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perox-pure™ Chemical Oxidation Technology

Peroxidation Systems, Inc.

Applications Analysis Report

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

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Notice

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Foreword

The Superfund Innovative Technology Evaluation (SITE) program was authorized in the 1986 Superfund Amendments and Reauthorization Act. The program is a joint effort between the U.S. Environmental Protection Agency's (EPA) Office of Research and Development and Office of Solid Waste and Emergency Response. The purpose of the program is to assist the development of innovative hazardous waste treatment technologies, especially those that offer permanent remedies for contamination commonly found at Superfund and other hazardous waste sites. The SITE program evaluates new treatment methods through technology demonstrations designed to provide engineering and cost data for selected technologies.

A field demonstration was conducted under the SITE program to evaluate the perox-pure™ chemical oxidation technology's ability to treat groundwater contaminated with volatile organic compounds. The technology demonstration took place at the Lawrence Livermore National Laboratory site in Tracy, California. The demonstration effort was directed to obtain information on the performance and cost of the technology and to assess its use at this and other uncontrolled hazardous waste sites. Documentation consists of two reports: (1) a Technology Evaluation Report, which describes field activities and laboratory results, and (2) this Applications Analysis Report, which interprets the data and discusses the potential applicability of the technology.

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E. Timothy Oppelt, Director

Risk Reduction Engineering Laboratory

Abstract

This report evaluates the perox-pure™ chemical oxidation technology's ability to remove volatile organic compounds (VOC) and other organic contaminants present in liquid wastes. This report also presents economic data from the Superfund Innovative Technology Evaluation (SITE) demonstration and three case studies.

The perox-pure™ chemical oxidation technology was developed by Peroxidation Systems, Inc. (PSI), to destroy dissolved organic contaminants in water. The technology uses ultraviolet (UV) radiation and hydrogen peroxide to oxidize organic compounds present in water at parts per million levels or less. This treatment technology produces no air emissions and generates no sludge or spent media that require further processing, handling, or disposal. Ideally, the end products are water, carbon dioxide, halides (for example, chloride), and in some cases, organic acids. The technology uses medium-pressure, mercury-vapor lamps to generate UV radiation. The principal oxidants in the system, hydroxyl radicals, are produced by direct photolysis of hydrogen peroxide at UV wavelengths.

The perox-pure™ chemical oxidation technology was demonstrated under the SITE program at Lawrence Livermore National Laboratory Site 300 in Tracy, California. Over a 3-week period in September 1992, about 40,000 gallons of VOC-contaminated groundwater was treated in the perox-pure™ system. For the SITE demonstration, the perox-pure™ system achieved trichloroethene (TCE) and tetrachloroethene (PCE) average removal efficiencies of about 99.7 and 97.1 percent, respectively. In general, the perox-pure™ system produced an effluent that contained (1) TCE, PCE, and 1,1-dichloroethane (DCA) below detection limits and (2) chloroform and 1,1,1-trichloroethane (TCA) slightly above detection limits. The system also achieved chloroform, DCA, and TCA average removal efficiencies of 93.1, 98.3, and 81.8 percent, respectively. The treatment system effluent met California drinking water action levels and federal drinking water maximum contaminant levels for TCE, PCE, chloroform, DCA, and TCA at the 95 percent confidence level.

The results from three case studies are also summarized in this report. All three case studies represent full-scale, currently operating commercial installations of perox-pure™ chemical oxidation systems. The contaminants of concern in these case studies include acetone, isopropyl alcohol (IPA), TCE, and pentachlorophenol (PCP). In the first case study, the perox-pure™ system treated industrial wastewater containing 20 milligrams per liter (mg/L) of acetone and IPA; the effluent met the discharge limit of 0.5 mg/L for each compound. In the second case study, the perox-pure™ system treated groundwater that was used as a municipal drinking water source. The groundwater initially contained 150 micrograms per liter (μg/L) of TCE. After treatment, the effluent TCE level was 0.5 μg/L, well below the TCE drinking water standard of 5 μg/L. In the third case study, the perox-pure™ system treated groundwater at a chemical manufacturing facility. The groundwater contained 15 mg/L of PCP; after treatment the effluent achieved the target effluent PCP level of 0.1 mg/L.

Potential sites for applying this technology include Superfund and other hazardous waste sites where groundwater or other liquid wastes are contaminated with organic compounds. Economic data indicate that groundwater remediation costs for a 50-gallon per minute perox-pure™ system could range from about $7 to $11 per 1,000 gallons, depending on contaminated groundwater characteristics. Of these, perox-pure™ system direct treatment costs could range from about $3 to $5 per 1,000 gallons.

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Acronyms, Abbreviations, and Symbols

AAR	Applications Analysis Report
ACL	Alternate concentration limit
AEA	Atomic Energy Act
AOX	Adsorbable organic halide
ARAR	Applicable or relevant and appropriate requirement
BTEX	Benzene, toluene, ethylbenzene, and xylene
BTX	Benzene, toluene, and xylene
CCl_4	Carbon tetrachloride
CDEP	Department of Environmental Protection, State of Connecticut
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CWA	Clean Water Act
DCA	1,1-dichloroethane
1,1-DCE	1,1-dichloroethene
1,2-DCE	1,2-dichloroethene
DIMP	Diisopropyl methylphosphonate
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FIFRA	Federal Insecticide, Fungicide, and Rodenticide Act
FS	Feasibility study
°F	Degree Fahrenheit
GC	Gas chromatography
gpd	Gallons per day
gpm	Gallons per minute
GSA	General Services Area
H_2O_2	Hydrogen peroxide
$h\nu$	Ultraviolet radiation
IPA	Isopropyl alcohol
kW	Kilowatt
kWh	Kilowatt-hour
LLNL	Lawrence Livermore National Laboratory
MCL	Maximum contaminant level
MeCl	Methylene chloride
MEK	Methyl ethyl ketone
μg/L	Micrograms per liter
mg/L	Milligrams per liter
MS	Mass spectrometry
NPDES	National Pollutant Discharge Elimination System
OH•	Hydroxyl radical
O&M	Operation and maintenance
ORD	Office of Research and Development
OSHA	Occupational Safety and Health Act
OSWER	Office of Solid Waste and Emergency Response
PAH	Polynuclear aromatic hydrocarbon
PCB	Polychlorinated biphenyl

Acronyms, Abbreviations, and Symbols (continued)

PCE	Tetrachloroethene
PCP	Pentachlorophenol
POC	Purgeable organic carbon
POTW	Publicly-owned treatment works
PPE	Personal protective equipment
ppm	Parts per million
PSI	Peroxidation Systems, Inc.
QA/QC	Quality assurance/quality control
RI	Remedial investigation
RCRA	Resource Conservation and Recovery Act
SARA	Superfund Amendments and Reauthorization Act
SDWA	Safe Drinking Water Act
SITE	Superfund Innovative Technology Evaluation
SVOC	Semivolatile organic compound
TC	Total carbon
TCA	1,1,1-trichloroethane
TCE	Trichloroethene
TER	Technology Evaluation Report
TIC	Tentatively identified compound
TOC	Total organic carbon
TOX	Total organic halide
TSCA	Toxic Substances Control Act
UCL	Upper confidence limit
UV	Ultraviolet
VOC	Volatile organic compound

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

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Section 1
Executive Summary

1.1 Introduction

The perox-pure™ chemical oxidation technology, developed by Peroxidation Systems, Inc. (PSI), was evaluated under the U.S. Environmental Protection Agency Superfund Innovative Technology Evaluation (SITE) program. The perox-pure™ technology demonstration was conducted at Lawrence Livermore National Laboratory (LLNL) Site 300 in Tracy, California, over a 3-week period in September 1992.

The perox-pure™ chemical oxidation technology is designed to destroy dissolved organic contaminants in water. The technology uses ultraviolet (UV) radiation and hydrogen peroxide to oxidize organic compounds present in water at parts per million levels or less. This treatment technology produces no air emissions and generates no sludge or spent media that require further processing, handling, or disposal. Ideally, end products are water, carbon dioxide, halides (for example, chloride), and in some cases, organic acids. The technology uses medium-pressure, mercury-vapor lamps to generate UV radiation. The principal oxidants in the system, hydroxyl radicals, are produced by direct photolysis of hydrogen peroxide at UV wavelengths.

The perox-pure™ chemical oxidation treatment system (Model SSB-30) used for the SITE technology demonstration was assembled from the following portable, skid-mounted components: a chemical oxidation unit, a hydrogen peroxide feed module, an acid feed module, a base feed module, a UV lamp drive, and a control panel. The oxidation unit has six reactors in series with one 5-kilowatt UV lamp in each reactor; the unit has a total volume of 15 gallons. The UV lamp is mounted inside a UV-transmissive quartz tube in the center of each reactor so that water flows through the space between the reactor walls and the quartz tube. Circular wipers are mounted on the quartz tubes to periodically remove any solids that have accumulated on the tubes.

The perox-pure™ system requires little attention during operation and can be operated and monitored remotely, if needed. Remotely monitored systems can be connected to devices that automatically dial a telephone to notify responsible parties at remote locations of alarm conditions. Remotely operated and monitored systems are hard-wired into centrally located control panels or computers through programmable logic controllers.

The technology demonstration had the following primary objectives: (1) determine the ability of the perox-pure™ system to remove volatile organic compounds (VOC) from groundwater at the LLNL site under different operating conditions, (2) determine whether treated groundwater met applicable disposal requirements at the 95 percent confidence level, and (3) gather information necessary to estimate treatment costs, including process chemical dosages and utility requirements. The secondary objective for the technology demonstration was to obtain information on the presence and types of by-products formed during treatment.

The purpose of this report is to present information from the SITE demonstration and several case studies that will be useful for implementing the perox-pure™ chemical oxidation technology at Superfund and Resource Conservation and Recovery Act hazardous waste sites. Section 2 presents an overview of the SITE program, describes the perox-pure™ technology, and lists key contacts. Section 3 discusses information relevant to the technology's application, including pretreatment and posttreatment requirements, site characteristics, operating and maintenance requirements, potential community exposures, and potentially applicable environmental regulations. Section 4 summarizes the costs associated with implementing the technology. Section 5 includes a list of references. Appendices A through C include the vendor claims for the technology, a summary of the SITE demonstration results, and summaries of three case studies, respectively.

1.2 Overview of the SITE Demonstration

Shallow groundwater at the LLNL site was selected as the waste stream for evaluating the perox-pure™ chemical oxidation technology. About 40,000 gallons of groundwater contaminated with VOCs was treated during the demonstration. The principal groundwater contaminants were trichloroethene (TCE) and tetrachloroethene (PCE),

which were present at concentrations of about 1,000 and 100 micrograms per liter (μg/L), respectively. Groundwater was pumped from two wells into a 7,500-gallon bladder tank to minimize variability in influent characteristics. In addition, cartridge filters were used to remove suspended solids greater than 3 micrometers in size from the groundwater before it entered the tank. Treated groundwater was stored in two 20,000-gallon steel tanks before being discharged.

The technology demonstration was conducted in three phases. Phase 1 consisted of eight runs using raw groundwater, Phase 2 consisted of four runs using spiked groundwater, and Phase 3 consisted of two runs using spiked groundwater to evaluate the effectiveness of quartz tube cleaning. These phases are described below.

The principal operating parameters for the perox-pure™ system, hydrogen peroxide dose, influent pH, and flow rate (which determines the hydraulic retention time), were varied during Phase 1 to observe treatment system performance under different operating conditions. Preferred operating conditions, those under which the concentrations of spiked groundwater effluent VOCs would be reduced to below target levels, were then determined for the system.

Phase 2 involved spiked groundwater and reproducibility tests. Groundwater was spiked with about 200 to 300 μg/L each of chloroform; 1,1-dichloroethane (DCA); and 1,1,1-trichloroethane (TCA). These compounds were chosen because they are difficult to oxidize and because they were not present in the groundwater at high concentrations. This phase was also designed to evaluate the reproducibility of treatment system performance at the preferred operating conditions determined in Phase 1.

During Phase 3, the effectiveness of quartz tube wipers was evaluated by performing two runs using spiked groundwater and scaled and clean quartz tubes.

During the demonstration, samples were collected at several locations, including the treatment system influent; effluent from Reactors 1, 2, and 3; and the treatment system effluent. Samples were analyzed for VOCs, semivolatile organic compounds, total organic carbon (TOC), total carbon, purgeable organic carbon (POC), total organic halides (TOX), adsorbable organic halides (AOX), metals, pH, alkalinity, turbidity, temperature, specific conductance, hydrogen peroxide residual, and hardness, as applicable. In addition, samples of influent to Reactor 1 and treatment system effluent were collected and analyzed for acute toxicity to freshwater organisms. In the bioassay tests, *Ceriodaphnia dubia* (water fleas) and *Pimephales promelas* (fathead minnows) were used as the test organisms. Hydrogen peroxide, acid, and base solutions were also sampled and analyzed to verify concentrations.

1.3 Results from the SITE Demonstration

For the spiked groundwater, PSI determined the following preferred operating conditions: (1) influent hydrogen peroxide level of 40 milligrams per liter (mg/L); (2) hydrogen peroxide level of 25 mg/L in the influent to Reactors 2 through 6; (3) an influent pH of 5.0; and (4) a flow rate of 10 gallons per minute (gpm). At these conditions, the effluent TCE, PCE, and DCA levels were generally below detection limit (5 μg/L) and effluent chloroform and TCA levels ranged from 15 to 30 μg/L. The average removal efficiencies for TCE, PCE, chloroform, DCA, and TCA were about 99.7, 97.1, 93.1, 98.3, and 81.8 percent, respectively.

For the unspiked groundwater, the effluent TCE and PCE levels were generally below detection limit (1 μg/L) with corresponding removal efficiencies of about 99.9 and 99.7 percent. The effluent TCA levels ranged from 1.4 to 6.7 μg/L with removal efficiencies ranging from 35 to 84 percent.

The perox-pure™ system effluent met California drinking water action levels and federal drinking water maximum contaminant levels for TCE, PCE, chloroform, DCA, and TCA at the 95 percent confidence level.

The quartz tube wipers were effective in keeping the tubes clean, and appeared to reduce the adverse effect scaling has on contaminant removal efficiencies.

Bioassay tests showed that the perox-pure™ system effluent was acutely toxic to freshwater test organisms, although the influent was not toxic. Comparison of effluent toxicity data with that of hydrogen peroxide residual in the effluent (10.5 mg/L) indicated that effluent toxicity may be due to hydrogen peroxide residual rather than perox-pure™ treatment by-products. Additional studies are needed to draw any conclusion on the effluent toxicity.

TOX removal efficiencies ranged from 93 to 99 percent. AOX removal efficiencies ranged from 95 to 99 percent.

For spiked groundwater, during reproducibility runs, the system achieved average removal efficiencies of 38 percent and about 93 percent for TOC and POC, respectively.

The temperature of groundwater increased at a rate of 12 °F per minute of UV exposure in the perox-pure™ system. Since the oxidation unit is exposed to the surrounding environment, the temperature increase may vary depending upon the ambient temperature or other atmospheric conditions.

1.4 Results from Case Studies

Information on the perox-pure™ technology's performance at three facilities was evaluated to provide additional performance data. The three case studies represent full-scale, currently operating commercial installations of perox-pure™ systems. The contaminants of concern in these case studies include acetone, isopropyl alcohol (IPA), TCE, and pentachlorophenol (PCP). The case studies are briefly summarized below.

The first case study involves wastewater treatment at the Kennedy Space Center in Florida. At this facility, a liquid-phase carbon adsorption system had originally been installed to treat wastewater containing acetone and IPA at levels of 20 mg/L. The treatment facility discharge requirement for both acetone and IPA is 0.5 mg/L. Because the carbon adsorption system did not achieve the discharge requirement, the perox-pure™ chemical oxidation technology was selected to replace the carbon adsorption system. At this facility, the perox-pure™ system initially treated wastewater in batches of about 5,000 gallons. Later, the system was converted to a flow-through mode. Currently, the system treats wastewater at a flow rate of 5 gpm and produces an effluent that meets the discharge standard.

The second case study involves treating groundwater used as a municipal drinking water source in Arizona. In 1989, a municipal drinking water well in Arizona was found to contain 50 to 400 μg/L of TCE. The well, capable of producing 2,000 gpm, was taken out of service while several treatment options were evaluated. Because the well is located on a city lot in the middle of a large residential area, the city preferred using a low-visibility, quiet treatment method that could consistently destroy TCE to concentrations below the drinking water standard of 5 μg/L. Given these requirements, chemical oxidation using the perox-pure™ system was selected. Currently, the system treats groundwater at a flow rate of 135 gpm and produces treated groundwater containing only 0.5 μg/L of TCE.

The third case study deals with treatment of PCP-contaminated groundwater at a chemical manufacturing company in Washington. Groundwater at the site was found to contain about 15 mg/L of PCP. In 1988, PSI installed a perox-pure™ system at the site under a Full Service Agreement. Because the groundwater was also found to contain high levels of iron (200 mg/L) and carbonates that could scale the quartz tubes and impair the treatment efficiency, PSI recommended groundwater pretreatment. Pretreatment consists of iron oxidation and removal, followed by pH adjustment to about 5. Pretreated groundwater is then treated by a perox-pure™ system equipped with automatic quartz tube cleaners. Currently, the perox-pure™ system treats groundwater at a flow rate of 70 gpm and produces an effluent that meets the discharge standard of 0.1 mg/L.

1.5 Waste Applicability

Potential sites for applying the perox-pure™ technology include Superfund and other hazardous waste sites where groundwater or other liquid wastes are contaminated with organic compounds. The technology has been used to treat landfill leachate, groundwater, and industrial wastewater, all containing a variety of organic contaminants, including chlorinated solvents, pesticides, polynuclear aromatic hydrocarbons, and petroleum hydrocarbons. In some applications, where the contaminant concentration was higher than about 500 mg/L, the perox-pure™ system was combined with other treatment technologies for cost effectiveness.

1.6 Economics

Using information obtained from the SITE demonstration, an economic analysis was performed to examine 12 separate cost categories for perox-pure™ systems treating about 260 million gallons of contaminated groundwater at a Superfund site. This analysis examined two cases based on groundwater characteristics. In Case 1, the groundwater was assumed to have five contaminants, two of which are easy to oxidize (TCE and PCE) and the remaining three are difficult to oxidize (chloroform, DCA, and TCA). In Case 2, the groundwater was assumed to have only two contaminants that are easy to oxidize (TCE and PCE). For each case, costs for three different flow rates (10, 50, and 100 gpm) were estimated. Detailed economic analysis for the three flow rates of each case is included in Section 4. Costs for the 50-gpm flow rate scenario for each case are summarized below.

For Case 1, capital costs are estimated to be about $906,000 of which the perox-pure™ system direct capital cost is $185,000. Annual operation and maintenance (O&M) costs are estimated to be about $188,000 of which perox-pure™ system direct O&M costs are $125,000. Groundwater remediation costs to treat 1,000 gallons of contaminated water are estimated to be about $11 of which perox-pure™ system direct treatment costs are $5.

For Case 2, capital costs are estimated to be about $776,000 of which the perox-pure™ system direct capital cost is $55,000. Annual O&M costs are estimated to be about $111,000 of which perox-pure™ system direct O&M costs are $61,000. Groundwater remediation costs to treat 1,000 gallons of contaminated water are estimated to be about $7 of which perox-pure™ system direct treatment costs are $3.

The case studies included in Appendix C have minimal cost data. According to PSI, in the case studies, the total O&M costs ranged from $0.28 to $3.90 per 1,000 gallons of water treated.

Section 2
Introduction

This section provides information about the Superfund Innovative Technology Evaluation (SITE) program, discusses the purpose of this report, and describes the perox-pure™ chemical oxidation technology developed by Peroxidation Systems, Inc. (PSI), of Tucson, Arizona. The perox-pure™ technology is designed to treat waters contaminated with organic compounds. For additional information about the SITE program, the perox-pure™ technology, or the demonstration site, key contacts are listed at the end of this section.

2.1 Purpose, History, and Goals of the SITE Program

The Superfund Amendments and Reauthorization Act (SARA) of 1986 mandates that the U.S. Environmental Protection Agency (EPA) select, to the maximum extent practicable, remedial actions at Superfund sites that create permanent solutions (as opposed to land-based disposal) for contamination that affects human health and the environment. In doing so, EPA is directed to use alternative or resource recovery technologies. In response, EPA's Office of Research and Development (ORD) and Office of Solid Waste and Emergency Response (OSWER) established three programs: (1) a program to accelerate the use of new or innovative technologies to clean up Superfund sites through field demonstrations; (2) a program to foster the further research and development of treatment technologies that are at the laboratory or pilot scale; and (3) a program to demonstrate and evaluate new or innovative measurement and monitoring technologies. Together, these three components make up the SITE program.

The primary purpose of the SITE program is to enhance the development and demonstration, and thereby establish the commercial availability, of innovative technologies applicable to Superfund sites. The SITE program has established the following goals:

- Identify and remove impediments to the development and commercial use of alternative technologies
- Demonstrate promising innovative technologies to establish reliable performance and cost information for site characterization and remediation decisions
- Develop procedures and policies that encourage the selection of alternative treatment remedies at Superfund sites
- Develop a program that promotes and supports emerging technologies

EPA recognizes that a number of forces inhibit the expanded use of new and alternative technologies at Superfund sites. The SITE program's goals are designed to identify the most promising new technologies, develop pertinent and useful data of known quality about them, and make the data available to Superfund decision makers. An additional goal is to promote the development of emerging innovative technologies from the laboratory- or bench-scale to the full-scale stage.

Implementation of the SITE program is a significant ongoing effort involving ORD, OSWER, various EPA Regions, and private sector business concerns, including technology developers and parties responsible for site remediation. The technology selection process and the demonstration program together provide objective and carefully controlled testing of field-ready technologies. Through government publications, the SITE program disseminates testing results to Superfund decision makers for use in evaluating the applicability of technologies to site-specific remediation efforts.

The demonstration process collects the following information for Superfund decision makers to consider when matching technologies with wastes, media, and sites requiring remediation:

- The technology's effectiveness based on field demonstration sampling and analytical data collected during the demonstration

- The potential need for pretreatment and posttreatment of wastes
- The site-specific wastes and media to which the technology can be applied
- Potential site-specific system operating problems as well as possible solutions
- The approximate capital, operating, and maintenance costs
- The projected long-term operation and maintenance (O&M) costs

Innovative technologies chosen for a SITE demonstration must be pilot- or full-scale applications and must offer some advantage over existing technologies. Mobile technologies are of particular interest. Each year the SITE program sponsors demonstrations of approximately 10 technologies.

2.2 Documentation of the SITE Demonstration Results

The results of each SITE demonstration are reported in two documents: the Applications Analysis Report (AAR) and the Technology Evaluation Report (TER). The AAR is intended for decision makers responsible for implementing specific remedial actions and is primarily used to assist in screening the demonstrated technology as an option for a particular cleanup situation. The purpose of the AAR is discussed in the following section.

The TER is published separately from the AAR and provides a comprehensive description of the demonstration and its results. A likely audience for the TER includes engineers responsible for evaluating the technology for specific site and waste situations. These technical evaluators seek to understand, in detail, the performance of the technology during the demonstration, as well as advantages, disadvantages, and costs of the technology for the given application. This information is used to produce conceptual designs in sufficient detail to enable preliminary cost estimates for the demonstrated technology. If the candidate technology appears to meet the needs of site engineers, a more thorough analysis will be conducted based on the TER, the AAR, and other site-specific information obtained from remedial investigations.

2.3 Purpose of the Applications Analysis Report

Information presented in the AAR is intended to assist Superfund decision makers in screening specific technologies for a particular cleanup situation. The report discusses the advantages, disadvantages, and limitations of the technology. Costs of the technology for different applications are estimated based on available data for pilot- and full-scale applications. The report discusses factors that have a major impact on cost and performance, such as site and waste characteristics.

To encourage the general use of demonstrated technologies, EPA will evaluate the applicability of each technology for specific sites and wastes, other than those already tested, and will study the estimated costs of the applications. The results are presented in the AAR. This AAR synthesizes available information on PSI's perox-pure™ chemical oxidation technology and draws reasonable conclusions regarding its range of applicability. This AAR will be useful to decision makers considering using the perox-pure™ technology. It represents a critical step in the development and commercialization of the treatment technology.

Each SITE demonstration evaluates a technology's performance in treating an individual waste at a particular site. To obtain data with broad applicability, priority is given to technologies that treat wastes frequently found at Superfund sites. However, in many cases, wastes at other sites will differ in some way from the waste at the demonstration site. Therefore, the successful demonstration of a technology at one site does not ensure its success at other sites. Data obtained from the demonstration may require extrapolation to estimate total operating ranges over which the technology performs satisfactorily. Any extrapolation of demonstration data should also be based on other available information from case studies about the technology.

The amount of available data for the evaluation of an innovative technology varies widely. Data may be limited to laboratory tests on synthetic wastes or may include performance data on actual wastes treated by pilot- or full-scale treatment systems. In addition, only limited conclusions regarding Superfund applications can be drawn from a single field demonstration. A successful field demonstration does not necessarily ensure that a technology will be widely applicable or that it will be fully developed to commercial scale.

2.4 Technology Description

In April 1991, EPA learned that PSI was contracted by Lawrence Livermore National Laboratory (LLNL) to perform pilot-scale studies as part of remediation activities at the LLNL site. At that time, EPA and PSI discussed the possibility of PSI participating in the SITE program to demonstrate how the perox-pure™ chemical oxidation technology could be used to treat contaminated groundwater at Site 300 of LLNL in Tracy, California. EPA subsequently accepted the perox-pure™ technology into the SITE demonstration program. Through a cooperative effort between EPA ORD, EPA Region IX, LLNL, and PSI, the

perox-pure™ technology was demonstrated at the LLNL site under the SITE program.

2.4.1 Treatment Technology

The perox-pure™ chemical oxidation treatment system was developed by PSI to destroy dissolved organic contaminants in water. The technology uses ultraviolet (UV) radiation and hydrogen peroxide to oxidize organic compounds present in water at parts per million (ppm) levels or less. In broad terms, oxidation is a chemical change in which electrons are lost by an atom or a group of atoms. Oxidation of an atom or group of atoms is always accompanied by the reduction of another atom or group of atoms. Reduction is a chemical change in which electrons are gained by an atom or group of atoms. The atom or group of atoms that has lost electrons has been oxidized, and the atom or group of atoms that has gained electrons has been reduced. The reduced atom or group of atoms is called an oxidant. Oxidation and reduction always occur simultaneously, and the total number of electrons lost in the oxidation must equal the number of electrons gained in the reduction. In the perox-pure™ technology, organic contaminants in water are oxidized by hydroxyl radicals, a powerful oxidant produced by UV radiation and hydrogen peroxide. Subsequently, the organic contaminants are broken down into carbon dioxide, water, halides, and in some cases, organic acids.

A variety of organic contaminants can be effectively oxidized by the combined use of (1) UV radiation and hydrogen peroxide, (2) UV radiation and ozone, or (3) ozone and hydrogen peroxide. The principal oxidants in the perox-pure™ system, hydroxyl radicals, are produced by direct UV photolysis of the hydrogen peroxide added to contaminated water. The perox-pure™ system generates UV radiation by using medium-pressure, mercury-vapor lamps.

In principle, the most direct way to generate hydroxyl radicals (OH•) is to cleave hydrogen peroxide (H_2O_2) through photolysis. The photolysis of hydrogen peroxide occurs when UV radiation ($h\upsilon$) is applied, as shown in the following reaction:

$$H_2O_2 + h\upsilon \rightarrow 2\ OH\bullet$$

Thus, photolysis of hydrogen peroxide results in a quantum yield of two hydroxyl radicals (OH•) formed per quantum of radiation absorbed. This ratio of hydroxyl radicals generated from the photolysis of hydrogen peroxide is high. Unfortunately, at 253.7 nanometers, the dominant emission wavelength of low-pressure UV lamps, the absorptivity (or molar extinction coefficient) of hydrogen peroxide is only 19.6 liters per mole-centimeter. This absorptivity is relatively low for a primary absorber in a photochemical process. Because of the low absorptivity value for hydrogen peroxide, a high concentration of residual hydrogen peroxide must be present in the treatment medium to generate a sufficient concentration of hydroxyl radicals. According to PSI, the perox-pure™ system overcomes this limitation by using medium-pressure UV lamps.

The hydroxyl radicals formed by photolysis react rapidly with organic compounds, with rate constants on the order of 10^8 to 10^{10} liters per mole-second; they also have a relatively low selectivity in their reactions (Glaze and others, 1987). However, naturally occurring water components, such as carbonate ion, bicarbonate ion, and some oxidizable species, act as free radical scavengers that consume hydroxyl radicals. Free radical scavengers are compounds that consume any species possessing at least one unpaired electron. In addition to naturally occurring scavengers, excess hydrogen peroxide can itself act as a free radical scavenger, decreasing the hydroxyl radical concentration. Reactions with hydroxyl radicals are not the only removal pathway possible in the perox-pure™ system; direct photolysis by UV radiation of organic compounds also provides a removal pathway for contaminants. With these factors affecting the reaction, the proportion of oxidants required for optimum removal is difficult to predetermine. Instead, the proportion for optimum removal must be determined experimentally for each waste.

The principal operating parameters for the perox-pure™ technology are hydrogen peroxide dose, influent pH, and flow rate (which determines hydraulic retention time). Typically, during treatability studies, initial values of these parameters are selected based on (1) the technology developer's experience and (2) the anticipated effects of the operating parameters on the treatment system's performance. These operating parameters are discussed briefly below. Their effects on the system's performance are discussed in detail in Section 3.

Hydrogen peroxide dose is selected based on treatment unit configuration, contaminated water chemistry, and contaminant oxidation rates. Because hydrogen peroxide is a hydroxyl radical scavenger, excess hydrogen peroxide can result in a net decrease in treatment efficiency. However, if the hydrogen peroxide dose is low, hydroxyl radical formation will also be low, decreasing treatment efficiency. Therefore, a balance must be maintained between excess and low levels of hydrogen peroxide.

Influent pH level controls the carbonate chemistry, which can affect treatment efficiency. Because carbonate and bicarbonate ions will scavenge hydroxyl radicals, groundwater pH may need to be adjusted before treatment to shift the carbonate equilibrium to carbonic acid, which is not a scavenger.

Flow rate through the treatment system will determine hydraulic retention time. Increasing or decreasing the flow rate will affect treatment efficiency by changing the time

available for hydroxyl radical formation and contaminant destruction.

2.4.2 System Components and Function

The perox-pure™ chemical oxidation systems are typically assembled from the following portable, skid-mounted components: a chemical oxidation unit, a hydrogen peroxide feed module, a UV lamp drive, and a control panel unit. In addition to these main system components, other equipment is used to address site-specific conditions or requirements, including contaminated water characteristics and effluent discharge limits. For example, Figure 2-1 presents a schematic diagram of the main and ancillary components of the perox-pure™ chemical oxidation system used for the SITE demonstration (Model SSB-30).

For the SITE demonstration, a skid-mounted acid feed module and a base feed module were used to adjust pH of water before and after treatment, respectively. PSI provided the acid (sulfuric acid) and base (sodium hydroxide) solutions in drums. Two cartridge filters arranged in parallel, capable of screening suspended silt larger than 3 micrometers, were used to remove particles from the groundwater, which was primarily contaminated with volatile organic compounds (VOC) including trichloroethene (TCE) and tetrachloroethene (PCE). A spiking solution feed module was used to spike effluent from cartridge filters with chloroform; 1,1-dichloroethane (DCA); and 1,1,1-trichloroethane (TCA) for certain demonstration runs. A 7,500-gallon bladder tank was used (1) as an equalization tank and (2) as a holding tank to perform a few demonstration runs at flow rates greater than the groundwater well yield. The bladder tank was useful in minimizing the volatilization of contaminants. To ensure a relatively homogeneous process water, static mixers were used after chemicals were added at upstream locations in the treatment system.

The SSB-30 model has six reaction chambers, or reactors, with one UV lamp in each reactor. Each UV lamp has a power rating of 5 kilowatts (kW), for a total system rating of 30 kW. The UV lamps are mounted inside UV-transmissive quartz tubes at the center of the reactors, so that water flows through the space between the reactor wall and the quartz tube. Circular wipers are mounted on the quartz tubes housing the UV lamps. The wipers are periodically used to remove any suspended particles that have coated the quartz tubes. In a coating environment, this coating diminishes the effectiveness of the system by blocking some of the UV radiation.

Contaminated water is pumped to the treatment system and enters the oxidation unit through a section of pipe containing a temperature gauge, a flow meter, an influent sampling port, and hydrogen peroxide and sulfuric acid addition points. Hydrogen peroxide is added to the contaminated water before it enters the oxidation unit; however, a splitter can be used to add hydrogen peroxide at the inlet of each lamp section to allow for different doses into each reactor. Inside the oxidation unit, the contaminated water follows a serpentine path that parallels each of the six UV lamps. The water passes each lamp individually, allowing lamps to be turned on or off as needed. Sample ports are located after each reactor. Inside the oxidation unit, photolysis of hydrogen peroxide by UV radiation results in the formation of hydroxyl radicals; these free radicals react rapidly with oxidizable compounds, such as organic contaminants.

Treated water exits the oxidation unit through an effluent pipe equipped with a temperature gauge and sample port. The hydrogen peroxide dose is usually set so that the concentration of the residual hydrogen peroxide in the treated water is less than 5 milligrams per liter (mg/L). Sodium hydroxide is then added to readjust the pH to meet discharge requirements.

The control panel on the perox-pure™ system monitors water flow rate, total flow through the system, UV lamp current in each reactor, and alarm conditions for the perox-pure™ unit. Hydrogen peroxide and acid injection are activated by switches on the control panel and are monitored with flow meters.

2.4.3 Innovative Features of the Technology

Common methods for treating groundwater contaminated with solvents and other organic compounds include air stripping, steam stripping, carbon adsorption, chemical oxidation, and biological treatment. As regulatory requirements for secondary wastes and treatment by-products became more stringent and expensive to comply with, oxidation technologies have been known to offer a major advantage over other treatment techniques: chemical oxidation technologies destroy contaminants rather than transferring them to another medium, such as activated carbon or the ambient air. Also, chemical oxidation technologies offer faster reaction rates than other technologies, such as some biological treatment processes. However, the oxidation of organics by ozone, hydrogen peroxide, or UV radiation alone has kinetic limitations, restricting its applicability to a narrow range of contaminants. As a result of these limitations, conventional chemical oxidation technologies have been slow to become cost-competitive treatment options.

The combined use of UV radiation and hydrogen peroxide in the perox-pure™ system increases the destruction efficiency of the treatment system and allows for the treatment of a wider range of contaminants. Hydroxyl radicals formed by UV photolysis of hydrogen peroxide rapidly oxidize the contaminants and exhibit little contaminant selectivity.

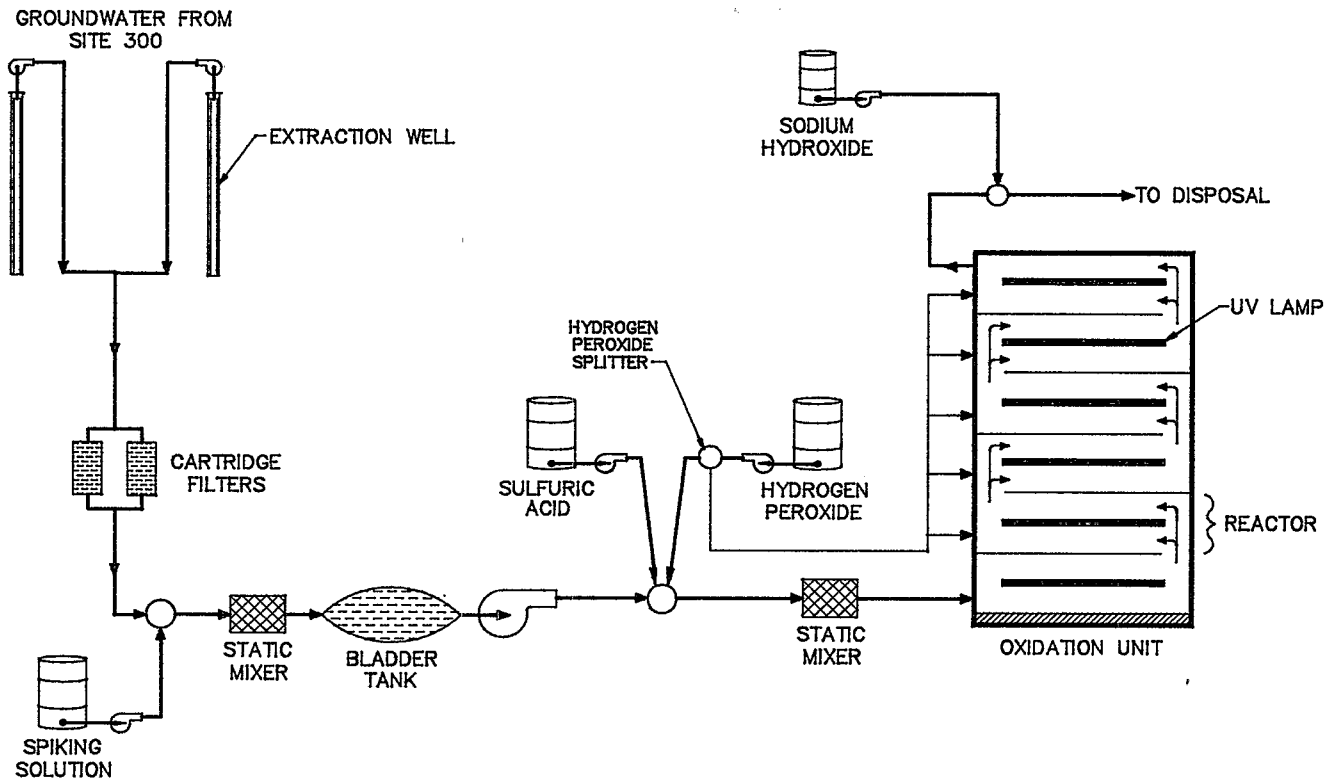

Figure 2-1 perox-pure™ Chemical Oxidation Treatment System

The perox-pure™ treatment system produces no air emissions and generates no sludge or spent media that require further processing, handling, or disposal. Ideally, end products include water, carbon dioxide, halides, and in some cases, organic acids. However, other oxidizable species present in the water (including metals in reduced form, cyanide, and nitrite) can also be oxidized in the process and can exert an additional oxidant demand.

Hydrogen peroxide is inexpensive, easy to handle, and readily available. As a result, its use with UV radiation in the perox-pure™ system offers considerable advantages over expensive and difficult to handle chemicals.

Table 2-1 compares several treatment options for water contaminated with VOCs. Similar comparisons can be made for semivolatile organic compounds (SVOC), polychlorinated biphenyls (PCB), and pesticides, although air stripping is not generally applicable to these types of contaminants.

2.5 Key Contacts

Additional information on the perox-pure™ chemical oxidation technology, the SITE program, and Site 300 at LLNL can be obtained from the following sources:

1. The perox-pure™ Technology

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Process Engineering Manager
Peroxidation Systems, Inc.
5151 East Broadway, Suite 600
Tucson, Arizona 85711
(602) 790-8383

2. The SITE Program

Norma Lewis
Section Chief, EPA Project Manager
EPA SITE Program
26 West Martin Luther King Drive
Cincinnati, Ohio 45268
(513) 569-7665

Table 2-1 Comparison of Technologies for Treating VOCs in Water

Technology	Advantages	Disadvantages
Air stripping	Effective at high concentrations; mechanically simple; relatively inexpensive	Inefficient at low concentrations; VOCs discharged to air
Steam stripping	Effective at all concentrations	VOCs discharged to air; high energy consumption
Air stripping with carbon adsorption of vapors	Effective at high concentrations	Inefficient at low concentrations; requires disposal or regeneration of spent carbon
Air stripping with carbon adsorption of vapors and spent carbon regeneration	Effective at high concentrations; no carbon disposal costs; can reclaim the product	Inefficient at low concentrations; high energy consumption
Carbon adsorption	Low air emissions; effective at high concentrations	Inefficient at low concentrations; requires disposal or regeneration of spent carbon; relatively expensive
Biological treatment	Low air emissions; relatively inexpensive	Inefficient at high concentrations; slow rates of removal; sludge treatment and disposal required
perox-pure™ technology	No air emissions; no secondary waste; VOCs destroyed	High energy consumption; not cost-effective at high concentrations

3. The Lawrence Livermore National Laboratory, Site 300

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Section 3
Technology Applications Analysis

This section addresses the applicability of the perox-pure™ chemical oxidation technology to treat water contaminated with organic compounds. The vendor claims regarding the applicability and performance of the perox-pure™ technology are included in Appendix A. Because results from the SITE demonstration provided an extensive data base, evaluation of the technology's effectiveness and its potential applicability to contaminated sites is mainly based on these results, which are presented in Appendix B. The SITE demonstration results are supplemented by results from other applications of the perox-pure™ technology, which are presented in Appendix C.

This section summarizes the effectiveness of the perox-pure™ chemical oxidation technology and discusses the following topics in relation to the applicability of the perox-pure™ technology: factors influencing performance, site characteristics, material handling requirements, personnel requirements, potential community exposures, and potential regulatory requirements.

3.1 Effectiveness of the perox-pure™ Technology

This section discusses the effectiveness of the perox-pure™ technology based on results from the SITE demonstration and three other case studies.

3.1.1 SITE Demonstration Results

The SITE demonstration was conducted at LLNL Site 300 in Tracy, California, over a 3-week period in September 1992. During the demonstration, a perox-pure™ unit (Model SSB-30) treated about 40,000 gallons of groundwater contaminated with VOCs. Principal groundwater contaminants included TCE and PCE, which were present at concentrations of about 1,000 and 100 micrograms per liter (μg/L), respectively. Other VOCs (such as chloroform; DCA; 1,1-dichloroethene; 1,2-dichloroethene; and TCA) were present at average concentrations below 15 μg/L. Groundwater was pumped from two wells into a 7,500-gallon bladder tank to minimize variability in influent characteristics. In addition, cartridge filters were used to remove suspended solids greater than 3 micrometers in size from the groundwater before it entered the bladder tank. Treated groundwater was stored in two 20,000-gallon steel tanks before being discharged.

The perox-pure™ chemical oxidation technology demonstration performed under the SITE program had the following primary objectives:

- Assess the technology's ability to destroy VOCs from groundwater at the LLNL site under different operating conditions
- Determine whether the treated water meets applicable disposal requirements at the 95 percent confidence level
- Obtain information required to estimate the operating costs for the treatment system, such as electrical power consumption and chemical doses

The secondary objective for the technology demonstration was to obtain preliminary information on the presence and types of by-products formed during the treatment.

The technology demonstration was conducted in three phases. Phase 1 consisted of eight runs using raw groundwater, Phase 2 consisted of four runs using spiked groundwater, and Phase 3 consisted of two runs using spiked groundwater to evaluate the effectiveness of quartz tube cleaning. The three phases are described below.

The principal operating parameters for the perox-pure™ system are hydrogen peroxide dose, influent pH, and flow rate. During Phase 1 of the demonstration, each of these operating parameters was varied to observe treatment system performance under different conditions. Preferred operating conditions, those under which the concentrations of spiked groundwater effluent VOCs would be reduced to below target levels, were then determined for the system. The target levels for the VOCs are given in Appendix B.

During Phase 2, groundwater was spiked with known concentrations of contaminants, and reproducibility tests were conducted. Spiked groundwater contained 200 to 300 μg/L each of DCA, TCA, and chloroform. These compounds were chosen because they are difficult to oxidize and because they were not present in the groundwater at high concentrations. This phase was also designed to evaluate the reproducibility of treatment system performance at the preferred operating conditions determined in Phase 1.

Phase 3 evaluated the effectiveness of the quartz tube wipers by performing two runs using spiked groundwater and scaled and clean quartz tubes.

During the demonstration, samples were collected at the following locations: treatment system influent, effluent from Reactor 1, effluent from Reactor 2, effluent from Reactor 3, and treatment system effluent. Samples were analyzed for VOCs, SVOCs, total organic carbon (TOC), total carbon, purgeable organic carbon (POC), total organic halides (TOX), adsorbable organic halides (AOX), metals, pH, alkalinity, turbidity, temperature, specific conductance, hydrogen peroxide residual, and hardness, as applicable. In addition, samples of influent to Reactor 1 and treatment system effluent were collected and analyzed for acute toxicity to freshwater organisms. Hydrogen peroxide, acid, and base solutions were also sampled and analyzed to verify concentrations.

Appendix B summarizes information from the SITE demonstration, including (1) site characteristics, (2) contaminated groundwater characteristics, (3) perox-pure™ system performance, and (4) technology evaluation results. Key findings of the demonstration are as follows:

- For the spiked groundwater, PSI determined the following preferred operating conditions: (1) influent hydrogen peroxide level of 40 mg/L; (2) hydrogen peroxide level of 25 mg/L in the influent to Reactors 2 through 6; (3) an influent pH of 5.0; and (4) a flow rate of 10 gallons per minute (gpm). At these conditions, the effluent TCE, PCE, and DCA levels were generally below the detection limit (5 μg/L) and effluent chloroform and TCA levels ranged from 15 to 30 μg/L. The average overall removal efficiencies for TCE, PCE, chloroform, DCA, and TCA were about 99.7, 97.1, 93.1, 98.3, and 81.8 percent, respectively.

- For the unspiked groundwater, the effluent TCE and PCE levels were generally below the detection limit (1 μg/L) with corresponding removal efficiencies of about 99.9 and 99.7 percent. The effluent TCA levels ranged from 1.4 to 6.7 μg/L with removal efficiencies ranging from 35 to 84 percent.

- The perox-pure™ system effluent met California drinking water action levels and federal drinking water maximum contaminant levels (MCL) for TCE, PCE, chloroform, DCA, and TCA at the 95 percent confidence level.

- The quartz tube wipers were effective in keeping the tubes clean and appeared to reduce the effect scaling has on contaminant removal efficiencies.

- TOX removal efficiencies ranged from 93 to 99 percent. AOX removal efficiencies ranged from 95 to 99 percent.

- For spiked groundwater, during reproducibility runs, the system achieved average removal efficiencies of 38 percent and greater than 93 percent for TOC and POC, respectively.

- The temperature of groundwater increased at a rate of 12 °F per minute of UV radiation exposure in the perox-pure™ system. Since the oxidation unit is exposed to the surrounding environment, the temperature increase may vary depending upon the ambient temperature or other atmospheric conditions.

3.1.2 Results of Other Case Studies

The perox-pure™ technology has been used to treat contaminated water at approximately 80 sites. Results from three of these applications are discussed as case studies in Appendix C. A brief summary of the effectiveness of the perox-pure™ technology at the three sites chosen as case studies is presented below.

All three case studies represent full-scale, currently operating commercial installations of perox-pure™ chemical oxidation systems. The contaminants of concern in these case studies include acetone, isopropyl alcohol (IPA), TCE, and pentachlorophenol (PCP). In the first case study, the perox-pure™ system treated industrial wastewater containing 20 mg/L of acetone and IPA; the effluent met the discharge limit of 0.5 mg/L. In the second case study, the perox-pure™ system treated groundwater that was used as a municipal drinking water source. The groundwater initially contained an average concentration of 150 μg/L TCE. After treatment, the effluent TCE level was 0.5 μg/L, well below the TCE drinking water standard of 5 μg/L. In the third case study, the perox-pure™ system treated groundwater at a chemical manufacturing facility. The groundwater contained 15 mg/L of PCP; treatment achieved the target effluent PCP level of 0.1 mg/L.

3.2 Factors Influencing Performance

Several factors influence the effectiveness of the perox-pure™ chemical oxidation technology. These factors can be grouped into three categories: (1) influent characteristics, (2) operating parameters, and (3) maintenance requirements. Each of these is discussed below.

3.2.1 Influent Characteristics

The perox-pure™ chemical oxidation technology is capable of treating water containing a variety of organic contaminants, including VOCs, SVOCs, pesticides, polynuclear aromatic hydrocarbons (PAH), PCBs, and petroleum hydrocarbons. Under a given set of operating conditions, contaminant removal efficiencies depend on the chemical structure of the contaminants. Removal efficiencies are high for organic contaminants with double bonds (such as TCE, PCE, and vinyl chloride) and aromatic compounds (such as phenol, toluene, benzene, and xylene), because these compounds are easy to oxidize. Organic contaminants without double bonds (such as TCA and chloroform) are not easily oxidized and are more difficult to remove.

Contaminant concentration also affects treatment system effectiveness. The perox-pure™ system is most effective in treating water with contaminant concentrations less than about 500 mg/L. If contaminant concentrations are greater than 500 mg/L, the perox-pure™ system may be used in combination with other treatment technologies, such as air stripping. For highly contaminated water, the perox-pure™ system can also be operated in a "flow-through with recycle" mode, in which part of the effluent is recycled back through the oxidation unit to improve overall removal efficiency.

The perox-pure™ system uses a chemical oxidation process to destroy organic contaminants; therefore, other species in the influent that consume oxidants are considered an additional load for the system. These species are called scavengers. A scavenger may be described as any species in water other than the target contaminants that consumes oxidants. Common scavengers include anions such as bicarbonate, carbonate, sulfide, nitrite, bromide, and cyanide. Metals present in reduced states, such as trivalent chromium, ferrous iron, manganous ion, and several others, are also likely to be oxidized. In addition to acting as scavengers, these reduced metals can cause additional concerns under alkaline pH conditions. For example, trivalent chromium can be oxidized to hexavalent chromium, which is more toxic. Ferrous iron and manganous ion are converted to less soluble forms, which precipitate in the reactor, creating suspended solids that can build up on the quartz tubes housing the UV lamps. Natural organic compounds, such as humic acid (often measured as TOC), are also potential scavengers in this treatment technology.

Other influent characteristics of concern include suspended solids, oil, and grease. These constituents can build up on the quartz tubes housing the UV lamps, resulting in reduced UV transmission and decreased treatment efficiency.

3.2.2 Operating Parameters

Operating parameters are those parameters that can be varied during the treatment process to achieve desired removal efficiencies. The principal operating parameters for the perox-pure™ system are hydrogen peroxide dose, influent pH, and flow rate.

Hydrogen peroxide dose is selected based on treatment unit configuration, contaminated water chemistry, and contaminant oxidation rates. Under ideal conditions, hydrogen peroxide is photolyzed to hydroxyl radicals, which are the principal oxidants in the system. Direct photolysis of each molecule of hydrogen peroxide results in a yield of two hydroxyl radicals. The molar extinction coefficient of hydrogen peroxide at 253.7 nanometers, the dominant emission wavelength of low-pressure UV lamps, is only 19.6 liters per mole-centimeter, which is low for a primary absorber in a photochemical process (Glaze and others, 1987). Therefore, although the yield of hydroxyl radicals from hydrogen peroxide photolysis is relatively high, the low molar extinction coefficient requires that a relatively high concentration of hydrogen peroxide exist in the water. However, because excess hydrogen peroxide is also a hydroxyl radical scavenger, hydrogen peroxide levels that are too high could result in a net decrease in treatment efficiency. According to PSI, the perox-pure™ system overcomes these limitations by using medium-pressure UV lamps.

The perox-pure™ system is equipped with a hydrogen peroxide splitter that allows the operator to inject hydrogen peroxide to the oxidation unit influent and directly to any of the individual oxidation reactors. The distribution of the total hydrogen peroxide dose is an important operating parameter, because the hydroxyl radical has a short lifetime. If the total hydrogen peroxide dose is delivered to the influent, depending on other operating conditions, the resulting hydroxyl radical concentration in the last reactor may be zero. Consequently, removal efficiency in the last reactor would decrease significantly. Distributing part of the hydrogen peroxide dose directly to the reactors guarantees that some hydroxyl radicals will be present throughout the oxidation unit.

Influent pH controls the equilibrium among carbonate, bicarbonate, and carbonic acid. This equilibrium is important to treatment efficiency because carbonate and bicarbonate ions are hydroxyl radical scavengers. If the influent carbonate and bicarbonate concentration is greater than about 400 mg/L as calcium carbonate, the pH should

be lowered to between 4 and 6 to improve the treatment efficiency. At low pH, the carbonate equilibrium is shifted to carbonic acid, which is not a scavenger.

Flow rate through the treatment system determines the hydraulic retention time. In general, increasing the hydraulic retention time improves treatment efficiency by increasing the time available for contaminant destruction. Theoretically, at a certain point, the reaction proceeds toward equilibrium, and increasing the hydraulic retention time no longer significantly increases removal efficiency. PSI did not observe this phenomenon in the range of hydraulic retention times provided by the perox-pure™ system.

3.2.3 Maintenance Requirements

The maintenance requirements for the perox-pure™ system summarized below are based on discussions with PSI during and after the SITE demonstration. Regular maintenance by trained personnel is essential for the successful operation of the perox-pure™ system. The only major system component that requires regular maintenance is the UV lamp assembly. A brief summary of the maintenance requirements for the UV lamp assembly and other miscellaneous components is presented below.

Regular UV lamp assembly maintenance includes periodically cleaning the quartz tubes housing the UV lamps. Eventually, the lamps may need to be replaced. The frequency at which the quartz tubes should be cleaned depends on the type and concentration of suspended solids present in the influent or formed during treatment. Cleaning frequency may range from once every month to once every 3 months. UV lamp assemblies can be removed from the oxidation unit to provide access to the quartz tubes, which can then be cleaned manually. The quartz tubes can also be cleaned automatically during operation with wipers. Automatic tube cleaning is a standard feature on most PSI treatment units. The quartz tube wipers require replacement once every 3 to 6 months depending upon the cleaning cycle frequency.

Maintenance requirements for the medium-pressure, mercury-vapor, broad-band UV lamps used in the perox-pure™ system are similar to those for conventional, low-pressure UV lamps. The life of low-pressure UV lamps normally cited by most manufacturers is 7,500 hours, based on a use cycle of 8 hours. The use cycle represents the length of time the UV lamp is operated between shutdowns. Decreasing the use cycle or increasing the frequency at which a UV lamp is turned on and off can lead to early lamp failure.

A number of factors contribute to UV lamp aging. These factors include plating of mercury to the interior lamp walls, a process called blackening, and solarization of the lamp enclosure material, which reduces its transmissibility. These factors cause steady deterioration in lamp output at the effective wavelength and may reduce output at the end of a lamp's life by 40 to 60 percent. This reduction in lamp output requires more frequent replacement of the UV lamps. According to PSI, no significant decline in UV lamp output occurs until after about 3,000 hours of operation. Therefore, PSI recommends replacing the UV lamps after 3,000 hours. PSI guarantees the UV lamps in the perox-pure™ unit for 3,000 hours when they are turned on and off no more than two or three times a day.

The only other part of the UV lamp assembly requiring periodic maintenance is the gasket between the UV lamp and the reactor. This gasket, which is used to maintain a water-tight seal on each reactor, is generally replaced once a year.

Other components of the perox-pure™ system, such as valves, flow meters, piping, hydrogen peroxide feed module, acid feed module, and base feed module, should be checked for leaks once a month. In addition, the influent, hydrogen peroxide, acid, and base feed pumps should be checked once a month for proper operation and maintenance. Feed pump heads are usually replaced annually. PSI offers a full-service program to its customers that covers all regular maintenance and replacement parts for the system.

3.3 Site Characteristics

In addition to influent characteristics and effluent discharge requirements, site characteristics are important when considering the perox-pure™ technology. Site-specific factors can impact the application of the perox-pure™ technology, and these effects should be considered before selecting the technology for remediation of a specific site. Site-specific factors include support systems, site area and preparation, site access, climate, utilities, and services and supplies. Tables 4-1 and 4-2 in Section 4 identify examples of categories that are specific to the perox-pure™ system and to a hazardous waste remediation site.

3.3.1 Support Systems

To clean up contaminated groundwater, extraction wells and a groundwater collection and distribution system must be installed to pump groundwater to a central facility where the perox-pure™ system is located. Because the perox-pure™ system is normally operated as a continuous flow-through system during site remediation, installation of several extraction wells may be required to provide a continuous supply of groundwater. An equalization tank may be required if flow rates from the groundwater wells fluctuate or if contaminant concentrations vary. When installing a groundwater collection and distribution system, preventive measures should be considered to reduce volatile contaminant losses.

Before choosing the perox-pure™ technology, the location, design, and installation of tanks, piping, and other equipment or chemicals associated with any pretreatment systems should be considered. Pretreatment is often desired to remove oil and grease, suspended solids, or metals. Any tanks that are part of pretreatment or other support systems should be equipped with vapor control devices (for example, floating lids) to prevent VOC losses.

If on-site facilities are not available for office and laboratory work, a small building or shed may be required near the treatment system. The on-site building should be equipped with electrical power to run laboratory equipment and should be heated or air-conditioned, depending on the climate. The on-site laboratory should contain equipment needed to perform simple analyses of the physical and chemical water characteristics required to monitor treatment system performance. Such characteristics may include pH, hydrogen peroxide dose, and temperature.

3.3.2 Site Area and Preparation

The perox-pure™ units are available in several sizes, ranging in combined UV lamp power from 10 to 720 kW. The perox-pure™ units have operated at flow rates between 5 and several thousand gpm, depending on the required hydraulic retention time. During the SITE demonstration, a 30-kW perox-pure™ unit with a total volume of 15 gallons was used. A 10- by 20-foot area was adequate for the perox-pure™ unit and associated chemical feed units. Larger systems would require slightly larger areas. Areas required for influent and effluent storage tanks, if needed, will depend on the number and size of tanks. Also, a 20- by 15-foot area may be required for an office or laboratory building.

The area containing the perox-pure™ unit and tanks should be relatively level and should be paved or covered with compacted soil or gravel.

3.3.3 Site Access

Site access requirements for treatment equipment are minimal. The site must be accessible to tractor-trailer trucks of standard size and weight. The roadbed must be able to support such a vehicle delivering the perox-pure™ system and tanks.

3.3.4 Climate

According to PSI, below-freezing temperatures and heavy precipitation do not affect the operation of the perox-pure™ system. The system is designed to withstand rain and snow and does not require heating or insulation, because the chemical oxidation process generates heat, increasing the water temperature about 12 °F per minute of contact time. However, if below-freezing temperatures are expected for a long period of time, chemical and influent storage tanks and associated plumbing should be insulated or kept in a heated shelter, such as a building or shed. Housing the system also facilitates regular system checks and maintenance. The perox-pure™ unit requires a high-voltage power supply, which should also be protected from heavy precipitation.

3.3.5 Utilities

The perox-pure™ system requires potable water and electricity. Potable water is required for a safety shower, an eye wash station, personnel decontamination, and cleaning field sampling equipment. The perox-pure™ unit requires 480-volt, 3-phase electrical service. Electrical power for the chemical feed modules can be supplied through the perox-pure™ unit. Additional 110-volt, single-phase electrical service is needed to operate the groundwater extraction well pumps, light the office and laboratory building, and operate on-site laboratory and office equipment.

A telephone connection or cellular phone is required to order supplies, contact emergency services, and provide normal communications.

3.3.6 Services and Supplies

A number of services and supplies are required for the perox-pure™ technology. Most of these services and supplies can be readily obtained.

If UV lamps, pumps, flow meters, or piping malfunctions, an adequate on-site supply of spare parts is needed. If an on-site parts inventory is not an option, site proximity to an industrial supply center is an important consideration. In addition, an adequate supply of chemicals, such as hydrogen peroxide, sulfuric acid, and sodium hydroxide, or proximity to a supply center carrying these chemicals is essential.

Complex laboratory services, such as VOC and SVOC analyses, that cannot usually be performed in an on-site field laboratory require contracting a local analytical laboratory for an ongoing monitoring program.

3.4 Material Handling Requirements

The perox-pure™ system does not generate treatment residuals, such as sludge or spent media, that require further processing, handling, or disposal. The chemical oxidation unit and other components of the system, such as the chemical feed units, are air-tight and produce no air emissions. Material handling requirements for the perox-pure™ technology include those for (1) pretreatment materials and (2) treated water. These are described below.

3.4.1 Pretreatment Materials

In general, pretreatment requirements for contaminated water entering the perox-pure™ system are minimal. Depending on the influent characteristics, pretreatment processing may involve one or more of the following: oil and grease removal, suspended solids removal, metals removal, or pH adjustment to reduce carbonate and bicarbonate levels. These pretreatment requirements are discussed below.

Water containing visible, free, or emulsified oil and grease requires pretreatment to separate and remove the oil and grease. If not treated, oil and grease will scale UV lamps and reduce UV transmission, which makes the oxidation process less effective. Separated oil and grease should be containerized and analyzed to determine disposal requirements.

Because suspended solids can also reduce UV transmission, water containing more than 30 mg/L of suspended solids should be pretreated. Depending on the concentration, cartridge filters, sand filters, or settling tanks may be used to remove suspended solids. Solids removed from the influent by pretreatment precipitation, filtration, or settling should be dewatered, containerized, and analyzed to determine whether they should be disposed of as hazardous or nonhazardous waste.

Pretreatment also may be necessary for water containing dissolved metals, such as iron and manganese. These metals are likely to be oxidized in the perox-pure™ unit and are less soluble at higher oxidation states under alkaline pH conditions. After oxidation, the metals will tend to precipitate as suspended solids in the perox-pure™ unit, resulting in UV lamp scaling. Removing these metals is often advised; however, removal may depend on the concentration of oxidizable metals in the contaminated water. The economics of metals removal should be compared to (1) predicted decreases in contaminant removal efficiency without metals removal and (2) the economics of more frequent UV lamp cleaning or replacement. Metals removed from the influent by precipitation should be containerized and analyzed to determine whether the metals should be disposed of as hazardous or nonhazardous waste.

If the contaminated water contains bicarbonate and carbonate ions at levels greater than 400 mg/L as calcium carbonate, pH adjustments are typically performed in-line. Carbonate and bicarbonate ions act as oxidant scavengers and present an additional load to the treatment system. The only material handling associated with pH adjustment involves handling chemicals such as acids and bases; pH adjustment should not create any waste streams requiring disposal.

3.4.2 Treated Water

Treated water can be disposed of either on or off site. Examples of on-site disposal options for treated water include groundwater recharge or temporary on-site storage for sanitary usage. Examples of off-site disposal options include discharge into surface water bodies, storm sewers, and sanitary sewers. Bioassay tests may be required in addition to routine chemical and physical analyses before treated water is disposed of. Depending on permit requirements and treatment unit operating conditions, treated water may require pH adjustment before discharge.

3.5 Personnel Requirements

Personnel requirements for the perox-pure™ system are minimal. Generally, one operator, trained by PSI, conducts a daily 30-minute system check. The unit operator should be capable of performing the following: (1) filling chemical feed tanks and adjusting chemical flow rates to achieve desired doses; (2) operating the control panel on the chemical oxidation unit; (3) collecting liquid samples and performing simple physical and chemical analyses and measurements (for example, pH, hydrogen peroxide concentration, temperature, and flow rate); (4) troubleshooting minor operational problems; and (5) collecting samples for off-site analyses. Analytical work requiring more technical skills, such as VOC analyses, can be performed by a local laboratory. The frequency of sample collection and analysis will depend on site-specific permit requirements.

The unit operator should also have completed an Occupational Safety and Health Act (OSHA) initial 40-hour health and safety training course and an annual 8-hour refresher course, if applicable, before operating the perox-pure™ system at hazardous waste sites. The operator also should participate in a medical monitoring program as specified under OSHA requirements.

For remote sites, where daily system checks by an operator are not feasible, the perox-pure™ system can be monitored remotely, or it can be remotely operated and monitored. Remotely monitored systems can be connected to devices that automatically dial a telephone to notify responsible parties at remote locations of alarm conditions. Remotely operated and monitored systems are hard-wired into centrally-located control panels or computers through programmable logic controllers.

3.6 Potential Community Exposures

The perox-pure™ system generates no chemical or particulate air emissions. Therefore, the potential for on-site personnel or community exposure to airborne contaminants is low. If a system malfunction occurs, alarms will sound, and all components of the system will shut off automatically.

Contaminated-water pumps can be hard-wired to the perox-pure™ unit control panel so that alarm conditions automatically stop flow through the unit, reducing the potential for a contaminated water release.

Hydrogen peroxide solution, which is a reactive substance, presents the greatest chemical hazard associated with the system. However, when handled appropriately, the potential for exposure to hydrogen peroxide by on-site personnel is low. Acids, bases, and hydrogen peroxide required for the perox-pure™ system are typically stored in polyethylene totes housed in metal frames or cages. The relatively small volumes of hydrogen peroxide used by the system and secure chemical storage practices result in a low potential threat of community exposure to hydrogen peroxide.

3.7 Potential Regulatory Requirements

This subsection discusses regulatory requirements pertinent to site remediation using the perox-pure™ technology. Regulations applicable to a particular application of this technology will depend on site-specific remediation logistics and the type of contaminated water being treated. Table 3-1 provides a summary of the potentially applicable regulations discussed below.

Depending on the characteristics of the water to be treated, pretreatment or posttreatment may be required for the successful operation of the perox-pure™ system. For example, solids may need to be prefiltered using cartridge filters, sand filters, or settling tanks. Metals, such as iron and manganese, may need to be removed by precipitation. Each pretreatment or posttreatment process may have additional regulatory requirements that need to be determined prior to use. This subsection focuses on regulations for the perox-pure™ system only.

3.7.1 Comprehensive Environmental Response, Compensation, and Liability Act

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended by SARA of 1986, authorizes the federal government to respond to releases into the environment of hazardous substances, pollutants, or contaminants that may present an imminent and substantial danger to public health or welfare (Federal Register, 1990a). 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 protective of human health and the environment.

Contaminated water treatment using the perox-pure™ system will generally take place on site, while treated water discharge may take place either on site or off site. On-site actions must meet all substantive state and federal applicable or relevant and appropriate requirements (ARAR). Substantive requirements pertain directly to actions or conditions in the environment (for example, effluent standards). Off-site actions must comply with legally applicable substantive and administrative requirements. Administrative requirements, such as permitting, facilitate the implementation of substantive requirements.

EPA allows an ARAR to be waived for on-site actions. Six ARAR waivers are provided by CERCLA: (1) interim measures waiver, (2) equivalent standard of performance waiver, (3) greater risk to health and the environment waiver, (4) technical impracticability waiver, (5) inconsistent application of state standard waiver, and (6) fund-balancing waiver. Justification for a waiver must be clearly demonstrated (EPA, 1988). Off-site remediations are not eligible for ARAR waivers, and all substantive and administrative applicable requirements must be met.

Additional regulations pertinent to use of the perox-pure™ system are discussed below. No air emissions or residuals (such as sludge or spent filter media) are generated by the perox-pure™ system. Therefore, only regulations addressing contaminated water treatment and discharge are presented.

3.7.2 Resource Conservation and Recovery Act

The Resource Conservation and Recovery Act (RCRA), as amended by the Hazardous and Solid Waste Amendments of 1984, regulates management and disposal of municipal and industrial solid wastes. The EPA and RCRA-authorized states [listed in 40 Code of Federal Regulations (CFR) Part 272] implement and enforce RCRA and state regulations.

The perox-pure™ system has been used to treat water contaminated with a variety of organic materials, including solvents, pesticides, PAHs, and petroleum hydrocarbons. Contaminated water treated by the perox-pure™ technology will most likely be hazardous or sufficiently similar to hazardous waste so that RCRA standards will be requirements. Criteria for identifying hazardous wastes are included in 40 CFR Part 261. Pertinent RCRA requirements are discussed below.

If the contaminated water to be treated is determined to be a hazardous waste, RCRA requirements for storage and treatment must be met. The perox-pure™ system may include tank storage. Tank storage of contaminated and treated water (if the waters are RCRA hazardous) must meet tank storage requirements of 40 CFR Parts 264 or 265, Subpart J. Although air emissions are not associated with the perox-pure™ system, any fugitive emissions from storage tank vents would be subject to forthcoming RCRA regulations (see 40 CFR Part 269) on air emissions from hazardous waste treatment, storage, and disposal facilities. When promulgated, these requirements will include

Table 3-1 Regulations Summary

Act	Applicability	Application to perox-pure™ Chemical Oxidation System	Citation
CERCLA	Superfund sites	The Superfund program authorizes and regulates the cleanup of environmental contamination. It applies to all CERCLA site cleanups.	40 CFR Part 300
RCRA	Superfund and RCRA sites	RCRA defines and regulates the treatment, storage, and disposal of hazardous wastes. RCRA also regulates corrective action at generator, treatment, storage, and disposal facilities.	40 CFR Parts 260 to 270, Part 280
CWA	Discharges to surface water bodies	NPDES requirements of CWA apply to both Superfund and RCRA sites where treated water is discharged to surface water bodies. Pretreatment standards apply to discharges to POTWs.	40 CFR Parts 122 to 125, Part 403
SDWA	Water discharges, water reinjection, and sole-source aquifer and wellhead protection	Maximum contaminant levels and contaminant level goals should be considered when setting water cleanup levels at RCRA corrective action and Superfund sites. (Water cleanup levels are also discussed under RCRA and CERCLA.) Reinjection of treated water would be subject to underground injection control program requirements, and sole source and protected wellhead water sources would be subject to their respective control programs.	40 CFR Part 141
TSCA	PCB contamination	If PCB-contaminated wastes are treated, TSCA requirements should be considered when determining cleanup standards and disposal requirements. RCRA also regulates solid waste containing PCBs.	40 CFR Part 761
AEA and RCRA	Mixed wastes	AEA and RCRA requirements apply to the treatment, storage, and disposal of mixed waste containing both hazardous and radioactive components. OSWER and DOE directives provide guidance for addressing mixed waste.	AEA and RCRA
FIFRA	Pesticides	FIFRA regulates pesticide manufacturing and labeling. However, if pesticide-contaminated water is treated, RCRA regulations will generally apply.	40 CFR Part 165
OSHA	All remedial actions	OSHA regulates on-site construction activities and the health and safety of workers at hazardous waste sites. Installation and operation of the system at Superfund or RCRA sites must meet OSHA requirements.	29 CFR Parts 1900 to 1926 29 CFR Part 1910.120 (hazardous waste and emergency response operations)

Note: Acronyms used in this table are defined in text.

standards for emissions from equipment leaks and process vents. Treatment requirements included in 40 Part 265, Subpart Q (Chemical, Physical, and Biological Treatment) would also apply. This subpart includes requirements for automatic influent shut-off, waste analysis, and trial tests.

The perox-pure™ system could also be used to treat contaminated water at RCRA-regulated facilities. Requirements for corrective action at RCRA-regulated facilities will be included in 40 CFR Part, 264 Subpart F (Regulated Units) and Subpart S (Solid Waste Management Units), as well as 40 CFR Part 280 (Underground Storage Tanks); these subparts generally will apply to remediation at Superfund sites. The regulations include requirements for initiating and conducting RCRA corrective actions, remediating groundwater, and ensuring that corrective

actions comply with other environmental regulations (Federal Register, 1990b).

Water quality standards included in RCRA (such as groundwater monitoring and protection standards), the Clean Water Act (CWA), and the Safe Drinking Water Act (SDWA) would be appropriate cleanup standards and would apply to discharges of treated water or reinjection of treated groundwater (EPA, 1989). The CWA and SDWA are discussed below.

3.7.3 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. If treated water is discharged to surface water bodies or publicly-owned treatment works (POTW), CWA regulations will apply. On-site discharges to surface water bodies must meet substantive National Pollutant Discharge Elimination System (NPDES) requirements, but do not require a NPDES permit. 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.

3.7.4 Safe Drinking Water Act

The SDWA, as amended in 1986, required EPA to establish regulations to protect human health from contaminants in drinking water. EPA has developed the following programs to achieve this objective: (1) drinking water standards program, (2) underground injection control program, and (3) sole-source aquifer and wellhead protection programs.

SDWA primary, or health-based, and secondary, or aesthetic, MCLs 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, alternate concentration limits (ACL) may be used. CERCLA and RCRA standards and guidance should be used in establishing ACLs (EPA, 1987a).

Water discharge through injection wells is regulated by the underground injection control program. Injection wells are categorized in Class 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.

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 perox-pure™ system, appropriate program officials should be notified, and any potential regulatory requirements should be identified. State groundwater antidegradation requirements and water quality standards may also apply.

3.7.5 Toxic Substances Control Act

Testing, premanufacture notification, and record-keeping requirements for toxic substances are regulated under the Toxic Substances Control Act (TSCA). TSCA also includes storage requirements for PCBs (see 40 CFR Part 761.65). The perox-pure™ system may be used to treat water contaminated with PCBs, and PCB storage requirements would apply to pretreatment storage of PCB-contaminated water. The SDWA MCL for PCBs is 0.05 μg/L; this MCL would generally be the treatment standard for groundwater remediation at Superfund sites and RCRA corrective action sites. RCRA land disposal requirements for PCBs (see 40 CFR Part 268) may also apply, depending on PCB concentrations. For example, liquid hazardous waste containing PCB concentrations between 50 and 499 ppm that will be treated by incineration or an equivalent method will meet the requirements of 40 CFR part 761.70.

3.7.6 Mixed Waste Regulations

Mixed waste contains both radioactive and hazardous components, as defined by the Atomic Energy Act (AEA) and RCRA, and is subject to the requirements of both acts. When the application of both regulations results in a situation that is inconsistent with the AEA (for example, an increased likelihood of radioactive exposure), AEA requirements supersede RCRA requirements. Use of the perox-pure™ system at sites with radioactive contamination might involve the treatment or generation of mixed waste.

The EPA OSWER, in conjunction with the Nuclear Regulatory Commission, has issued several directives to assist in the identification, treatment, and disposal of low-level radioactive, mixed waste. Various OSWER directives include guidance on defining, identifying, and disposing of commercial, mixed, low-level radioactive and hazardous waste (EPA, 1987b). If the perox-pure™ system is used to treat low-level mixed wastes, these directives should be considered. If high-level mixed waste or transuranic mixed waste is treated, internal orders from the U.S. Department of Energy (DOE) should be considered when developing a protective remedy (DOE, 1988).

3.7.7 Federal Insecticide, Fungicide, and Rodenticide Act

The perox-pure™ technology can treat water contaminated with pesticides. EPA regulates pesticide

product sale, distribution, and use through product licensing or registration under the authority of the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) (see 40 CFR Part 165). Use of a pesticide product in a manner inconsistent with its labeling violates FIFRA. Compliance with FIFRA by following labeling directions may not be required at Superfund or RCRA corrective action sites, because the pesticide may be a RCRA hazardous waste at that point. In such cases, requirements for hazardous wastes containing pesticide constituents must be met.

3.7.8 Occupational Safety and Health Act

OSHA regulations, contained in 29 CFR Parts 1900 through 1926, are designed to protect worker health and safety. Both Superfund and RCRA corrective actions must meet OSHA requirements, particularly Part 1910.120, Hazardous Waste Operations and Emergency Response. Part 1926, Safety and Health Regulations for Construction, applies to any on-site construction activities. For example, electric utility hookups for the perox-pure™ system must comply with Part 1926, Subpart K, Electrical. Product chemicals, such as hydrogen peroxide, sulfuric acid, and sodium hydroxide, used with the perox-pure™ system must be managed in accordance with OSHA requirements (for example, Part 1926, Subpart D, Occupational Health and Environmental Controls, and Subpart H, Materials Handling, Storage, and Disposal). Any more stringent state or local requirements must also be met.

Section 4
Economic Analysis

This section presents cost estimates for using the perox-pure™ system to treat groundwater. Two cases, based on groundwater characteristics, are presented. In Case 1, the groundwater contains both contaminants that are difficult to oxidize and contaminants that are easy to oxidize. In Case 2, the groundwater contains only contaminants that are easy to oxidize. In each case, treatment costs are compared at three different flow rates: 10 gpm, 50 gpm, and 100 gpm.

Cost estimates presented in this section are based primarily on data compiled during the SITE demonstration. Costs have been placed in 12 categories applicable to typical cleanup activities at Superfund and RCRA sites (Evans, 1990). Costs are presented in April 1993 dollars and are considered to be order-of-magnitude estimates with an accuracy of plus 50 percent and minus 30 percent.

Table 4-1 presents a breakdown of costs for the 12 categories for Case 1, and Table 4-2 presents those costs for Case 2. The tables also present total one-time costs and total annual O&M costs; the total costs for a hypothetical, long-term, groundwater remediation project; the net present values of the long-term project; and the costs per 1,000 gallons of water treated. Both tables highlight in boldface type the direct cost associated with using the perox-pure™ system. Each table concludes with a presentation of total direct one-time costs, total direct annual O&M costs, and the direct costs per 1,000 gallons of water treated.

4.1 Basis of Economic Analysis

A number of factors affect the estimated costs of treating groundwater with the perox-pure™ chemical oxidation system. Factors affecting costs generally include flow rate, type and concentration of contaminants, groundwater chemistry, physical site conditions, geographical site location, contaminated groundwater plume size, and treatment goals.

The perox-pure™ technology can treat several types of liquid wastes, including contaminated groundwater, landfill leachate, and industrial wastewater. Contaminated groundwater was selected for this economic analysis because it is commonly found at Superfund and RCRA corrective action sites and because this waste treatment scenario involves most of the cost categories. In addition, two groundwater remediation cases based on groundwater characteristics are analyzed. In Case 1, the groundwater contains five contaminants, three of which are difficult to oxidize and two of which are easy to oxidize. In Case 2, the groundwater contains two contaminants that are easy to oxidize. The following presents the assumptions and conditions as they apply to each case. Next, the assumptions and conditions used only for Case 1 are presented, and then those used only for Case 2.

For each case, this analysis assumes that the perox-pure™ system will treat contaminated groundwater on a continuous flow cycle, 24 hours per day, 7 days per week. Based on this assumption, during a 1-year period, the 10-gpm unit will treat about 5.2 million gallons, the 50-gpm unit will treat about 26 million gallons, and the 100-gpm unit will treat about 52 million gallons. Because most groundwater remediation projects are long-term, this analysis assumes that a treatment project will last 50 years using the 10-gpm flow rate, 10 years using the 50-gpm flow rate, and 5 years at the 100-gpm flow rate. Treating groundwater at these rates involves remediation of a contaminated groundwater plume that contains approximately 260 million gallons of water. While it is difficult in practice to determine both the volume of groundwater to treat and the actual duration of a project, these figures are used in order to perform this economic analysis.

The total costs for a groundwater remediation project for each case and each flow rate scenario are presented as future values. Using the time periods described above, this analysis assumes a 5 percent inflation rate to estimate the total costs. The future values are then presented as a net present value using a discount rate of 5 percent. A higher discount rate will make the initial costs weigh more heavily in the calculation, and a lower discount rate will make the future operating costs weigh more heavily. Because the costs of demobilization will occur at the end of the project, the appropriate future values of those costs presented in the tables were used in calculating the final values. The costs

Table 4-1 Costs Associated with the perox-pure™ Technology - Case 1

Cost Categories	Estimated Costs (1993 $)					
	10 gpm		50 gpm		100 gpm	
Site Preparation (a)	$168,000		$171,000		$171,000	
Administrative		35,000		35,000		35,000
Treatability Study		**5,000**		**5,000**		**5,000**
System Design		120,000		123,000		123,000
Mobilization		**8,000**		**8,000**		**8,000**
Permitting and Regulatory Requirements (a)	41,000		45,000		51,000	
Capital Equipment (a)	819,000		906,000		1,015,000	
Extraction Wells, Pumps, and Piping		146,000		158,000		158,000
Shelter Building		455,000		455,000		455,000
Treatment Equipment		**110,000**		**185,000**		**290,000**
Auxiliary Equipment		108,000		108,000		112,000
Startup (a)	5,000		5,000		5,000	
Labor (b)	39,000		39,000		39,000	
Operations Staff (c)		**36,000**		**36,000**		**36,000**
Health and Safety Refresher Course		3,000		3,000		3,000
Consumables and Supplies (b)	13,000		30,000		54,000	
Hydrogen Peroxide		**450**		**2,200**		**4,450**
Sulfuric Acid		**600**		**3,000**		**6,000**
Sodium Hydroxide		**2,000**		**10,000**		**20,000**
Cartridge Filters		200		200		200
Carbon Columns		1,000		1,000		1,000
PPE		600		600		600
Disposal Drums for PPE		50		50		50
UV Lamps		**4,500**		**9,000**		**18,000**
Sampling Supplies		1,000		1,000		1,000
Propane		3,000		3,000		3,000
Utilities (b)	12,000		60,000		119,000	
Treatment System		**9,200**		**45,900**		**91,700**
Auxiliary Equipment		2,800		13,800		27,500
Effluent Treatment and Disposal (c)	0		0		0	
Residuals and Waste Shipping and Handling (b)	6,000		6,000		8,000	
Analytical Services (b)	24,000		24,000		24,000	
Maintenance and Modifications (b)	22,000		29,000		40,000	
Treatment System		**11,000**		**18,500**		**29,000**
Auxiliary Equipment		10,800		10,800		11,200
Demobilization (a)	40,000		40,000		40,000	
Treatment System		**10,000**		**10,000**		**10,000**
All Other		30,000		30,000		30,000
Total One-Time Costs	$1,073,000		$1,167,000		$1,283,000	
Total Annual O&M Costs	$116,000		$188,000		$285,000	
Groundwater Remediation:						
Total Costs (d,e)	$25,776,000		$3,558,000		$2,863,000	
Net Present Value (f)	$9,411,000		$2,747,000		$2,479,000	
Costs per 1,000 Gallons (g)	$36		$11		$10	
Total perox-pure™ direct one-time costs	**$144,000**		**$227,000**		**$342,000**	
Total perox-pure™ direct O&M costs	**$64,000**		**$125,000**		**$205,000**	
Costs per 1,000 Gallons--Direct Costs (g)	**$19**		**$5**		**$5**	

Notes:
Items in bold denote perox-pure™ system direct costs

a One-time costs
b Annual O&M costs
c See text for explanation of these costs
d Future value using annual inflation rate of 5 percent
e To complete this project, it is assumed that the 10-gpm flow rate will take 50 years, the 50-gpm flow rate will take 10 years, and the 100-gpm flow rate will take 5 years to treat 260 million gallons total.
f Annual discount rate of 5 percent
g Presented as a net present value using the same assumptions used elsewhere in this table.

Table 4-2 Costs Associated with the perox-pure™ Technology - Case 2

Cost Categories	Estimated Costs (1993 $)					
	10 gpm		50 gpm		100 gpm	
Site Preparation (a)	$168,000		$171,000		$171,000	
Administrative		35,000		35,000		35,000
Treatability Study		**5,000**		**5,000**		**5,000**
System Design		120,000		123,000		123,000
Mobilization		**8,000**		**8,000**		**8,000**
Permitting and Regulatory Requirements (a)	38,000		39,000		39,000	
Capital Equipment (a)	764,000		776,000		780,000	
Extraction Wells, Pumps, and Piping		146,000		158,000		158,000
Shelter Building		455,000		455,000		455,000
Treatment Equipment		**55,000**		**55,000**		**55,000**
Auxiliary Equipment		108,000		108,000		112,000
Startup (a)	5,000		5,000		5,000	
Labor (b)	39,000		39,000		39,000	
Operations Staff (c)		**36,000**		**36,000**		**36,000**
Health and Safety Refresher Course		3,000		3,000		3,000
Consumables and Supplies (b)	10,000		22,000		38,000	
Hydrogen Peroxide		**300**		**1,600**		**3,100**
Sulfuric Acid		**600**		**3,000**		**6,000**
Sodium Hydroxide		**2,000**		**10,000**		**20,000**
Cartridge Filters		200		200		200
Carbon Columns		1,000		1,000		1,000
PPE		600		600		600
Disposal Drums for PPE		50		50		50
UV Lamps		**1,500**		**1,500**		**3,000**
Sampling Supplies		1,000		1,000		1,000
Propane		3,000		3,000		3,000
Utilities (b)	4,000		4,000		8,000	
Treatment System		**3,100**		**3,100**		**6,100**
Auxiliary Equipment		900		900		1,800
Effluent Treatment and Disposal (c)	0		0		0	
Residuals and Waste Shipping and Handling (b)	6,000		6,000		8,000	
Analytical Services (b)	24,000		24,000		24,000	
Maintenance and Modifications (b)	16,000		16,000		17,000	
Treatment System		**5,500**		**5,500**		**5,500**
Auxiliary Equipment		10,800		10,800		11,200
Demobilization (a)	40,000		40,000		40,000	
Treatment System		**10,000**		**10,000**		**10,000**
All Other		30,000		30,000		30,000
Total One-Time Costs	$1,015,000		$1,032,000		$1,036,000	
Total Annual O&M Costs	$99,000		$111,000		$134,000	
Groundwater Remediation:						
Total Costs (d,e)	$25,159,000		$2,453,000		$1,787,000	
Net Present Value (f)	$8,091,000		$1,894,000		$1,547,000	
Costs per 1,000 Gallons (g)	$31		$7		$6	
Total perox-pure™ direct one-time costs	**$84,000**		**$84,000**		**$84,000**	
Total perox-pure™ direct O&M costs	**$49,000**		**$61,000**		**$80,000**	
Costs per 1,000 Gallons--Direct Costs (g)	**$15**		**$3**		**$2**	

Notes:
Items in bold denote perox-pure™ system direct costs

a One-time costs
b Annual O&M costs
c See text for explanation of these costs
d Future value using annual inflation rate of 5 percent
e To complete this project, it is assumed that the 10-gpm flow rate will take 50 years, the 50-gpm flow rate will take 10 years, and the 100-gpm flow rate will take 5 years to treat 260 million gallons total.
f Annual discount rate of 5 percent
g Presented as a net present value using the same assumptions used elsewhere in this table.

per 1,000 gallons treated are derived from the net present values. Capital equipment is not depreciated in this economic analysis.

Further assumptions about groundwater conditions and treatment for each case include the following:

- Any suspended solids present in groundwater are removed before entering the perox-pure™ system.
- Alkalinity is about 250 mg/L as calcium carbonate.
- The influent has a pH of 8 that is lowered to 5.5 via pretreatment.
- The treated effluent has a pH between 4 and 5 that is adjusted to between 6.5 and 8.5 via posttreatment to meet discharge standards.

This analysis assumes that treated water for each case will be discharged to surface water, and MCLs specified in the SDWA are the treatment target levels. Based on results of the SITE demonstration, the perox-pure™ system should achieve these levels.

The following assumptions were also made for each case in this analysis:

- The site is a Superfund site located in a rural area of the Midwest.
- Contaminated water is located in a shallow aquifer.
- The groundwater contains negligible amounts of iron and manganese and will not require pretreatment for metals.
- Suitable site access roads exist.
- Utility lines, such as electricity and telephone lines, exist overhead on site.
- A 4,000-square-foot building will be needed to house the treatment system and auxiliary equipment for all three flow rate scenarios.
- The treatment system operates automatically.
- One technician will be required to operate the equipment, collect all required samples, and perform equipment maintenance and minor repairs.
- One treated water sample and one untreated water sample will be collected daily to monitor system performance.
- Treated and untreated water samples will be collected monthly and analyzed off site for VOCs.
- Labor costs associated with major repairs are not included.
- PSI will dispose of spent UV lamps from the perox-pure™ system at no cost.

For Case 1, the chemical feed rates and the hydraulic retention time required to meet treatment goals listed in Appendix B were estimated based on the perox-pure™ system performance during Runs 10, 11, and 12 of the SITE demonstration. Based on the demonstration, VOC levels in the groundwater, and perox-pure™ system operating conditions assumed for Case 1 include the following:

- Chloroform at 200 μg/L
- DCA at 150 μg/L
- TCA at 130 μg/L
- TCE at 700 μg/L
- PCE at 100 μg/L
- Hydrogen peroxide dose of 85 mg/L
- Hydraulic retention time of 0.75 minute

For Case 2, the chemical feed rates and hydraulic retention time required to meet treatment goals listed in Appendix B were estimated based on the perox-pure™ system performance during Run 8. Based on the demonstration, the VOC levels in the groundwater, and perox-pure™ system operations include the following:

- TCE at 1,070 μg/L
- PCE at 108 μg/L
- Hydrogen peroxide dose of 60 mg/L
- Hydraulic retention time of 0.05 minute

4.2 Cost Categories

Cost data associated with the perox-pure™ technology have been assigned to the following 12 categories: (1) site preparation; (2) permitting and regulatory requirements; (3) capital equipment; (4) startup; (5) labor; (6) consumables and supplies; (7) utilities; (8) effluent treatment and disposal; (9) residuals and waste shipping and handling; (10) analytical services; (11) maintenance and modifications; and (12) demobilization. Costs associated with each category are presented in the sections that follow. Each section presents

the costs that are identical for each case. If applicable, differences between the costs of Case 1 and Case 2 are then discussed. Some categories end with a summary of the significant costs within the category. All direct costs associated with operating the perox-pure™ system are identified as perox-pure™ direct costs; all costs associated with the hypothetical remediation and auxiliary equipment are identified as groundwater remediation costs.

4.2.1 Site Preparation Costs

Site preparation costs include administrative, treatability study, system design, and mobilization costs. For this analysis, administrative costs, such as legal searches, access rights, and other site planning activities, are associated with a groundwater remediation project and are estimated to be $35,000.

A treatability study will need to be performed to determine the appropriate specifications of the perox-pure™ system for the site as well as the amounts of chemicals and reagents needed for optimal performance. PSI estimates the cost for this study, which is directly associated with operating the perox-pure™ treatment system, to be about $5,000.

System design costs include designing the site layout and the treatment system operations and are associated with a groundwater remediation project. Design costs are typically 20 percent of the total construction costs. Construction costs include constructing a shelter building for the treatment and auxiliary equipment and installing extraction wells and piping (see Capital Equipment Costs). Construction costs are about $600,000 for the 10-gpm flow rate scenario and about $613,000 for the 50- and 100-gpm flow rate scenarios. Therefore, design costs would be about $120,000 for the 10-gpm flow rate scenario and about $123,000 for the 50- and 100-gpm flow rate scenarios.

Mobilization involves transporting all equipment to the site, assembling it, performing optimization and shakedown activities, and operator training. Transportation costs are site-specific and will depend on the location of the site in relation to all equipment vendors. The skid-mounted perox-pure™ system is delivered to each site in one semitrailer from Tucson, Arizona. PSI will position the system and perform optimization and shakedown activities as part of the mobilization. Initial operator training is needed to ensure safe, economical, and efficient operation of the system. PSI estimates mobilization costs to be about $8,000 and to take about 1 week to complete.

For each case, total site preparation costs are estimated to be $168,000 for the 10-gpm flow rate scenario and $171,000 for the 50- and 100-gpm flow rate scenarios. System design constitutes about 71 percent of the total site preparation costs, and administrative costs make up about 20 percent. As such, about 7 percent of the site preparation costs are associated with the perox-pure™ treatment system.

4.2.2 Permitting and Regulatory Requirements Costs

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

Permitting and regulatory costs are associated with a groundwater remediation project and are assumed to be about 5 percent of the total capital equipment costs for a treatment operation that is part of a Superfund site remediation project. This estimate does not include annual discharge permit costs, which may vary significantly depending on state and local requirements.

For Case 1, permitting and regulatory costs are estimated to be $41,000 for the 10-gpm flow rate scenario; $45,000 for the 50-gpm flow rate scenario; and $51,000 for the 100-gpm flow rate scenario. For Case 2, these costs are estimated to be $38,000 for the 10-gpm, and $39,000 for the 50- and 100-gpm flow rate scenarios. The costs in Case 2 are similar because total capital equipment costs are nearly the same for each flow rate. The difference in costs between the two cases is due to the lower perox-pure™ system capital equipment costs associated with Case 2.

4.2.3 Capital Equipment Costs

Capital equipment costs include installing extraction wells; constructing a building to shelter the treatment and auxiliary equipment; and purchasing and installing all treatment equipment, including auxiliary equipment and monitoring equipment.

Extraction well installation costs are associated with a groundwater remediation project and include installing the well and pump and connecting the pumps, piping, and valves from the wells to the perox-pure™ system. This analysis assumes that four, 150-foot extraction wells will be required to maintain the flow rate in each scenario. Extraction wells can be installed at about $150 per foot per well. Total well construction costs for each case will be about $90,000.

Pumps, piping, and valve connection costs are associated with a groundwater remediation project and will depend on the following factors: the number of extraction wells needed,

the flow rate, the distance of the extraction wells from the treatment system, and the climate of the area. This analysis assumes that four extraction wells are located about 200 feet from the perox-pure™ system. Four 2.5-gpm pumps will be required to maintain a 10-gpm flow rate. The total cost for these four pumps is about $8,000. Four 12.5-gpm pumps will be required to maintain a 50-gpm flow rate, at a total cost of about $20,000. Four 25-gpm pumps will be required to maintain a 100-gpm flow rate, at a total cost of about $20,000. Piping and valve connection costs are about $60 per foot, including underground installation. Therefore, total piping costs will be an additional $48,000.

A building will need to be constructed to shelter the perox-pure™ system and all auxiliary equipment, because the site is assumed to be located in the Midwest, and remediation will likely be conducted in adverse weather conditions. The building will require about 4,000 square feet and will cost about $100 per square foot, including construction and materials, for a total cost of $400,000. Costs associated with designing the building are included in the system design costs (see Site Preparation Costs). Heating costs included in this analysis assume that the building site is remote and will require a propane or liquid petroleum gas heating system with a 3,000-gallon tank and fuel delivery service. The propane tank, heating unit, and duct work will cost about $25,000 to install. Finally, utility connections to the building are estimated to cost $30,000. Total building costs for each case will be about $455,000 for each flow rate scenario and are associated with a groundwater remediation project.

Treatment equipment typically consists of chemical feed modules and the skid-mounted components of the perox-pure™ system. The cost of the perox-pure™ unit will vary depending on the size of the unit needed. PSI identifies unit sizes by their kW usage. To meet the treatment goals for Case 1, PSI estimates that the 10-gpm unit will require 15 kW, the 50-gpm unit will require 75 kW, and the 100-gpm unit will require 150 kW. However, the nearest commercially available perox-pure™ units PSI offers are 30 kW, 90 kW, and 180 kW respectively. These will cost $100,000, $175,000, and $280,000 respectively. PSI recommends turning off any lamps in excess of the necessary electrical power.

To meet the treatment goals of Case 2, PSI estimates that the 10-gpm unit will require 1 kW, the 50-gpm unit will require 5 kW, and the 100-gpm unit will require 10 kW. However, the nearest commercially available unit PSI offers is 10 kW. Therefore, perox-pure™ unit cost will be $45,000 for each flow rate scenario of Case 2.

This analysis assumes that the site treatment scenarios for each case will include acid feed and base feed modules. The chemical feed modules consist of one 2,000-gallon hydrogen peroxide tank and two feed pumps, one 500-gallon acid storage tank and two feed pumps, and one 500-gallon base storage tank and two feed pumps. The total additional cost for all three chemical feed modules for each case will be about $10,000.

Auxiliary equipment considered in this analysis is associated with a groundwater remediation project and includes one sedimentation tank, two equalization tanks, two cartridge filters, one filter press, and monitoring equipment. One 2,000-gallon sedimentation tank will be located downstream of the extraction wells and upstream of the cartridge filters to allow solids to settle out before treatment. This tank costs about $5,000. Two 5,000-gallon equalization tanks are needed to minimize fluctuations in VOC concentrations. While one tank is being filled, the other will be emptied. These tanks will be located downstream of the cartridge filters. Both equalization tanks will cost a total of about $14,000. All tanks used during the remediation are assumed to have closed tops with vents. A venting system that includes duct work and carbon columns will be needed to eliminate fugitive emissions from the tanks. This venting system will cost about $25,000.

Filtration will be required to remove any suspended solids from the sedimentation tank effluent. Two cartridge filters will be installed on the perox-pure™ feed line. Cartridges cost about $2,000 each for the 10- and 50-gpm flow rate scenarios, for a total cost of $4,000. Cartridges cost about $4,000 each for the 100-gpm flow rate scenario, for a total cost of $8,000. The costs of replacement filters are included in Consumables and Supplies Costs.

A filter press will be needed to dewater the sediment collected in the sedimentation tank and any other tanks that may accumulate sediment. The size of the filter press will be determined after a bench-scale study is performed. This analysis assumes that a 4-cubic-foot filter press will be used, at a cost of about $50,000.

Monitoring equipment includes a spectrophotometer to measure hydrogen peroxide concentration, a pH meter, a thermometer, and other as needed. This equipment can be purchased for about $10,000.

Total auxiliary equipment costs, including venting duct work, for the 10- and 50-gpm flow rate scenarios will be about $108,000. The total auxiliary equipment costs for the 100-gpm flow rate scenario will be about $112,000.

For Case 1, total capital costs will be about $819,000 for the 10-gpm flow rate scenario; $906,000 for the 50-gpm flow rate scenario; and $1,015,000 for the 100-gpm flow rate scenario. Of these costs, only the perox-pure™ and feed modules are associated with operating the perox-pure™ system. The costs of these components account for about 13 percent of total capital costs for the 10-gpm flow rate scenario, 20 percent for the 50-gpm flow rate scenario, and

29 percent for the 100-gpm flow rate scenario. In addition, the shelter building accounts for about 56 percent of the total capital costs for the 10-gpm flow rate scenario, about 50 percent for the 50-gpm flow rate scenario, and about 45 percent for the 100-gpm flow rate scenario.

For Case 2, total capital costs will be about $764,000 for the 10-gpm flow rate scenario; $776,000 for the 50-gpm flow rate scenario; and $780,000 for the 100-gpm flow rate scenario. Of these costs, only the perox-pure™ system and feed modules are associated with operating the perox-pure™ system. The costs of these components account for about 7 percent of total capital costs for the each flow rate scenario. In addition, the shelter building accounts for about 60 percent of the total capital costs for the 10-gpm flow rate scenario, about 59 percent for the 50-gpm flow rate scenario, and about 58 percent for the 100-gpm flow rate scenario. The cost differences between the two cases are due to lower system costs associated with Case 2.

4.2.4 Startup Costs

Startup costs include the cost of developing a health and safety program. For each case, developing a health and safety program will also include providing a 40-hour health and safety training course. This cost is associated with a groundwater remediation project and is estimated to cost about $5,000.

4.2.5 Labor Costs

Labor costs include the total staff needed for operating and maintaining the perox-pure™ system, conducting an annual health and safety refresher course, and medical monitoring. The labor wage rates provided in this analysis do not include overhead or fringe benefits. Once the system is functioning, it is assumed to operate continuously at the designed flow rate, except during routine maintenance. One operator will monitor the equipment, make any required hydrogen peroxide dose and pH adjustments, perform routine maintenance, and perform routine monitoring and sample analysis. PSI estimates that under normal operating conditions, an operator will be required to work only 3.5 hours per week. However, because finding a person willing to work for this short period of time may be difficult; this analysis assumes that the operator will work 8 hours during the weekdays, and 2 hours, at time and one-half, during each day of the weekend. Annual staff costs for each case will be about $36,000. The annual health and safety refresher course and medical monitoring are associated with a groundwater remediation project and will cost about $3,000 per person.

For each case, total annual labor costs will be about $39,000. Of these costs, about 92 percent is associated with operating the perox-pure™ treatment system.

4.2.6 Consumables and Supplies Costs

Consumables and supplies costs include hydrogen peroxide, sulfuric acid and sodium hydroxide solutions for pH adjustment, cartridge filters, activated carbon columns, disposable personal protective equipment (PPE) and PPE disposal drums, UV lamps, sampling supplies, and propane. Costs of these items are discussed below.

Hydrogen peroxide is commercially available in solutions of 30 to 50 percent by weight. It can be purchased in bulk, delivered to the site when needed, and stored in a 2,000-gallon tank (see Capital Equipment Costs). Hydrogen peroxide has a shelf life of over 1 year and a density of about 10 pounds per gallon. A 50 percent solution can be purchased for about $0.12 per pound including delivery; this cost is associated with operating the perox-pure™ treatment system. The quantities of hydrogen peroxide consumed depend on the system flow rate and the waste characteristics. Based on the SITE demonstration, the annual hydrogen peroxide costs for the 10-gpm flow rate scenario would be about $450 for Case 1 and $300 for Case 2. Annual hydrogen peroxide costs for the 50-gpm flow rate scenario would be about $2,200 for Case 1 and $1,600 for Case 2. For the 100-gpm flow rate scenario, annual hydrogen peroxide costs would be about $4,450 for Case 1 and $3,100 for Case 2.

This analysis assumes sulfuric acid will be used to adjust pH before treatment, and sodium hydroxide will be used to adjust pH after treatment. In addition, this analysis assumes that a 93 percent solution of sulfuric acid can be purchased in bulk, delivered to the site when needed, and stored in a 500-gallon tank (see Capital Equipment Costs). Sulfuric acid has a shelf life of over 1 year and a density of 15 pounds per gallon. It can be purchased for about $0.09 per pound. The quantities of sulfuric acid consumed depend on the flow rate and the initial pH of the contaminated groundwater. Based on the SITE demonstration, annual sulfuric acid costs for the 10-gpm flow rate scenario would be about $600 for each case. Annual acid costs for the 50-gpm flow rate scenario would be about $3,000 for each case. For the 100-gpm flow rate scenario, annual acid costs would be about $6,000 for each case.

Sodium hydroxide solution has a shelf life of over 1 year and a density of 15 pounds per gallon. A 50 percent solution of sodium hydroxide can be purchased for about $0.10 per pound. Based on the SITE demonstration, annual sodium hydroxide costs for the 10-gpm flow rate scenario would be about $2,000 for each case. Annual sodium hydroxide costs for the 50-gpm flow rate scenario would be about $10,000 for each case. For the 100-gpm flow rate scenario, the annual sodium hydroxide costs would be about $20,000 for each case.

This analysis assumes two cartridge filters capable of screening material larger than 3 micrometers will be installed upstream of the perox-pure™ unit and downstream of the sedimentation tank. These filters should remove any suspended solids in the sedimentation tank effluent. Replacement frequency depends on the quality of the groundwater to be treated and the flow rate. However, this analysis assumes one filter will need to be changed every 3 months and is associated with a groundwater remediation project. The dual filter system allows one filter to be used while the other is replaced. For each case, replacement filters will cost about $50 each or $200 per year.

Activated carbon columns on the venting system for the sedimentation and equalization tanks are assumed to be replaced every 6 months and are associated with a groundwater remediation project. For each case, replacement columns cost about $500 each, for a total of $1,000 per year. The actual rate at which these carbon columns will need replacement depends on the concentrations of VOCs in the water being treated.

PPE is associated with a groundwater remediation project and typically consists of nondisposable and disposable equipment. Nondisposable equipment consists of steel-toe boots and a full-face air respirator. For each case, disposable PPE includes latex inner gloves, nitrile outer gloves, and safety glasses. Disposable PPE for each case is assumed to cost about $600 per year for the one operator, regardless of flow rate. Disposable PPE is assumed to be hazardous and will need to be disposed of in 24-gallon fiber drums. Any potentially hazardous wastes will also be disposed of in these drums. One drum is assumed to be filled every 3 months. Drums cost about $12 each. For each case, total annual drum costs will be about $50.

UV lamp usage is associated with operating the perox-pure™ treatment system. PSI warranties its UV lamps for 3,000 hours of use. At this rate, the lamps will need to be changed three times per year. Five-kW lamps cost about $500 each and 15-kW lamps cost about $600. For Case 1, three 5-kW lamps are used during treatment in the 10-gpm unit for a total annual cost of $4,500. Five 15-kW lamps are used in the 50-gpm unit for a total annual cost of $9,000. Ten 15-kW lamps are used in the 100-gpm unit for a total annual cost of $18,000. For Case 2, one 5-kW lamp is used during treatment in the 10- and 50-gpm units for a total annual cost of $1,500. Two 5-kW lamps are used in the 100-gpm unit for a total annual cost of $3,000. PSI will dispose of used UV lamps at no cost.

Sampling supplies are associated with a groundwater remediation project and consist of sampling bottles and containers, ice, labels, shipping containers, and laboratory forms for off-site analyses. For routine monitoring, laboratory glassware will also be needed. The number and types of sampling supplies will be based on the analyses to be performed. Costs for laboratory analyses are presented in the Analytical Services Costs section. For each case, these costs are assumed to be $1,000 per year.

Propane use is associated with a groundwater remediation project and will be needed to heat the shelter building during the colder months of the year. Annual propane usage will be based on the square footage of the shelter building, number of cold days, building materials, and other variables. For each case, propane is assumed to be $3,000 per year.

For Case 1, total consumables and supplies costs are estimated to be $13,000 for the 10-gpm flow rate scenario; $30,000 for the 50-gpm flow rate scenario; and $54,000 for 100-gpm flow rate scenario. Of these costs, feed chemicals and the UV lamps are direct costs of operating the perox-pure™ system. These costs account for about 58 percent of the total consumables and supplies costs for the 10-gpm flow rate scenario, about 81 percent for the 50-gpm flow rate scenario, and about 90 percent for the 100-gpm flow rate scenario. UV lamps account for between 30 and 35 percent of the total consumables and supplies costs. Feed chemicals account for between 23 and 56 percent of the total consumables and supplies costs.

For Case 2, total consumables and supplies costs are estimated to be $10,000 for the 10-gpm flow rate scenario; $22,000 for the 50-gpm flow rate scenario; and $38,000 for 100-gpm flow rate scenario. Of these costs, feed chemicals and the UV lamps are direct costs of operating the perox-pure™ treatment system. These costs account for about 44 percent of the total consumables and supplies costs for the 10-gpm flow rate scenario, and about 73 percent for the 50-gpm flow rate scenario and about 84 percent for the 100-gpm flow rate scenario. Feed chemicals account for between 29 and 77 percent of the total consumables and supplies costs. UV lamps account for between 8 and 15 percent of the total consumables and supplies costs.

The difference in costs between the two cases is attributable to the higher power requirements and, hence, the higher number of UV lamps needed to treat the groundwater characteristics of Case 1.

4.2.7 Utilities Costs

Total utility costs are based on the electrical power used to operate the entire treatment system and all auxiliary equipment including the shelter building. The mercury-vapor UV lamps, which are associated with operating the perox-pure™ unit, draw significant electricity. This analysis assumes that electricity costs about $0.07 per kilowatt-hour (kWh), inclusive of usage and demand charges. In addition, this analysis assumes that all auxiliary equipment, which is associated with a groundwater remediation project, will draw

an additional 30 percent of the total electrical power of the perox-pure™ system.

For Case 1, the 10-gpm unit annually draws about 131,000 kWh, the 50-gpm unit draws about 655,200 kWh, and the 100-gpm unit draws about 1,310,400 kWh. Total annual utility costs for operating the lamps only will be about $9,200, $45,900, and $91,700 for the 10-, 50-, and 100-gpm flow rate scenarios, respectively. Auxiliary equipment usage will cost an additional $2,800, $13,800, and $27,500 for the respective three flow rate scenarios. Operating the perox-pure™ system accounts for about 77 percent of total utility costs for all three flow rate scenarios.

For Case 2, the 10- and 50-gpm units annually draw about 43,680 kWh, and the 100-gpm unit draws about 87,360 kWh. Total annual utility costs for operating the lamps only will be about $3,100 for the 10- and 50-gpm flow rate scenarios, and $6,100 for the 100-gpm flow rate scenario. Auxiliary equipment usage will cost an additional $900 for the 10- and 50-gpm flow rate scenarios, and $1,800 for the 100-gpm flow rate scenario. Operating the treatment system accounts for about 77 percent of total utility costs for all three flow rate scenarios.

The difference in costs between the two cases is attributable to the higher power requirement to operate the UV lamps, needed for treating the groundwater in Case 1.

Electrical costs can vary by as much as 50 percent depending on the geographical location and local utility rates. A diesel gas-powered generator can also be used as a backup or alternate source of electric power, but it will cost considerably more than similar power supplied by local utilities.

4.2.8 Effluent Treatment and Disposal Costs

The perox-pure™ system does not generate sludge or spent carbon that requires further processing, handling, or disposal. Ideally, the end products of the process are water, carbon dioxide, halides, and sometimes organic acids. Effluent monitoring will be conducted routinely by the operator (see Labor Costs). The effluent can be discharged directly to a nearby surface water body, provided the appropriate permits have been obtained (see Permitting and Regulatory Requirements Costs).

4.2.9 Residuals and Waste Shipping and Handling Costs

Spent cartridge filters and PPE drums are associated with a groundwater remediation project. These wastes are considered hazardous and will require disposal at a permitted facility. For each case, this analysis assumes that about six drums will be disposed of annually for the 10- and 50-gpm flow rate scenarios, and eight drums will be disposed of for the 100-gpm flow rate scenario. The cost of shipping, handling, and transporting drums to a hazardous waste disposal facility are assumed to be $1,000 per drum. Total drum disposal costs for each case will be about $6,000 for the 10- and 50-gpm flow rate scenarios and $8,000 for the 100-gpm flow rate scenario.

In addition, filter cake from the filter press is considered hazardous waste and will require disposal at a permitted facility. Because the amount of filter cake generated will vary greatly from site to site, this analysis does not present the costs of filter cake disposal. PSI will dispose of used UV lamps at no cost.

4.2.10 Analytical Services Costs

Analytical costs are associated with a groundwater remediation project and include laboratory analyses, data reduction and tabulation, quality assurance/quality control (QA/QC), and reporting. For each case, this analysis assumes that one sample of untreated water and one sample of treated water will be analyzed for VOCs each month, along with trip blank, duplicate, and matrix spike/matrix spike duplicate samples. Monthly laboratory analyses will cost about $1,250; data reduction, tabulation, QA/QC, and reporting is estimated to cost about $750 per month. Total annual analytical services costs for each case are estimated to be about $24,000 per year.

4.2.11 Maintenance and Modifications Costs

Annual repair and maintenance costs apply to all equipment involved in every aspect of groundwater remediation with the perox-pure™ system. No modification costs are assumed to be incurred. Total annual maintenance costs are estimated to be about 10 percent of capital equipment costs. For Case 1, total annual maintenance costs for the perox-pure™ system are estimated to be about $11,000 for a 10-gpm unit; $18,500 for a 50-gpm unit; and $29,000 for a 100-gpm unit. Total annual maintenance costs for the auxiliary equipment are estimated to be about $10,800 for the 10- and 50-gpm units, and $11,200 for a 100-gpm unit.

For Case 2, total annual maintenance costs for the perox-pure™ treatment system are estimated to be about $5,500 for each flow rate scenario. Total annual maintenance costs for the auxiliary equipment are estimated to be about $10,800 for the 10- and 50-gpm units, and $11,200 for a 100-gpm unit.

The difference in costs between the two cases is attributable to the higher capital equipment costs in Case 1. These costs are higher because more power is required to achieve treatment goals.

4.2.12 Demobilization Costs

Site demobilization includes shutdown, disassembly, transportation, and disposal of perox-pure™ equipment and auxiliary equipment at a licensed hazardous waste disposal facility. This analysis assumes the perox-pure™ system will have no salvage value at the end of the project. Site cleanup and restoration are also included in demobilization costs. For each case, this analysis assumes the costs from shutdown to disposal for all activities associated with a groundwater remediation project will be about $30,000, including site cleanup, restoration, and building decontamination. This analysis assumes the shelter building will remain standing at the site. All disposal activities associated with operating the perox-pure™ system are estimated to be about $10,000. For each case, demobilization is estimated to take about 1 week to complete and will cost a total of about $40,000.

The costs of demobilization, however, will occur at the end of the remediation project. To complete the project, this analysis assumes that the 10-gpm unit will be used for 50 years, the 50-gpm unit will be used for 10 years, and the 100-gpm unit will be used for 5 years. Therefore, based on the annual inflation rate of 5 percent, the net future values of this cost for 10-gpm, 50-gpm, and 100-gpm units are estimated to be about $459,000; $65,000; and $51,000, respectively. These figures were used to calculate the total costs for a groundwater remediation project presented in Tables 4-1 and 4-2.

Section 5
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Appendix A
Vendor Claims for the Technology

A.1 Introduction

Because 50 percent of U.S. drinking water is obtained from groundwater resources, the removal of contaminants from polluted groundwater has become a major environmental priority. Increasing groundwater pollution has been caused by leaking underground fuel and chemical storage tanks, accumulations of pesticides and herbicides, landfill leachates, and improper handling and disposal of industrial chemicals and wastewater effluent. Contaminants often migrate through soil into municipal water wells, aquifers, and other water resources. The U.S. Environmental Protection Agency has identified 129 priority organic contaminants; with such diversity in molecular structure and chemical properties, these contaminants present a challenge to traditional treatment technologies.

The perox-pure™ advanced chemical oxidation system, developed by Peroxidation Systems, Inc. (PSI), of Tucson, Arizona, provides an on-site treatment process that destroys contaminants in groundwater and wastewater. The patented system design has been used to meet the most stringent federal and state groundwater cleanup regulations.

Since it entered the market in 1987, the perox-pure™ system has been used on site to treat organic contamination in groundwater at approximately 80 locations in the United States, Canada, Puerto Rico, and Europe. The perox-pure™ system has been used to treat groundwater, wastewater, leachate, dredge water, bioeffluent, and municipal water contaminated with volatile organic compounds, semivolatile organic compounds, aromatic compounds, polynuclear aromatic hydrocarbons, phenols, petroleum hydrocarbons, and a number of other organic compounds.

A.2 Description of the perox-pure™ System

The perox-pure™ system rapidly breaks the bonds between atoms in organic molecules, thereby allowing the atoms to form simpler, nontoxic compounds, such as carbon dioxide and water. In the perox-pure™ system, water pumped from a contaminated source is combined with hydrogen peroxide, a chemical oxidant. Hydrogen peroxide is preferred to ozone as a chemical oxidant, because ozone is not very soluble in water, which results in long oxidation times. The higher solubility of hydrogen peroxide in water greatly simplifies the reactor design in terms of oxidant addition, mixing of reactants, and reduction of toxic gas emissions. Hydrogen peroxide is commercially available in solutions of 30 to 50 percent by weight. Systems using hydrogen peroxide also require significantly less storage and feed equipment and are less expensive relative to those using ozone, because ozone must be generated on site. Finally, because ozone is a toxic gas, it requires a special gas phase decomposition system and an air discharge permit.

The mixture of contaminated water and hydrogen peroxide passes through a series of reactor chambers that expose it to high intensity ultraviolet (UV) lamps mounted inside protective quartz tubes. Inside each of the UV lamp chambers, a photochemical reaction occurs that forms highly reactive hydroxyl radicals (OH•) from hydrogen peroxide (see Table A-1). Energy from the UV lamps absorbed by the target compounds also increases the compounds' oxidation rate.

Hydrogen peroxide injection points at the inlet of each lamp section allow hydrogen peroxide to be added to each reactor separately. This arrangement, called the splitter, aids the operator in maintaining the ideal balance of hydroxyl radicals.

Hydroxyl radicals destroy the bonds in organic contaminants between carbon and the attached groups of atoms, forming simpler, nontoxic chemical compounds. The treated water exits the system at the top of the reactor chambers. The only additive to the system, hydrogen peroxide, is consumed in the process, and the system generates no air emissions or by-products that require disposal.

The perox-pure™ system is effective in treating a variety of organic compounds present in contaminated waters and is not limited by mass transfer, as are liquid-phase carbon adsorption and air stripping.

Table A-1 Oxidation Potential of Oxidants

Relative Oxidation Power Chlorine = 1.00	Oxidative Species	Potential (Volts)
2.23	Fluorine	3.03
2.06	Hydroxyl Radical	2.80
1.78	Atomic Oxygen	2.42
1.52	Ozone	2.07
1.31	Hydrogen Peroxide	1.78
1.25	Perhydroxyl Radical	1.70
1.24	Permanganate	1.69
1.17	Hypobromous Acid	1.59
1.15	Chlorine Dioxide	1.56
1.10	Hypochlorous Acid	1.50
1.07	Hypoiodous Acid	1.46
1.00	Chlorine	1.36
0.80	Bromine	1.09
0.54	Iodine	0.73

A.3 perox-pure™ Systems

The perox-pure™ systems are compact and designed to operate unattended on a continuous basis. The skid-mounted unit consists of a control panel, lamp drive enclosures, and a reactor chamber. An accompanying hydrogen peroxide module is also skid-mounted and provides storage, feed pumps, and an eye wash station and safety shower. For sites where pH adjustment of influent wastewater or effluent is necessary, a skid-mounted acid feed module or base feed module is used in addition to the equipment listed above.

The combined use of UV lamps and hydrogen peroxide results in improved reaction rates. Moreover, a smaller, simpler design is possible, which reduces space requirements, the number of potential replacement parts, and corresponding maintenance costs.

PSI can supply perox-pure™ units in various sizes. PSI has designed, built, and installed systems capable of treating flow rates varying from 5 gallons per minute to thousands of gallons per minute. The unit size required for a particular application is determined through laboratory treatability studies and on-site tests.

A diagram of the perox-pure™ unit is shown in Figure A-1. The perox-pure™ oxidation unit consists of multiple horizontal sections connected in series. Inside each section, one high intensity, medium-pressure UV lamp is mounted inside a quartz tube. The lamp and tube assembly are positioned perpendicular to the side walls of the chamber.

A.4 Design Improvements

The advanced design of current perox-pure™ systems decreased the costs of earlier systems by 50 percent or more. Improvements include an innovative reactor design, anticorrosion lining in the reactors, better conversion efficiencies from electrical power to UV energy, and improved methods for sequential hydrogen peroxide addition. Engineering design improvements also make it easier to adjust such parameters as flow rate, pH, UV energy, and the addition of hydrogen peroxide to individual reactor chambers to maximize destruction rates. An optional programmable logic controller can be installed to integrate the system into a fully automated remote treatment system.

Advanced perox-pure™ systems include a patented, automated, self-cleaning mechanism for the UV lamps that virtually eliminates the scaling of the quartz tubes. The cleaning mechanism consists of a wiper that fits in the annular space between the quartz tube and the oxidation chamber wall. Propelled by water being treated in the system, the wiper regularly removes deposits from the quartz tubes. As a result, costs associated with unscheduled maintenance to the system have been substantially reduced.

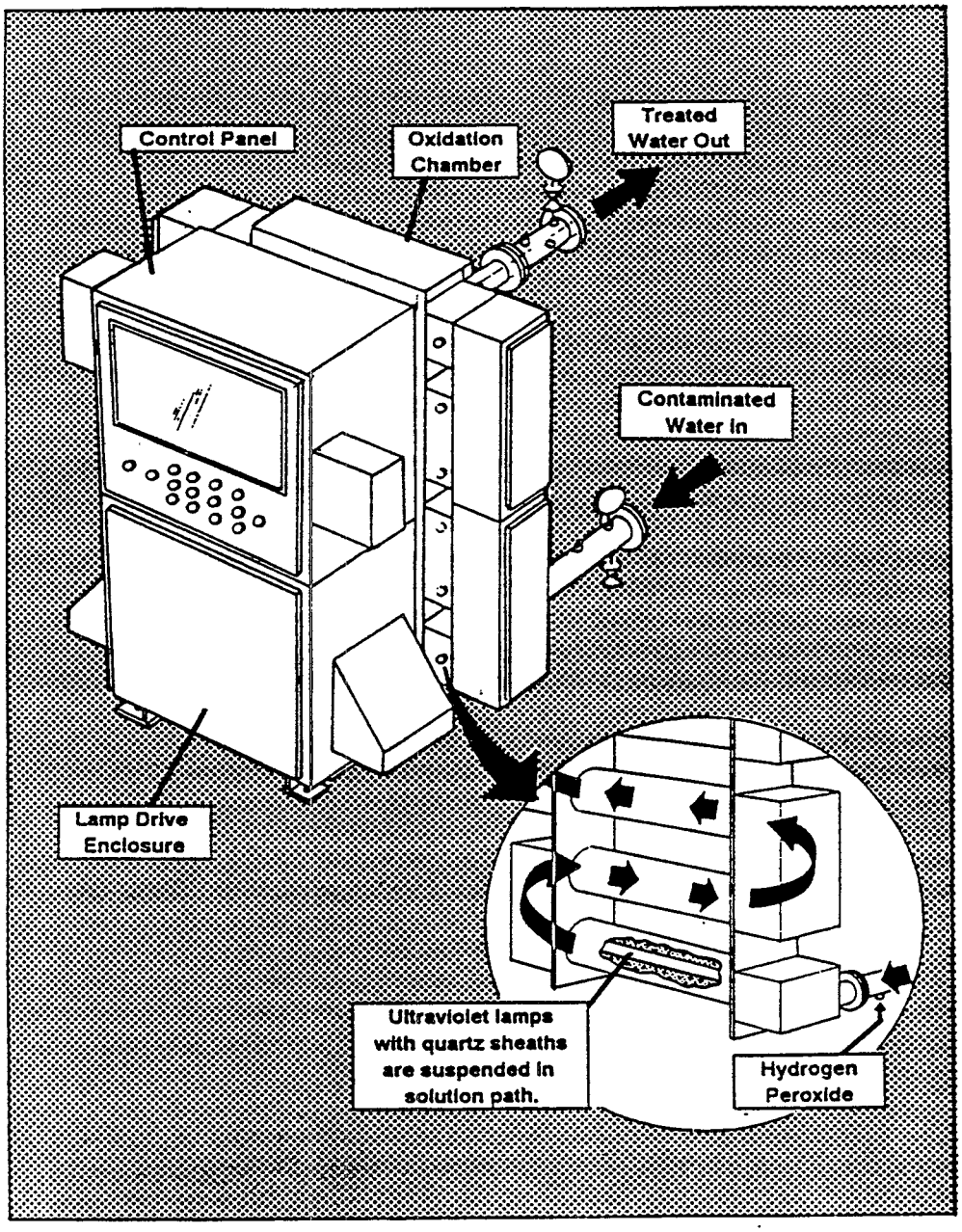

Figure A-1 Isometric Diagram of perox-pure™ Unit

These engineering improvements have transformed the perox-pure™ system into an efficient, low maintenance, and highly reliable advanced oxidation system that is cost competitive with carbon adsorption and air stripping technologies.

A.5 Pretreatment

A pretreatment system is sometimes needed to reduce the levels of certain inorganic species in the water. If high levels of suspended solids or turbidity are present, filtration and clarification may be required to provide optimum treatment. Acid can also be added to increase treatment efficiency by shifting the equilibrium from carbonate and bicarbonate species to carbonic acid.

A.6 perox-pure™ Applications

Although a broad spectrum of aqueous wastes can be treated with the perox-pure™ technology, the most common application is for water containing less than 500 milligrams per liter of organic compounds. Higher concentrations can be treated; however, the longer oxidation times needed to treat higher concentrations may require batch or partial recycle treatment. In addition, treated water may need to be cooled to keep it from overheating the system. A partial list of applications of the perox-pure™ technology is shown in Table A-2.

While the chemistry of the perox-pure™ technology has a number of complex interactions which depend on the characteristics of the water, a large database is available from which initial predictions can be made.

To determine if the perox-pure™ system is applicable to a specific contamination problem, a team of application specialists is available at the PSI corporate headquarters in Tucson, Arizona (800-552-8064). After gathering the information available from the potential user, the application specialists can assess the general applicability of the perox-pure™ technology and, in most cases, provide an estimate of the capital and operating costs for perox-pure™ technology. If requested, written estimates are prepared which document the figures and provide information on the available perox-pure™ systems and services.

PSI requires the following information to evaluate the application of the perox-pure™ technology:

- Contaminated water flow rate or production rate
- Identities and concentrations of organic contaminants
- Treatment objectives

Other information that allows PSI to provide a more reliable estimate of treatment includes the following:

- Source of contaminated water
- Identity and concentrations of inorganics such as iron, chloride, and nitrate
- Levels of total organic carbon, chemical oxygen demand, pH, alkalinity, dissolved solids, turbidity, color, and suspended solids
- Current treatment and pretreatment systems in use

The estimates provided by PSI are intended to be used to determine if the perox-pure™ technology is an economically feasible method of treatment compared with the costs of other potential treatment processes. Since the water quality has such a significant impact on the perox-pure™ system performance, a process assessment at the PSI Testing Laboratory, or in the field, with an actual sample of the water is necessary to provide definitive treatment cost projections.

A.7 Advantages over Carbon Adsorption and Air Stripping Technologies

The perox-pure™ advanced chemical oxidation technology has demonstrated major advantages over carbon adsorption and air stripping technologies. From a regulatory perspective, the major advantage of the perox-pure™ technology is that it creates no secondary pollutants to treat or haul away. This benefit has become more important as federal, state, and local regulations become more stringent regarding the allowable contaminant concentrations of air emissions generated using air stripping as well as the disposal of secondary pollutants such as spent carbon. These regulations have increased the costs of monitoring and disposal as well as the risk of legal liability associated with treatment technologies. The perox-pure™ technology greatly reduces the risk of future liability associated with the creation of secondary pollutants.

The perox-pure™ technology is advantageous for treating contaminated groundwater in residential neighborhoods and highly technical industrial complexes because the system offers a low-profile, on-site treatment that produces minimal noise. In addition, the perox-pure™ systems are very compact and can be positioned among existing equipment. As a result, public relations problems are minimized.

The perox-pure™ technology is ideal for those applications where carbon adsorption and air stripping are not viable. For example, some priority pollutants, such as methyl-tert-butyl ether, vinyl chloride, and methylene chloride, are not readily adsorbed by carbon. Many common organic contaminants, such as isopropyl alcohol and acetone,

Table A-2 Partial List of perox-pure™ Technology Applications

Waste Stream	*Principal Contaminants*[a]	*Site Location*
Bioeffluent	*Chlorobenzene*	*Connecticut*
Dredge Water	*Polychlorinated Biphenyls*	*Massachusetts*
Effluent	*BTX*	*California*
	Phenol	*New Jersey*
	MeCl, Phenol, PAH	*North Carolina*
	Nitrated Esters	*Pennsylvania*
	Phenol	*Pennsylvania*
	Phenols, Nitrophenols	*Texas*
	IPA, TOC, TCA, DCE, MEK	*Utah*
Groundwater	*Acrylic Acid, Butyl Acrylate*	*Arizona*
	BTEX	*Arizona*
	TCE	*Arizona*
	BTX	*California*
	BTX	*California*
	TCA, Freon, MeCl, BTX	*California*
	TCA, TCE	*California*
	TCE	*California*
	TCE, PCE, BTX, TCA	*California*
	TCE, PCE, DCE, TCA, MeCl, Chloroform	*California*
	TCE, PCE, TCA, DCE	*California*
	TCE, TCA, CCl_4, MeCl	*California*
	TCE, TCA, PCE, DCE	*California*
	Tetrahydrofuran	*California*
	BTX	*Colorado*
	TCE, PAHs	*Louisiana*
	TCE, PCE, TCA, DCE	*Maryland*
	BTX	*Massachusetts*
	MeCl, TCA	*Massachusetts*
	TCE, DCE, PCE, MeCl	*New Jersey*
	TCE, DCE, PCE, TCA	*New York*
	Pentachlorophenol	*Washington*

Table A-2 Partial List of perox-pure™ Technology Applications (continued)

Waste Stream	Principal Contaminants[a]	Site Location
Leachate	Mixed Organic Acids, Ketones, and VOCs	New Hampshire
Municipal Water	Humic Acid/Color Control	California
Recycle	Chemical Oxygen Demand	Arizona
	Bacteria, Phenol, Formaldehyde	Ohio
Miscellaneous	Hydrazine	Colorado
	Hydrazine, DIMP	Colorado

Notes:

[a] *Acronyms used in this table are defined as follows:*

BTEX	Benzene, toluene, ethylbenzene, and xylene
BTX	Benzene, toluene, and xylene
CCl_4	Carbon tetrachloride
DCE	Dichloroethene
DIMP	Diisopropyl methylphosphonate
IPA	Isopropyl alcohol
MeCl	Methylene chloride
MEK	Methyl ethyl ketone
PAH	Polynuclear aromatic hydrocarbon
PCE	Tetrachloroethene
TOC	Total organic carbon
TCE	Trichloroethene
TCA	Trichloroethane
VOC	Volatile organic compound

are not removed by air stripping. The perox-pure™ technology provides reliable, consistent destruction of these contaminants.

A.8 Other Advantages

To minimize capital investment and avoid an unreasonably long-term commitment to the treatment process, PSI offers a 5-year plan in which equipment, maintenance, technical services, and hydrogen peroxide are provided in one monthly fee. This plan allows customers to accurately budget costs over the life cycle of the project, and it allows PSI to respond to changing regulations on behalf of the client and initiate process changes and improvements as needed. In some cases, the monthly fee has been reduced as the process or water quality has improved.

A.9 Technology Combinations

In many water treatment systems, the perox-pure™ technology has been paired with carbon adsorption, air stripping, or biological treatment. Depending on the water quality and treatment objectives, the perox-pure™ technology can be combined with other technologies to produce a more cost-effective solution than is achieved with any single process.

Appendix B
SITE Demonstration Results

In April 1991, the U.S. Environmental Protection Agency (EPA) learned that Peroxidation Systems, Inc. (PSI), was contracted by Lawrence Livermore National Laboratory (LLNL) to perform pilot-scale chemical oxidation studies as part of remediation activities at the LLNL site. At that time, EPA and PSI discussed the possibility of PSI participating in the Superfund Innovative Technology Evaluation (SITE) program to demonstrate how PSI's perox-pure™ chemical oxidation technology could be used to treat contaminated groundwater at LLNL Site 300 in Tracy, California. EPA subsequently accepted the perox-pure™ technology into the SITE demonstration program. Through a cooperative effort between the EPA Office of Research and Development (ORD), EPA Region IX, LLNL, and PSI, the perox-pure™ technology was demonstrated at the LLNL site under the SITE program. This appendix briefly describes the LLNL site and summarizes the SITE demonstration activities and demonstration results.

B.1 Site Description

LLNL is a 640-acre research facility about 45 miles east of San Francisco and 3 miles east of Livermore, California (see Figure B-1). Development of the site began in 1942, when it was used as a U.S. Navy aviation training base. Subsequent activities at LLNL varied considerably under the management of several government agencies, including the Atomic Energy Commission, the Energy Research and Development Agency, and the U.S. Department of Energy, which is the present owner. Various hazardous materials, including volatile organic compounds (VOC), metals, and tritium were used and released at the site.

The SITE demonstration was conducted at Site 300, which is operated by LLNL but is located separately from the LLNL main campus (see Figure B-1). LLNL established Site 300 as a high-explosives test area in 1955. Site 300 occupies 11 square miles in the Altamont Hills about 15 miles southeast of Livermore and 8.5 miles southwest of Tracy, California. Site 300 operations consist of four activities: (1) hydrodynamic testing; (2) charged particle-beam research; (3) physical, environmental, and dynamic testing; and (4) high-explosive formulation and fabrication.

EPA chose a specific area of Site 300 for the technology demonstration. This area is called the General Services Area (GSA). The GSA occupies about 80 acres in the southeastern corner of Site 300. Various administrative, medical, engineering, and maintenance operations are conducted in buildings located in the GSA. Before 1982, several GSA facilities used dry wells to dispose of waste rinse, process, and wash waters. Wastes from these facilities might have included the following: photo laboratory rinse water; water- and oil-based paint waste; automotive shop waste containing degreasing solvents; and acid dip rinse water. Between 1983 and 1984, the dry wells were investigated and closed. After the dry well closure, wastewater from these activities was shipped off site for treatment and disposal. Other wastes are currently stored on site in a permitted hazardous waste storage area. The suspected sources of groundwater contamination in the GSA are the dry wells, accidental releases and leaks during facility operations, and leaking underground fuel storage tanks.

LLNL's Environmental Restoration Division submitted a remedial investigation (RI) report and a feasibility study (FS) report to EPA Region IX in May and December 1990, respectively. The FS report outlined a treatment system for contaminated groundwater from the central GSA. The system will be designed to treat both vapor and groundwater obtained from extraction wells in the area. Groundwater will be collected both on and off site for remediation. Currently, several treatment alternatives are being evaluated at the site.

B.2 Site Contamination Characteristics

Dry wells, accidental releases and leaks during facility operations, and leaking underground fuel storage tanks are suspected sources of groundwater contamination in the central GSA. Data from the RI report (LLNL, 1990) were used to select the shallow aquifer at the site as the candidate waste stream for the technology demonstration.

In May 1992, LLNL performed an 8-hour drawdown pump test using existing groundwater extraction wells. The groundwater was sampled throughout the test and analyzed for VOCs, semivolatile organic compounds (SVOC), metals,

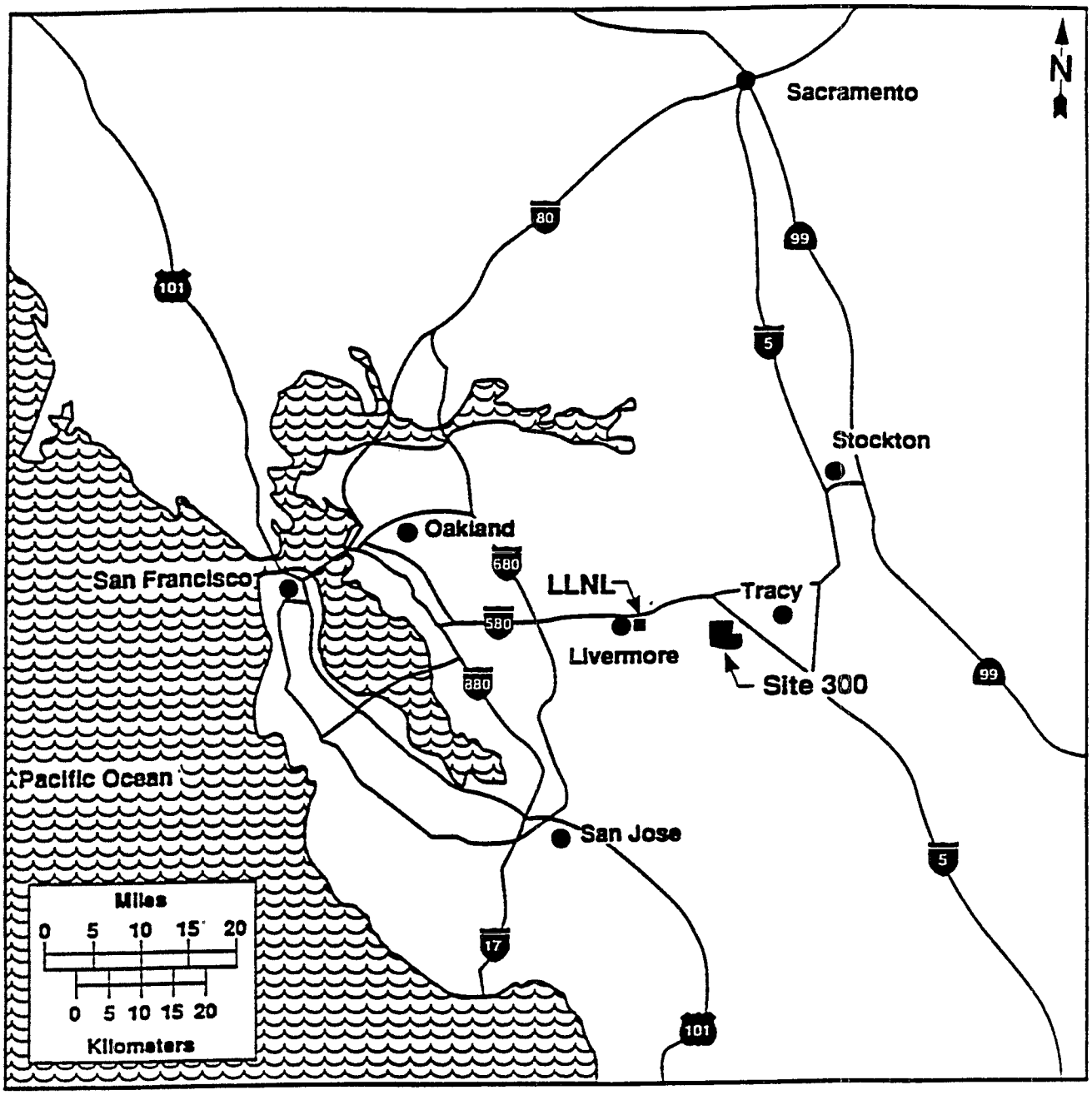

Figure B-1 LLNL Site Location

and a variety of other parameters, such as pH and alkalinity. Samples for VOC and SVOC analyses were collected after approximately 1, 3, 6, and 8 hours of pumping time. These analyses showed that (1) only five VOCs were present above detection limits, (2) SVOCs were not present above detection limits, and (3) all five VOCs detected showed gradual decreases in concentration over the 8-hour test duration. At the end of 8 hours, trichloroethene (TCE); tetrachloroethene (PCE); 1,1-dichloroethene (1,1-DCE); 1,2-dichloroethene (1,2-DCE); and 1,1,1-trichloroethane (TCA) were present at 1,200 micrograms per liter (μg/L), 95 μg/L, 7.1 μg/L, 8.7 μg/L, and 7.5 μg/L, respectively.

The following parameters were also measured in the groundwater samples collected after 6 hours of pumping: (1) pH was 7.8; (2) alkalinity was 300 milligrams per liter (mg/L) as calcium carbonate; (3) the concentration of total dissolved solids was 930 mg/L; (4) the concentration of iron was 10 μg/L, and (5) the concentration of manganese was 20 μg/L.

B.3 Review of SITE Demonstration

The SITE demonstration was divided into three phases: (1) site preparation; (2) technology demonstration; and (3) site demobilization. These activities and a review of technology and perox-pure™ system performance during the phases are described below.

B.3.1. Site Preparation

Approximately 10,000 square feet of relatively flat ground surface was used for the perox-pure™ chemical oxidation system and support equipment and facilities, such as treated and untreated water storage tanks, nonhazardous and potentially hazardous waste storage containers, an office and field laboratory trailer, and a parking area. A temporary enclosure covering approximately one-fourth of the demonstration area was erected to provide shelter for the perox-pure™ system during inclement weather. Site preparation included setting up major support equipment, on-site support services, and utilities. These activities are discussed below.

Major Support Equipment

Support equipment for the perox-pure™ system demonstration included a cartridge filtration system to remove suspended solids from groundwater, storage tanks for untreated and treated groundwater, an acid feed module for untreated groundwater, a base feed module for treated groundwater, a spiking solution feed system, a static mixer, two 55-gallon drums for collecting equipment wash water and decontamination rinse water, a dumpster, a forklift with operator, pumps, sampling equipment, health- and safety-related gear, and a van. Specific items included the following:

- One cartridge filtration system containing two filters upstream of the treatment unit; the filters were capable of removing suspended solids greater than 3 micrometers in size from groundwater.
- One 55-gallon closed-top, polyethylene drum containing spiking solution; the drum was equipped with a floating lid and a mixing device. During the demonstration, a spiking solution containing chloroform; 1,1-dichloroethane (DCA); and TCA was added inline to the groundwater to evaluate the perox-pure™ system's ability to treat compounds that are difficult to oxidize.
- One static mixer to mix the spiking solution and groundwater before the mixture entered the untreated groundwater storage tank
- One 7,500-gallon bladder tank to store untreated groundwater and minimize VOC losses during storage. The tank was used (1) as an equalization tank and (2) as a storage tank for a few demonstration runs performed at flow rates greater than the groundwater yield.
- One pump for transferring contaminated water from the bladder tank to the perox-pure™ system and one pump for adding spiking solution inline to the groundwater
- One sulfuric acid feed module to adjust the pH of the influent to the perox-pure™ system; PSI provided the module, which consisted of a 55-gallon acid feed drum, two pumps, and flow measuring devices.
- One sodium hydroxide feed module to adjust the pH of the effluent from the perox-pure™ system; PSI provided the module, which consisted of a 55-gallon base feed drum, two pumps, and flow measuring devices.
- One solid waste dumpster to store nonhazardous wastes before disposal
- A number of 55-gallon drums to contain used disposable field sampling and analytical equipment, used disposable health and safety gear, and field laboratory wastes before disposal
- A forklift with operator for setting up equipment and for moving drummed wastes
- Sampling equipment for aqueous media and process chemical solutions

- Analytical equipment for measuring field parameters at the demonstration site

- Two 20,000-gallon steel tanks to store treated groundwater before analysis and disposal

- Health and safety-related equipment, such as a first-aid kit and protective coveralls, latex or similar inner gloves, nitrile outer gloves, steel-toe boots and disposable overboots, safety glasses, and a hard hat

- A van to transport oversight personnel and supplies

On-Site Support Services

On-site laboratory analyses were conducted in a field trailer measuring 12 by 44 feet. The field trailer also served as an office for field personnel and provided shelter and storage for small equipment and supplies. Two toilets were available near the demonstration area.

Utilities

Utilities required for the demonstration included water, electricity, and telephone service. Water was required for equipment and personnel decontamination, for field laboratory use, and for drinking purposes. During operation of the demonstration unit, personnel and equipment decontamination required about 10 gallons per day (gpd) of potable water. About 5 gpd of distilled, deionized water was needed for field laboratory use, and about 5 to 10 gpd were needed for drinking water.

Electricity was needed for the perox-pure™ system, the office trailer, and the laboratory equipment. The perox-pure™ system required 480-volt, 3-phase electrical service. Additional electrical power (110-volt, single-phase) was needed for operating the pumps, the mixing device in the spiking solution feed system, the office trailer lights, and the on-site laboratory and office equipment.

Telephone service was required mainly for ordering equipment, parts, reagents, and other chemical supplies; scheduling deliveries; and making emergency communications. LLNL provided most of the support required to arrange utilities for the demonstration.

B.3.2 Technology Demonstration

This section discusses (1) operational/equipment problems and (2) health and safety considerations associated with the SITE demonstration.

Operational/Equipment Problems

The SITE team, consisting of EPA's contractors, experienced a few operational/equipment problems during the demonstration. Some of these problems resulted in changes in the demonstration schedule, while the others required making decisions in the field to solve the problems. These problems and solutions include the following:

- Based on the 8-hour drawdown test performed in May 1992, LLNL estimated that during the demonstration, contaminated groundwater could be extracted from Wells W-7-O and W-875-08 at approximately 9 gallons per minute (gpm) and 3 gpm, respectively. The demonstration tests were designed assuming that the combined stream would be the influent to the perox-pure™ system. However, based on observations made in early September 1992, LLNL informed the SITE team that the wells might not provide the estimated yield throughout the demonstration. The SITE team resolved this issue by reducing the extraction rates from both wells in the same proportion, so that the influent characteristics would be approximately the same as those estimated before the demonstration. The SITE team extracted groundwater from Wells W-7-O and W-875-08 at 6 gpm and 2 gpm, respectively. This approach did not affect the demonstration schedule or the technology evaluation.

- PSI requested that one of its operating facilities ship three scaled and three clean quartz tubes to perform Phase 3 test runs. However, of the six quartz tubes, one tube was broken in transit. PSI did not have enough time to replace the broken tube. Therefore, Phase 3 tests (Runs 13 and 14) were performed using only two ultraviolet (UV) lamps, instead of three. As a result, perox-pure™ system performance with scaled tubes and clean tubes was compared based on the removals achieved in two reactors, instead of those achieved in three reactors.

- Late arrival of the perox-pure™ system (particularly the hydrogen peroxide feed tank) and other auxiliary equipment (such as the bladder tank, pumps, and other miscellaneous items) delayed the technology demonstration by 3 days. However, the SITE team completed the demonstration on schedule by working late evenings and weekends.

- At the beginning of the demonstration, while setting the operating parameters, water inside the oxidation unit overheated and burned the gaskets that maintain a water-tight seal in two of the reactors. As a result, water leaked out of the treatment unit,

which PSI collected in a 55-gallon drum. PSI explained that because of its oversight a few pneumatically operated valves did not have an air supply, resulting in a stagnant volume of water that overheated. PSI also stated that the temperature sensor inside the unit, which is located in the top reactor, did not detect the high water temperature because the unit was only partially filled. Later, PSI connected an air compressor to the unit to avoid reoccurrence of this situation. Replacement gaskets arrived the following day, causing the demonstration to be postponed 1 day.

- During the initial stage of the demonstration, due to improper operation of valves downstream of the perox-pure™ system, the pressure inside the perox-pure™ unit exceeded the design limit and the pressure relief gasket gave way. PSI immediately collected the leaking water in a drum and shut off the influent. Because PSI had a replacement gasket on site, this operational problem did not cause a significant delay.

- Halfway through the demonstration, while one test run was in progress, the sulfuric acid level in the acid feed tank decreased significantly. As a result, the influent pH could not be lowered to the desired level, and the SITE team discontinued the run. The run was repeated after PSI filled the acid feed tank with sulfuric acid.

- Flow rates through the perox-pure™ system for Runs 7 and 8 were planned to be 50 gpm. In order to maintain the preferred influent pH of approximately 5, the system flow rate was reduced to 40 gpm. PSI's acid feed pumps were not capable of providing enough acid to the process flow to increase the system flow rate. This deviation did not alter the selection of preferred conditions from Phase 1 of the technology evaluation despite the increased hydraulic retention time (inversely proportional to flow rate) resulting from the change in flow rate.

- The SITE team initially encountered problems measuring the effluent pH at the sampling location downstream of the sodium hydroxide addition point. Because no static mixer was used, sodium hydroxide added to raise the effluent pH did not adequately mix with the effluent. Lack of proper mixing caused problems in measuring the true effluent pH after sodium hydroxide addition. The SITE team resolved this issue by installing another sampling port about 100 feet downstream, just before the treated water entered the storage tanks. This modification significantly reduced fluctuations in pH and provided a good measure of effluent pH.

Health and Safety Considerations

In general, potential health hazards associated with the demonstration resulted from the possibility of exposure to contaminated groundwater and process chemicals, including hydrogen peroxide, sulfuric acid, and sodium hydroxide solutions. Although the treatment system was entirely closed, potential routes of exposure during the demonstration included inhalation, ingestion, and skin and eye contact from possible splashes or spills during sample collection.

All personnel working in the demonstration area had, at a minimum, 40 hours of health and safety training and were under routine medical surveillance. Personnel were required to wear protective equipment appropriate for the activity being performed. Steel-toe boots were required in the exclusion zone. Personnel working in direct contact with contaminated groundwater and process chemicals wore modified Level D protective equipment, including safety shoes, latex inner gloves, nitrile outer gloves, and safety glasses.

B.3.3 Site Demobilization

After the demonstration was completed and on-site equipment was disassembled and decontaminated, equipment and site demobilization activities began. Equipment demobilization included loading the skid-mounted units on a flat-bed trailer and transporting them off site, returning rented support equipment, and disconnecting utilities.

Decontamination was necessary for the perox-pure™ unit, the storage tanks, and field sampling and analytical equipment. Demonstration equipment was either cleaned with potable water or steam, as required. The treated water collected during the demonstration was tested, and the results were provided to LLNL. LLNL disposed of this water appropriately. LLNL also disposed of all hazardous wastes at a permitted landfill. All nonhazardous wastes were routinely disposed of along with similar wastes generated by LLNL.

B.4 Experimental Design

The technology demonstration had the following primary objectives: (1) determine VOC removal efficiencies in the treatment system under different operating conditions, (2) determine whether treated water met applicable disposal requirements at the 95 percent confidence level, and (3) gather information necessary to estimate treatment costs, including process chemical dosages and utility requirements. The secondary objective for the technology demonstration was to obtain preliminary information on the type of by-products formed during the treatment. To accomplish these objectives, the following test approach and sampling and analytical procedures were used.

B.4.1 Testing Approach

The perox-pure™ chemical oxidation technology was demonstrated over a 3-week period in September 1992. During the demonstration the perox-pure™ unit treated about 40,000 gallons of groundwater contaminated with VOCs. Principal groundwater contaminants included TCE and PCE, which were present at concentrations of about 1,000 and 100 μg/L, respectively. Groundwater was pumped from two wells into a 7,500-gallon bladder tank to minimize variability in influent characteristics. In addition, cartridge filters were used to remove suspended solids greater than 3 micrometers in size from the groundwater before it entered the bladder tank. Treated groundwater was stored in two 20,000-gallon steel tanks before being discharged.

The technology demonstration was conducted in three phases (see Table B-1). Phase 1 consisted of eight runs of raw groundwater, Phase 2 consisted of four runs of spiked groundwater, and Phase 3 consisted of two runs of spiked groundwater to test the effect of quartz tube cleaning. These phases are described below.

The principal operating parameters for the perox-pure™ system include hydrogen peroxide dose, influent pH, and flow rate, which determines the hydraulic retention time. These parameters were varied during Phase 1 to observe treatment system performance under different operating conditions. For Phase 1 runs, the initial operating conditions were based on groundwater characterization performed by LLNL in May 1992 and PSI's professional judgment and experience. In Runs 1, 2, and 3 the influent pH was varied while the other parameters were held constant to determine preferred operating conditions. The preferred operating conditions were those under which the concentration of effluent VOCs would be reduced below target levels (see Table B-2) for spiked groundwater. After the preferred value for pH was determined, that value was held constant, while the other parameters were varied. Preferred operating conditions for each parameter were determined based on quick turnaround analytical data for three selected indicator VOCs: TCE, PCE, and TCA. Even though TCE and PCE are easily oxidized, they were chosen because they were present in relatively high concentrations. TCA was chosen because it is relatively difficult to oxidize, although it was present at a low concentration. Based on quick turnaround analytical data, PSI selected Run 3 operating conditions as the preferred operating conditions for spiked groundwater.

Phase 2 involved spiked groundwater and reproducibility tests. Groundwater was spiked with sufficient chloroform, DCA, and TCA so that the spiked groundwater contained about 200 to 300 μg/L of each of these VOCs. These compounds were chosen because they are relatively difficult to oxidize and because they were not initially present in the groundwater at high concentrations. Phase 2 increased the applicability of the demonstration data to other sites that may be contaminated with VOCs that are difficult to oxidize. Phase 2 was also designed to evaluate the reproducibility of perox-pure™ system performance at the preferred operating conditions determined in Phase 1. Specifically, Runs 10, 11, and 12 were performed at Run 3 conditions to evaluate the reproducibility of perox-pure™ system's performance.

During Phase 3, the effectiveness of the quartz tube wipers was evaluated by performing two runs using spiked groundwater at the preferred operating conditions. The quartz tubes used in Phase 3 tests were obtained from a hazardous waste site where the water hardness and iron content caused scaling on the quartz tubes. PSI obtained two sets of quartz tubes for Phase 3 tests. One set of quartz tubes was relatively clean, because the wipers were routinely used to minimize scaling. The other set of tubes had significant scaling because wipers were not used. Because only two tubes of each type (scaled and clean) were available, only two reactors were used during Phase 3. Specifically, Run 13 was performed using scaled quartz tubes, while Run 14 was performed using clean quartz tubes. In both runs only two UV lamps were used.

B.4.2 Sampling and Analytical Procedures

Liquid samples were collected from the perox-pure™ treatment system at the locations shown in Figure B-2. Table B-3 lists analytical and measurement methods used during the demonstration. Total organic halides (TOX) and adsorbable organic halides (AOX) listed in Table B-3 were added to the analyte list as requested by German Federal Ministry of Research and Technology, under a U.S.-German bilateral technology transfer program. The following parameters were considered critical for evaluating the perox-pure™ technology: (1) VOC, hydrogen peroxide, and acid concentrations; and (2) flow rate and pH. VOCs were measured by both gas chromatography (GC) and GC/mass spectrometry (MS) methods. Only GC measurement of VOCs was considered critical, because GC data were planned for quantitative use; GC/MS data were planned for qualitative use.

Because the perox-pure™ technology was developed to treat organics, and because VOCs were the principal contaminants in groundwater, four replicate samples were collected for GC analysis of VOCs. For other analytes, the number of samples was based on (1) the intended use of the data, (2) analytical costs, (3) sampling time, and (4) the discretion of analytical laboratory. EPA-approved sampling, analytical, quality assurance, and quality control (QA/QC) procedures were followed to obtain reliable data. Details on QA/QC procedures are presented in the demonstration plan (PRC, 1992).

Table B-1 Experimental Matrix for perox-pure™ Technology Demonstration

Run Number	Influent pH	Hydrogen Peroxide at Influent to Reactor 1 (mg/L)	Hydrogen Peroxide at Influent to Reactors 2 to 6 (mg/L)	Flow Rate (gpm)
		Phase 1 (Raw Groundwater Runs)		
1	8.0	40	25	10
2	6.5	40	25	10
3	5.0	40	25	10
4	5.0	70	50	10
5	5.0	30	15	10
6	5.0	240	Hydrogen Peroxide was added at Influent to Reactor 1 only	10
7	5.0	240		40
8	5.0	60		40
		Phase 2 (Spiked Groundwater and Reproducibility Runs)		
9	5.0	70	50	10
10	5.0	40	25	10
11	5.0	40	25	10
12	5.0	40	25	10
		Phase 3 (Quartz Tube Cleaner Runs)		
13	5.0	40	25	10
14	5.0	40	25	10

B.5 Review of Treatment Results

This section summarizes the results of both critical and noncritical parameters for the perox-pure™ chemical oxidation system demonstration, and it evaluates the technology's effectiveness in treating groundwater contaminated with VOCs. Data are presented in graphic or tabular form. For samples with analyte concentrations at nondetectable levels, one-half the detection limit was used as the estimated concentration. However, if more than one replicable sample had concentrations at nondetectable levels, using one-half the detection limit as the estimated concentration for all replicable samples with nondetectable levels of contaminants will significantly reduce the standard deviation of the mean and will affect the statistical inferences made. For this reason, 0.5, 0.4, 0.6, and 0.4 times the detection limit were used as estimated concentrations for the first, second, third, and fourth replicate samples, respectively. Throughout this appendix, the terms "Reactor 6 effluent," "perox-pure™ effluent," and "effluent" are used synonymously.

B.5.1 Summary of the Results for Critical Parameters

Results for the critical parameters are presented below for each phase of the demonstration.

Phase 1 Results

In Phase 1 (Runs 1 through 8), only three VOCs were detected in the influent to and effluent from the perox-pure™ system. In general, TCE and PCE were present above detection limits only in the influent. TCA could not be measured in the influent, because it was present at concentrations two orders of magnitude lower than the average TCE concentration and was diluted out during the analysis. However, because effluent samples did not require dilution, the TCA concentration could be measured in treated groundwater. In general, TCA was present in the effluent from the perox-pure™ system. Phase 1 VOC concentration data are presented for TCE and PCE in Figures B-3 through B-5. TCA concentrations are not shown in figures because TCA levels in the influent could not be measured.

Table B-2 Target Levels for VOCs in Effluent Samples

VOC	Target Level (μg/L)
Chloroform	100
1,1-Dichloroethane (DCA)	5
1,1-Dichloroethene (1,1-DCE)	6
1,2-Dichloroethene (1,2-DCE)	6
1,1,1-Trichloroethane (TCA)	200
Trichloroethene (TCE)	5
Tetrachloroethene (PCE)	5

Figure B-3 presents TCE and PCE concentrations in the influent and Reactors 1, 3, and 6 effluent for Runs 1, 2, and 3. Concentrations are expressed as a function of influent pH. In all three runs, the effluent TCE and PCE concentrations were well below the target level of 5 μg/L and below the detection limit of 1 μg/L. Figure B-3 shows that the perox-pure™ system performed best in Run 1, when the influent pH was 8 (the unadjusted pH of groundwater). In this run, the Reactor 1 effluent had lower levels of TCE and PCE than in Runs 2 and 3, and it had the same levels of TCE and PCE as the Reactor 6 effluent in Runs 2 and 3. However, Reactor 6 effluent TCA concentration was lowest in Run 3 at 1.4 μg/L (Reactor 6 effluent TCA concentrations in Runs 1 and 2 were 6.7 and 3.1 μg/L, respectively). Because TCA is difficult to oxidize, PSI selected Run 3 as the preferred operating condition, with an influent pH of 5.0.

Figure B-4 presents a comparison of VOC concentrations in Runs 3, 4, and 5 as a function of hydrogen peroxide levels. Although the effluent TCE and PCE concentrations were the same in all runs, the data show that Reactor 1 effluent TCE and PCE concentrations were the lowest in Run 4 (with the highest hydrogen peroxide level) and in Run 5 (with the lowest hydrogen peroxide level). Higher levels of TCE and PCE in the Reactor 1 effluent at intermediate hydrogen peroxide levels cannot be explained. The Reactor 6 effluent TCA concentrations in Runs 3, 4, and 5 were 1.4, 1.8, and 2.1 μg/L, respectively. No definite trend can be identified based on TCE, PCE, and TCA data in Runs 3, 4, and 5.

Figure B-5 presents TCE and PCE concentrations at different flow rates and hydrogen peroxide levels. Runs 4 and 6 were performed at a flow rate of 10 gpm. Runs 7 and 8 were performed at a flow rate of 40 gpm. In Runs 4 and 6, the same total amount of hydrogen peroxide was added to the contaminated groundwater. However, in Run 4, hydrogen peroxide was added at multiple points in the system using the splitter, while in Run 6, all hydrogen peroxide was added at the influent to the system. Based on a comparison of TCE and PCE levels in Runs 4 and 6, the effect of adding hydrogen peroxide at multiple points in the perox-pure™ system cannot be evaluated, because in both runs, TCE and PCE levels in treated groundwater were below the detection limit of 1.0 μg/L. However, effluent TCA levels in Runs 4 and 6 were 1.8 and 3.0 μg/L, respectively. Based on this data, adding hydrogen peroxide at multiple points in the perox-pure™ system appears to enhance the system's performance.

A comparison of TCE and PCE levels in Runs 6 and 7 shows that both TCE and PCE concentrations in Reactor 1 effluent were higher in Run 7 than in Run 6. Similarly, the effluent TCA level in Run 7 (3.9 μg/L) was higher than in Run 6 (3.0 μg/L). These observations are consistent with the operating conditions, because contaminated groundwater had a much longer UV exposure time in Run 6 than in Run 7. UV exposure times were 1.5 and 0.4 minutes in Runs 6 and 7, respectively.

A comparison of TCE and PCE levels in Runs 7 and 8 shows that both TCE and PCE concentrations in Reactor 1 effluent were higher in Run 7 than in Run 8. Effluent TCA levels were about the same in both runs (3.9 and 4.0 μg/L in Runs 7 and 8, respectively). The higher Reactor 1 effluent TCE level in Run 7 may be attributed to higher influent TCE levels in that run. Reactor 1 effluent TCE levels correspond to 99.5 and 99.9 percent TCE removal in Runs 7 and 8, respectively. Similarly, the Reactor 1 effluent PCE levels correspond to 92.9 and 99.2 percent PCE removal in Runs 7 and 8. These data seem to indicate that higher doses of hydrogen peroxide may have scavenged hydroxyl radicals or excess hydrogen peroxide reduced UV

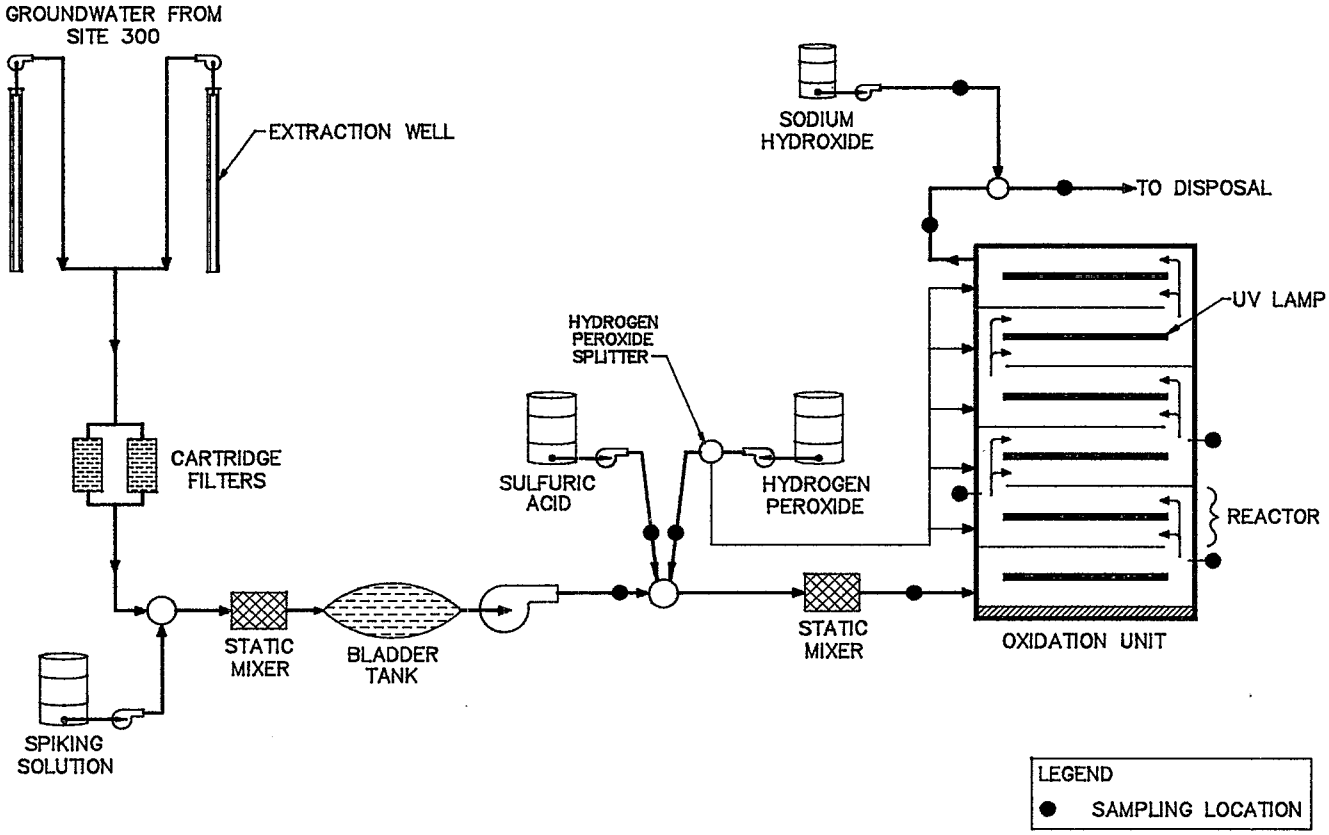

Figure B-2 perox-pure™ Chemical Oxidation Treatment System Sampling Locations

transmittance through water, which resulted in lower removal efficiencies for Run 7 than those for Run 8.

Based on quick turnaround analyses performed during Runs 1 through 6, PSI selected Run 3 operating conditions as the preferred operating conditions for spiked groundwater. As a result, Runs 10 through 14 were performed using Run 3 operating conditions.

Phase 2 Results

Phase 2 (Runs 9 through 12) results for VOC removal in the perox-pure™ system are presented in Figures B-6 through B-8. A comparison of the perox-pure™ system's performance in treating spiked groundwater (Run 9) and unspiked groundwater (Run 4) is presented in Figure B-6. Figure B-6 shows that TCE and PCE levels in treated groundwater were higher in Run 9 (spiked groundwater) than in Run 4 (unspiked groundwater). These data suggest that spiking compounds (chloroform, DCA, and TCA) affected the perox-pure™ system's performance in removing TCE and PCE, perhaps because of the additional oxidant demand. However, treated groundwater TCE and PCE levels plotted in Figure B-6 are estimated concentrations. Because the detection limit for TCE and PCE in Run 9 was 5 μg/L and in Run 4 was 1 μg/L, and because TCE and PCE were present at nondetectable levels in treated groundwater in both runs, the estimated concentrations in Run 9 are higher than in Run 4. Therefore, the data are inconclusive with regard to the effect of spiking compounds on the removal of TCE and PCE.

During the reproducibility runs (Runs 10, 11, and 12), the effluent TCE, PCE, and DCA levels were generally below detection limit (5 μg/L) and effluent chloroform and TCA levels ranged from 15 to 30 μg/L. VOC removal efficiencies in reproducibility runs are plotted in Figure B-7. Figure B-7 shows that for TCE and PCE, which are easy to oxidize, most of the removal occurred in Reactor 1, leaving only trace quantities of TCE and PCE to be removed in the rest of the perox-pure™ system. However, for chloroform, DCA, and TCA, which are difficult to oxidize, considerable removal occurred beyond Reactor 1. During the three reproducibility runs, average removal efficiencies for TCE, PCE, chloroform, DCA, and TCA after Reactor 1 were 99.5, 95.9, 41.3, 67.0, and 17.4 percent, respectively. After Reactor 6, overall removal efficiencies for TCE, PCE, chloroform, DCA, and TCA increased to 99.7, 97.1, 93.1, 98.3, and 81.8, respectively. The overall removal efficiencies of the perox-pure™ system were reproducible for all VOCs. However, for

Table B-3 Analytical and Measurement Methods

Parameter	Method Type	Method Source	Name of Method
Acid	Field	Acid-base titration	Titration with sodium hydroxide
Alkalinity	Laboratory	MCAWW 310.1[a]	Alkalinity (titrimetric)
AOX	Laboratory	DIN 38409 H14[b]	Adsorbable organic halide measurement
Base	Field	Acid-base titration	Titration with sulfuric acid
Bioassay	Laboratory	EPA/600/4-85/013[c]	48-hour static acute toxicity test (definitive) using Ceriodaphnia dubia
	Laboratory	EPA/600/4-85/013[c]	96-hour static acute toxicity test (definitive) using Pimephales promelas
Electricity consumption	Field	None	Electricity consumption
Flow rate	Field	None	Flow rate measurement using monitoring equipment on the treatment system
Hardness	Laboratory	MCAWW 130.2[a]	Hardness
Hydrogen peroxide	Field	Boltz and Howell, 1979	Colorimetric method for hydrogen peroxide measurement
Metals (iron and manganese)	Laboratory	SW-846 3010/6010[d]	Metals by inductively coupled plasma-atomic emission spectroscopy
pH	Field	MCAWW 150.1[a]	pH electrometric measurement
Purgeable organic carbon (POC)	Laboratory	SM 5310B[e]	Carbon measurement by combustion-infrared method
SVOCs	Laboratory	SW-846 3510/3640/8270[d]	GC/MS for SVOCs: capillary column technique
Specific conductance	Field	SW-846 9050[d]	Specific conductance
Total carbon (TC) and Total organic carbon (TOC)	Laboratory	SM 5310C[e]	Carbon measurement by persulfate-ultraviolet oxidation method
Temperature	Field	MCAWW 170.1[a]	Temperature
TOX	Laboratory	SW-846 9020[d]	Total organic halide measurement
Turbidity	Laboratory	MCAWW 180.1[a]	Turbidity (nephelometric)
VOCs (GC)	Laboratory	SW-846 5030/8010[d]	Halogenated VOCs by GC: purge and trap
VOCs (GC/MS)	Laboratory	SW-846 8240[d]	VOCs by GC/MS: capillary column technique

Notes:

[a] EPA, 1983.
[b] Steffens, 1992.
[c] EPA, 1985.
[d] EPA, 1986.
[e] APHA, AWWA, and WPCF, 1989.

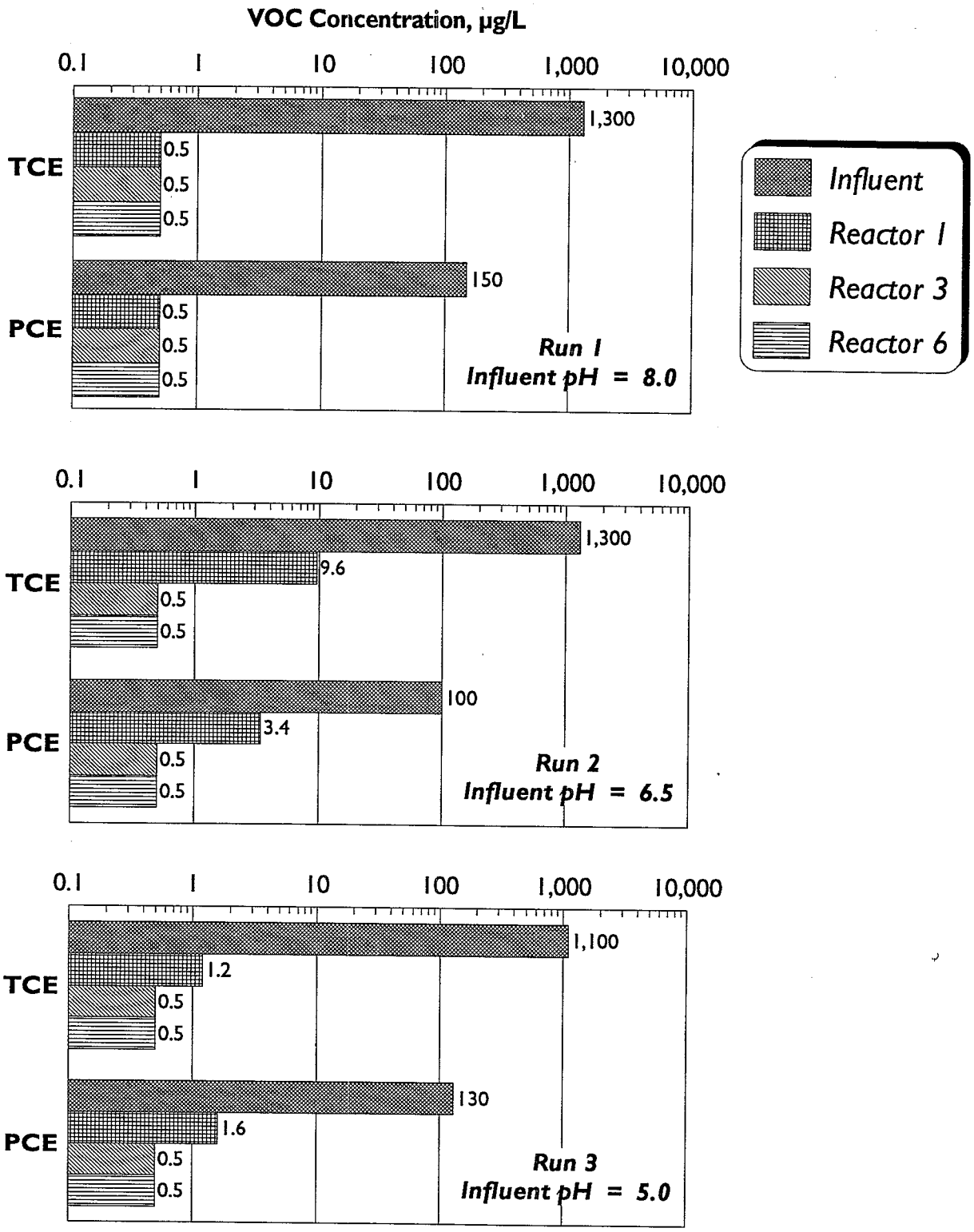

Figure B-3 Comparison of VOC Concentrations at Different Influent pH Levels
(Hydrogen Peroxide Level at Reactor 1 = 40 mg/L; Hydrogen Peroxide Level at Reactors 2 through 6 = 25 mg/L; Flow Rate = 10 gpm)

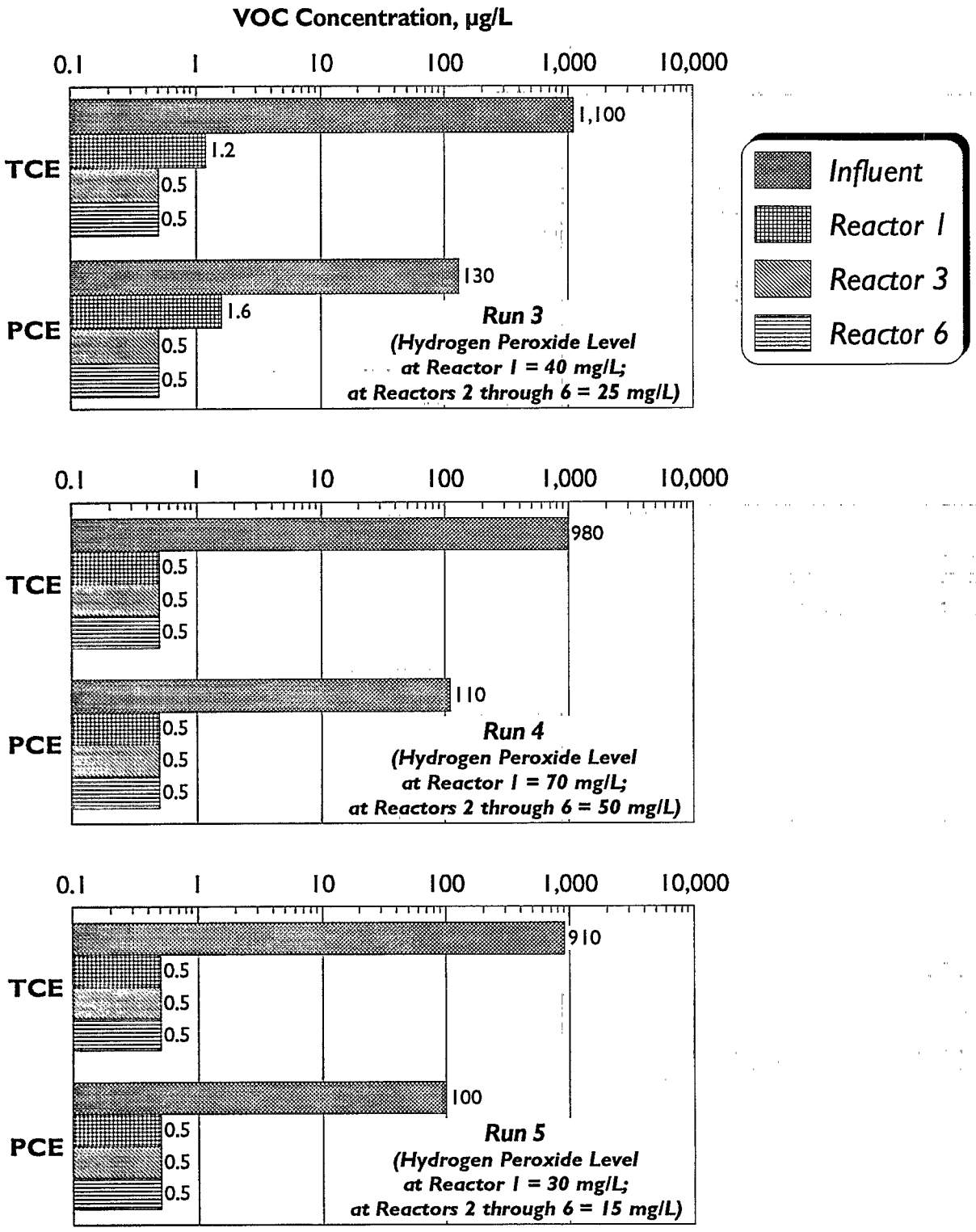

Figure B-4 Comparison of VOC Concentrations at Different Hydrogen Peroxide Levels (Influent pH = 5.0; Flow Rate = 10 gpm)

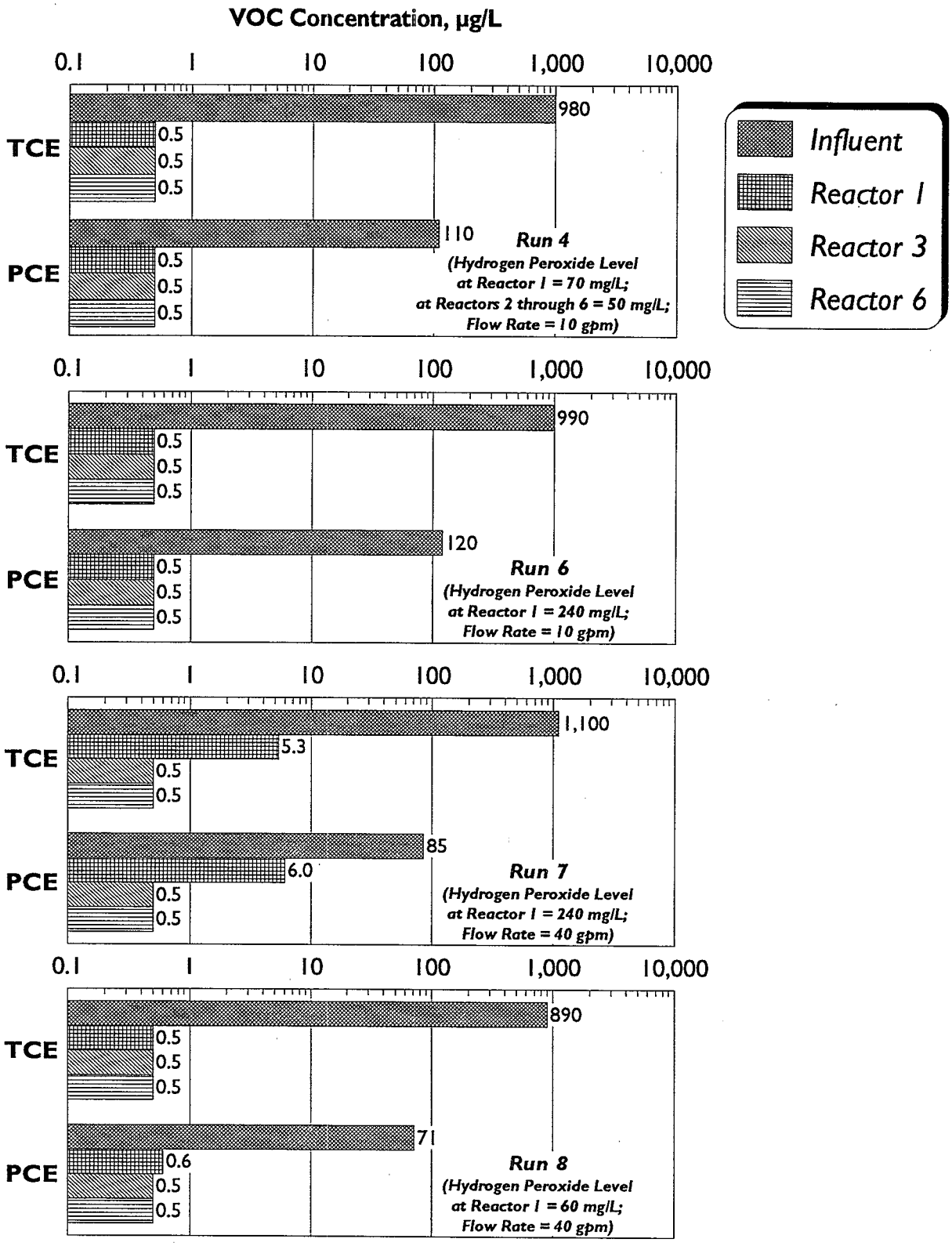

Figure B-5 Comparison of VOC Concentrations at Different Flow Rates and Hydrogen Peroxide Levels (Influent pH = 5.0)

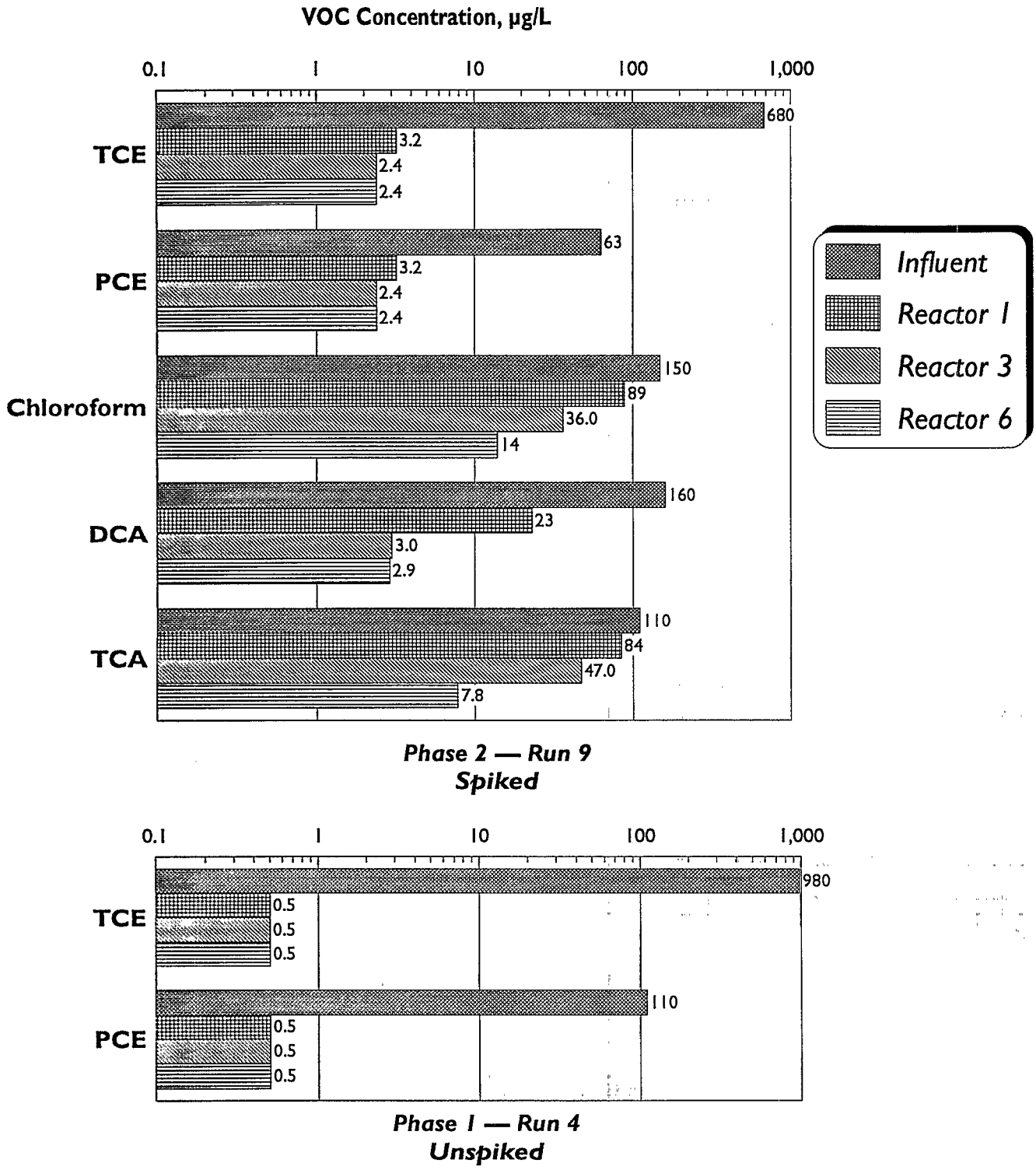

Figure B-6 Comparison of VOC Concentrations in Spiked and Unspiked Groundwater (Influent pH = 5.0; Hydrogen Peroxide Level at Reactor 1 = 70 mg/L; Hydrogen Peroxide Level at Reactors 2 through 6 = 50 mg/L; Flow Rate = 10 gpm)

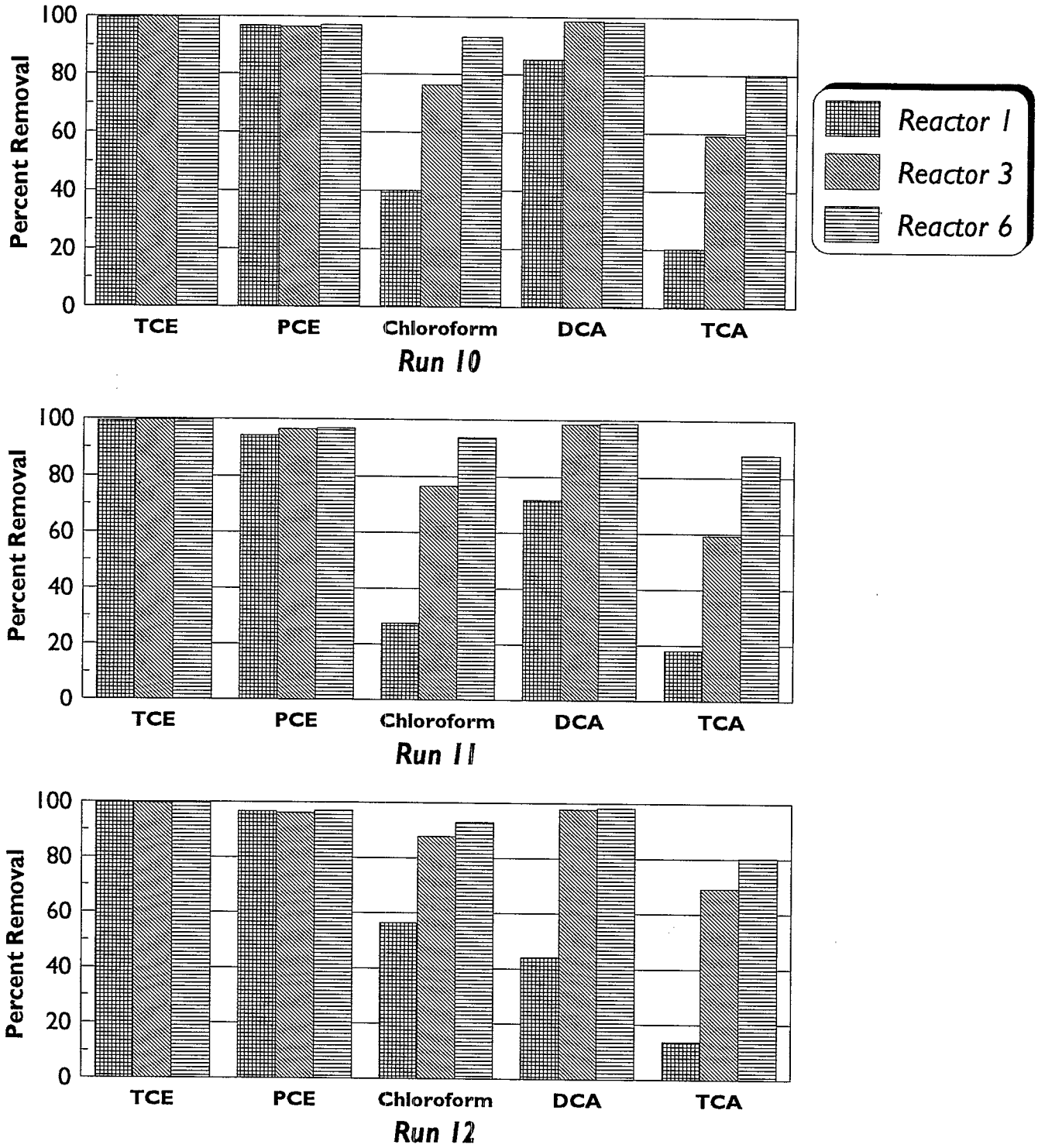

Figure B-7 VOC Removal Efficiencies in Reproducibility Runs
(Influent pH = 5.0; Hydrogen Peroxide Level at Reactor 1 = 40 mg/L; Hydrogen Peroxide Level at Reactors 2 through 6 = 25 mg/L; Flow Rate = 10 gpm)

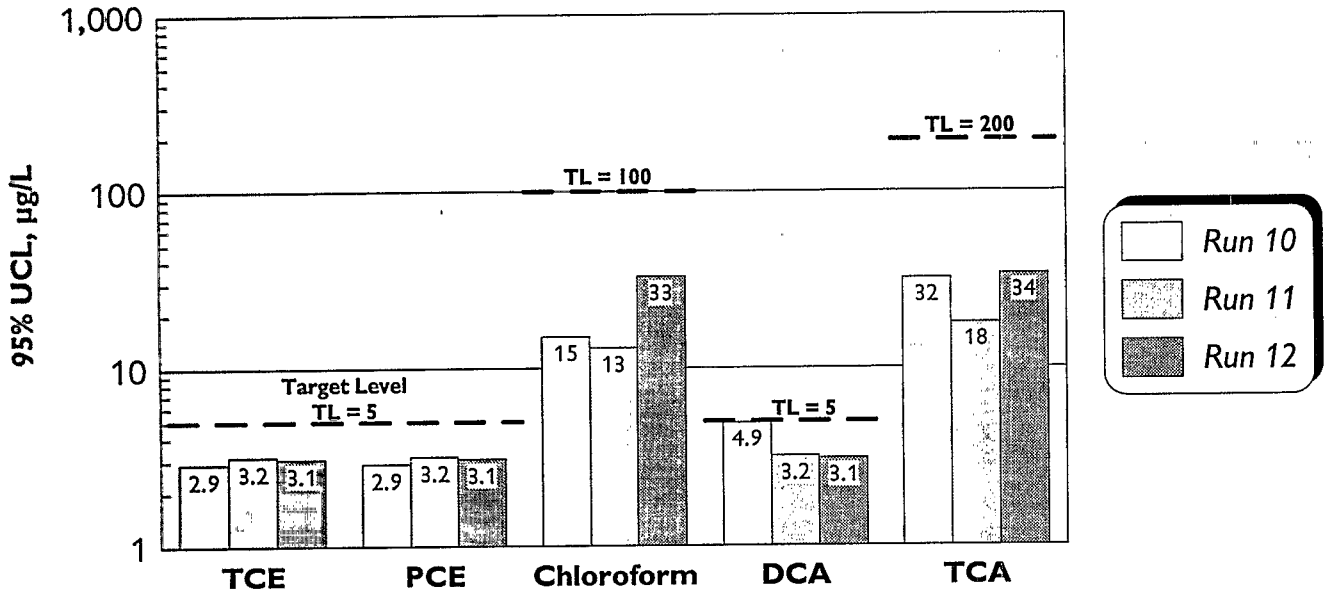

Figure B-8 Comparison of 95 Percent UCLs for Effluent VOC Concentrations with Target Levels in Reproducibility Runs (Influent pH = 5.0; Hydrogen Peroxide Level at Reactor 1 = 40 mg/L; Hydrogen Peroxide Level at Reactors 2 through 6 = 25 mg/L; Flow Rate = 10 gpm)

certain compounds, the removal efficiencies after Reactor 1 were quite variable (for example, chloroform removal efficiencies ranged from 27.4 to 56.3 percent). This variability may be associated with sampling and analytical precision.

Figure B-8 compares the 95 percent upper confidence limits (UCL) of effluent VOC concentrations with target levels in reproducibility runs. For this project, the target level for a given VOC was set at the most stringent limit in cases where the VOC has multiple regulatory limits. For all VOCs but chloroform, the most stringent limit is the California drinking water action level. For chloroform, the most stringent limit is the maximum contaminant level (MCL) specified in the Safe Drinking Water Act. Figure B-8 shows that perox-pure™ system effluent met the target levels at the 95 percent confidence level in all three reproducibility runs, indicating that the system performance was reproducible.

Phase 3 Results

Figure B-9 presents VOC concentrations in Runs 12, 13, and 14, which were conducted to evaluate quartz tube cleaning. In Run 12, quartz tubes from the previous demonstration runs were used. In Run 13, scaled quartz tubes were used. These tubes had been exposed to an environment that encouraged scaling, but they had not been maintained with cleaners or wipers. In Run 14, quartz tubes that had been maintained by cleaners or wipers were used.

A comparison of removal efficiencies for TCE in Reactors 1 and 2 shows that TCE removal efficiencies were about the same in all runs. PCE removal efficiencies were about 3 percent less in Run 13 than that in Runs 12 or 14. Removal efficiencies for chloroform, DCA, and TCA were consistently less in Run 13 than in Run 14, indicating that periodic cleaning of quartz tubes by wipers is required to maintain the perox-pure™ system's performance. Without such cleaning, the removal efficiencies will likely decrease in an aqueous environment that would cause scaling of quartz tubes. For example, after Reactor 2, chloroform removal efficiency in Run 13 was 53.4 percent, compared to 61.3 percent removal efficiency in Run 14. Because the quartz tubes used in Run 12 had little coating, it was expected that the removal efficiencies in Run 12 would be higher than those in Run 13. However, the demonstration did not confirm this for all VOCs. For example, Run 12 TCA removal efficiencies were less than Run 13 TCA removal efficiencies; this inconsistency cannot be explained.

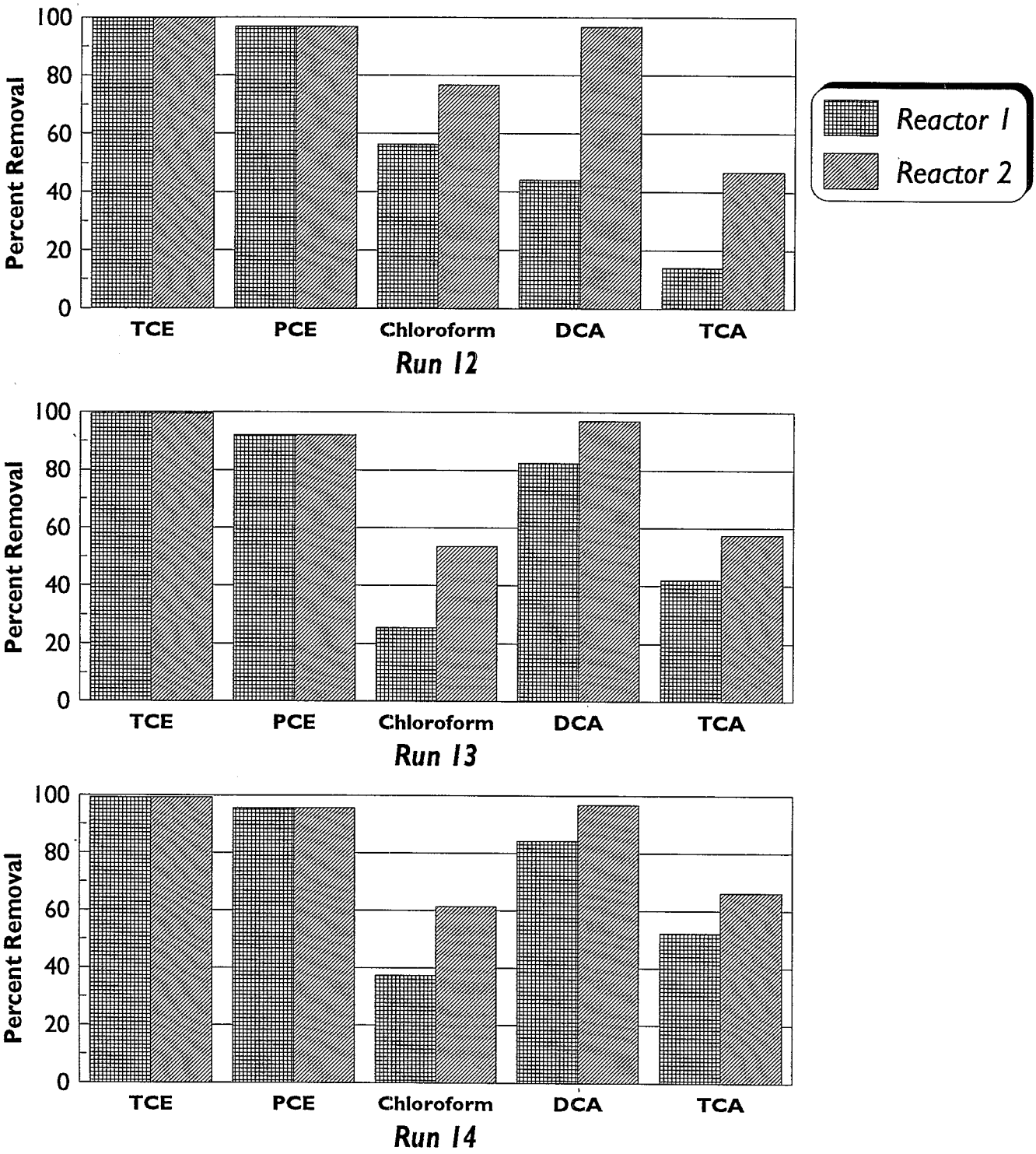

Figure B-9 VOC Removal Efficiencies in Quartz Tube Cleaner Runs
(Influent pH = 5.0; Hydrogen Peroxide Level at Reactor 1 = 40 mg/L; Hydrogen Peroxide Level at Reactors 2 through 6 = 25 mg/L; Flow Rate = 10 gpm)

B.5.2 Summary of Results for Noncritical Parameters

The technology demonstration also evaluated analytical results of several noncritical parameters. These results are summarized below.

GC/MS analysis of influent and effluent samples for VOCs indicated that new target compounds or tentatively identified compounds (TIC) were not formed during the treatment.

GC/MS analysis of influent and effluent samples for SVOCs showed that target SVOCs were not present at detectable levels. However, several unknown TICs were present in both the influent and effluent samples.

Average influent TOX and AOX levels were 800 μg/L and 730 μg/L, respectively. The perox-pure™ system achieved TOX removal efficiencies that ranged from 93 to 99 percent and AOX removal efficiencies that ranged from 95 to 99 percent.

The TC, TOC, and POC concentrations in influent and effluent samples in Runs 10, 11, and 12 are presented in Figure B-10. Average TC concentrations in the influent and effluent were 75 mg/L and 55 mg/L, respectively. The decrease in TC concentration in the perox-pure™ system may be due to the loss of dissolved carbon dioxide that occurred as a result of the turbulent movement of contaminated groundwater in the perox-pure™ system.

Figure B-10 shows a decrease in TOC of about 40 percent during treatment. The decrease corresponds to the amount of organic carbon that was converted to inorganic carbon during treatment, suggesting that about 40 percent of the organic carbon was completely oxidized to carbon dioxide. However, the TOC data do not indicate whether the organic carbon that was completely oxidized had originated from the VOCs present in groundwater or from some other compounds present in groundwater.

Effluent POC concentration was about 0.02 mg/L which is below the reporting limit of 0.035 mg/L. POC concentration data show that the average POC removal efficiency was about 93 percent. Assuming that the majority of organic carbon associated with VOCs could be measured as POC, this indicates that about 93 percent of volatile organic carbon was converted to either carbon dioxide or nonpurgeable organic carbon.

During Runs 10, 11, and 12, bioassay tests were performed to evaluate the acute toxicity of influent to and effluent from the perox-pure™ systems. Two freshwater test organisms, a water flea (*Ceriodaphnia dubia*) and a fathead minnow (*Pimephales promelas*), were used in the bioassay tests. Toxicity was measured as the lethal concentration at which 50 percent of the organisms died (LC_{50}), and expressed as the percent of effluent (or influent) in the test water. One influent and one effluent sample were tested in each run. One control sample was also tested to evaluate the toxicity associated with hydrogen peroxide residual present in the effluent. The control sample had about 10.5 mg/L of hydrogen peroxide (average effluent residual in Runs 10, 11, and 12), and had characteristics (alkalinity, hardness, and pH) similar to that of effluent in Runs 10, 11, and 12.

In general, the influent was not found to be acutely toxic to either test organism. The effluent was found to be acutely toxic to both test organisms. The influent LC_{50} values for both organisms indicated that in the undiluted influent sample more than 50 percent of the organisms survived. However, LC_{50} values for the water flea were estimated to be 35, 13, and 26 percent effluent in Runs 10, 11, and 12, respectively; and LC_{50} values for the fathead minnow were estimated to be 65 and 71 percent effluent in Runs 10 and 11, respectively. In Run 12, more than 50 percent of the fathead minnows survived in the undiluted effluent. The LC_{50} value for the water flea was estimated to be 17.7 percent in the control sample, indicating that the sample contained hydrogen peroxide at a concentration that was acutely toxic to water fleas. However, more than 50 percent of the fathead minnows survived in the undiluted control sample indicating hydrogen peroxide was not acutely toxic to fathead minnows at a concentration of 10.5 mg/L. This observation, however, is not entirely consistent with observations made by the Department of Environmental Protection, State of Connecticut (CDEP). The CDEP Water Toxics Section of Water Management Division reports LC_{50} value of 18.2 mg/L of hydrogen peroxide with 95 percent confidence limits of 10 mg/L and 25 mg/L (CDEP, 1993).

Comparison of the LC_{50} value of the control sample with LC_{50} values of effluent samples for water fleas indicates the toxicity associated with the effluent samples is probably due to hydrogen peroxide residual in the effluent. However, no conclusion can be drawn on the effluent toxicity to fathead minnows because the control sample toxicity results from the SITE demonstration data are not entirely consistent with the data collected by CDEP.

Iron and manganese were present at trace levels in the influent. In general, iron was present at levels less than 45 μg/L, and manganese was present at an average level of 15 μg/L. Removal of iron or manganese did not occur in the perox-pure™ system, because these metals were present only at trace levels in the influent.

No changes in pH, alkalinity, hardness, or specific conductance were observed during treatment.

Average influent temperature was about 72 °F. Average effluent temperatures were about 90 °F and 76 °F, at influent flow rates of 10 gpm and 40 gpm, respectively.

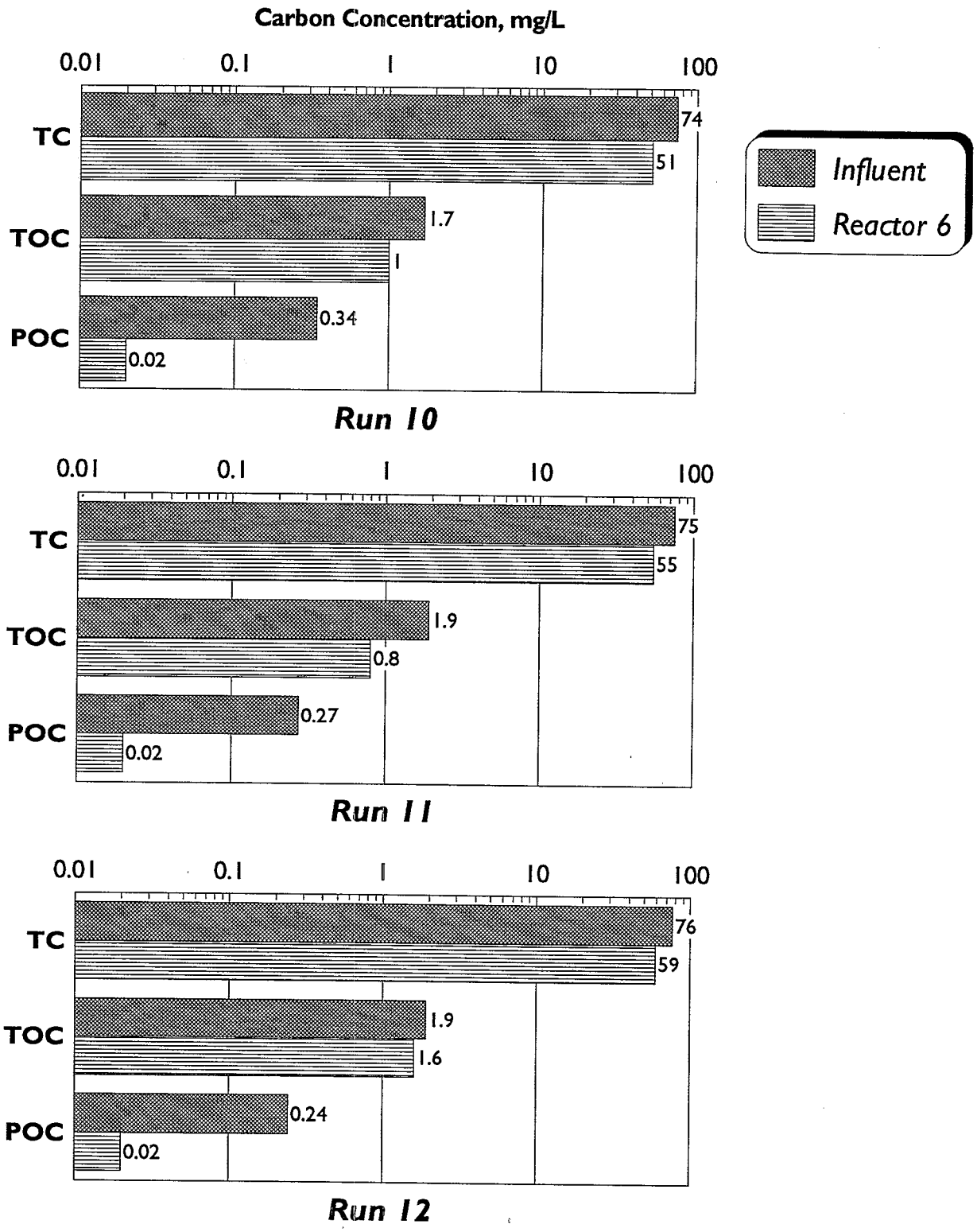

Figure B-10 Carbon Concentrations in Reproducibility Runs
(Influent pH = 5.0; Hydrogen Peroxide Level at Reactor 1 = 40 mg/L; Hydrogen Peroxide Level at Reactors 2 through 6 = 25 mg/L; Flow Rate = 10 gpm)

Because 10 gpm corresponds to a hydraulic retention time of 1.5 minutes and 40 gpm corresponds to a retention time of 0.4 minutes, the average temperature increase due to 1 minute of UV radiation exposure in the perox-pure™ system is about 12 °F.

B.6 Conclusions

For the spiked groundwater, PSI determined the following preferred operating conditions: (1) influent hydrogen peroxide level of 40 mg/L, (2) hydrogen peroxide level of 25 mg/L in the influent to Reactors 2 through 6, (3) influent pH of 5.0, and (4) flow rate of 10 gpm. At these conditions, the effluent TCE, PCE, and DCA levels were generally below detection limit (5 μg/L) and TCA levels ranged from 15 to 30 μg/L. The average removal efficiencies for TCE, PCE, chloroform, DCA, and TCA were about 99.7, 97.1, 93.1, 98.3, and 81.8 percent, respectively.

For the unspiked groundwater, the effluent TCE and PCE levels were generally below the detection limit (1 μg/L), with corresponding removal efficiencies of about 99.9 and 99.7 percent. The effluent TCA levels ranged from 1.4 to 6.7 μg/L with removal efficiencies ranging from 35 to 84 percent.

The perox-pure™ system effluent met California drinking water action levels and federal drinking water MCLs for TCE, PCE, chloroform, DCA, and TCA at the 95 percent confidence level.

The quartz tube wipers were effective in keeping the tubes clean and appeared to reduce the adverse effect scaling has on contaminant removal efficiencies.

TOX removal efficiencies ranged from 93 to 99 percent. AOX removal efficiencies ranged from 95 to 99 percent.

For spiked groundwater, during reproducibility runs, the system achieved average removal efficiencies of 38 percent and greater than 93 percent for TOC and POC, respectively.

The temperature of groundwater increased at a rate of 12 °F per minute of UV exposure in the perox pure™ system. Since the oxidation unit is exposed to the surrounding environment, the temperature increase may vary depending upon the ambient temperature or other atmospheric conditions.

B.7 References

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Appendix C
Case Studies

This appendix summarizes three case studies on the use of the perox-pure™ chemical oxidation system developed by Peroxidation Systems, Inc. (PSI). The perox-pure™ system has proven to be a technically and economically viable alternative to conventional technologies. It should be evaluated in cases requiring treatment of water contaminated with organic contaminants. All three case studies represent full-scale, currently operating commercial installations. The contaminants of concern in these case studies include acetone, isopropyl alcohol (IPA), trichloroethene (TCE), and pentachlorophenol (PCP). The scope of the case studies is limited to basic information concerning the following topics: site conditions, system performance, and costs. The following case studies are discussed in this appendix:

- Wastewater Treatment System, Kennedy Space Center, Florida
- Municipal Drinking Water System, Arizona
- Chemical Manufacturing Company, Washington

C.1 Wastewater Treatment System, Florida

This case study describes the performance and treatment costs of the perox-pure™ system treating industrial wastewater containing acetone and IPA at the Kennedy Space Center site in Florida.

C.1.1 Site Conditions

Effluent from the existing wastewater treatment system at the Kennedy Space Center in Florida frequently exceeded the permitted levels for discharges of acetone and IPA. Discharges were reported at levels up to 20 milligrams per liter (mg/L) for both compounds. The treatment facility discharge requirement for both acetone and IPA is 0.5 mg/L. A liquid-phase carbon adsorption system had originally been installed as part of the treatment system, but was found to be inadequate. Subsequently, perox-pure™ chemical oxidation technology was selected as the new method of treatment.

After selecting the perox-pure™ chemical oxidation technology, the facility contractor installed a perox-pure™ Model SSB-30R in the fall of 1992. The system was used to treat 5,000- to 6,000-gallon batches of contaminated water. A demineralization system operated by another contractor received effluent from the perox-pure™ unit. Facility requirements specified a maximum treatment time of 24 hours for each batch.

C.1.2 System Performance

The perox-pure™ unit is currently treating maximum levels of acetone and IPA (both 20 mg/L) to less than 0.5 mg/L for each compound. The treatment objectives were easily met, even when the wastewater contained twice the maximum expected acetone and IPA concentrations. Treatment objectives were achieved for each batch in less than the specified 24-hour maximum treatment time. In addition, effluent from the perox-pure™ unit met the demineralization discharge standards, making treatment by the demineralization system unnecessary.

Due to the efficiency of treatment, the contractor was able to treat wastewater in a flow-through mode rather than in batches. The resulting flow rate of 5 gallons per minute (gpm) for a period of 20 hours per day requires 10 kilowatts (kW) to power the ultraviolet (UV) radiation lamps. The additional capacity of the perox-pure™ unit will be used in contaminant spill situations, which would produce much higher acetone and IPA concentrations. The influent hydrogen peroxide dosage for flow-through operation was 100 mg/L.

C.1.3 Costs

The operation and maintenance (O&M) costs for flow-through operation of the perox-pure™ unit include electricity, chemicals (hydrogen peroxide), and general maintenance. The following items are used at the indicated rate for each 1,000 gallons treated: electricity at $0.06 per kilowatt-hour (kWh) costs $2.00; 50 percent hydrogen peroxide at $0.35 per pound costs $0.60; and estimated maintenance

requirements cost $1.00. The total O&M cost per 1,000 gallons treated is $3.60.

C.2 Municipal Drinking Water System, Arizona

This case study describes the performance and treatment costs of the perox-pure™ system treating groundwater containing TCE. The groundwater was a source of municipal drinking water in Arizona.

C.2.1 Site Conditions

In 1989, a municipal groundwater well in Arizona used for drinking water was found to contain 50 to 400 micrograms per liter (μg/L) of TCE. The well, capable of producing 2,000 gpm, was taken out of service while treatment options were considered. Because the well is located on a city lot in the middle of a large residential area, the city preferred using a low-visibility, quiet treatment method that could consistently destroy TCE to concentrations below the drinking water standard of 5 μg/L. Moreover, treatment to below the drinking water standard was desirable because of the high profile of the site remediation. Given these requirements, the perox-pure™ chemical oxidation technology was selected.

An on-site performance evaluation was initiated in December 1989 using a perox-pure™ pilot system to treat contaminated groundwater pumped from the well at a flow rate of 135 gpm. Testing showed that TCE could be destroyed to below the analytical detection limit of 0.5 μg/L.

C.2.2 System Performance

A perox-pure™ Model SSB-30R is currently in operation at the site, treating organic contamination to below detectable levels at a flow rate of 135 gpm. Treatment is accomplished with only 15 kW of power, one-half the capacity of the unit. The average influent concentration of TCE is 150 μg/L, and the effluent TCE concentration is less than 0.5 μg/L.

C.2.3 Costs

O&M costs for continuous operation of the perox-pure™ system at a flow rate of 135 gpm include electricity, chemicals (hydrogen peroxide), and general maintenance. The following items are consumed at the indicated rate for each 1,000 gallons treated: electricity at $0.06 per kWh costs $0.11; 50 percent hydrogen peroxide at $0.35 per pound costs $0.12; and estimated maintenance requirements cost $0.05. The total O&M cost per 1,000 gallons treated is $0.28.

C.3 Chemical Manufacturing Company, Washington

This case study describes the performance and treatment costs of the perox-pure™ system treating groundwater containing PCP at a chemical manufacturing facility in Washington.

C.3.1 Site Conditions

PCP contamination was discovered in local groundwater surrounding a chemical manufacturing company in Washington. The company had produced PCP for more than 30 years. Because of the site geology, the groundwater was brackish and contained high concentrations of iron and calcium carbonate. The chemical company initiated a remediation effort that included a pump-and-treat process. After bench-scale testing, the perox-pure™ chemical oxidation system was selected to destroy PCP to below a target level of 0.1 mg/L.

A full-scale perox-pure™ system was installed in 1988 under a Full Service Agreement with PSI. When the remediation effort began, groundwater was contaminated with PCP at levels of up to 15 mg/L, three times higher than expected. Iron was detected at levels of up to 200 mg/L, 20 times higher than expected. PSI made pretreatment recommendations and assisted with the selection of an iron oxidation and removal system, which included clarification and multimedia filtration. Treatment with the perox-pure™ system reduced iron concentrations in the groundwater to acceptable levels. The groundwater was stabilized and the scaling tendency was reduced by adding acid to lower the groundwater pH to approximately 5.

The original perox-pure™ unit did not have enough capacity to treat the unexpectedly high PCP levels. However, as part of the Full Service Agreement, a perox-pure™ Model CEBX-360R was installed to replace the original unit. The new model incorporated the latest improvements in the perox-pure™ unit, including an automatic tube cleaning device.

C.3.2 System Performance

The groundwater is being successfully treated at a flow rate of about 70 gpm, and a power requirement of 180 kW. The pH of the influent groundwater is adjusted to 5 by adding acid, and hydrogen peroxide is added to the influent to achieve a concentration of 150 mg/L. The perox-pure™ system is currently treating maximum influent PCP concentrations of 15 mg/L to average effluent concentration of 0.1 mg/L.

C.3.3 Costs

O&M costs for continuous operation of the perox-pure™ system at a flow rate of 70 gpm include electricity, chemicals (hydrogen peroxide and acid), and general maintenance. The following items are used at the indicated rate for each 1,000 gallons treated: electricity at $0.06 per kWh costs $2.57; 50 percent hydrogen peroxide at $0.35 per pound costs $0.87; acid at $0.085 per pound costs $0.03; and estimated maintenance requirements cost $0.43. The total O&M cost per 1,000 gallons treated is $3.90.

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