turn, TCE influent concentrations. The manifold was also equipped with a sampling port. The combined groundwater flows exited the manifold and entered a bulk tank for equalization. Because of problems with the bulk tanks (see Subsection 4.2.3), the demonstration team eventually bypassed the tanks and pumped groundwater directly to the ZENON system. During the demonstration, untreated groundwater was pumped from the wells at 2.1 to about 11.2 gpm. Before entering the system, the untreated groundwater was passed through a 200-micron prefilter to remove any debris or silt particles. It then entered a heat exchanger,

raising the temperature to about 165 °F (75 °C). From the heat exchanger, the water flowed into a series of two pervaporation modules for separation of VOCs from the groundwater. The treated water exited the pervaporation modules and was passed through a series of two 1,000-pound carbon filters to ensure the removal of SVOCs. The treated water then entered a steel 21,000-gallon bulk tank and was stored until it was discharged to the industrial sewer, located about 500 feet northeast of the demonstration area.

The VOC-laden vapors from the pervaporation modules were passed through a condenser. Most aqueous phase permeate was returned to the pervaporation modules, while organic phase permeate was contained in 55-gallon drums.

Heat for the heat exchanger was supplied by a steam cleaner converted to a boiler, and cool air for the condenser was supplied by a chiller. Both the boiler and chiller were separate from the pervaporation unit. All electrical power was supplied by a direct hookup installed at the site by the Naval Public Works Center, San Diego.

4.2.3 Demonstration Delays

Demonstration sampling from the ZENON technology was initially scheduled to occur during October 1994, and mobilization began in September 1994. As noted in Subsection 4.2.2, four 21,000-gallon steel bulk tanks were brought to the site for storage of untreated and treated groundwater. Pumping of untreated groundwater from the bulk tanks began during middle October 1994, and ZENON immediately began experiencing problems with rust particles from the bulk tanks mixing with the groundwater. Larger particles tended to clog the 200-micron prefilter, and smaller particles fouled and scaled the pervaporation module membranes, reducing treatment efficiency. After several failed attempts to keep the filter clear, combined with frequent acid washings of the modules, the demonstration team began pumping groundwater directly from the monitoring wells to the system. Bypassing the tanks eliminated the filter clogging, along with fouling and scaling from the rust particles; however, high concentrations of calcium bicarbonate in the groundwater continued to cause the membranes to become scaled and fouled. During late November, after attempts with a variety of chemicals, ZENON selected an anti-scalent similar to zinc phosphate, which proved fairly effective.

During this time, ZENON also had difficulty regulating steam for the heat exchanger entering the system. The boiler was composed of a rented steam cleaner modified for the demonstration. ZENON eventually corrected this problem by altering a valve configuration on the system.

Other mechanical problems plagued the demonstration. The sight glass on the permeate collection tank leaked, which did not allow the system to maintain pressure inside the tank. The drains on the pervaporation modules were too small and became plugged with sediment fines carried by the groundwater. Sediment fines also partially plugged a number of check valves, which allowed unwanted backflow. Also, TCE continually coming in contact with the pump seals caused premature degradation and eventual failure of the pumps.

The natural conditions at Site 9 also caused various problems. Salty air caused a number of metal components to fail prematurely. Dusty conditions caused grit to build up on some components. Heavy rains caused electrical shorts in the system control panel and in an electrical panel for the boiler. The boiler pilot light was repeatedly extinguished by strong winds prevalent in the area.

Because of continuing pump problems, pump shipping delays, a GC malfunction, travel difficulties, and uncharacteristically poor weather conditions during January 1995, demonstration sampling was postponed until February 1995.

4.2.4 Demonstration Design

This section describes the sampling and analysis program and sample collection frequency and locations. The objective of the demonstration design was to collect and analyze samples of known and acceptable quality to achieve the objectives in the QAPP.

Groundwater Pumping and Gas Chromatograph Analysis

To achieve various TCE concentrations, groundwater was pumped from combinations of monitoring wells. The demonstration team planned to use four monitoring wells; however, after pumping for about 10 minutes at 5 gpm, monitoring well 9-CW-5 was pumped dry and not used during the rest of the demonstration. Groundwater from monitoring wells 9-DMW-1, 9-IMW-1, and 9-IMW-2

was used to provide all groundwater. Groundwater samples were collected from a polyvinyl chloride (PVC) manifold combining the flows from each well, and analyzed with an on-site GC. Based on the analytical results, which were available after about 40 minutes, the flow rates were adjusted to achieve desired TCE concentrations. Also, during the first few hours of pumping a particular well, the groundwater was analyzed for chromium and cyanide with field test kits. Moderately elevated concentrations of these two analytes were found during past sampling events from well 9-IMW-2, causing discharge concerns; however, negligible concentrations were detected in the groundwater during the demonstration.

The GC was also used to determine the optimum operating conditions for the system. Samples of untreated and treated groundwater were analyzed, results were compared, and the system was adjusted accordingly. Finally, samples of treated water, after it passed through the two 1,000-pound carbon filters, were analyzed with the GC to confirm that water discharged to the industrial sewer was within designated permit limits.

Groundwater Sampling and Analysis Program

After achieving a designated flow rate and sustained concentration of TCE, samples of untreated and treated groundwater were collected. As noted, untreated samples were collected from a port on the manifold (S1) that combined groundwater from the separate wells (see Figure 1-2). Samples of treated groundwater were collected from a port on the discharge line of the ZENON system (S2).

The demonstration was composed of 4.5 days of sampling, with each day referred to as a sampling run. Four grab samples of untreated water were collected per run, along with four samples of treated water. A sampling overview is shown in Table 4-2.

The demonstration QAPP specified that most sampling from the system would occur at the start of the demonstration. The system would then operate for a 3-week period with little maintenance. After the 3-week period, additional sampling would occur. Before demonstration sampling began, the SITE team elected to not run the system for 3 weeks and then resample because (1) component failures caused continual treatment difficulties with the pervaporation system, (2) adequate information pertaining to scaling (a primary reason for the 3-week test period) was gathered before demonstration sampling, and (3) cost concerns had arisen due to project delays. As explained in Subsection 4.2.3, problems ranging from temperature regulation difficulties to premature failure of seals on various pumps, interfered with the treatment efficiency of the ZENON technology. After weighing several options, the demonstration team elected to limit sampling to six 8-hour runs. When a stainless tube on the pervaporation module failed, demonstration sampling ended 4 hours into the fifth run.

Vapor Samples and Sampling Methodology

Vapor samples were collected from the vacuum vent from the system (S3) and from the vent after the vapor passed through a single air carbon filter (S4). Samples at S3 were collected to determine the amount of VOCs released from the vacuum vent relative to the concentrations of contaminants in groundwater treated by the system and the influent flow rate. The amount of VOCs released would provide an indication of the amount of VOCs not converted to liquid by the condenser. To comply with state and local air regulations, two carbon filters were attached to the vacuum vent to capture VOCs that would otherwise be released to the outside air. Sampling point S4, located between the carbon filters, provided a verification that all VOCs not condensed in the ZENON system were captured by the first carbon filter. Sampling point S4 was not intended to provide data on releases of VOCs from the vacuum vent of the ZENON system. Data from S4 was only intended to verify that VOCs were not released to the outside air. Therefore, the data for sampling point S4 is not included with this document.

Vapor samples were collected in 6-liter SUMMA™ polished stainless steel canisters. Two samples per 8-hour run were collected, except for the fifth day, when only one sample was collected because the run was abbreviated. For vapor sampling, each SUMMA™ canister was attached, via a male/female connector, directly to a shut-off valve that was connected to the vacuum vent. After the canister was attached, the shut-off valve on the vacuum vent was opened. The valve on the SUMMA™ canister was then opened for about 5 seconds until the sound of the vacuum began to decrease. The SUMMA™ canister valve was then closed, followed by the shut-off valve on the vacuum vent. The SUMMA™ canister was then removed from the shut-off valve and packaged for shipment to the laboratory. Canister vacuum measurements were not taken before and after sampling.

Table 4-2. Sampling Overview

Sampling Location	Parameter	Frequency	Classification	Type	Purpose [1]
Untreated Water S-1	VOCs	Four and one half sampling runs; four samples per run	Critical	Laboratory analytical	P1, P2, S5
	SVOCs	Four and one half sampling runs; four samples per run	Noncritical	Laboratory analytical	S1, S5
	TRPH	Four and one half sampling runs; four samples per run	Noncritical	Laboratory analytical	S1, P2, S5
	TSS	Four and one half sampling runs; one sample per run	Noncritical	Laboratory analytical	S4, S5
	Carbonate alkalinity, fluoride, sulfate, silica, strontium, calcium, barium, magnesium, and iron	Two sampling runs; one sample of each per run	Noncritical	Laboratory analytical	S4, S5
	pH, conductivity, and temperature	Four and one half sampling runs; three measurements per sampling run	Noncritical	Field measurement	S6
Treated Water S-2	VOCs	Four and one half sampling runs; four samples per run	Critical	Laboratory analytical	P1, P2, S5
	SVOCs	Four and one half sampling runs; four samples per run	Noncritical	Laboratory analytical	S1, S5
	TRPH	Four and one half sampling runs; four samples per run	Noncritical	Laboratory analytical	S1, S5
	TSS	Two sampling runs; one sample per run	Noncritical	Laboratory analytical	S4, S5
	Carbonate alkalinity, fluoride, sulfate, silica, strontium, calcium, barium, magnesium, and iron	Two sampling runs; one sample of each per run	Noncritical	Laboratory analytical	S4, S5
	pH, conductivity, and temperature	Four and one half sampling runs; three measurements per sampling run	Noncritical	Field measurement	S6
Air Monitoring at Vacuum Pump Vent Before and After Carbon Filter S-3 and S-4	Total VOCs	Four and one half sampling runs; two measurements per run	Noncritical	Laboratory analytical	S3, S5

Notes:

[1] The parameter was analyzed to meet the indicated primary or secondary objective.
VOC Volatile organic compounds
SVOC Semivolatile organic compounds
TRPH Total recoverable petroleum hydrocarbons
TSS Total suspended solids

4.2.5 Analytical Methodology

Liquid samples were analyzed for the required parameters by the methods specified in Table 4-3. TCE in untreated and treated water was the only critical parameter for this demonstration. All air samples were analyzed by Method TO-14 using gas chromatograph/mass spectrophotometer (GC/MS) full scan detection.

Method 8260, which was used to measure concentrations of TCE and other VOCs, involves the use of a GC/MS system operated under recommended conditions. The volatile components of an aliquot of the sample are introduced into the GC/MS system using a purge and trap procedure with detection of analytes using a mass spectrometer. Compounds are identified by comparing peak retention times and mass fragmentation patterns to the known retention times and known fragmentation patterns of the target compounds. The concentration of each target compound detected is determined from the peak response by comparison with the associated internal standard and the external calibration standards.

For each analyte of interest, initial calibration was performed using calibration standards at a minimum of five concentrations. One of the initial calibration standards was at a concentration near, but above, the MDL. The other concentrations corresponded to the expected range of sample concentrations or defined the working range of the detector.

Each calibration standard was analyzed by the same technique used to introduce the samples into the GC. Peak or area responses were tabulated against the mass injected. The results were used to prepare a calibration curve for each compound. In addition, the ratio of the response (relative to the internal standard) to the amount introduced, or the relative response factor (RRF), was calculated for each compound at each standard concentration. If the percent relative standard deviation (%RSD) of the relative response factor met the method criteria of 30 percent over the working range, linearity through the origin can be assumed, and the average RRF can be used in place of a calibration curve.

Table 4-3. Analytical Methods

Matrix	Parameter	Method	Reference[1]
Liquid	VOCs[2]	8260	SW-846
	SVOCs[3]	3520/8270A	SW-846
	TRPH[4]	418.1	MCAWW
	TSS[5]	160.2	MCAWW
	Cations	6010A	SW-846
	Sulfate	375.4	MCAWW
	Fluoride	340.2	MCAWW
	Carbonate	403	MCAWW
	pH	150.1	MCAWW
	Specific Conductance	120.1	MCAWW
	Temperature	170.1	MCAWW
Air	VOCs	T014	EPA 1988a

Notes:
[1] SW-846: (EPA 1992); MCAWW: (EPA 1983)
[2] VOC Volatile organic compounds
[3] SVOC Semivolatile organic compounds
[4] TRPH Total recoverable petroleum hydrocarbons
[5] TSS Total suspended solids

4.2.6 Quality Assurance and Quality Control Program

QC checks and procedures were an integral part of the SITE demonstration to ensure that the QA objectives were met. These checks and procedures focused on the collection of representative samples absent of external contamination and the analysis of comparable data. The QC checks and procedures conducted during the demonstration were of two kinds: (1) checks of field activities, such as sample collection and shipping, and (2) checks of laboratory activities, such as extraction and analysis. These are discussed below. A data quality summary is provided in Section 4.3.4.

Field Quality Control Checks

As a check on the quality of field activities such as sample collection, shipment, and handling, three types of field QC checks (duplicate samples, field blanks, and trip blanks) were collected. In general, these QC checks assessed possible contamination or the representativeness of the samples. Any QC results that failed acceptance criteria and could not readily be corrected in the laboratory were reported to the PRC project manager or PRC QA manager as soon as possible to effect corrective action. If a field QC check sample exceeded the established criteria for any analytical parameter, analytical results of that parameter for all associated samples having the analyte concentration above the quantitation limit were flagged during postlaboratory validation.

Duplicate samples (DUP), separated aliquots of the sample analyzed by the same method, were collected to assess the laboratory's precision. Field blanks were collected to assess the potential for contamination of the sample from dust or other sources at the site during sample collection. Trip blanks were prepared to determine whether contamination was introduced through sampling containers or as a result of exposure during shipment.

Laboratory Quality Control Checks

Laboratory QC checks were designed to determine precision and accuracy of the analyses, to demonstrate the absence of interferences and contamination from glassware and reagents, and to ensure the comparability of data. Laboratory-based QC checks consisted of method blanks, MS/MSDs, surrogate spikes, blank spikes and blank spike duplicates, and other checks specified in the analytical methods. The laboratory also performed initial calibrations and continuing calibration checks according to the specified analytical methods.

Field and Laboratory Audits

EPA conducted internal and external system audits to evaluate field and laboratory QC procedures. Because of delays in performing the demonstration sampling, the field audit was conducted before data collection and analysis activities commenced. The laboratory audit was performed while samples from the demonstration were analyzed. The results of both EPA audits are presented in the TER (PRC 1996).

4.3 Demonstration Results and Conclusions

This section presents the operating conditions, system maintenance, results and discussion, data quality, and conclusions of the SITE demonstration of the ZENON technology. The demonstration results have been supplemented by information provided by ZENON on other tests involving the technology.

4.3.1 Operating Conditions and Parameters

This section summarizes the operating conditions and parameters for the system during the 5-day SITE demonstration. During the demonstration, the pervaporation system was operated at conditions determined by ZENON and EPA. To document the system's operating conditions, untreated and treated groundwater, along with vapor released from the vacuum vent were monitored and sampled. The system operated 8 hours per day for 4 days, and about 4 hours on the a fifth day. It was allowed to run for about 0.5 hour before the first sampling of a particular run to allow all components to reach normal operating temperatures. All samples were shipped to the laboratory the same day they were collected. Untreated water flow rates through the system were varied from 2.10 to 11.23 gpm. Weather conditions during the sampling days were consistently clear with an average temperature of about 68 °F. Wind speed usually increased during the afternoons to about 10 miles per hour. After the first 2 days, sampling was delayed for 3 days due to severe weather at the work site, which did not allow the boiler to remain ignited.

The pervaporation system was continually monitored by ZENON, and samples of untreated and treated groundwater, along with vented vapor, were collected to evaluate the system's performance. The system operating parameters monitored by the developer included heat exchanger temperature, module pressure, and groundwater flow rates. VOC removal from the treated groundwater was monitored with the on-site GC to maintain system efficiency.

4.3.2 System Maintenance

During the time spent at NASNI, ZENON performed frequent chemical washings of the system to alleviate scale buildup on the pervaporation module membranes. A sodium metabisulfite solution was used to remove iron buildup resulting from materials released from the bulk tanks. High concentrations of calcium bicarbonate in the groundwater led to calcium scaling on the membranes. This required frequent washings with a phosphoric acid solution. During demonstration sampling, a phosphoric acid washing was performed on the system after 3 days of operation. Depending on the groundwater or process water treated in future applications, frequent acid washings of the membranes may be necessary to allow efficient removal of VOCs.

Biological buildup accumulated on system components during downtime from early December to late January. This was alleviated with a sodium metabisulfite wash. For future field applications, before a prolonged downtime the system may be subjected to a sodium metabisulfite wash to prevent biological buildup.

ZENON claims that a typical full-scale pervaporation system would require maintenance once every 1 or 2 weeks. Maintenance requirements would mainly depend on the groundwater's potential to foul and scale the membranes and other components of the system. Other components, such as pumps, motors, and valves, typically would be checked two to four times per year, depending on a particular component's service requirements.

While under a vacuum, the condensate pump operated at irregular intervals and could not be relied on to properly remove permeate from a holding reservoir to storage. While operating at normal atmospheric conditions, the pump operated correctly. This malfunction required the ZENON on-site operator to manually control the pump during the demonstration. Because of the high concentrations of TCE in the groundwater, seals of the condensate pump degraded and failed prematurely, requiring frequent replacement by the developer. The seals were replaced three times during the five days of demonstration runs. For a long-term field application involving high concentrations of TCE, seals composed of a material able to withstand the TCE would be required to alleviate shutting down the system every few days.

4.3.3 Results and Discussion

This section presents the results of the SITE demonstration of the ZENON technology. The results are presented by project objective and have been interpreted in relation to each objective. The specific primary and secondary objectives are shown at the top of each section in italics followed by a discussion of the objective-specific results. Data quality and conclusions based on these results are presented in Subsections 4.3.4 and 4.3.5. Appendix A presents analytical data generated during the demonstration.

Primary Objectives

Primary objectives were considered critical for evaluating the ZENON pervaporation technology. Two primary objectives were selected for the SITE demonstration, and because of similarities, are discussed together.

P1) Determine if the ZENON technology can remove TCE from groundwater to below the federal MCL at varying flow rates, at the 95 percent confidence level.

P2) Determine the removal efficiency of the system for TCE.

During the demonstration, TCE was present in varying concentrations in all four wells used to supply groundwater to the pervaporation system. As noted, TCE influent concentrations were varied by altering the flow rates into the system from the selected wells. Demonstration objectives were achieved by collecting samples of untreated and treated groundwater over four 8-hour and one four-hour sampling runs. Flow rates of the system ranged from about 2 to 11 gpm, and influent TCE concentrations ranged from 33 to 240 mg/L. As noted, the

demonstration was scheduled for seven sampling runs; however, sampling ended after 4 hours into the fifth run because of a corroded stainless steel tube on the pervaporation module.

Analysis of groundwater for TCE was performed by EPA Method 8260 (EPA 1987). Analytical results from the demonstration indicate that the ZENON technology, when operating at optimum conditions, effectively removed TCE from the groundwater at NASNI Site 9. Analytical results for TCE in untreated and treated water are shown in Table 4-4. Removal efficiencies for TCE averaged 97.3 percent. Sixteen of 18 comparisons of treated water samples to untreated samples showed average TCE removal efficiencies of 99.3 percent. The highest levels of contaminant removal expressed as a percentage were achieved during the fourth run, when the system operated at a flow rate of about 5.5 gpm with an influent concentration of about 230 mg/L of TCE. Removal efficiencies were lowest during the first run, when the system operated at about 2.1 gpm with an influent concentration of about 40 mg/L of TCE. Generally, the data indicate that treatment efficiency increased slightly after the first run, which could be attributed to minor adjustments made to the system by ZENON. However, during the fourth run, treatment efficiency dropped due to the high volume of groundwater processed by the technology.

Although the system significantly reduced TCE concentrations in the groundwater to an average of 1.49 mg/L (1,490 µg/L), the federal MCL of 5 µg/L was not achieved. The lowest concentration achieved during the demonstration occurred during the second run, when the system was operating at about 5.2 gpm with a TCE influent concentration of 44 mg/L. This effluent sample was taken after operating the system for about 2.5 hours, and indicated that TCE was reduced to 0.09 mg/L (99.8 percent removal).

Because all comparisons of TCE concentrations in untreated water to treated water were above the MCL, it was not necessary to calculate the upper confidence level.

A mass balance was calculated for the demonstration data using TCE contaminant concentrations for untreated groundwater, treated groundwater and vapor (see Table 4-5). The following equation (4-1) was used for the calculation of water and vapor contaminant loads:

Flow Rate x Time x TCE Concentration x Conversion Factor = Contaminant Load per Sampling Run (4-1)

No analysis was performed on permeate generated by the system because of the high concentrations of TCE expected compared to the untreated and treated water. Permeate TCE concentrations were estimated based on analysis of untreated and treated water and vapor. TCE losses could have occurred from other portions of the system (valves, connectors, and piping).

When expressed as a percentage of total TCE load into the system, treated groundwater from the system averaged about 2.6 percent TCE. For the second, third, and fourth runs, TCE load to treated water averaged 0.6 percent. As detailed in Table 4-5, the system was most efficient in removing TCE from the groundwater during these three sampling runs. The highest release to treated water occurred during the first run and was 9.7 percent. This figure corresponds to the poorest TCE removal efficiency obtained during the demonstration.

Secondary Objectives

Secondary objectives provided additional information that was useful, but not critical for the evaluation of the ZENON technology. Eight secondary objectives were selected for the SITE demonstration. The results of each secondary objective are discussed in the following subsections.

S1) Assess the pervaporation system's ability to remove nontarget VOCs, SVOCs, and TRPH from contaminated groundwater

Concentrations and removal percentages for VOCs other than TCE in groundwater at Site 9 varied considerably, and are presented in tabular format in the TER. The following VOCs other than TCE were detected in Site 9 groundwater during the demonstration:

- vinyl chloride
- 4-methyl-2-pentanone
- 2-butanone
- methylene chloride
- 1,1,-dichloroethene
- toluene
- cis-1,2-dichloroethene

As expected, concentrations of particular contaminants in

Table 4-4. Trichloroethene Concentration Summary

Run	Flow Rate (gallons per minute)	Well	Event Number	Untreated Concentration (mg/L)[a]	Treated Concentration (mg/L)	Percent Removal
1	2.1	IMW-1[b]	1	40	0.17	99.5%
			2	43	1.0	97.7%
			3	33	3.8	88.5%
			4	42	11	73.8%
	Average			40	3.9	89.9%
2	5.2	IMW-1	1	41	[0.10][c]	99.8%
			2	44	0.09	99.8%
			3	48	0.16	99.7%
			4	48	0.19	99.6%
	Average			45.3	0.14	99.7%
3	9.0	IMW-1	1	33	0.32	99.0%
		and	2	35	0.27	99.2%
		DMW-1[d]	3	38	0.22	99.4%
			4	37	0.24	99.4%
	Average			36	0.26	99.3%
4	5.5	IMW-2	1	220	0.45	99.8%
		and	2	220	0.40	99.8%
		DMW-1	3	240	0.51	99.8%
			4	240	0.46	99.8%
	Average			230	0.46	99.8%
5[f]	11.2	IMW-1, IMW-2,	1	130	2.7	97.9%
		and DMW-1	2	120	2.7	97.8%
	Average			125	2.7	97.9%
Total Average Percent Removal						97.3%[g]

Notes:
a mg/L = milligram per liter
b IMW-1 = Intermediate monitoring well No. 1
c [ ] = Indicates compound was analyzed for but not detected above the sample quantitation limit. The treated concentration is half of the sample quantitation limit.
d DMW-1 = Deep monitoring well No. 1
e IMW-2 = Intermediate monitoring well No. 2
f Sampling run was abbreviated due to system failure
g Total average computed from the averages of the five runs

Table 4-5. Mass Balance Figures

Run Number	Total Water Treated (gallons)	Untreated Groundwater TCE Load (mg/Run)	Treated Groundwater TCE Load (mg/Run)	Treated Groundwater TCE, Percent	Vapor TCE Load from Vacuum Vent (mg/Run)	Vapor TCE, Percent	Permeate TCE Load (mg/Run)*	Permeate TCE, Percent*
1	1032	152,813	14,899	9.7%	75,152	49.2%	62,762	41.1%
2	2496	428,531	1,324	0.3%	40,656	0.9%	386,351	90.2%
3	4320	589,421	4,257	0.7%	172,480	29.3%	412,684	70.0%
4	2640	2,301,288	4,603	0.2%	251,328	11.0%	2,045,357	88.9%
5[1]	2688	1,273,440	27,506	2.2%	246,400	19.3%	997,309	78.5%
Averages:				2.6%		21.9%		73.7%

Notes:

mg/Run milligrams per 8-hour sampling run

[1] Sampling run was abbreviated due to system failure. Calculations were based on a 4-hour sampling run.

* Calculated mass and percent

untreated groundwater changed based on the well configurations used for each run. For instance, methylene chloride and 1,1-dichloroethene were not detected until monitoring well IMW-2 was used, which occurred during the fourth and fifth runs. During the demonstration, the ZENON system removed vinyl chloride, 1,1-dichloroethene, toluene, and cis-1,2-dichloroethene at an average above 90 percent. The highest average removal rate for a VOC other than TCE was that for toluene at 94.3 percent. The highest removal for toluene occurred during the second run where the removal rate averaged 97.8 percent while the system operated at about 5.18 gpm. The lowest average removal rate for toluene was during the first run where removal averaged 84.3 percent while the flow rate was at about 2.12 gpm. As noted above, the data indicate that treatment efficiency increased slightly after the first run, which could be attributed to minor adjustments made to the system by ZENON.

Detected VOCs removed at less than 90 percent included 4-methyl-2-pentanone (49.1 percent), 2-butanone (18.2 percent), and methylene chloride (80.6 percent). It should be noted that 2-butanone is fairly soluble in water and has a low Henry's Law constant, thus making it similar to an SVOC and difficult to remove by pervaporation. These compounds tend to remain in the aqueous phase after the influent is heated, and are thus not removed through the membrane.

Vinyl chloride was present in untreated groundwater at an average of 12.9 mg/L over the five sampling runs. Although it has a low Henry's Law constant, it was removed by the ZENON technology at an average of 99.7 percent, to 0.29 mg/L. The highest concentration of vinyl chloride was detected at 120 mg/L in the fourth sample of the first run. The vinyl chloride concentration in the corresponding treated sample was not detected above the method detection limit of 250 µg/L, for greater than 99.9 percent removal.

Removal of VOCs generally was best when the system operated at lower flow rates (2.1 to 5.2 gpm), allowing greater retention time for groundwater passing through the pervaporation modules. Elevated VOC concentrations appeared to have little effect on the treatment capability of the unit, as seen from the TCE analytical results. Analytical results for other VOCs is less conclusive. It appears that variations in concentrations of VOCs, across the concentration levels found in Site 9 groundwater, has little effect on the treatment capability of the technology.

SVOCs

As expected, SVOC removal efficiencies were much lower than those for VOCs. SVOCs detected in Site 9 groundwater during the demonstration included the following:

- phenol
- 2-methylphenol
- 4-methylphenol
- 2,4-dimethylphenol
- 4-chloro-3-methylphenol
- bis (2-ethylhexyl) phthalate

SVOC concentrations in groundwater at Site 9 proved to be consistently lower than those for detected VOCs. The highest concentrations of SVOCs were for 4-methylphenol, averaging 7.4 mg/L. The highest influent concentration for this compound, which was the highest concentration of a single SVOC during the demonstration, was during the first run at 19.3 mg/L. Because of the lower influent concentrations, percent removals for SVOCs appear much less dramatic than those for VOCs.

Removal rates for detected SVOCs ranged from a high of 64.9 percent for bis(2-ethyhexyl) phthalate to a low of 7.4 percent for 4-methylphenol. As with VOCs, treatment efficiency generally decreased as groundwater flow through the system increased. For instance, with an average influent concentration of 5.9 mg/L, the average removal efficiency of phenol during the first run (average of 2.1 gpm) was 17.7 percent. During the third run (flow rate of 9 gpm), with an average influent concentration of 6.5 mg/L, the average removal percentage was 3.5 percent.

TRPH

The removal efficiency of TRPH was monitored during the demonstration because of the variety of contaminants known to be present at Site 9, and because of previous success of the pervaporation system at removing these materials from contaminated groundwater. Four untreated and four treated water samples were collected during each run and analyzed for TRPH. Analytical data are presented in the TER.

Average TRPH removal during the demonstration was 68.5 percent; however, the true removal efficiency of the technology may have been higher because about half of the

analytical results for treated groundwater were below the laboratory's lower analytical detection limit of 0.3 mg/L. This value was used in calculating removal for these runs. The highest TRPH removal rate occurred during the third run (flow rate of 9 gpm) at an average efficiency of 80.5 percent. The lowest average removal rate occurred during the fifth run (flow rate of 11.2 gpm) at 56.7 percent. Because both the highest and lowest removal efficiencies occurred when groundwater flow rates were high, no correlation between removal of TRPH and flow rate can be drawn. The highest average concentration of TRPH in untreated groundwater was 3.18 mg/L occurring in the second run. The removal efficiency during this round averaged 60.4 percent.

S2) Monitor the volume of recovered liquid permeate generated during each run

After exiting the pervaporation module of the ZENON system, VOCs are condensed to the liquid phase, producing permeate. The permeate generally separates into aqueous and organic phases. The aqueous phase can be sent back to the pervaporation unit for retreatment, while the organic phase can either be disposed of or sent off site for further processing to recover the organics.

During the demonstration, the amount of permeate generated by the system during each run was determined by the developer and provided to the SITE team. Much of the aqueous phase permeate generated during the demonstration would normally have been returned to the system. However, problems involving the seals and pumping controls of the condensate pump did not always allow aqueous phase permeate to be returned to the system for retreatment, and some was discharged with the organic phase permeate to a holding drum, along with a higher then normal volume of water. Because of the failure of the condensate pump, the amount of organic phase permeate generated by a typical ZENON system could only be estimated. Table 4-6 displays the amount of organic phase permeate generated per run in relation to the flow rate and TCE concentrations in untreated groundwater. The system generated an average of about 2.9 gallons of permeate per hour, equaling 23 gallons per 8-hour run. The average amount of untreated groundwater passed through the system was 441 gallons per hour (gph) (about 3,525 gallons per 8-hour run).

The mass balance calculation was used to determine TCE contaminant loads in concentrated permeate. Because flow rates and contaminant concentrations were not available for permeate, the following equation (4-2) was used to provide a permeate figure:

Untreated Groundwater TCE Load - Treated Groundwater TCE Load = Vapor TCE Load (4-2)

Permeate TCE Load

TCE concentrations in permeate, when expressed as a percentage of total TCE load into the system, averaged 73.7 percent. TCE permeate load was highest during the second and fourth sampling runs, averaging 89.6 percent of the total TCE contaminant load. The lowest percentage of TCE load was occurred during the first run and was 41.1 percent.

Variations in flow rates, influent contaminant concentrations, or TCE treatment efficiency, appeared to have no effect on the amount of permeate generated during the demonstration. When the condensate pump is operating correctly, the amount of organic phase permeate generated by a typical ZENON pervaporation system should be lower than the amount generated during the demonstration. Also, total organic phase permeate generation should rise with elevated influent contaminant concentrations.

S3) Measure VOC vapor vented from the pervaporation system

Samples of vapor from the vacuum vent of the ZENON pervaporation technology were collected directly from the vent (S3) and after the vapor passed through a 55-gallon carbon canister (S4). Samples from S3 allowed the determination of the amount of VOCs removed from untreated groundwater but not captured by the condensing process. As noted in Section 4.2.4, samples from S4 were collected to determine if VOCs were released to the atmosphere. Sampling point S4, which was between the two carbon filters, provided a verification that all VOCs not condensed in the ZENON system were captured by the first carbon filter. Sampling point S4 was not intended to provide data on releases of VOCs from the vacuum vent of the ZENON system – data from S4 was only intended to verify that VOCs were not released to the outside air. Therefore, the data for sampling point S4 is not included with this document.

Two samples from each location were collected during each run, except for the fifth run when only one sample

Table 4-6. Estimated Permeate Generation

Run Number	Flow Rate (gallons per minute)	Average Untreated TCE Concentration (mg/L)	Average Treated TCE Concentration (mg/L)	Total Permeate (U.S. gallons)	Average Amount Per Hour (U.S. gallons)
1	2.1	40	3.9	20.8	2.6
2	5.2	42	0.11	20.8	2.6
3	9	36	0.26	28.0	3.5
4	5.5	230	0.46	21.0	2.6
5[1]	11.2	125	2.7	12.0	3.0
Average	--	--	--	20.5	2.9

Notes:

mg/L Milligrams per liter
1 Sampling run was abbreviated due to system failure

was collected. All samples were analyzed for VOCs by Method TO-14.

Analytical results for TCE from vapor vented from the system (sampling point S3) are shown in Table 4-7. TCE concentrations in the vented vapor ranged from 14,000 milligrams per cubic meter (mg/m^3), which occurred during the second run, to 110,000 mg/m^3 during the fourth and fifth runs. The rise in discharges of TCE vapor from the vacuum vent of the system correspond to higher concentrations of TCE in the untreated groundwater. When considered as a percentage of contaminant load, releases from the vacuum vent were inconsistent, ranging from 10.3 to 49.2 percent. The mass balance calculation was used to provide the percentage of TCE contaminant load released from the vacuum vent. Vapor release velocity (supplied by ZENON) from the vacuum vent was used for the flow rate of equation 4-1. When the groundwater flow rate through the system was near 5 gpm, the vapor flow rate was at about 0.30 cubic meters per hour (m^3/hr); when the groundwater flow rate was near 9 gpm, the vapor flow rate was about 0.55 m^3/hr. The average release of TCE from the vacuum vent as a percentage of total TCE entering the system was 21.9 percent. The lowest, 0.9 percent, occurred during the second run, when groundwater flow through the system was 5.2 gpm. The highest TCE release from the vacuum vent when expressed as a percentage of total TCE was 49.2 percent, during the first run.

For a few other VOCs, higher concentrations in untreated water provided higher concentrations of VOCs released from the vacuum vent. For instance, the second and fourth runs were conducted with varying concentrations at similar flow rates. During the second run, cis-1,2-dichloroethene was detected at 62.8 mg/L in untreated groundwater, and releases of this compound from the vacuum vent averaged 32,000 mg/m^3. During the fourth run, cis-1,2-dichloroethene was detected at 5.9 mg/L, while its concentration in vented vapor was 9,000 mg/m^3. This general reduction of VOCs in vacuum vapor with lower influent concentrations also applied to 4-methyl-2-pentanone.

For the remaining VOCs detected during the demonstration, no clear removal characteristics could be gathered. For instance, during the second run 2-butanone was detected in untreated groundwater at 93.8 mg/L, and releases of this compound from the vacuum vent averaged 6,500 mg/m^3. During the fourth run, 2-butanone was detected at 108 mg/L, while concentrations of this compound in vented vapor averaged 3,040 mg/m^3.

Because some other compounds were not detected during each run, the analytical data available does not provide

Table 4-7. TCE Concentrations in Vented Vapor

Run Number	Flow Rate (gpm)	Average Groundwater TCE Concentration (mg/L)	Grab Number	Concentration of TCE in Vented Vapor (mg/m^3)	Concentration of TCE in Vented Vapor (ppm)
1[1]	2.1	40	1	32,000	6,100
			2	29,000	5,500
2	5.2	42	1	19,000	3,700
			2	14,000	2,500
3	9.0	36	1	39,000	7,300
			2	38,000	7,200
4	5.5	230	1	94,000	18,000
			2	110,000	20,000
5[2]	11.2	125	1	110,000	21,000
Average:		95		53,889	10,100

Notes:

mg/L	Milligrams per liter
mg/m^3	Milligrams per cubic meters
ppm	Parts per million
[1]	A sampling run is defined as one 8-hour period for a given flow rate
[2]	Sampling run was abbreviated due to system failure

significant information to allow a definite conclusion concerning VOCs other than TCE released with vacuum vapor in relation to concentrations of VOCs in the influent and changes in flow rates through the system. As noted, the monitoring wells used during the demonstration were varied to provide varying concentrations of TCE.

S4) Determine requirements for anti-scaling additions, and monitor the potential of the system, by identifying reductions in TSS, and concentrations of carbonate, fluoride, sulfate, silica, strontium, calcium, barium, magnesium, and iron in treated and untreated water

To identify significant removal or scaling of materials from the groundwater at Site 9, samples of untreated and treated groundwater were collected during runs one, three, and five, and analyzed for the above-listed materials. Data for these analyses are presented in the TER. As detailed in previous sections, scaling of the pervaporation module membranes reduced the system's ability to correctly function.

In comparing untreated to treated groundwater samples, no significant reductions in any of the materials were noted, except in TSS. Untreated groundwater samples collected during the first run contained 12.4 mg/L TSS, and the corresponding treated sampled contained TSS at a concentration below the method detection limit of 4.0 mg/L. During the fifth run, untreated groundwater contained TSS at 3.67 mg/L, and the corresponding treated sample was again below the detection limit of 4.0 mg/L. No correlation could be made between changes in analytical results for the above-listed materials and scaling buildup on the pervaporation membranes.

ZENON attributed the scaling problems during the demonstration to the deposition of magnesium and calcium bicarbonate ions, which precipitated out of the groundwater as it was heated. Magnesium concentrations in the Site 9 groundwater averaged 468 mg/L, while calcium concentrations averaged about 201 mg/L. To counter this deposition, ZENON used two additives similar to zinc phosphate. These materials were steadily added to the untreated groundwater at from 5 to 20 mg/L and served to change the chemistry of the ions that prevented their precipitation at the system operating temperatures used during the demonstration. After the additive feed system was operating, scaling problems decreased substantially. According to ZENON, both of the additives performed well at lower temperatures,

though the second worked best at higher temperatures (ZENON 1996). Because the technology was operated for only a limited time period, long-term effects of scaling could not be assessed during the demonstration.

ZENON considered the groundwater conditions at NASNI Site 9 to be atypical of most aquifers, presenting a worst-case scenario. Contaminants found in groundwater or wastewater at separate sites can vary tremendously. Therefore, if scaling is a problem, additives used to control it may vary. Companies manufacturing anti-scalent materials can analyze a sample of the expected influent and determine the anti-scalent material best suited for that particular application. A determination of this sort would always be made on a site-by-site basis.

S5) Determine if the technology's efficiency in removing VOCs, SVOCs, and TRPH is reduced after a 3-week period, and if scaling occurs after a 3-week period due to the precipitation of the analytes listed under secondary objective S4.

Before demonstration sampling began, the SITE team elected not to run the system for 3 weeks and then resample because (1) component failures caused continual treatment difficulties with the pervaporation system and (2) cost concerns had arisen due to project delays.

At the start of sampling, the demonstration team was concerned that the technology would not operate for 3 full weeks. Problems ranging from temperature regulation difficulties to premature failure of seals on various pumps interfered with the treatment efficiency of the ZENON technology. Scaling of the pervaporation membranes proved to be a continuous problem that required frequent acid washings of the technology until an adequate anti-scaling additive was provided. According to ZENON representatives, the company had a set budget to perform the demonstration at NASNI, and as difficulties continued, which required much more time in the field than was expected, budget problems became a concern. Without any of the above-listed problems, this objective could not have been accomplished because of the failure of the stainless tube on the pervaporation module, which ended demonstration sampling 4 hours into the fifth run.

As discussed in the results of Secondary Objective S4, scaling potential must be assessed on a site-by- site basis. After a proper anti-scaling additive is selected, frequent monitoring of the performance of the technology is necessary, especially during the initial period of a treatment job, to determine the necessity for acid washings of the system. Once additional determinations have been made for monitoring requirements, a schedule of routine maintenance involving washings can then be established.

S6) Determine the physical effects the ZENON technology has on treated groundwater

Samples of untreated and treated groundwater were collected three times per run, and measurements of temperature, pH, and conductivity were collected with a multitesting meter. The main purpose of this sampling was to identify physical changes caused by heat from the pervaporation system or from additions of anti-scaling chemicals.

The average change in temperature between untreated groundwater (before entering the system) and treated groundwater (discharged groundwater) was 4.0 °C. The greatest daily average change in temperature was 11.7 °C and occurred during the first run. During this run, water was passed through the system at 2.10 to 2.15 gpm, the slowest of the demonstration. The higher average temperature change can be attributed to the higher retention time of the groundwater in the system. Groundwater pH increased an average of 0.56 during the demonstration. A change of 0.90, the highest of the demonstration, occurred during the second run. The change in conductivity of treated groundwater compared to untreated groundwater was negligible. Data tables containing this information are provided in the TER.

S7) Document the operating conditions of the ZENON technology

The particulate and scaling problems that delayed the start of the demonstration caused problems with many components of the system, including sight glasses, valves, and several component surfaces. This complicated the monitoring of operating conditions of the system, and caused difficulty in keeping all parameters within specified control limits. The various parameters recorded in the field, such as flow rates, temperature, and pressure are probably imprecise (due to varying interference). No independent measurements are available to verify these results. Therefore, data gathered for these parameters should be used qualitatively. Data in this section were provided by ZENON (ZENON 1995).

Average daily values for the temperature of water entering and exiting the pervaporation unit is presented under Secondary Objective S6; flow rates for the demonstration are presented Table 4-5. Permeate was discharged from the unit in bulk, so flow rates for permeate do not apply. Values for feed pressure, vacuum, and chilled water temperature were provided by ZENON and are presented in the TER.

The highest feed pressure of water entering the pervaporation module during the demonstration occurred during the fifth run at 10.9 pounds per square inch (psi); the lowest was during the second run and was 5.1 psi. For water exiting the module, the highest feed pressure was during the fifth run at 7.4 psi; the lowest was during the first run at 2.3 psi.

The pervaporation module is subjected to a vacuum that removes organics in the vapor phase. During the demonstration, the vacuum on the module averaged 0.50 psi. The vacuum was highest during the fifth run and averaged 0.72 psi-absolute (psia). It was lowest during the third run and averaged 0.40 psia. The vacuum during the first, second, and third runs were all near 0.41 psia.

The temperature of water entering the system from the chiller averaged 4 °C; the temperature of water returning to the chiller from the system varied between 4 °C and 5 °C.

S8) Estimate the capital and operating costs of treating contaminated groundwater at Site 9 with ZENON pervaporation systems identical to that used for the demonstration

This objective was achieved by using capital cost information provided by the developer, measuring electricity consumption, and estimating labor requirements. A detailed estimate of the capital and operating costs of constructing a single treatment unit to remediate groundwater contaminated with TCE is presented in Section 3.0. Cost have been placed in 12 categories applicable to typical cleanup activities at RCRA sites and include fixed and annual variable costs. Operating conditions consist of treating the groundwater at 8 gpm for a period of 15 years. Total fixed costs are $189,500. Equipment costs comprise 79 percent of the total fixed costs. Total annual variable costs are $118,100. Utility costs comprise 47 percent of the variable costs, and residual waste handling services comprise 28 percent.

After operating for 15 years, the total cost of the groundwater remediation scenario presented in this analysis is $1,961,000. Annual costs were not adjusted for inflation. A total of 63 million gallons of groundwater would be treated over this time period. The total cost per 1,000 gallons treated is $31, or roughly 3 cents per gallon.

Based on the performance of the technology during the demonstration at NASNI, a strong potential exists for a typical application to experience down-time from mechanical problems, including scaling difficulties, seal, pump, and valve failures, along with unknown difficulties that may be caused by extreme changes in weather conditions (temperatures). Problems such as these over an extended period of time could increase treatment costs substantially.

4.3.4 Data Quality

A data quality assessment was conducted to incorporate the analytical data validation results with the field 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 draw conclusions. The QA objectives for this project were established in the QAPP.

A data validation review of the analytical data for groundwater and air samples collected during the ZENON SITE demonstration was conducted to ensure that all laboratory data generated and processed are scientifically valid, defensible, and comparable. Data validation was conducted using both field QC samples and laboratory QC analyses. The field samples included field blanks and trip blanks. Laboratory samples included method blanks, surrogate recoveries, initial and continuing calibration, and MS/MSD results. Results from these samples were used to calculate the precision, accuracy, representativeness, comparability, and completeness of the data. In general, all data quality indicators met the QA objectives specified in the QAPP, indicating that general data quality was good and that the sample data are useable as reported. Conformance with data quality objectives for the critical and non critical parameters, along with conformance with field QA/QC procedures, calibration requirements, and internal QC procedures, is discussed below.

Critical Parameter

The one critical parameter was the TCE concentrations in untreated and treated groundwater. All QA objectives for TCE in groundwater were met except the TRL. Most samples were diluted ten-fold or more because of concentrations of TCE and other VOCs that exceeded the calibration range for an undiluted sample, so the sample reporting levels in the data tables are generally correspondingly higher than the TRL. However, because the ZENON technology was not capable of reducing TCE to concentrations approaching the requirements of Primary Objective P1 (reduce TCE to below an MCL of 5 μg/L), the TRL was not a factor.

Noncritical Parameters

The noncritical parameters include VOCs other than TCE, SVOC, various inorganic parameters (metals, fluoride, silica, sulfate, pH), and some collective parameters (total petroleum hydrocarbons, alkalinity, total suspended solids, conductivity). Most of the QA objectives for these parameters were met.

Since TCE was analyzed by Method 8260, a number of other VOC could be determined simultaneously. One of the precision objectives for these noncritical parameters was not met. In the MS/MSD analysis of treated water from Day 2, recovery of 2-butanone was 136 percent in both the MS and MSD samples, slightly about the acceptance criterion of 70 to 130 percent. The 2-butanone results in that sample are considered qualified, but are still usable.

There were greater problems with the SVOC MS/MSD analyses. In all cases, the phenol results are not usable because the spike was much less than the native sample concentration. In seven of the eight spiked samples, there was excessive recovery of 4-chloro-3-methylphenol. There was also excessive recovery of 2-chlorophenol in one untreated water MS/MSD pair and of pyrene in one untreated water and one treated water MS/MSD pair. In addition, there was a high relative percent difference of recoveries of acenaphthene and 4-nitrophenol in one treated water MS/MSD pair. These results provide evidence of significant matrix interference with the acidic fraction (phenol and its derivatives, benzoic acid, and so on) of the SVOC analysis. This matrix effect is probably associated with the sample alkalinity. The acidic fraction results in all samples should be used with caution.

The laboratory noted that most volatile organic analysis (VOA) vials had a pH exceeding 2 when they were opened. The samplers added a standard amount of hydrochloric acid to preserve each vial. However, the groundwater samples had very high alkalinity, 1,184 to 1,740 milligrams per liter as calcium carbonate. That standard amount of acid was insufficient to neutralize the actual alkalinity of the samples. This would not affect the samples to a significant extent. The chemicals most susceptible to degradation in unpreserved samples are the aromatic hydrocarbons, which are minor constituents of these samples, if present at all. The high ionic strength associated with the alkalinity is also a reasonably effective bacterial inhibitor (that is, preservative) which would supplement the effects of the acid. Verifying the pH of a preserved VOC sample is not acceptable because the sample disturbance can cause outgassing and loss of VOC content.

All QA objectives for the air samples were met. These objectives included laboratory (method) blanks, laboratory duplicates, and MS/MSD for each batch of samples, plus holding times and surrogate spikes for each sample.

Conformance With Field QA/QC Procedures

During the demonstration, the sample collection and field measurement procedures described in Section 4.0 of the QAPP were generally followed. At least one VOC was found in at least one of the three blanks (field blanks for untreated and treated water and trip blank) on each day of sampling. Acetone was found in eight blanks on three days at concentrations of 18 to 34 μμg/L. Methylene chloride was found in all three of the Day 4 blanks at 2.4 to 3.1 μμg/L. 2-Butanone was found in two of the Day 1 blanks at 4.7 and 5.2 μμg/L. Those three chemicals are frequently found contaminants. In addition, one Day 2 blank contained 5.5 μμg/L of chloromethane and one Day 3 blank contained 15 μμg/L of 4-methyl-2-pentanone. Therefore, similar concentrations of these compounds are considered artifacts and the results flagged as "undetected." No field blanks contained TCE. The laboratory (method) blanks were free of VOC contamination. These blank analysis results are within the acceptable range. The overall results are not significantly affected.

Conformance With Calibration Requirements

Section 5.0 of the QAPP specifies the calibration

procedures and acceptance criteria for the demonstration. The only significant calibration problem was with some continuing calibration of the VOC analysis. In those instances, the response factors for acetone and 2-hexanone, two of the well-known poorly responding target compounds, exceeded the percent difference criterion. Associated results for those noncritical compounds are considered estimates.

Conformance With Internal QC Procedures

Table 7-1 of the QAPP summarizes the internal QC and corrective action procedures for the demonstration. None of the 19 VOC method blanks and five SVOC method blanks contained any chemicals at or above the reporting limits. All three BS/BSD and VOC analyses gave results within the specified precision and accuracy limits. All VOC surrogate recovery results were within the acceptance criteria. Therefore, no corrective actions by the laboratory were required.

4.3.5 Conclusions

The ZENON cross-flow pervaporation system provides an alternative approach to treating organic-contaminated water at sites where conventional treatment technologies are used, such as air stripping or carbon adsorption.

Analytical results from the demonstration indicate that the ZENON technology, when operating at optimum conditions, effectively removed TCE from the groundwater at NASNI Site 9. Removal efficiencies for TCE averaged 97.3 percent. Sixteen of 18 comparisons of treated water samples to untreated samples showed average TCE removal efficiencies of 99.3 percent. Although the system significantly reduced TCE concentrations in the groundwater to an average of 1.49 mg/L (1,490 µg/L), the federal MCL of 5 µg/L was not achieved. Lowering TCE concentrations to below MCLs may require multiple passes through the pervaporation module, which can prove impractical when compared to other technologies, such as carbon adsorption. The technology is best suited for reducing high concentrations of VOCs to levels that can be reduced further and more economically by conventional treatment technologies. The ZENON system appeared to remove TCE from groundwater most efficiently when the groundwater flow rate was just over 5 gpm, achieving near 100 percent removal.

The technology proved effective in removing certain VOCs other than TCE from the Site 9 groundwater, performing best on highly volatile compounds. VOCs with solubilities of greater than 2 percent are generally not suited for removal by pervaporation. Removal efficiencies for SVOCs detected were 50 percent or less. Because of some data quality flaws, namely VOC presence in trip blanks and SVOC MS/MSD results outside of QA objectives, the usefulness of the VOC and SVOC results is considered limited. TRPH removal for the demonstration averaged 68.5 percent and was fairly consistent over each sampling run.

Problems involving the seals and pumping controls of the condensate pump did not always allow aqueous phase permeate to be returned to the system for retreatment. Because of the failure of these items, the amount of permeate generated by a typical pervaporation system could only be estimated. ZENON estimated that the system at NASNI generated an average of 2.9 gallons of permeate per hour, equaling 23 gallons per 8-hour run. The average amount of untreated groundwater passed through the system was 441 gph (about 3,525 gallons per 8-hour run).

TCE contained in vapor discharged from the pervaporation module averaged 53,889 mg/m^3. As a percentage of the total TCE contaminant load, volatilized TCE discharged from the module averaged 21.7 percent. When the influent flow rate was near 5 gpm, TCE vapor releases averaged 0.9 percent of the total TCE contaminant load. For highly volatile VOCs, the amount of these compounds released from the module generally appeared to increase in relation to higher concentrations of those particular contaminants in the untreated groundwater. For VOCs that are less volatile, no clear removal similarities could be gathered.

Because of variations in water chemistry, potential scaling of the module membranes should be considered on a site-by-site basis. Treatability studies should be performed on groundwater or wastewater to be treated to determine if pervaporation can be applied. If necessary, a proper anti-scaling additive could then be selected. Scaling problems during the demonstration at NASNI were due to high concentrations of magnesium and calcium in the groundwater at Site 9, and its high salinity. To limit scaling of the membranes, ZENON eventually used an anti-scalent similar to zinc phosphate.

The average temperature of groundwater as it passed through the ZENON system was 4.0 °C. Groundwater pH

increased an average of 0.56, though changes in conductivity were negligible.

Estimated costs for operating a ZENON system at NASNI Site 9 at 8 gallons per minute for a period of 15 years, treating 63 million gallons of groundwater, are $1,961,000. The total cost per $1,000 gallons of treated groundwater is $31, or about 3 cents per gallon.

Section 5
ZENON Technology Status

The ZENON cross-flow pervaporation technology is a membrane-based process that removes VOCs from aqueous matrices. The SITE demonstration at NASNI represents the first full-scale use of the ZENON cross-flow pervaporation technology. The unit was returned to ZENON's base office in Ontario immediately following the demonstration for refurbishing. An application of the technology was recently performed at a separate location in California; however, analytical data and operational information for that application is not available.

A number of bench-scale studies of the technology involving varying types of VOC-contaminated influent have been performed and can be acquired by contacting ZENON at the address provided in Section 1.0. A pilot-scale study of the technology was conducted by EPA in late 1993 at a former petroleum pumping station in Burlington, Ontario. The pilot-scale test was performed to assess the technology's ability to remove low levels of benzene, toluene, ethylbenzene, and xylene (BETX) in contaminated groundwater. Sampling for the pilot-scale test was performed over a single 8-hour period.

According to ZENON, pervaporation systems are available for immediate implementation, and require minimal site preparation. Pervaporation is ideally suited for applications that require the removal of high concentrations of VOC contamination to levels where other, more cost-effective technologies could be used to reduce contamination levels to regulatory standards. Although the demonstration at NASNI dealt strictly with groundwater, the technology is available for industrial applications, as well as applications involving surface water.

Section 6
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Appendix A
Analytical Data Tables

Table A1. Groundwater Monitoring Well Data[a]

Well ID	IMW-1[b]	IMW-2[c]	DMW-1[d]	CW-5[e]
Screened Interval[f]	17 - 38 feet	17 - 38 feet	43 - 64 feet	5 - 20 feet
Volatile Organic Compounds (mg/L)[g]				
Trichlorethene	61.0	420	5.30	0.77
Vinyl chloride	3.30 J[h]	25.0 U[i]	0.17	4.3 J
Methylene chloride	0.38	15	0.01 U	0.10 U
Acetone	7.70 J	25.0 U	0.01 U	720
2-butanone	170	130	0.01 U	140
Toluene	2.50 J	8.00 J	0.13 J	3.10 J
4-Methyl-2-pentanone	10.0 J	25.0 U	1.40 J	70.0
2-Hexanone	0.10 U	25.0 U	0.12	0.01 U
Carbon disulfide	0.10 U	25.0 U	0.12	0.01 U
Cis-1,2-dichloroethene	54.0	25.0 U	8.10	0.68
Semivolatile organic compounds (mg/L)				
Phenol	24.4	2.41	0.17	3.53 J
2-Methylphenol	3.17	0.17	0.08 J	1.21 J
4-Methylphenol	46.6	1.72	0.42	355
2,4-dinitrophenol	0.25 U	0.25 U	0.03 U	0.25 U
4-Nitrophenol	0.25 U	0.25 U	0.03 U	0.25 U
4,6-Dinitro-2-methylphenol	0.25 U	0.25 U	0.03 U	0.25 U
Pentachlorophenol	0.25 U	0.25 U	0.03 U	0.25 U
Metals				
Barium	0.22	0.03 J	0.03 J	0.13 J
Calcium	163	111	355	7.79
Chromium, total	0.96	0.34	0.01 U	0.77
Cyanide	0.20	1.57	0.01	0.15
Iron	604	0.67	0.12 J	5.21
Magnesium	360	679	800	491
Manganese	0.42	0.86	0.86	0.08

Table A1. Groundwater Monitoring Well Data (continued)

Well ID	IMW-1	IMW-2	DMW-1	CW-5
Screened Interval	**17 - 38 feet**	**17 - 38 feet**	**43 - 64 feet**	**5 - 20 feet**
Metals (mg/L)				
Potassium	182	301	419	31.0
Sodium	4,510	2,500	8,950	1,800
Total Suspended Solids	NZ[j]	NZ	28	NZ
Alkalinity	NZ	NZ	1,041	NZ
Sulfate	NZ	NZ	521	NZ
Petroleum Hydrocarbons	NZ	NZ	NZ	NZ

Notes:

a Source: Southwest Division Naval Facilities, 1994
b IMW-1 = Intermediate monitoring well No. 1
c IMW-2 = Intermediate monitoring well No. 2
d DMW-1 = Deep monitoring well No. 1
e CW-5 = Shallow monitoring well No. 5
f The measurement for the screened interval is below the ground surface
g mg/L = milligram per liter
h J = Indicates an estimated concentration value. The result is considered qualitatively acceptable, but quantitatively unreliable.
i U = Indicates that the substance was analyzed for but not detected above the concentration listed. The value listed is the sample quantitation limit.
j Not analyzed

Table A2. Trichloroethene Concentration Summary

Run	Flow Rate (gallons per minute)	Well	Event Number	Untreated Concentration (mg/L)[a]	Treated Concentration (mg/L)	Percent Removal
1	2.1	IMW-1[b]	1	40	0.17	99.5%
			2	43	1.0	97.7%
			3	33	3.8	88.5%
			4	42	11	73.8%
	Average			40	3.9	89.9%
2	5.2	IMW-1	1	41	[0.10][c]	99.8%
			2	44	0.09	99.8%
			3	48	0.16	99.7%
			4	48	0.19	99.6%
	Average			45.3	0.14	99.7%
3	9.0	IMW-1	1	33	0.32	99.0%
		and	2	35	0.27	99.2%
		DMW-1[d]	3	38	0.22	99.4%
			4	37	0.24	99.4%
	Average			36	0.26	99.3%
4	5.5	IMW-2	1	220	0.45	99.8%
		and	2	220	0.40	99.8%
		DMW-1	3	240	0.51	99.8%
			4	240	0.46	99.8%
	Average			230	0.46	99.8%
5[f]	11.2	IMW-1, IMW-2,	1	130	2.7	97.9%
		and DMW-1	2	120	2.7	97.8%
	Average			125	2.7	97.9%
Total Average Percent Removal						97.3%[g]

Notes:
a mg/L = milligram per liter
b IMW-1 = Intermediate monitoring well No. 1
c [ ] = Indicates compound was analyzed for but not detected above the sample quantitation limit. The treated concentration is half of the sample quantitation limit.
d DMW-1 = Deep monitoring well No. 1
e IMW-2 = Intermediate monitoring well No. 2
f Sampling run was abbreviated due to system failure
g Total average computed from the averages of the five runs

Table A3. Vinyl Chloride Concentration Summary

Run	Flow Rate (gallons per minute)	Well	Event Number	Untreated Concentration (mg/L)[a]	Treated Concentration (mg/L)	Percent Removal
1	2.1	IMW-1[b]	1	11	0.11	99.0%
			2	11	[0.7][c]	93.6%
			3	8.3	[0.7]	91.6%
			4	120	[0.7]	99.4%
	Average			37.6	0.6	95.9%
2	5.2	IMW-1	1	12	[0.13]	98.9%
			2	11	[0.13]	98.8%
			3	12	[0.13]	98.9%
			4	11	[0.13]	98.8%
	Average			11.5	[0.13]	98.9%
3	9.0	IMW-1	1	9.3	0.18J[d]	98.1%
		and	2	8.9	[0.13]	98.5%
		DMW-1[e]	3	9.8	0.15	98.5%
			4	8.7	[0.13]	98.5%
	Average			9.2	0.15	98.4%
4	5.5	IMW-2[f]	1	NA[g]	NA	NA
		and	2	NA	NA	NA
		DMW-1	3	NA	NA	NA
			4	NA	NA	NA
	Average			NA	NA	NA
5[h]	11.2	IMW-1, IMW-2,	1	[5]	0.27	94.6%
		and DMW-1	2	6.3	[0.3]	95.2%
	Average			5.7	0.29	94.9%
Total Average Percent Removal						97.0%[i]

Notes:
a mg/L = milligram per liter
b IMW-1 = Intermediate monitoring well No. 1
c [ ] = Indicates compound was analyzed for but not detected above the sample quantitation limit. The untreated concentration is the sample quantitation limit and the treated concentration is half of the sample quantitation limit.
d J = Indicates an estimated concentration value. The result is considered qualitatively acceptable, but quantitatively unreliable.
e DMW-1 = Deep monitoring well No. 1
f IMW-2 = Intermediate monitoring well No. 2
g NA = Contaminant was not detected in influent or effluent, therefore, event is negated
h Sampling run was abbreviated due to system failure.
i Total average computed from the averages of the five runs

Table A4. Acetone Concentration Summary

Run	Flow Rate (gallons per minute)	Well	Event Number	Untreated Concentration (mg/L)[a]	Treated Concentration (mg/L)	Percent Removal
1	2.1	IMW-1[b]	1	30J[c]	21	30.0%
			2	51J	20UJ[d]	60.8%
			3	33UJ	20UJ	39.4%
			4	29UJ	15UJ	48.3%
	Average			35.6	19	44.6%
2	5.2	IMW-1	1	41UJ	35	14.6%
			2	43UJ	18	58.1%
			3	41UJ	33	19.5%
			4	37UJ	35	5.4%
	Average			40.5	30.3	24.4%
3	9.0	IMW-1	1	23UJ	20	13.0%
		and	2	27UJ	32	0.0%
		DMW-1[e]	3	27UJ	21	22.2%
			4	30UJ	33	0.0
	Average			26.8	26.5	8.8%
4	5.5	IMW-2[f]	1	37UJ	9.1	75.4%
		and	2	12UJ	9.6	20.0%
		DMW-1	3	14.6UJ	8.7UJ	40.4%
			4	15UJ	10	33.3%
	Average			19.7	9.4	42.3%
5[g]	11.2	IMW-1, IMW-2,	1	27UJ	16	40.7%
		and DMW-1	2	31UJ	41J	0.0%
	Average			29	28.5	20.35%
Total Average Percent Removal						28.1%[h]

Notes:
a mg/L = milligram per liter
b IMW-1 = Intermediate monitoring well No. 1
c J = Indicates an estimated concentration value. The result is considered qualitatively acceptable, but quantitatively unreliable.
d UJ = Estimated value that was 10 times less than the contract required quantitation limit
e DMW-1 = Deep monitoring well No. 1
f IMW-2 = Intermediate monitoring well No. 2
g Sampling run was abbreviated due to system failure
h Total average computed from the averages of the five runs

Table A5. 4-Methyl-2-Pentanone Concentration Summary

Run	Flow Rate (gallons per minute)	Well	Event Number	Untreated Concentration (mg/L)[a]	Treated Concentration (mg/L)	Percent Removal
1	2.1	IMW-1[b]	1	64	12	81.3%
			2	70	17	75.7%
			3	53	24	54.7%
			4	57	31	45.6%
	Average			61	21	64.3%
2	5.2	IMW-1	1	45	19	57.8%
			2	66	25	62.1%
			3	46	9.5	79.3%
			4	35	13	62.9%
	Average			48	16.6	65.5%
3	9.0	IMW-1	1	39	23	41.0%
		and	2	45	25	44.4%
		DMW-1[c]	3	39	21	46.2%
			4	42	21	50.0%
	Average			41.3	22.5	45.4%
4	5.5	IMW-2[d]	1	28	17	39.3%
		and	2	28	14	50.0%
		DMW-1	3	37	18	51.4%
			4	30	18	40.0%
	Average			30.8	16.8	45.2%
5[e]	11.2	IMW-1, IMW-2,	1	40	30	25.0%
		and DMW-1	2	24	32	0.0%
	Average			32	31	12.5%
Total Average Percent Removal						46.6%[F]

Notes:
a mg/L = milligram per liter
b IMW-1 = Intermediate monitoring well No. 1
c DMW-1 = Deep monitoring well No. 1
d IMW-2 = Intermediate monitoring well No. 2
e Sampling run was abbreviated due to system failure
f Total average computed from the averages of the five runs

Table A6. 2-Butanone Concentration Summary

Run	Flow Rate (gallons per minute)	Well	Event Number	Untreated Concentration (mg/L)[a]	Treated Concentration (mg/L)	Percent Removal
1	2.1	IMW-1[b]	1	120	86	28.3%
			2	53	70	0.0%
			3	90	62	31.1%
			4	100	63	37.0%
	Average			90.8	70.3	24.1%
2	5.2	IMW-1	1	94	79	16.0%
			2	110	86J[c]	21.8%
			3	100	46	54.0%
			4	71	58	18.3%
	Average			93.8	67.3	27.5%
3	9.0	IMW-1	1	79	77	2.5%
		and	2	84	82	2.4%
		DMW-1[d]	3	85	61	28.2%
			4	88	76	13.6%
	Average			84	74	11.7%
4	5.5	IMW-2[e]	1	110	100	9.1%
		and	2	90	95	NA
		DMW-1	3	120	94	21.7%
			4	110	99	10.0%
	Average			107.5	97	13.6%
5[f]	11.2	IMW-1, IMW-2,	1	96	90	6.3%
		and DMW-1	2	65	100	0.0%
	Average			80.5	95	3.2%
Total Average Percent Removal						16.0%[g]

Notes:
a mg/L = milligram per liter
b IMW-1 = Intermediate monitoring well No. 1
c J = Indicates an estimated concentration value. The result is considered qualitatively acceptable, but quantitatively unreliable.
d DMW-1 = Deep monitoring well No. 1
e IMW-2 = Intermediate monitoring well No. 2
f Sampling run was abbreviated due to system failure
g Total average computed from the averages of the five runs

Table A7. Methylene Chloride Concentration Summary

Run	Flow Rate (gallons per minute)	Well	Event Number	Untreated Concentration (mg/L)[a]	Treated Concentration (mg/L)	Percent Removal
1	2.1	IMW-1[b]	1	NA[c]	NA	NA
			2	NA	NA	NA
			3	NA	NA	NA
			4	NA	NA	NA
	Average			NA	NA	NA
2	5.2	IMW-1	1	NA	NA	NA
			2	NA	NA	NA
			3	NA	NA	NA
			4	NA	NA	NA
	Average			NA	NA	NA
3	9.0	IMW-1	1	NA	NA	NA
		and	2	NA	NA	NA
		DMW-1[d]	3	NA	NA	NA
			4	NA	NA	NA
	Average			NA	NA	NA
4	5.5	IMW-2[e]	1	38UJ[f]	2.4UJ	93.7%
		and	2	33UJ	2.0UJ	93.9%
		DMW-1	3	34UJ	2.4UJ	92.9%
			4	38UJ	2.2UJ	94.2%
	Average			35.8UJ	2.25UJ	93.7%
5[g]	11.2	IMW-1, IMW-2,	1	12UJ	3.8UJ	68.3%
		and DMW-1	2	12UJ	4.0UJ	66.7%
	Average			12UJ	3.9UJ	67.5%
Total Average Percent Removal						80.6%[h]

Notes:
a mg/L = milligram per liter
b IMW-1 = Intermediate monitoring well No. 1
c NA = Contaminant was not detected in influent or effluent, therefore, event is negated
d DMW-1 = Deep monitoring well No. 1
e IMW-2 = Intermediate monitoring well No. 2
f UJ = Estimated value that was 10 times less than the contract required quantitation limit
g Sampling run was abbreviated due to system failure
h Total average computed from the averages of the five runs

Table A8. 1,1-Dichloroethene Concentration Summary

Run	Flow Rate (gallons per minute)	Well	Event Number	Untreated Concentration (mg/L)[a]	Treated Concentration (mg/L)	Percent Removal
1	2.1	IMW-1[b]	1	NA[c]	NA	NA
			2	NA	NA	NA
			3	NA	NA	NA
			4	NA	NA	NA
	Average			NA	NA	NA
2	5.2	IMW-1	1	NA	NA	NA
			2	NA	NA	NA
			3	NA	NA	NA
			4	NA	NA	NA
	Average			NA	NA	NA
3	9.0	IMW-1	1	NA	NA	NA
		and	2	NA	NA	NA
		DMW-1[d]	3	NA	NA	NA
			4	[2.5][e]	[0.13]	94.8%
	Average			NA	NA	NA
4	5.5	IMW-2[f]	1	11	[0.3]	97.3%
		and	2	10	[0.13]	98.7%
		DMW-1	3	11	[0.3]	97.3%
			4	11	[0.3]	97.3%
	Average			10.75	[0.3]	97.7%
5[g]	11.2	IMW-1, IMW-2,	1	4.4J[h]	[0.13]	97.0%
		and DMW-1	2	4.6J	[0.3]	93.5%
	Average			4.5J	[0.25]	95.3%
Total Average Percent Removal						96.5%[i]

Notes:
a mg/L = milligram per liter
b IMW-1 = Intermediate monitoring well No. 1
c NA = Contaminant was not detected in both influent and effluent and thus cannot be used
d DMW-1 = Deep monitoring well No. 1
e [ ] = Indicates compound was analyzed for but not detected above the sample quantitation limit. The untreated concentration is the sample quantitation limit and the treated concentration is half of the sample quantitation limit.
f IMW-2 = Intermediate monitoring well No. 2
g Sampling run was abbreviated due to system failure
h J = Indicates an estimated concentration value. The result is considered qualitatively acceptable, but quantitatively unreliable.
i Total average computed from the averages of the five runs

Table A9. Toluene Concentration Summary

Run	Flow Rate (gallons per minute)	Well	Event Number	Untreated Concentration (mg/L)[a]	Treated Concentration (mg/L)	Percent Removal
1	2.1	IMW-1[b]	1	6.4	0.037J[c]	99.4%
			2	6.4	[0.65][d]	89.8%
			3	4.7	0.79J	83.2%
			4	6.5	2.3	64.6%
	Average			6.0	0.94	84.3%
2	5.2	IMW-1	1	6.1	[0.13]	97.9%
			2	6.3	[0.13]	97.9%
			3	6.0	[0.13]	97.8%
			4	6.0	[0.13]	97.8%
	Average			6.1	[0.13]	97.9%
3	9.0	IMW-1	1	4.2	[0.13]	96.9%
		and	2	4.4	[0.13]	97.0%
		DMW-1[e]	3	4.3	[0.07]	98.4%
			4	4.5	[0.13]	97.1%
	Average			4.4	[0.12]	97.4%
4	5.5	IMW-2[f]	1	NA[g]	NA	NA
		and	2	3.9	[0.13]	96.7%
		DMW-1	3	NA	NA	NA
			4	NA	NA	NA
	Average			3.9	0.13	96.7%
5[h]	11.2	IMW-1, IMW-2,	1	4.8J	0.16J	96.7%
		and DMW-1	2	4.2J	[0.3]	92.9%
	Average			4.5J	0.23	94.2%
Total Average Percent Removal						94.3%[i]

Notes:
a mg/L = milligram per liter
b IMW-1 = Intermediate monitoring well No. 1
c J = Indicates an estimated concentration value. The result is considered qualitatively acceptable, but quantitatively unreliable.
d [ ] = Indicates compound was analyzed for but not detected above the sample quantitation limit. The untreated concentration is the sample quantitation limit and the treated concentration is half of the sample quantitation limit.
e DMW-1 = Deep monitoring well No. 1
f IMW-2 = Intermediate monitoring well No. 2
g NA = Contaminant was not detected in infleunt or effluent; therefore, event is negated
h Sampling run was abbreviated due to system failure
i Total average computed from the averages of the five runs

Table A10. cis-1,2-DichloroetheneConcentration Summary

Run	Flow Rate (gallons per minute)	Well	Event Number	Untreated Concentration (mg/L)[a]	Treated Concentration (mg/L)	Percent Removal
1	2.1	IMW-1[b]	1	77	1.1	98.6%
			2	80	2.9	96.4%
			3	58	6.8	88.2%
			4	68	13	80.9%
	Average			70.8	6.0	90.9%
2	5.2	IMW-1	1	69	0.86	98.8%
			2	64	0.87	98.6%
			3	62	0.99	98.4%
			4	56	0.92	98.4%
	Average			62.8	0.91	98.6%
3	9.0	IMW-1	1	48	2.4	95.0%
		and	2	45	2.1	95.3%
		DMW-1[c]	3	46	1.8	96.1%
			4	44	1.9	95.8%
	Average			45.8	2.1	95.6%
4	5.5	IMW-2	1	6.4J[e]	[0.3][f]	95.3%
		and	2	54	[0.13]	99.8%
		DMW-1	3	NA[g]	NA	NA
			4	NA	NA	NA
	Average			30.2	[0.26]	97.6%
5[d]	11.2	IMW-1, IMW-2,	1	34	3.8	88.8%
		and DMW-1	2	29	3.6	87.6%
	Average			31.5	3.7	88.2%
Total Average Percent Removal						94.2%[h]

Notes:
a mg/L = milligram per liter
b IMW-1 = Intermediate monitoring well No. 1
c DMW-1 = Deep monitoring well No. 1
d IMW-2 = Intermediate monitoring well No. 2
e J = Indicates an estimated concentration value. The result is considered qualitatively acceptable, but quantitatively unreliable.
f [ ] = Indicates compound was analyzed for but not detected above the sample quantitation limit. The untreated concentration is the sample quantitation limit and the treated concentration is half of the sample quantitation limit.
g Sampling run was abbreviated due to system failure
h Total average computed from the averages of the five runs

Table A11. Phenol Concentration Summary

Run	Flow Rate (gallons per minute)	Well	Event Number	Untreated Concentration (mg/L)[a]	Treated Concentration (mg/L)	Percent Removal
1	2.10 - 2.15	IMW-1[b]	1	5.5	4.5	18.2%
			2	5.5	5.1	7.3%
			3	5.8	5.2	10.3%
			4	6.6	4.3	34.8%
	Average			5.9	4.8	17.7%
2	5.16 - 5.21	IMW-1	1	4.2	5.3	0.0%
			2	4.3	5.3	0.0%
			3	4.6	4.5	2.2%
			4	4.6	4.4	4.3%
	Average			4.43	4.9	1.6%
3	9.0	IMW-1	1	5.9	6.8	O.O%
		and	2	6.8	6.4	5.9%
		DMW-1[c]	3	6.8	6.8	0.0%
			4	6.5	6.2	4.6%
	Average			6.5	6.6	2.6%
4	5.46	IMW-2[d]	1	5.2	5.0	3.8%
		and	2	5.3	6.8	0.0%
		MW-1	3	5.4	4.0	25.9%
			4	5.2	4.8	7.7%
	Average			5.3	5.2	9.4%
5[e]	11.18 - 11.23	IMW-1, IMW-2,	1	4.6	4.5	2.2%
		and DMW-1	2	4.1	4.2	0.0%
	Average			4.4	4.4	1.1%
Total Average Percent Removal						6.5%[f]

Notes:
a mg/L = milligram per liter
b IMW-1 = Intermediate monitoring well No. 1
c DMW-1 = Deep monitoring well No. 1
d IMW-2 = Intermediate monitoring well No. 2
e Sampling run was abbreviated due to system failure
f Total average computed from the averages of the five runs

Table A12. 2-Methylphenol Concentration Summary

Run	Flow Rate (gallons per minute)	Well	Event Number	Untreated Concentration (mg/L)[a]	Treated Concentration (mg/L)	Percent Removal
1	2.1	IMW-1[b]	1	4.6	3.6	21.7%
			2	4.5	3.9	13.3%
			3	4.8	3.8	20.8%
			4	5.4	3.2	40.7%
	Average			4.8	3.6	24.1%
2	5.2	IMW-1	1	3.3	3.9	0.0%
			2	3.4	4.0	0.0%
			3	3.7	3.5	5.4%
			4	3.7	3.4	8.1%
	Average			3.5	3.7	3.4%
3	9.0	IMW-1	1	2.7	3.1	0.0%
		and	2	3.1	2.9	6.5%
		DMW-1[c]	3	3.1	3.0	3.2%
			4	2.9	2.7	6.9%
	Average			3.0	2.9	4.2%
4	5.5	IMW-2[d]	1	2.0	2.0	0.0%
		and	2	2.0	2.7	0.0%
		DMW-1	3	2.1	1.5	28.6%
			4	1.9	1.8	5.3%
	Average			2.0	2.0	8.5%
5[e]	11.2	IMW-1, IMW-2,	1	2.9	2.8	3.4%
		and DMW-1	2	2.6	2.7	0.0%
	Average			2.75	2.75	1.7%
Total Average Percent Removal						8.4%[f]

Notes:
a mg/L = milligram per liter
b IMW-1 = Intermediate monitoring well No. 1
c DMW-1 = Deep monitoring well No. 1
d IMW-2 = Intermediate monitoring well No. 2
e Sampling run was abbreviated due to system failure
f Total average computed from the averages of the five runs

Table A13. 4-Methylphenol Concentration Summary

Run	Flow Rate (gallons per minute)	Well	Event Number	Untreated Concentration (mg/L)[a]	Treated Concentration (mg/L)	Percent Removal
1	2.1	IMW-1[b]	1	19	16	15.8%
			2	18	16	10.5%
			3	19	16	15.8%
			4	21	15	28.6%
	Average			19.3	15.8	17.7%
2	5.2	IMW-1	1	13	14	0.0%
			2	13	15	0.0%
			3	14	13	7.1%
			4	14	13	7.1%
	Average			13.5	13.8	3.6%
3	9.0	IMW-1	1	12	13	0.0%
		and	2	13	13	0.0%
		DMW-1[c]	3	13	13	0.0%
			4	13	13	0.0%
	Average			12.8	13	0.0%
4	5.5	IMW-2[d]	1	2.9	2.8	3.4%
		and	2	2.9	3.8	0.0%
		DMW-1	3	3.1	2.2	29.0%
			4	2.8	2.7	3.6%
	Average			2.9	2.9	9.0%
5[e]	11.2	IMW-1, IMW-2,	1	7.6	7.6	0.0%
		and DMW-1	2	7.3	7.4	0.0%
	Average			7.45	7.5	0.0%
Total Average Percent Removal						6.1%[f]

Notes:
a mg/L = milligram per liter
b IMW-1 = Intermediate monitoring well No. 1
c DMW-1 = Deep monitoring well No. 1
d IMW-2 = Intermediate monitoring well No. 2
e Sampling run was abbreviated due to system failure
f Total average computed from the averages of the five runs

Table A14. 2,4-Dimethylphenol Concentration Summary

Run	Flow Rate (gallons per minute)	Well	Event Number	Untreated Concentration (mg/L)[a]	Treated Concentration (mg/L)	Percent Removal
1	2.1	IMW-1[b]	1	2.4	1.8	25.0%
			2	2.4	1.9	20.8%
			3	2.6	1.9	26.9%
			4	2.9	1.6	44.8%
	Average			2.6	1.8	29.4%
2	5.2	IMW-1	1	1.9	2.1	0.0%
			2	1.9	2.0	0.0%
			3	2.1	1.9	9.5%
			4	2.1	1.8	14.3%
	Average			2.0	2.0	6.0%
3	9.0	IMW-1	1	1.5	1.7	0.0%
		and	2	1.8	1.6	11.1%
		DMW-1[c]	3	1.8	1.7	5.6%
			4	1.7	1.4	17.6%
	Average			1.7	1.6	8.6%
4	5.5	IMW-2[d]	1	NA[e]	NA	NA
		and	2	NA	NA	NA
		DMW-1	3	NA	NA	NA
			4	NA	NA	NA
	Average			NA	NA	NA
5[f]	11.2	IMW-1, IMW-2,	1	0.72	0.81	0.0%
		and DMW-1	2	0.71	0.82	0.0%
	Average			0.715	0.815	0.0%
Total Average Percent Removal						11.0%[g]

Notes:
a mg/L = milligram per liter
b IMW-1 = Intermediate monitoring well No. 1
c DMW-1 = Deep monitoring well No. 1
d IMW-2 = Intermediate monitoring well No. 2
e NA = Contaminant was not detected in both influent and effluent and thus cannot be used
f Sampling run was abbreviated due to system failure
g Total average computed from the averages of the five runs

Table A15. 4-Chloro-3-Methylphenol Concentration Summary

Run	Flow Rate (gallons per minute)	Well	Event Number	Untreated Concentration (mg/L)[a]	Treated Concentration (mg/L)	Percent Removal
1	2.1	IMW-1[b]	1	0.6J[c]	0.46J	23.3%
			2	0.62J	0.51J	17.7%
			3	0.67J	0.49J	26.9%
			4	0.76J	0.46J	39.5%
	Average			0.66J	0.48	26.9%
2	5.2	IMW-1	1	NA[d]	NA	NA
			2	NA	NA	NA
			3	NA	NA	NA
			4	NA	NA	NA
	Average			NA	NA	NA
3	9.0	IMW-1	1	0.34J	0.38J	0.0
		and	2	0.4J	0.35J	12.5%
		DMW-1[e]	3	0.38J	0.37J	2.6%
			4	0.37J	0.37J	0.0%
	Average			0.37J	0.37J	5.0%
4	5.5	IMW-2[f]	1	NA	NA	NA
		and	2	NA	NA	NA
		DMW-1	3	NA	NA	NA
			4	NA	NA	NA
	Average			NA	NA	NA
5[g]	11.2	IMW-1, IMW-2,	1	NA	NA	NA
		and DMW-1	2	NA	NA	NA
	Average			NA	NA	NA
Total Average Percent Removal						16.0%[h]

Notes:
a mg/L = milligram per liter
b IMW-1 = Intermediate monitoring well No. 1
c J = Indicates and estimated concentration value. The result is considered qualitatively acceptable, but quantitatively unreliable.
d NA = Contaminant was not detected in both influent and effluent and thus cannot be used
e DMW-1 = Deep monitoring well No. 1
f IMW-2 = Intermediate monitoring well No. 2
g Sampling run was abbreviated due to system failure
h Total average computed from the averages of the five runs

Table A16. bis (2-Ethylhexyl) Phthalate Concentration Summary

Run	Flow Rate (gallons per minute)	Well	Event Number	Untreated Concentration (mg/L)[a]	Treated Concentration (mg/L)	Percent Removal
1	2.1	IMW-1[b]	1	NA[c]	NA	NA
			2	NA	NA	NA
			3	NA	NA	NA
			4	NA	NA	NA
	Average			NA	NA	NA
2	5.2	IMW-1	1	NA	NA	NA
			2	NA	NA	NA
			3	NA	NA	NA
			4	NA	NA	NA
	Average			NA	NA	NA
3	9.0	IMW-1	1	NA	NA	NA
		and	2	NA	NA	NA
		DMW-1[d]	3	NA	NA	NA
			4	NA	NA	NA
	Average			NA	NA	NA
4	5.5	IMW-2[e]	1	2.8	0.25	91.1%
		and	2	3.5	1.5	57.1%
		DMW-1	3	3.0	1.0	66.7%
			4	2.9	3.0	0.0%
	Average			3.1	1.4	53.7%
5[f]	11.2	IMW-1, IMW-2,	1	2.3	1.1	52.2%
		and DMW-1	2	1.7	0.61	64.1%
	Average			2.0	0.86	58.2%
Total Average Percent Removal						56.0%[g]

Notes:
a mg/L = milligram per liter
b IMW-1 = Intermediate monitoring well No. 1
c NA = Contaminant was not detected in both influent and effluent and thus cannot be used
d DMW-1 = Deep monitoring well No. 1
e IMW-2 = Intermediate monitoring well No. 2
f Sampling run was abbreviated due to system failure
g Total average computed from the averages of the five runs

Table A17. Total Recoverable Petroleum Hydrocarbons Concentration Summary

Run	Flow Rate (gallons per minute)	Well	Event Number	Untreated Concentration (mg/L)[a]	Treated Concentration (mg/L)	Percent Removal
1	2.1	IMW-1[b]	1	2.18	[0.3][c]	86.2%
			2	2.76	[0.3]	89.1%
			3	2.82	0.75	73.3%
			4	2.58	1.14	55.8%
	Average			2.59	0.62	76.1%
2	5.2	IMW-1	1	2.78	[0.3]	89.2%
			2	3.54	0.71	79.9%
			3	3.28	0.65	80.3%
			4	3.11	0.58	81.4%
	Average			3.18	0.56	60.4%
3	9.0	IMW-1	1	2.0	[0.3]	85.0%
		and	2	1.35	[0.3]	77.8%
		DMW-1[d]	3	1.7	[0.3]	82.4%
			4	1.29	[0.3]	76.7%
	Average			1.59	[0.3]	80.5%
4	5.5	IMW-2[e]	1	1.36	0.59	56.5%
		and	2	1.41	0.59	58.0%
		DMW-1	3	1.33	[0.3]	77.4%
			4	1.7	[0.3]	82.4%
	Average			1.45	0.45	68.6%
5[f]	11.2	IMW-1, IMW-2,	1	1.36	0.568	58.2%
		and DMW-1	2	1.43	0.64	55.2%
	Average			1.4	0.60	56.7%
Total Average Percent Removal						68.5%[g]

Notes:
a mg/L = milligram per liter
b IMW-1 = Intermediate monitoring well No. 1
c [ ] = Indicates compound was analyzed for but not detected above the sample quantitation limit. The untreated concentration is the sample quantitation limit and the treated concentration is half of the sample quantitation limit.
d DMW-1 = Deep monitoring well No. 1
e IMW-2 = Intermediate monitoring well No. 2
f Sampling run was abbreviated due to system failure
g Total average computed from the averages of the five runs

Table A18. Metals Concentration Summary

Run	Flow Rate (gallons per minute)	Well	Event	Metal	Untreated Concentration (mg/L)[a]	Treated Concentration (mg/L)
1	2.1	IMW-1[b]	1	Barium	0.228	0.170
				Calcium	174	160
				Iron	8.73	5.58
				Magnesium	381	337
				Strontium	1.64	1.61
3	5.2	IMW-1 and DMW-1[c]	1	Barium	0.121	0.129
				Calcium	240	239
				Iron	3.04	3.10
				Magnesium	573	567
				Strontium	2.81	2.79
5[d]	11.2	IMW-1, IMW-2[e], and DMW-1	2	Barium	0.0954	0.101
				Calcium	190	187
				Iron	4.1	3.97
				Magnesium	450	443
				Strontium	2.14	2.13

Notes:
a mg/L = milligram per liter
b IMW-1 = Intermediate monitoring well No. 1
c DMW-1 = Deep monitoring well No. 1
d Sampling run was abbreviated due to system failure.
e IMW-2 = Intermediate monitoring well No. 2

Table A19. General Chemistry Concentration Summary

Run	Flow Rate (gallons per minute)	Well	Event	General Chemistry	Untreated Concentration (mg/L)[a]	Treated Concentration (mg/L)
1	2.1	IMW-1[b]	1	Carbonate alkalinity	ND[c]	60.6
				Total alkalinity	1,740	1,740
				Fluoride	0.402	0.366
				Silica	42.4	42.5
				Sulfate	399	466
				Total suspended solids	12.4	ND
3	9.0	IMW-1 and DMW-1[d]	1	Carbonate alkalinity	ND	ND
				Total alkalinity	1,180	1,190
				Fluoride	0.392	0.345
				Silica	573	567
				Sulfate	2.81	2.79
				Total suspended solids	ND	ND
5[e]	11.2	IMW-1, IMW-2[f], and DMW-1	2	Carbonate alkalinity	ND	ND
				Total alkalinity	1,410	1,390
				Fluoride	1.43	1.39
				Silica	26.5	27.5
				Sulfate	863	860
				Total suspended solids	3.67	ND

Notes:
a mg/L = milligram per liter
b IMW-1 = Intermediate monitoring well No. 1
c ND = Not detected
d DMW-1 = Deep monitoring well No. 1
e Sampling run was abbreviated due to system failure
f IMW-2 = Intermediate monitoring well No. 2

Table A20. Trichloroethene Concentrations in Air

Run	Flow Rate (gpm)[a]	Average Groundwater TCE Concentration (mg/L)[b]	Grab Number	Concentration of TCE in Vented Vapor (mg/m^3)[c]	Concentration of TCE in Vented Vapor (ppm)[d]
1	2.1	40	1	32,000	6,100
			2	29,000	5,500
2	5.2	42	1	19,000	3,700
			2	14,000	2,500
3	9.0	36	1	39,000	7,300
			2	38,000	7,200
4	5.5	230	1	94,000	18,000
			2	110,000	20,000
5[e]	11.2	125	1	110,000	21,000
Average:		95		53,889	10,100

Notes:
a gpm = gallons per minute
b mg/L = milligram per liter
c mg/m^3 = milligram per cubic meter
d ppm = parts per million
e Sampling run was abbreviated due to system failure

Table A21. Vinyl Chloride Concentrations in Air

Run	Flow Rate (gpm)[a]	Average Groundwater Vinyl Chloride Concentration (mg/L)[b]	Grab Number	Concentration of Vinyl Chloride in Vented Vapor (mg/m^3)[c]	Concentration of Vinyl Chloride in Vented Vapor (ppm)[d]
1	2.1	37.6	1	16,000	6,200
			2	15,000	5,900
2	5.2	11.5	1	13,000	5,000
			2	5,100	2,000
3	9.0	9.2	1	19,000	7,300
			2	8,700	3,400
4	5.5	8.1	1	[1,000][e]	[395]
			2	[1,000]	[395]
5[f]	11.2	5.7	1	14,000	5,500
Average:		14.4		10,311	4,010

Notes:
a gpm = gallons per minute
b mg/L = milligram per liter
c mg/m^3 = milligram per cubic meter
d ppm = parts per million
e [ ] = Indicates compound was analyzed for but not detected above the sample quantitation limit. The concentration shown is half the sample quantitation limit.
f Sampling run was abbreviated due to system failure

Table A22. Acetone Concentrations in Air

Run	Flow Rate (gpm)[a]	Average Groundwater Acetone Concentration (mg/L)[b]	Grab Number	Concentration of Acetone in Vented Vapor (mg/m^3)[c]	Concentration of Acetone in Vented Vapor (ppm)[d]
1	2.1	35.6	1	4,800	2,000
			2	4,000	1,700
2	5.2	40.5	1	1,900 TR[e]	820
			2	1,800	760
3	9.0	26.8	1	2,100 TR	900 TR
			2	[1,000][f]	[420]
4	5.5	19.7	1	[2,000]	[850]
			2	[2,000]	[850]
5[g]	11.2	29	1	[2,000]	[850]
Average:		30.3		2,400	1,017

Notes:
a gpm = gallons per minute
b mg/L = milligram per liter
c mg/m^3 = milligram per cubic meter
d ppm = parts per million
e TR = Detected below the indicated reporting limit
f [ ] = Indicates compound was analyzed for but not detected above the sample quantitation limit. The concentration shown is half the sample quantitation limit.
g Sampling run was abbreviated due to system failure

Table A23. 4-Methyl-2-Pentanone Concentrations in Air

Run	Flow Rate (gpm)[a]	Average Groundwater 4-Methyl-2-pentanone Concentration (mg/L)[b]	Grab Number	Concentration of 4-Methyl-2-pentanone in Vented Vapor (mg/m^3)[c]	Concentration of 4-Methyl-2-pentanone in Vented Vapor (ppm)[d]
1	2.1	61	1	12,000	3,000
			2	11,000	2,800
2	5.2	48	1	7,600	1,800
			2	4,400	1,100
3	9.0	41.3	1	3,800	920
			2	6,400	1,600
4	5.5	30.8	1	2,700	670 TR[e]
			2	[2,000][f]	[490]
5[g]	11.2	32	1	[2,000]	[490]
Average:		42.6		5,767	1,430

Notes:
a gpm = gallons per minute
b mg/L = milligram per liter
c mg/m^3 = milligram per cubic meter
d ppm = parts per million
e TR = Detected below the indicated reporting limit
f [ ] = Indicates compound was analyzed for but not detected above the sample quantitation limit. The concentration shown is half the sample quantitation limit.
g Sampling run was abbreviated due to system failure

Table A24. 2-Butanone Concentrations in Air

Run	Flow Rate (gpm)[a]	Average Groundwater 2-Butanone Concentration (mg/L)[b]	Grab Number	Concentration of 2-Butanone in Vented Vapor (mg/m^3)[c]	Concentration of 2-Butanone in Vented Vapor (ppm)[d]
1	2.1	90.8	1	17,000	5,900
			2	14,000	4,700
2	5.2	93.8	1	8,400	2,900
			2	4,600	1,600
3	9.0	84.0	1	5,000	1,700
			2	5,700	1,900
4	5.5	107.5	1	4,100	1,400
			2	3,900 TR[e]	1,300 TR
5[f]	11.2	80.5	1	[2,000][g]	[700]
Average:		91.3		7,189	2,456

Notes:
a gpm = gallons per minute
b mg/L = milligram per liter
c mg/m^3 = milligram per cubic meter
d ppm = parts per million
e TR = Detected below the indicated reporting limit
f Sampling run was abbreviated due to system failure
g [ ] = Indicates compound was analyzed for but not detected above the sample quantitation limit. The concentration shown is half the sample quantitation limit.

Table A25. Methylene Chloride Concentrations in Air

Run	Flow Rate (gpm)[a]	Average Groundwater Methylene Chloride Concentration (mg/L)[b]	Grab Number	Concentration of Methylene Chloride in Vented Vapor (mg/m^3)[c]	Concentration of Methylene Chloride in Vented Vapor (ppm)[d]
1	2.1	2.8	1	830 TR[e]	240 TR
			2	[500][f]	[145]
2	5.2	2.5	1	[500]	[145]
			2	450	130
3	9.0	2.5	1	770 TR	230 TR
			2	[500]	[145]
4	5.5	10.75	1	32,000	9,300
			2	43,000	13,000
5[g]	11.2	4.5J	1	23,000	6,800
Average:		4.6J		11,283	2,321

Notes:
a gpm = gallons per minute
b mg/L = milligram per liter
c mg/m^3 = milligram per cubic meter
d ppm = parts per million
e TR = Detected below the indicated reporting limit
f [ ] = Indicates compound was analyzed for but not detected above the sample quantitation limit. The concentration shown half the sample quantitation limit.
g Sampling run was abbreviated due to system failure

Table A26. 1,1-Dichloroethene Concentrations in Air

Run	Flow Rate (gpm)[a]	Average Groundwater 1,1-Dichloroethene Concentration (mg/L)[b]	Grab Number	Concentration of 1,1-Dichloroethene in Vented Vapor (mg/m^3)[c]	Concentration of 1,1-Dichloroethene in Vented Vapor (ppm)[d]
1	2.1	2.8	1	[500][e]	[125]
			2	[500]	[125]
2	5.2	2.5	1	[500]	[125]
			2	[200]	[50]
3	9:0	2.5	1	900 TR[f]	230 TR
			2	[500]	[125]
4	5.5	35.8UJ[g]	1	14,000	3,600
			2	20,000	5,000
5[h]	11.2	12UJ	1	13,000	3,400
Average:		11.1UJ		5,588	1,420

Notes:
a gpm = gallons per minute
b mg/L = milligram per liter
c mg/m^3 = milligram per cubic meter
d ppm = parts per million
e [ ] = Indicates compound was analyzed for but not detected above the sample quantitation limit. The concentration shown is half the sample quantitation limit.
f TR = Detected below the indicated reporting limit
g UJ = Estimated value that was 10 times less than the contract required quantitation limit
h Sampling run was abbreviated due to system failure

Table A27. cis-1,2-Dichloroethene Concentrations in Air

Run	Flow Rate (gpm)[a]	Average Groundwater cis-1,2-Dichloroethene Concentration (mg/L)[b]	Grab Number	Concentration of cis-1,2-Dichloroethene in Vented Vapor (mg/m^3)[c]	Concentration of cis-1,2-Dichloroethene in Vented Vapor (ppm)[d]
1	2.1	70.8	1	63,000	16,000
			2	57,000	15,000
2	5.2	62.8	1	44,000	11,000
			2	20,000	5,200
3	9.0	45.8	1	66,000	17,000
			2	48,000	12,000
4	5.5	20.1	1	14,000	3,600
			2	8,000	2,000
5[e]	11.2	31.5	1	49,000	12,000
Average:		46.2		41,000	10,422

Notes:
a gpm = gallons per minute
b mg/L = milligram per liter
c mg/m^3 = milligram per cubic meter
d ppm = parts per million
e Sampling run was abbreviated due to system failure

Table A28. Carbon Disulfide Concentrations in Air

Run	Flow Rate (gpm)[a]	Average Groundwater Carbon disulfide Concentration (mg/L)[b]	Grab Number	Concentration of Carbon disulfide in Vented Vapor (mg/m^3)[c]	Concentration of Carbon disulfide in Vented Vapor (ppm)[d]
1	2.1	5.5	1	[500][e]	[160]
			2	[500]	[160]
2	5.2	5.0	1	[500]	[160]
			2	1,000	320
3	9.0	5.0	1	1,500	500
			2	[500]	[160]
4	5.5	16.3	1	[1,000]	[320]
			2	[1,000]	[320]
5[f]	11.2	10.0	1	[1,000]	[320]
Average:		8.4		833	269

Notes:
a gpm = gallons per minute
b mg/L = milligram per liter
c mg/m^3 = milligram per cubic meter
d ppm = parts per million
e [ ] = Indicates compound was analyzed for but not detected above the sample quantitation limit. The concentration shown is half the sample quantitation limit.
f Sampling run was abbreviated due to system failure

Table A29. Trichlorotrifluoroethane Concentrations in Air

Run	Flow Rate (gpm)[a]	Average Groundwater Trichlorotri-fluoroethane Concentration (mg/L)[b]	Grab Number	Concentration of Trichlorotri-fluoroethane in Vented Vapor (mg/m^3)[c]	Concentration of Trichlorotri-fluoroethane in Vented Vapor (ppm)[d]
1	2.1	2.8	1	3,900	510
			2	[500]	[65]
2	5.2	2.5	1	[500]	[65]
			2	[200]	[21]
3	9.0	2.5	1	[650]	[90]
			2	[500]	[65]
4	5.5	8.1	1	[1,000]	[130]
			2	2,600	340
5[f]	11.2	5.0	1	1,900TR[g]	250TR
Average:		4.2		1,305	171

Notes:
a gpm = gallons per minute
b mg/L = milligram per liter
c mg/m^3 = milligram per cubic meter
d ppm = parts per million
e [ ] = Indicates compound was analyzed for but not detected above the sample quantitation limit. The concentration shown is half the sample quantitation limit.
f Sampling run was abbreviated due to system failure
g TR = Compound was detected below the reporting limit

Table A30. Aquifer Temperature, pH, Conductivity Summary

Run	Time	Temperature (° C)[a]		pH		Conductivity (mmhos/cm)[b]	
		Untreated	Treated	Untreated	Treated	Treated	Untreated
1	0850	23	34	NA[c]	NA	NA	NA
	1031	NA	NA	6.5	6.5	NA	NA
	1115	23.0	36.0	NA	NA	NA	NA
2	0925	21.7	22.8	6.65	7.46	22.0	22.4
	1200	21.7	22.5	6.70	7.50	22.2	22.4
	1700	21.7	22.6	7.00	7.60	22.3	22.7
3	0900	21.6	23.9	6.78	7.45	31.8	31.7
	1350	21.8	24.6	6.86	7.47	29.5	31.2
	1625	21.9	25.7	6.84	7.45	31.5	31.3
4	1015	21.1	22.7	7.63	7.77	21.4	23.4
	1158	22.9	22.4	7.71	6.66	23.0	23.3
	1435	23.0	25.0	7.70	8.03	23.0	22.7
	1635	21.9	24.0	7.67	8.02	23.2	22.6
5[d]	0950	22.3	24.9	7.09	7.54	26.2	25.8
Average		22.1	25.5	7.09	7.5	25.1	25.4

Notes:
a °C = degrees celsius
b mmhos/cm = millimhos per centimeter
c NA = Not analyzed due to a faulty meter
d Sampling run was abbreviated due to system failure

Table A31. ZENON System Operating Parameters

Time	Flow Rate (gpm)[a]	Total Water (gal)[b]	Feed Temperature		Feed Pressure		Vacuum (mbar)[c]	Chilled Water		Total Air (ft^3)[f]	Vacuum Disc Pressure (" hg)[g]	Compressor Pressure (kPa)
			In (°C)[c]	Out (°C)	In (kPa)[d]	Out (kPa)		TI-400 (°C)	TI-401 (°C)			
					Run 1							
0815	1.93[h]	43.9	66	67	60	41	25	4	4	93.1	23	90
0845		103.1	68	68	60	41	25	4	5	101.3	23	75
1000		256.4	70	70	61	41	32	4	4	113.7	23	85
1030		312.7	70	70	61	41	33	4	5	118.4	23	85
1100		372.8	70	70	60	41	25	4	5	124.2	23	85
1205		488.3	71	70	60	41	30	4	5	133.0	23	85
1300		601.4	70	70	60	41	30	4	4	143.2	23	85
1400		711.2	71	70	61	41	33	4	4	152.7	23	85
1500		829.1	70	69	61	41	29	4	5	162.2	23	85
1545		912.1	70	70	61	41	30	4	5	168.7	23	85
					Run 2							
0850	5.0	57.4	60	62	35	16	35	4	4	178.7	24	85
0900		95.3	60	60	35	16	34	4	4	180.9	24	85
1000		408.8	60	59	35	18	30	4	4	191.2	24	85
1100		NR[i]	60	58	35	18	22	4	5	NR	24	85
1130		859.9	60	58	35	19	22	4	4	211.5	23	80
1200		1010.1	60	59	35	20	20	4	5	217.2	22	85
1300		1304.8	60	59	35	20	20	4	4	248.7	21	140
1400		1596.6	61	60	35	20	23	4	5	294.0	21	135
1500		1928.1	60	58	36	20	23	4	4	349.4	21	135
1600		2199.7	59	59	36	20	25	4	4	396.2	20	135
1630		2358.6	60	60	36	20	28	4	5	423.8	21	135

Table A31. ZENON System Operating Parameters (continued)

Time	Flow Rate (gpm)[a]	Total Water (gal)[b]	Feed Temperature		Feed Pressure		Vacuum (mbar)[e]	Chilled Water		Total Air (ft^3)[f]	Vacuum Disc Pressure (" hg)[g]	Compressor Pressure (kPa)
			In (°C)[c]	Out (°C)	In (kPa)[d]	Out (kPa)		TI-400 (°C)	TI-401 (°C)			
Run 3												
0830	8.3	491.8	59	58	50	32	35	4	4	474.8	22	100
0900		738.3	59	59	50	32	27	4	5	482.3	22	100
1000		NR	60	59	51	32	27	4	4	NR	22	100
1100		1730.9	60	59	51	33	22	4	4	519.8	22	100
1200		2263.4	60	60	51	35	20	4	5	540.5	21	100
1300		2778.4	60	60	54	36	20	4	4	562.2	22	100
1330		3034.8	60	59	54	36	20	4	5	573.1	22	100
1400		3297.8	60	60	55	36	20	4	4	586.9	22	100
1500		3774.5	60	60	56	36	23	4	4	613.8	22	100
1600		4317.2	60	59	56	36	30	4	4	656.3	17	120
1630		4515.5	70	69	56	36	30	4	4	677.9	17	140
Run 4												
0900	5.2	14.6	56	44	35	18	25	4	4	695.2	22	50
0930		155.4	60	60	35	19	26	4	4	705.7	22	85
1000		298.1	60	59	35	19	28	4	5	717.8	21	100
1100		624,8	60	59	35	19	34	4	4	735.8	21	100
1200		941.8	60	59	36	20	42	4	5	753.8	21	100
1300		1274.1	60	60	36	21	42	4	4	744.9	22	100
1400		1587.7	61	60	37	21	35	4	5	791.8	22	100
1430		1740.0	61	60	38	21	38	4	5	800.3	22	100
1500		1887.9	61	60	40	22	40	4	4	808.6	22	100
1600		2199.8	62	60	41	22	32	4	5	825.3	22	100
1645		2452.2	60	59	41	22	37	4	5	838.8	22	100

Table A31. ZENON System Operating Parameters (continued)

Time	Flow Rate (gpm)[a]	Total Water (gal)[b]	Feed Temperature		Feed Pressure		Vacuum (mbar)[e]	Chilled Water		Total Air (ft^3)[f]	Vacuum Disc Pressure (" hg)[g]	Compressor Pressure (kPa)
			In (°C)[c]	Out (°C)	In (kPa)[d]	Out (kPa)		TI-400 (°C)	TI-401 (°C)			
					RUN 5							
0815	10.7	119.6	50	45	75	50	64	4	4	857.7	21	50
0835		305.6	60	60	75	50	55	4	4	862.5	21	85
0900		611.1	60	59	75	50	56	4	5	867.2	22	90
1000		1247.9	60	60	75	51	45	4	4	872.6	22	90
1100		1885.9	60	59	76	51	30	4	5	884.6	22	100

Notes:
a gpm = gallons per minute
b gal = U.S. gallons
c °C = degrees celsius
d kPA = kilopascal
e mbar = millibar
f ft^3 = cubic feet
g "hg = inches of mercury
h Flow rates shown in this table were calculated from volume of water amassed during each run. The flow rates shown on all other tables in Appendix A were taken from a flow meter on the effluent line from the system.
i NR = not recorded

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