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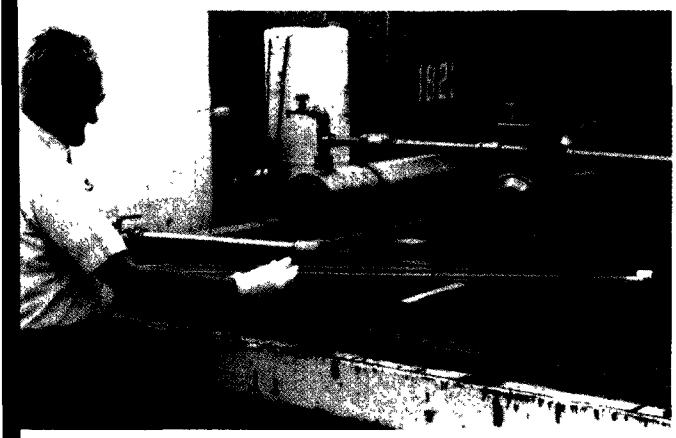
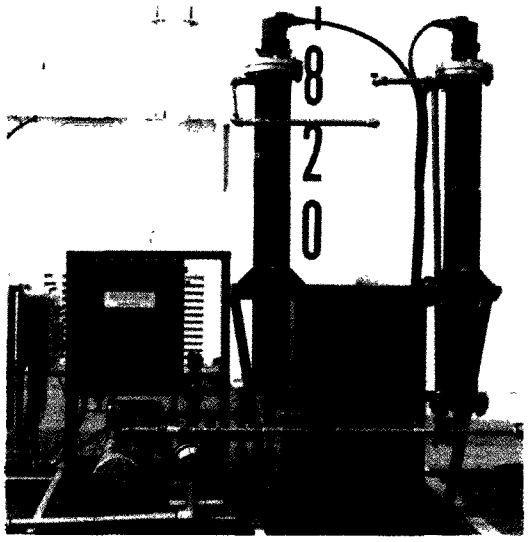
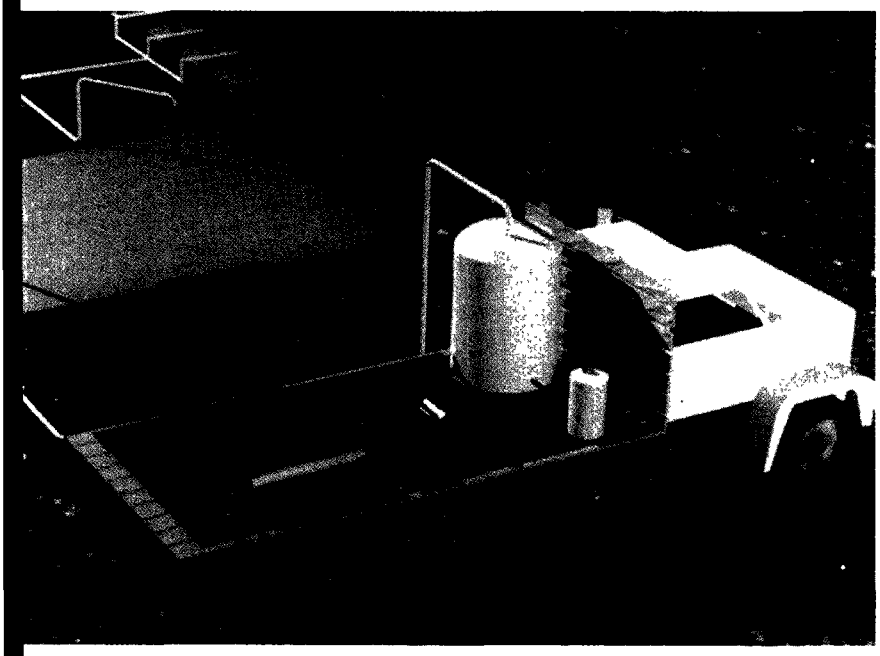
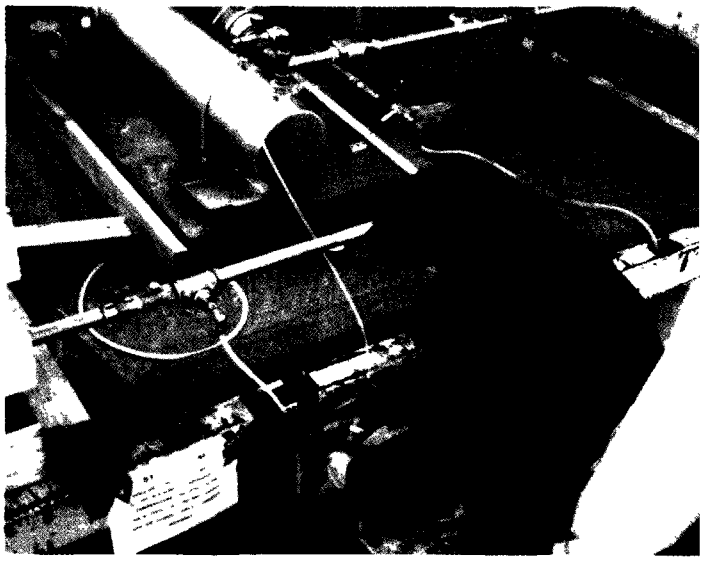
CAV-OX® Cavitation Oxidation Process Magnum Water Technology, Inc.

Applications Analysis Report









SITE
SUPERFUND INNOVATIVE
TECHNOLOGY EVALUATION

OLS-2801

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May 1994

CAV-OX® Cavitation Oxidation Process

Magnum Water Technology, Inc.

Applications Analysis Report

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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 ability of the CAV-OX® process to treat groundwater contaminated with volatile organic compounds. The demonstration took place at Edwards Air Force Base Site 16, California. The demonstration was directed toward obtaining information on the performance and cost of the technology and assessing its use at this and other hazardous waste sites. Documentation consists of a technology evaluation report, which describes field activities and laboratory results, and this applications analysis report, which interprets the data and discusses the potential applicability of the technology.

A limited number of copies of this report will be available at no charge from EPA's Center for Environmental Research Information, 26 West Martin Luther King Drive, Cincinnati, Ohio 45268, (513) 569-7562. Requests for copies should include the EPA document number found on the report's cover. When this supply is exhausted, additional copies can be purchased from the National Technical Information Service, Ravensworth Building, Springfield, Virginia 22161, (703) 487-4600. Reference copies will be available at EPA libraries in the Hazardous Waste Collection.

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

Abstract

This report evaluates the ability of the CAV-OX® cavitation oxidation process to remove volatile organic compounds (VOC) present in aqueous wastes. This report also presents economic data based on the Superfund Innovative Technology Evaluation (SITE) Program demonstration and nine case studies.

The patented CAV-OX® process was developed by Magnum Water Technology (Magnum) to destroy organic contaminants in water. The process uses hydrodynamic cavitation, ultraviolet (UV) radiation, and hydrogen peroxide to oxidize organic compounds in water at or below milligrams-per-liter levels. 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, and in some cases, organic acids. The process uses mercury vapor lamps to generate UV radiation. The principal oxidants in the process, hydroxyl and hydroperoxyl radicals, are produced by hydrodynamic cavitation and direct photolysis of hydrogen peroxide at UV wavelengths.

The CAV-OX® process was demonstrated under the SITE Program at Edwards Air Force Base (Edwards) Site 16, California. Over a 4-week period in March 1993, about 8,500 gallons of VOC-contaminated groundwater was treated with both the CAV-OX® I low-energy process and the CAV-OX® II high-energy process. For the SITE demonstration, some configurations of the CAV-OX® process achieved trichloroethene (TCE) and benzene removal efficiencies of greater than 99.9 percent. Likewise, some configurations of the CAV-OX® process met State of California drinking water action levels and federal drinking water maximum contaminant levels for TCE and benzene at the 95 percent confidence level. Influent concentrations of TCE and benzene ranged from 1,500 to 2,000 and 250 to 500 micrograms per liter, respectively. No scaling was observed on any of the UV tubes. Magnum reports that scaling does not occur in the CAV-OX® process.

Potential sites for applying this technology include Superfund and other hazardous waste sites that have groundwater or aqueous wastes contaminated with organic compounds. Economic data indicate that groundwater remediation costs could range from about $13 to $31 per 1,000 gallons, depending on individual site characteristics. Of these costs, CAV-OX® process direct treatment costs could range from about $5 to $11 per 1,000 gallons.

The document includes three appendixes. Appendix A describes Magnum's experience in developing and applying the principles of hydrodynamic cavitation in combination with advanced oxidation for the treatment of industrial effluents and groundwater. Appendix B briefly describes Edwards Site 16 and summarizes the SITE demonstration activities and demonstration results. Appendix C summarizes nine case studies provided by Magnum.

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Abbreviations, Acronyms, and Symbols

AAR	Applications Analysis Report
ACL	Alternate concentration limit
AEA	Atomic Energy Act
ARAR	Applicable or relevant and appropriate requirement
BOD	Biochemical oxygen demand
BTEX	Benzene, toluene, ethylbenzene, and xylene
°C	Degrees Celsius
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CFU	Colony-forming unit
Ciba	Ciba-Geigy Corporation
CWA	Clean Water Act
DOE	U.S. Department of Energy
Edwards	Edwards Air Force Base
EPA	U.S. Environmental Protection Agency
FIFRA	Federal Insecticide, Fungicide, and Rodenticide Act
°F	Degrees Fahrenheit
GC	Gas chromatography
gpd	Gallons per day
gpm	Gallons per minute
H_2O_2	Hydrogen peroxide
$h\upsilon$	Ultraviolet radiation
kW	Kilowatt
kWh	Kilowatt-hour
°K	Degrees Kelvin
Magnum	Magnum Water Technology
Mannesmann	Mannesmann Anlagenbau
MCL	Maximum contaminant level
MEK	Methyl ethyl ketone
MIBK	Methyl isobutyl ketone
μg/L	Micrograms per liter
mg/L	Milligrams per liter
nm	Nanometers
NPDES	National Pollutant Discharge Elimination System
NTU	Nephelometric turbidity unit
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
PCB	Polychlorinated biphenyl
PCP	Pentachlorophenol
POC	Purgeable organic carbon
POTW	Publicly owned treatment works

PPE	Personal protective equipment
psi	Pounds per square inch
QA	Quality assurance
QC	Quality control
RCRA	Resource Conservation and Recovery Act
RFP	Request For Proposal
RREL	Risk Reduction Engineering Laboratory
SARA	Superfund Amendments and Reauthorization Act
SDWA	Safe Drinking Water Act
SITE	Superfund Innovative Technology Evaluation
SVOC	Semivolatile organic compound
TC	Total carbon
TCE	Trichloroethene
TCU	Total color units
TER	Technology Evaluation Report
TIC	Tentatively identified compound
TOC	Total organic carbon
TPH	Total petroleum hydrocarbons
TRPH	Total recoverable petroleum hydrocarbons
TSCA	Toxic Substances Control Act
UCL	Upper confidence limit
UV	Ultraviolet
VOC	Volatile organic compound

Conversion Factors

Measurement	*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	*megajoule*	*kilowatt-hour*	*0.2776*
Power	*horsepower*	*kilowatt*	*0.7457*
Temperature	*(°Fahrenheit - 32)*	*° Celsius*	*0.556*

Acknowledgements

This report was prepared under the direction and coordination of Mr. Richard G. Eilers, U.S. Environmental Protection Agency (EPA), Superfund Innovative Technology Evaluation (SITE) Program Project Manager in the Risk Reduction Engineering Laboratory (RREL), Cincinnati, Ohio. Contributors and reviewers for this report were Mr. Richard G. Eilers, Mr. Albert Venosa, Ms. Norma Lewis, and Mr. Gordon Evans of EPA RREL, Cincinnati, Ohio; and Mr. Dale Cox and Mr. Jack Simser of Magnum Water Technology.

The cooperation and participation of the Edwards Air Force Base personnel throughout the demonstration is gratefully acknowledged.

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Section 1
Executive Summary

The patented CAV-OX® cavitation oxidation process, developed by Magnum Water Technology (Magnum), was demonstrated under the U.S. Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) Program. The CAV-OX® process demonstration was conducted over a 4-week period in March 1993, at Edwards Air Force Base (Edwards) Site 16, California.

The CAV-OX® process is designed to destroy dissolved organic contaminants in water. The process uses hydrodynamic cavitation, ultraviolet (UV) radiation, and hydrogen peroxide to oxidize organic compounds in water. This treatment process 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. In the process a cavitation chamber induces hydrodynamic cavitation, which occurs when a liquid undergoes a dynamic pressure reduction while under constant temperature. The pressure reduction causes gas bubbles to explosively develop, grow, and then collapse. Cavitation decomposes water into extremely reactive hydrogen atoms and hydroxyl radicals, which recombine to form hydrogen peroxide and molecular hydrogen (Suslick 1989). The process also includes hydrogen peroxide and UV radiation generated by mercury vapor lamps. The principal oxidants in the process, hydroxyl and hydroperoxyl radicals, are produced by both hydrodynamic cavitation and direct photolysis of hydrogen peroxide at UV wavelengths.

The skid-mounted CAV-OX® process consists of the cavitation chamber, UV reactor, and control panel unit. Contaminated water is pumped through the cavitation chamber where hydroxyl and hydroperoxyl radicals are produced. The water then either enters the UV reactor or is recycled through the cavitation chamber; the rate of recycle determines the hydraulic retention time. Magnum recycles water through the cavitation chamber to continue generation of hydroxyl and hydroperoxyl radicals. Hydrogen peroxide is usually injected into the process, in-line, between the cavitation chamber and the UV reactor. In the UV reactor, the water flows through the space between the reactor wall and a UV-transmissive quartz tube in which a UV lamp is mounted. The treated water exits the UV reactor through an effluent line.

For the demonstration, groundwater from Edwards Site 16 monitoring wells was pumped into an equalization tank. From this tank, the water was pumped to an influent holding tank. Hydrogen peroxide was added to the water in the influent holding tank. Water was then pumped through a flow indicator and past an influent sample port, then through the cavitation chamber and UV reactor.

Three configurations of the CAV-OX® process were demonstrated: the CAV-OX® I low-energy process; the CAV-OX® II high-energy process operating at 5 kilowatts (kW); and the CAV-OX® II high-energy process operating at 10 kW. The CAV-OX® I process contained six 60-watt UV lamps in one reactor, and the CAV-OX® II process contained two UV reactors with one UV lamp each operating at 2.5 or 5 kW. The CAV-OX® I and the CAV-OX® II processes were operated simultaneously. Flow for the CAV-OX® I process varied from 0.5 to 1.5 gallons per minute (gpm). Flow for the CAV-OX® II process varied from 1 to 4 gpm.

Primary objectives for the demonstration were to:

- Determine trichloroethene (TCE) and benzene, toluene, ethylbenzene, and xylene (BTEX) removal efficiencies under different operating conditions
- Determine whether TCE and BTEX levels in treated groundwater meet applicable discharge limits to the sanitary sewer at the 95 percent confidence level
- Compare TCE and BTEX removal efficiencies among the three process configurations

Secondary objectives for the demonstration were to:

- Collect information, including process chemical dosage and utility requirements, needed to estimate treatment costs
- Assess the presence of degradation by-products in the treated water
- Collect groundwater characterization data for both influent and effluent streams

This report presents information from the SITE demonstration and several case studies that will be useful for implementing the CAV-OX® process at hazardous waste sites regulated by the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and the Resource Conservation and Recovery Act (RCRA). Section 2 presents an overview of the SITE Program, discusses the purpose of this report, describes the CAV-OX® process, and lists key contacts. Section 3 discusses information relevant to the process'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. Appendixes A through C include the vendor claims for the process, a summary of the demonstration results, and summaries of nine case studies, respectively.

Overview of the SITE Demonstration

Shallow groundwater at Edwards Site 16 was selected as the waste stream for evaluating the CAV-OX® process. About 8,500 gallons of groundwater contaminated with volatile organic compounds (VOC) was treated during the demonstration. The principal groundwater contaminants were TCE and BTEX, which were present at concentrations of up to 2,100 micrograms per liter (µg/L). Groundwater was pumped from three monitoring wells into a 7,500-gallon equalization (bladder) tank to minimize variability in influent characteristics. Treated groundwater was stored in a 21,000-gallon steel tank to await disposal.

The CAV-OX® equipment was transported in and operated from the bed of a 1-ton stake body truck. The process equipment functioned as planned after completing electrical and plumbing connections. Equipment did not malfunction or require maintenance during the 2-week demonstration.

The demonstration consisted of 15 planned runs for each CAV-OX® configuration. Each run varied the operating parameters of the CAV-OX® process. Samples from all three configurations for one run were collected before the next run began. The runs were conducted to demonstrate each configuration under different operating conditions and to compare the operation of the configurations.

The principal operating parameters for the CAV-OX® process, hydrogen peroxide dose, hydraulic retention time (determined by flow rate), and UV output, were varied to allow observation of treatment process performance under different operating conditions. Three hydrogen peroxide dosages were demonstrated over three flow rates. UV output varied with the three configurations. The process was also operated under additional conditions as determined by Magnum. Groundwater pH was lowered during two runs while operating under these conditions. Although Magnum does not consider influent pH to be a principal operating parameter and reports that pH has only a minimal effect on the CAV-OX® process, influent pH was varied in two runs because of its impact on other UV treatment systems.

During the demonstration, samples were collected from the influent and effluent lines of the CAV-OX® I and CAV-OX® II processes. Influent and effluent samples were analyzed for TCE, BTEX, other VOCs, semivolatile organic compounds (SVOC), total organic carbon (TOC), total carbon (TC), purgeable organic carbon (POC), metals, pH, alkalinity, hardness, temperature, total recoverable petroleum hydrocarbons (TRPH), specific conductance, hydrogen peroxide, and turbidity. These samples were also analyzed for acute toxicity to freshwater organisms using *Ceriodaphnia dubia* (water flea) and *Pimephales promelas* (fathead minnow) as the test organisms.

Results from the SITE Demonstration

The following preferred operating conditions (those conditions that reduced effluent VOCs to below target levels) were determined for the CAV-OX® I configuration: an influent hydrogen peroxide concentration of 23.4 milligrams per liter (mg/L) and a flow rate of 0.6 gpm. At these conditions, the effluent TCE and benzene levels were generally below target levels (5 µg/L and 1 µg/L, respectively). The average removal efficiencies for TCE and benzene were about 99.9 percent.

The following preferred operating conditions were determined for the 5-kW CAV-OX® II configuration: an influent hydrogen peroxide concentration of 48.3 mg/L and a flow rate of 1.4 gpm. At these conditions, the effluent TCE and benzene levels were generally below target levels. Average removal efficiencies for TCE and benzene were about 99.8 percent.

The following preferred operating conditions were determined for the 10-kW CAV-OX® II configuration: an influent hydrogen peroxide concentration of 48.3 mg/L and a flow rate of 1.4 gpm. At these conditions, the effluent TCE and benzene levels were generally below target levels. Average removal efficiencies for TCE and benzene were about 99.7 and 99.8 percent, respectively.

While operating under the preferred conditions, all CAV-OX® configuration effluents met State of California drinking water action levels and federal drinking water maximum contaminant levels (MCL) for BTEX at the 95 percent confidence level. Effluent from the CAV-OX® I process met the State of California drinking water action level and federal drinking water MCL for TCE at the 95 percent confidence level.

Bioassay analyses showed that influent was generally toxic to both the fathead minnow and the water flea, and that the CAV-OX® process effluent from runs without hydrogen peroxide was nontoxic to the fathead minnow but moderately toxic to the water flea. Bioassay analyses also showed that the CAV-OX®

process effluent from runs with hydrogen peroxide was toxic to both the fathead minnow and the water flea. Comparison of effluent toxicity data with that of hydrogen peroxide concentration in the effluent indicates that effluent toxicity may be due partially to hydrogen peroxide rather than CAV-OX® treatment by-products. Additional studies are needed to draw definitive conclusions on effluent toxicity.

One change in groundwater characteristics was temperature. In the CAV-OX® I configuration, the water temperature increased at an average rate of about 0.26 °F per minute of UV exposure. In the 5-kW CAV-OX® II process, the water temperature increased at an average rate of about 2.36 °F per minute of UV exposure. In the 10-kW CAV-OX® II process, the water temperature increased at an average rate of 4.29 °F per minute of UV exposure. Since the equipment was exposed to the surrounding environment, the temperature increase may vary with the ambient temperature or other atmospheric conditions.

Vendor-Provided Results From Case Studies

Nine case studies provided by Magnum are included in Appendix C as additional performance data for the CAV-OX® process. These cases involve both pilot- and full-scale units treating contaminated groundwater and industrial wastewaters. The contaminants of concern include pentachlorophenol (PCP), total petroleum hydrocarbons (TPH), BTEX, biochemical oxygen demand (BOD), TOC, atrazine, cyanide, and the bacterium *Salmonella*.

Waste Applicability

Potential sites for applying the CAV-OX® process include Superfund and other hazardous waste sites where groundwater or aqueous wastes are contaminated with organic compounds at mg/L levels or less. The process has been used to treat groundwater and industrial wastewater containing a variety of organic contaminants including phenols, herbicides, polynuclear aromatic hydrocarbons, and petroleum hydrocarbons. During the demonstration, influent concentrations of TCE and benzene ranged from 1,500 to 2,000 and 250 to 500 µg/L, respectively. Magnum reports that the CAV-OX® process has also treated cyanide-contaminated wastewater and drinking water infected with the bacterium *Salmonella*.

Economics

Using information from the SITE demonstration, 12 separate cost categories for CAV-OX® treatment of contaminated groundwater at a Superfund site were analyzed. This analysis examined costs for the CAV-OX® I low-energy configuration and the CAV-OX® II high-energy configuration using flow rates of 10 and 25 gpm. Costs (in October 1993 dollars) for each configuration are summarized below.

For the CAV-OX® I low-energy process, capital costs are estimated to be about $314,500 for the 10-gpm process, of which the CAV-OX® I process direct capital cost is $48,000. For the 25-gpm process, capital costs are estimated at about $342,500, of which the CAV-OX® I process direct capital cost is $64,000. Annual operation and maintenance (O&M) costs are estimated to be about $71,000 for the 10-gpm process and $78,000 for the 25-gpm process. Groundwater remediation costs are estimated to be about $30 per 1,000 gallons for the 10-gpm process, of which CAV-OX® I process direct costs are $10. For the 25-gpm process, groundwater remediation costs are estimated to be about $13 per 1,000 gallons, of which CAV-OX® I process direct costs are $5.

For the CAV-OX® II high-energy process, capital costs are estimated to be about $314,500 for the 10-gpm process, of which the CAV-OX® II process direct capital cost is $48,000. For the 25-gpm process, capital costs are estimated at about $342,500, of which the CAV-OX® II process direct capital cost is $64,000. Annual O&M costs are estimated to be about $75,000 for the 10-gpm process and $86,000 for the 25-gpm process. Groundwater remediation costs are estimated to be about $31 per 1,000 gallons for the 10-gpm process, of which CAV-OX® II process direct costs are $11. For the 25-gpm process, groundwater remediation costs are estimated to be about $14 per 1,000 gallons, of which CAV-OX® II process direct costs are $5. Table 1 summarizes CAV-OX® process costs.

For the case studies provided by Magnum, costs ranged from $1.62 to $1.93 per 1,000 gallons of water containing organic contaminants. For one case study, the cost to reduce BOD using only the cavitation chamber was $0.13 per 1,000 gallons.

Table 1. *CAV-OX® Process Cost Summary*

	CAV-OX® I Low-Energy Process Costs ($)		CAV-OX® II High-Energy Process Costs ($)	
	10 gpm	25 gpm	10 gpm	25 gpm
Capital	314,500	342,500	314,500	342,500
CAV-OX® Process Direct Capital	48,000	64,000	48,000	64,000
Annual O&M	71,000	78,000	75,000	86,000
Groundwater Remediation per 1,000 gallons	30	13	31	14
CAV-OX® Process Direct per 1,000 gallons	10	5	11	5

Section 2
Introduction

This section describes the SITE Program, the purpose of this report, and the CAV-OX® cavitation oxidation process developed by Magnum. The CAV-OX® process is designed to treat waters contaminated with low concentrations of organic compounds. For additional information about the SITE Program, the CAV-OX® process, or the demonstration site, key contacts are listed at the end of this section.

Purpose, History, and Goals of the SITE Program

The Superfund Amendments and Reauthorization Act (SARA) of 1986 mandates that 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 four programs: (1) one program to accelerate the use of new or innovative technologies to clean up Superfund sites through field demonstrations, (2) one to foster the further research and development of treatment technologies that are at the laboratory or pilot scale, (3) one to demonstrate and evaluate new or innovative measurement and monitoring technologies, and (4) one to disseminate technical information to the user community. Together, these four programs 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 that can be used 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 several factors 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 these technologies, and make the data available to Superfund decision-makers. An additional goal is to promote the development of emerging innovative technologies from the laboratory-, pilot-, or bench-scale stage to the full-scale stage.

Implementation of the SITE Program is a significant ongoing effort involving ORD, OSWER, various EPA Regions, and private businesses, including technology developers and parties responsible for site remediation. The technology selection process and the field demonstration 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 sites requiring remediation.

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
- Site-specific wastes and media to which the technology can be applied

- Potential site-specific process operating problems as well as possible solutions
- Approximate capital, operating, and maintenance costs
- Projected long-term operating and maintenance costs

Innovative technologies chosen for a demonstration must be pilot- or full-scale applications and must offer some advantage over existing technologies. Mobile technologies are of particular interest. Cooperative agreements between EPA and the developer determine responsibilities for demonstrating and evaluating the technology. The developer is responsible for operating the technology at the selected site and is expected to pay the costs to transport, operate, and remove the equipment. EPA is responsible for project planning, sampling and analyses, quality assurance (QA), quality control (QC), report preparation, and technology transfer. Each year the SITE Program sponsors demonstrations of approximately 10 technologies.

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 more detail 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 performance for specific sites and wastes. These technical evaluators seek to thoroughly understand the performance of the technology during the demonstration as well as advantages, disadvantages, and costs of the technology for a specific application. The report also provides a detailed QA/QC discussion. This information is used to produce conceptual designs in sufficient detail to develop preliminary cost estimates for the demonstrated technology. If the candidate technology appears to meet the needs of site engineers, it will be analyzed more thoroughly using the TER, the AAR, and other site-specific information obtained from remedial investigations.

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 advantages, disadvantages, and limitations of the technology. Costs of the technology for different applications are estimated on the basis of 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. In addition, EPA evaluates the applicability of each technology for specific sites and wastes, other than those already tested, and studies the estimated costs of the applications. These results are also presented in the AAR.

Each demonstration evaluates a technology's performance in treating an individual waste type at a particular site. To obtain data with broad applicability, priority is given to technologies that treat wastes frequently found at Superfund sites. In many cases, however, wastes at other sites will differ in some way from the waste treated at the demonstration site. Therefore, the successful demonstration of a technology at one site does not ensure its success at others. 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 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.

This AAR synthesizes available information on Magnum's CAV-OX® process and draws reasonable conclusions regarding its range of applicability. This AAR will be useful to decision-makers considering using the CAV-OX® process. It represents a critical step in the development and commercialization of this treatment technology.

Technology Description

In February 1992, Magnum responded to EPA's request for proposal (RFP) for participation in the SITE Program. Magnum proposed demonstrating the CAV-OX® process to treat contaminated groundwater at Edwards under the SITE Program. EPA subsequently accepted the CAV-OX® process into the SITE Program. Through a cooperative effort among EPA ORD, EPA Region 9, the State of California, Edwards, and Magnum, the CAV-OX® process was demonstrated at Edwards Site 16.

Treatment Technology

The CAV-OX® process was developed by Magnum to destroy dissolved organic contaminants in water. Two United States patents and two U.S. patents pending protect the CAV-OX® process.

The process uses hydrodynamic cavitation, UV radiation, and hydrogen peroxide to oxidize organic compounds present in water at mg/L levels or less. 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 number of electrons lost in oxidation must equal the number of electrons gained in reduction. In the CAV-OX® process, organic contaminants in water are oxidized by hydroxyl and hydroperoxyl radicals, produced by hydrodynamic cavitation, 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 CAV-OX® process, hydroxyl and hydroperoxyl radicals, are produced by either hydrodynamic cavitation or direct UV photolysis of hydrogen peroxide that has been added to contaminated water.

In principle, the most direct way to generate hydroxyl radicals is to cleave hydrogen peroxide through photolysis. Photolysis of hydrogen peroxide occurs when UV radiation is applied, as shown in the following reaction:

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

where:

H_2O_2=	hydrogen peroxide
$h\nu$ =	UV radiation
OH =	hydroxyl radicals

Thus, photolysis of hydrogen peroxide results in a quantum yield of two hydroxyl radicals 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 (nm), the dominant emission wavelength of low-pressure UV lamps (CAV-OX® I), 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.

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 and thus slowing reaction rates.

Magnum adds the component of hydraulic cavitation; that is, the expansion and activity of bubbles generated by static or dynamic pressure reductions in a liquid. Boiling, a similar and more familiar event, is the expansion and activity of bubbles generated by temperature increases in a liquid. Cavitation can be induced by several means. For example, sound waves can cause pressure reductions resulting in acoustic cavitation. Also, the flow path of a liquid can be manipulated to reduce pressure, resulting in hydrodynamic cavitation. The CAV-OX® cavitation chamber is designed to generate hydrodynamic cavitation by manipulating the flow path of water. The bubbles produced in cavitation may contain gas, vapor, or a mixture of gas and vapor. Bubbles explosively develop, grow, and then collapse at a microscopic level. Research of acoustical cavitation reports the temperature of the bubble collapse to be about 5,000 degrees Kelvin (Flint and Suslick 1991). Additional research has shown that acoustical cavitation decomposes water into extremely reactive hydrogen atoms and hydroxyl radicals, which recombine to form hydrogen peroxide and molecular hydrogen (Suslick 1989). Numerous reduction or oxidation reactions may occur under these conditions. The rate at which cavitation decomposes water into hydrogen atoms and hydroxyl radicals is not known.

Reaction with hydroxyl radicals is not the only removal pathway possible in the CAV-OX® process; hydraulic cavitation destruction and direct photolysis by UV radiation of organic compounds also provide 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 type.

The principal operating parameters for the CAV-OX® process are hydrogen peroxide dose, hydraulic retention time (determined by flow rate), and UV output. Typically, during treatability studies, initial values of these parameters are selected based on Magnum's experience and the anticipated effects of the operating parameters on treatment process performance. These operating parameters are discussed briefly below. Their effects on performance are discussed in detail in Section 3.

Process Components and Function

Each CAV-OX® process consists of a portable, truck- or skid-mounted module, with the following components: cavitation chamber, cavitation pump, UV reactor, and control panel unit. The control panel unit includes electrical switches, indicator lamps, circuit breakers, and UV ballasts. In addition to these main process components, other equipment is used to address site-specific conditions or requirements, including contaminated water characteristics and effluent discharge limits. Figure 1 illustrates the main and ancillary components of the CAV-OX® technology demonstrated at Edwards Site 16.

For the SITE demonstration, groundwater was pumped from three monitoring wells into a 7,500-gallon equalization (bladder) tank to minimize variability in influent characteristics. Groundwater was primarily contaminated with VOCs, including TCE and BTEX. Treated groundwater was stored in a 21,000-gallon steel tank to await disposal.

Both the CAV-OX® I low-energy process and the CAV-OX® II high-energy process were demonstrated at Edwards. Three configurations of the CAV-OX® process were demonstrated. One configuration was the CAV-OX® I process, which contained one reactor with six 60-watt low-pressure UV lamps and operated at 360 watts. The second and third configurations were the CAV-OX® II process which operated at 5 and 10 kW, respectively. The CAV-OX® II process contained two UV reactors with one high-pressure UV lamp operating at 2.5 or 5 kW each. The CAV-OX® process generates UV radiation by mercury-vapor lamps. Each UV lamp is housed in a UV-transmissive quartz tube, mounted entirely within the UV reactor. The low-energy reactor has a volume of about 10 gallons and each high-energy reactor has a volume of about 6 gallons. Water flows through the space between the reactor wall and the quartz tube.

Contaminated water is pumped to the treatment process and enters the cavitation chamber through a section of pipe also containing a flow meter and an influent sampling port. Inside the cavitation chamber, the contaminated water undergoes extreme pressure variations resulting in hydrodynamic cavitation. Hydrogen peroxide is usually added to the contaminated water in-line between the cavitation chamber and the UV reactor. However, for the demonstration, hydrogen peroxide was added to the influent holding tank. Inside the UV reactor, photolysis of hydrogen peroxide by UV radiation results in additional formation of hydroxyl radicals; these free radicals then react rapidly with the organic contaminants. Treated water exits the UV reactor through an effluent pipe equipped with a flow gauge and effluent sample port.

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 compliance with regulatory requirements for secondary wastes and treatment by-products has become more stringent and expensive, 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 systems. However, the oxidation of organics by ozone, hydrogen peroxide, or UV radiation alone has kinetic limitations, thus restricting its applicability to a range of contaminants. Because of these limitations, conventional chemical oxidation technologies have been slow to become cost-competitive treatment options.

A combination of oxidative forces generally increases destruction efficiency, allowing more contaminants to be treated. In the CAV-OX® process Magnum combines hydrodynamic cavitation, UV radiation, and hydrogen peroxide. Hydroxyl and hydroperoxyl radicals formed by hydrodynamic cavitation and UV photolysis of hydrogen peroxide rapidly oxidize the contaminants and exhibit little contaminant selectivity.

The CAV-OX® process 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, cyanides, and nitrites) may also be oxidized in the process and can exert an additional oxidant demand. In other UV systems, after oxidation, metals tend to precipitate as suspended solids resulting in UV lamp scaling. However, Magnum reports that scaling does not occur in the CAV-OX® process.

Hydrogen peroxide is inexpensive, easy to handle, and readily available. As a result, its use with hydrodynamic cavitation and UV radiation in the CAV-OX® process offers considerable advantages over expensive and difficult-to-handle chemicals.

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

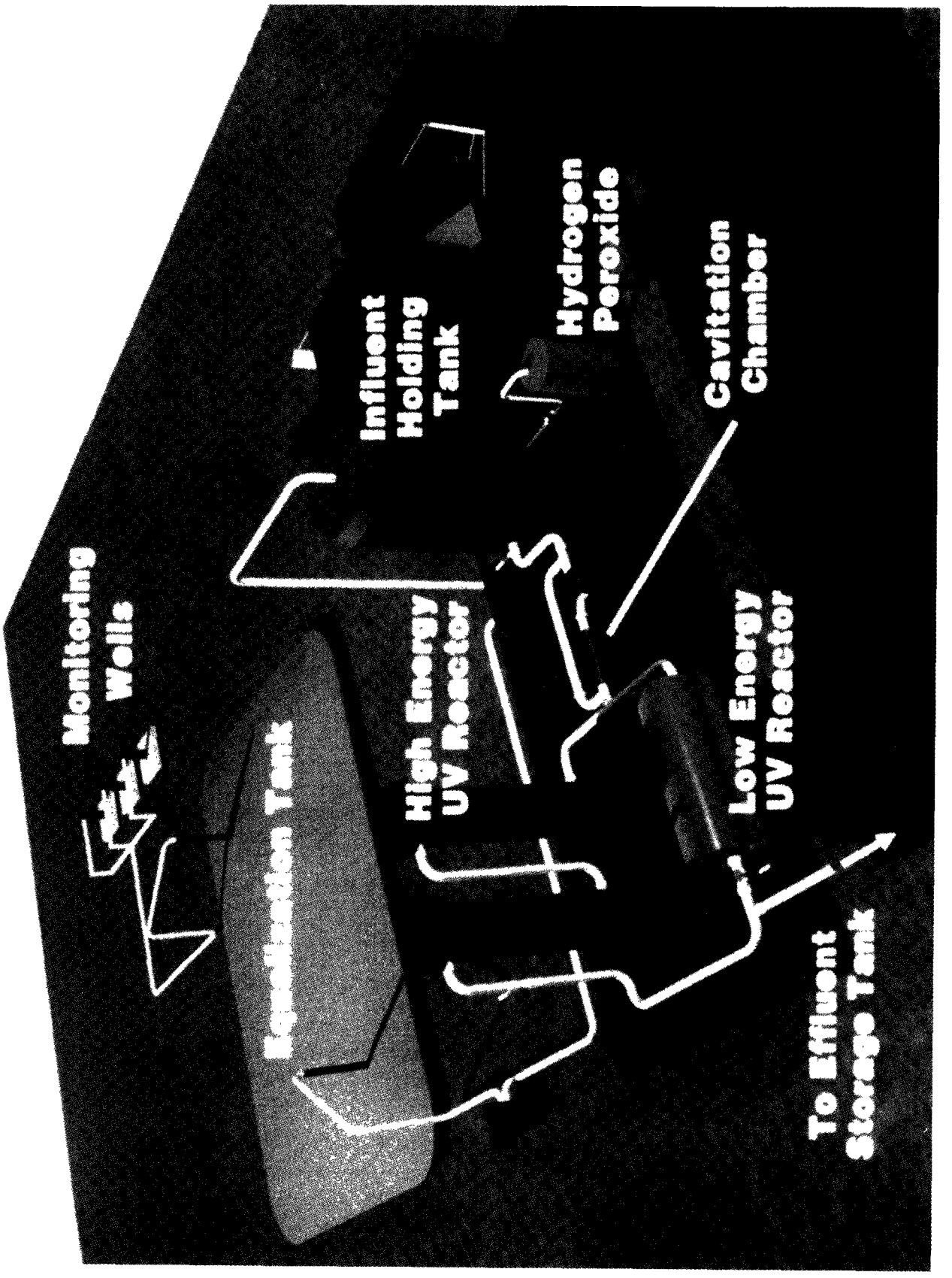

Figure 1. *The CAV-OX® Process as Demonstrated*

Table 2. Comparison of Technologies for Treating VOCs in Water

Technology	Advantages	Disadvantages
Air stripping	Effective at all concentrations; mechanically simple; relatively inexpensive	Innefficient at low concentrations; VOCs discharged to air
Steam stripping	Effective at all concentrations; removes a wide variety of VOCs	VOCs discharged to air; high energy consumption
Air stripping with carbon adsorption of vapors	Effective at all concentrations	Inefficient at low concentrations; generates large volumes of spent carbon requiring disposal or regeneration
Air stripping with carbon adsorption of vapors combined with spent carbon regeneration	Effective at all concentrations; no carbon disposal costs; can reclaim the product	Inefficient at low and high concentrations; high energy consumption
Carbon adsorption (liquid phase)	Effective at all concentrations; low air emissions; relatively inexpensive	Inefficient at low concentrations; requires disposal or regeneration of spent carbon
Biological treatment	Low air emissions; relatively inexpensive; low energy requirements; VOCs destroyed	Inefficient at high concentrations; generally not effective for chlorinated aliphatic compounds; slow rates of removal; sludge treatment and disposal required
Other enhanced oxidation processes	Effective at low concentrations; no air emissions; no secondary waste; VOCs destroyed	High energy consumption; not cost effective at high concentrations
CAV-OX® process	Effective at low concentrations; no air emissions; no secondary waste; VOCs destroyed	High energy consumption; not cost effective at high concentrations; process mechanisms not well documented

Key Contacts

Additional information on the CAV-OX® process, the SITE Program, and Edwards Site 16 can be obtained from the following sources:

The CAV-OX® Process
Dale Cox
President
Magnum Water Technology
600 Lairport Street
El Segundo, CA 90245
(310) 640-7000

The SITE Program
Richard G. Eilers
EPA Project Manager
EPA SITE Program
26 West Martin Luther King Drive
Cincinnati, OH 45268
(513) 569-7809

Edwards Air Force Base
John Haire
Environmental Coordinator
AFFTC/Public Affairs
2 S. Rosamond Boulevard
Edwards Air Force Base, CA 93524-1225
(805) 277-3510

Section 3
Technology Applications Analysis

This section addresses the applicability of the CAV-OX® process for treatment of water contaminated with organic compounds. Magnum's claims regarding the applicability and performance of the CAV-OX® technology are included in Appendix A. Because results from the SITE demonstration provided an extensive database, 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 nine case studies, which are presented in Appendix C.

This section summarizes the effectiveness of the CAV-OX® process and discusses the following topics in relation to its applicability: effectiveness of the process, factors influencing performance, site characteristics, material handling requirements, personnel requirements, potential community exposures, and potential regulatory requirements.

Effectiveness of the CAV-OX® Process

This section discusses the effectiveness of the CAV-OX® process based on results from the SITE demonstration and nine other case studies.

Results of the SITE Demonstration

The SITE demonstration was conducted at Edwards Site 16 in California over a 4-week period in March 1993. During the demonstration, both the CAV-OX® I low-energy process and the CAV-OX® II process treated about 8,500 gallons of groundwater contaminated with VOCs, mainly TCE and BTEX. Other VOCs (methylene chloride, acetone, and 1,2-dichloroethene) were present at low levels. Groundwater was pumped from three monitoring wells into a 7,500-gallon equalization (bladder) tank to minimize variability in influent characteristics. Treated groundwater was stored in a 21,000-gallon steel tank to await disposal. During the demonstration, flow for the CAV-OX® I process varied from 0.5 to 1.5 gpm. Flow for the CAV-OX® II process varied from 1 to 4 gpm. These pilot-scale flow rates are directly applicable to a full-scale process.

The CAV-OX® process demonstration had both primary and secondary objectives. Primary objectives were considered critical for the technology evaluation. Secondary objectives provided additional information that was useful but not critical. The primary demonstration objectives were to:

- Determine TCE and BTEX removal efficiencies in the treatment process under different operating conditions
- Determine whether TCE and BTEX levels in treated groundwater meet applicable discharge limits to the sanitary sewer at the 95 percent confidence level
- Compare TCE and BTEX removal efficiencies among the three process configurations

Secondary objectives for the demonstration were to:

- Collect information, including process chemicaldosage and utility requirements, needed to estimate treatment costs
- Assess the presence of degradation by-products in the treated water
- Collect groundwater characterization data for both influent and effluent streams

The demonstration consisted of 15 planned runs for each configuration. The first run was conducted using the operating conditions recommended by Magnum. For subsequent runs, operating parameters were varied, as discussed in Appendix B, to allow observation of each treatment process performance under different operating conditions.

During the demonstration, samples were collected from the main feed line from the influent holding tank and the effluent lines from the CAV-OX® I and CAV-OX® II UV reactors. Influent and effluent samples were analyzed for TCE, BTEX, other VOCs, SVOCs, TOC, TC, POC, metals, pH, alkalinity, hardness, temperature, TRPH, specific conductance, hydrogen peroxide, and turbidity. These samples were also analyzed for acute toxicity to freshwater organisms.

Appendix B summarizes (1) the site description, (2) the site contamination characteristics, (3) the SITE demonstration, (4) the experimental design, and (4) the treatment results. Key findings of the demonstration are as follows:

- The following preferred operating conditions were determined for the CAV-OX® I configuration: an influent hydrogen peroxide level of 23.4 mg/L and a flow rate of 0.6 gpm. At these conditions, the effluentTCE and benzene levels were generally below target levels (5 µg/L and 1 µg/L, respectively). The average removal efficiencies for TCE and benzene were about 99.9 percent.

- The following preferred operating conditions were determined for the CAV-OX® II configuration: an influent hydrogen peroxide level of 48.3 mg/L and a flow rate of 1.4 gpm. At these conditions, the effluent TCE and benzene levels were generally below target levels. The average removal efficiencies for TCE and benzene were about 99.7 and 99.8 percent, respectively.

- While operating under the preferred conditions, effluents from all CAV-OX® configurations met State of California drinking water action levels and federal drinking water MCLs for BTEX at the 95 percent confidence level. Effluent from the CAV-OX® I process met State of California drinking water action levels and federal drinking water MCLs for TCE at the 95 percent confidence level.

- Bioassay analyses showed that untreated influent was generally toxic to both the fathead minnow and the water flea and that the CAV-OX® process effluent from runs without hydrogen peroxide was nontoxic to the fathead minnow but moderately toxic to the water flea. Bioassay analyses also showed that the CAV-OX® process effluent from runs with hydrogen peroxide was toxic to both the fathead minnow and the water flea. Comparison of effluent toxicity data with that of hydrogen peroxide concentration in the effluent indicates that effluent toxicity may be due partially to hydrogen peroxide rather than CAV-OX® treatment by-products. Additional studies are needed to draw definitive conclusions on the effluent toxicity.

- One change in groundwater characteristics was temperature. In the CAV-OX® I configuration, the water temperature increased at an average rate of about 0.26 °F per minute of UV exposure. In the 5-kW CAV-OX®II process, the water temperature increased at an average rate of about 2.36 °F per minute of UV exposure. In the 10-kW CAV-OX® II process, the water temperature increased at an average rate of 4.29 °F per minute of UV exposure. Since the equipment was exposed to the surrounding environment, the temperature increase may vary with the ambient temperature or other atmospheric conditions.

- No scaling was observed on any of the tubes. Magnum reports that scaling does not occur in the CAV-OX® process. Scaling increases maintenance costs and decreases efficiency.

- Electricity is the only utility requirement for the CAV-OX® process. Electricity demand was 2.2 kW for the CAV-OX® I process, 6.4 kW for the 5-kW CAV-OX®II process, and 13 kW for the 10-kW CAV-OX® II process.

Results of Other Case Studies

Results of nine case studies provided by Magnum (Appendix C) are included as additional performance data for the CAV-OX® process. These claims and interpretations are those made by Magnum and have not necessarily been substantiated by test data. These cases involve both pilot- and full-scale units treating contaminated groundwater and industrial wastewaters. Contaminants of concern included PCP, TPH, BTEX, BOD, TOC, atrazine, cyanide, phenol, and the bacterium *Salmonella*.

Factors Influencing Performance

Several factors influence the effectiveness of the CAV-OX® process. These factors can be grouped into three categories: (1) influent characteristics, (2) operating parameters, and (3) maintenance requirements. Each of these is discussed below.

Influent Characteristics

The CAV-OX® process uses chemical oxidation to destroy organic contaminants; therefore, other species in the influent that consume oxidants present an additional load for the process. 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 bicarbonates, carbonates, sulfides, nitrites, bromides, and cyanides. Metals present in reduced states, such as trivalent chromium, ferrous ion (Fe^{+2}), manganous ion (Mn^{+2}), and several others, are also likely to be oxidized. In addition to acting as scavengers, these reduced metals can cause concerns under alkaline conditions. For example, trivalent chromium can be oxidized to hexavalent chromium, which is more toxic. Ferrous ion 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 that can affect treatment efficiency.

The concentrations of carbonate and bicarbonate influence the performance of the CAV-OX® process. These ions exert an oxidant demand on the process by absorbing UV light and scavenging hydroxyl radicals. However, influent pH can be adjusted to minimize these effects.

Metals present in a reduced state (such as iron or manganese) are oxidized by the UV process. Conversion of metals to forms that are less soluble at higher oxidation states (for example, Fe^{+2} to Fe^{+3}) may result in coating of the quartz tubes housing the UV lamps; this would cause poor UV transmission and therefore interfere with contaminant destruction. However, Magnum reports that scaling of this nature has never occurred with the CAV-OX® process.

The CAV-OX® process can treat water containing a variety of VOCs, such as TCE and BTEX. 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 and vinyl chloride) and aromatic compounds (such as phenol, benzene, toluene, and xylene), because these compounds are easy to oxidize. Organic contaminants without double bonds (such as chloroform) are not easily oxidized and are thus more difficult to remove.

Contaminant concentration is a major factor affecting treatment process effectiveness. The CAV-OX® process is most effective in treating water with contaminant concentrations present in water at mg/L levels or less. If contaminant concentrations are greater, the CAV-OX® process may be used in combination with other treatment technologies such as air stripping. For highly contaminated water, Magnum increases the flow of water recycled through the cavitation chamber for continued production of hydroxyl and hydroperoxyl radicals.

Operating Parameters

Operating parameters are those procedures that can be varied during the treatment process to achieve desired removal efficiencies. The principal operating parameters for the CAV-OX® process are hydrogen peroxide dose, hydraulic retention time, and UV output. During the demonstration, each of these parameters was varied to observe each treatment process performance under different operating conditions.

The hydrogen peroxide dose is based on treatment process configuration, contaminated water chemistry, and contaminant oxidation rates. Under ideal conditions, hydrogen peroxide is photolyzed to hydroxyl and hydroperoxyl radicals, which oxidize contaminants in the groundwater. 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 nm, 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 a relatively high concentration of hydrogen peroxide 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. Thus, an optimum concentration of hydrogen peroxide must be maintained at all times.

Flow rate through the treatment process determines UV reactor retention time. Increasing or decreasing the flow rate will affect the treatment efficiency by changing the time available for hydroxyl radical formation and contaminant destruction. During the demonstration, flow for the CAV-OX® I process varied from 0.5 to 1.5 gpm. Flow for the CAV-OX® II process varied from 1 to 4 gpm. These pilot-scale flow rates are directly applicable to a full-scale process.

UV output varies with the type of CAV-OX® process being operated. The CAV-OX® I low-energy process has a UV output of 360 watts, while the CAV-OX® II high-energy process can operate at 2.5, 5, 7.5, or 10 kW.

Influent pH is a critical operating parameter in other UV systems. It 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. However, Magnum does not consider influent pH a principal operating parameter for the CAV-OX® process.

Maintenance Requirements

The maintenance requirements for the CAV-OX® process are based on discussions with Magnum during and after the SITE demonstration. Magnum bases its information on (1) production units operating in the field, (2) the SITE demonstration at Edwards, and (3) research and development testing performed by Magnum over several years. Regular maintenance by trained personnel is essential for the successful operation of the CAV-OX® process. However, the only major process component that requires regular maintenance is the UV lamp assembly.

Regular UV lamp assembly maintenance includes periodic cleaning of the quartz tubes housing the UV lamps. Eventually, the lamps may need to be replaced. The frequency of quartz tube cleaning depends on the type and concentration of suspended solids present in the influent or formed during treatment. UV lamp assemblies can be removed from the oxidation unit to

provide access to the quartz tubes, which can then be cleaned manually. Magnum recommends cleaning the quartz tubes by wiping them monthly with a clean cloth, although at existing CAV-OX® operations, this maintenance is performed once every 3 months.

The life of UV lamps used in the CAV-OX® process normally cited by most manufacturers is 7,500 hours, given a use cycle of 8 hours, which 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 Magnum, based on lamp specifications, UV lamp output does not decline significantly until after about 10,000 hours of operation for the CAV-OX® I process and 3,000 hours of operation for the CAV-OX® II process. Therefore, Magnum recommends replacing the UV lamps after about 7,500 hours and 2,000 hours, respectively

During and after the demonstration, no scaling was observed on any of the UV tubes. Magnum reports that scaling does not occur in the CAV-OX® process. The equipment functioned as planned after completing electrical and plumbing connections. No equipment malfunctioned or required maintenance during the 2-week demonstration.

The CAV-OX® process 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 divergent operating conditions in the CAV-OX® equipment. Remotely operated and monitored systems are hard-wired into central control panels or computers through programmable logic controllers.

Other components of the CAV-OX® process, such as valves, flow meters, tanks, piping, and the hydrogen peroxide feed module should be visually checked for leaks once a week. Monthly maintenance includes inspection of all electrical components, pumps, and the UV reactor. Monthly maintenance of the UV reactor includes removing aluminum seals and removing, inspecting, and wiping the quartz tubes. Annual maintenance (or more frequent if indicated by monthly inspections) should include replacement of UV lamps and quartz tubes. Magnum reports that corrosion of the cavitation chamber due to cavitation does not occur.

Site Characteristics

In addition to influent characteristics and effluent discharge requirements, site characteristics are important when considering the CAV-OX® process. Site-specific factors can impact the CAV-OX® process, and should be considered before selecting the technology for remediation of a specific site. Site-specific factors include support systems, site access, climate, utilities, and services and supplies. Section 4 identifies examples of categories that are specific to the CAV-OX® process and to a hazardous waste remediation site.

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. Because the CAV-OX® process is normally operated as a continuous flow-through process, it may be necessary to install several extraction wells in order 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 CAV-OX® process, 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 process. 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 for simple analyses of the physical and chemical water characteristics required to monitor performance. Such characteristics may include pH, hydrogen peroxide dose, and temperature.

The CAV-OX® process is available in many sizes. During the SITE demonstration, a 2,000-square-foot area was adequate for both CAV-OX® configurations, support facilities, nonhazardous and hazardous waste storage containers, and the office and field laboratory trailer. A larger process may require a slightly larger area, depending on the required support facilities. Areas required for influent and effluent storage tanks or pretreatment equipment, if needed, will depend on the number and size of the tanks. Also, a 10-by-40-foot area may be required for an office or laboratory building.

The area containing the CAV-OX® process and tanks should be relatively level and should be paved or covered with compacted soil, gravel, or a concrete pad.

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 CAV-OX® equipment and tanks.

Climate

According to Magnum, sub-freezing temperatures and heavy precipitation do not affect the operation of the CAV-OX® process. The process 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. However, if sub-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 process also facilitates regular process checks and maintenance. The CAV-OX® process requires a high-voltage power supply, which should also be protected from heavy precipitation.

Utilities

Operation of the CAV-OX® process requires water and electricity. Water is required for personnel and equipment decontamination. The CAV-OX® I process requires 230-volt, 3-phase, 30-ampere electrical service. The CAV-OX® II process requires 480-volt, single-phase, 30-ampere electrical service. Additional 120-volt, single-phase, 10-ampere electrical service is needed for UV power supply controls. The office and laboratory trailer used for the SITE demonstration required 220-volt, 3-phase, 50-ampere electrical service.

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

Services and Supplies

A number of services and supplies are required for operating the CAV-OX® process, most of which can be readily obtained. During the demonstration, subcontractors, off-site facilities, or Edwards furnished the required major services.

An adequate on-site supply of spare parts is needed for malfunction of UV lamps, pumps, flow meters, or piping. If an on-site parts inventory is not an option, proximity to an industrial supply center is an important consideration. In addition, an adequate supply of chemicals, such as hydrogen peroxide, or proximity to a supply center carrying this chemical, is essential.

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

Material Handling Requirements

The CAV-OX® process does not generate treatment residuals, such as sludge or spent filter media, that require further processing, handling, or disposal. The cavitation chamber, UV reactor, control panel unit and other components of the process, such as the chemical feed units, are air tight and produce no air emissions that require special controls. Material handling requirements for the CAV-OX® process include those for (1) pretreatment materials and (2) treated water. These are described below.

Pretreatment Materials

In general, pretreatment requirements for contaminated water entering the CAV-OX® process are minimal. Depending on the influent characteristics, pretreatment 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 adversely affects the oxidation process. Separated oil and grease should be collected 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 CAV-OX® process and are less soluble at higher oxidation states under alkaline conditions. After oxidation, the metals will tend to precipitate as suspended solids in the CAV-OX® process, 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 predicted decreases in contaminant removal efficiency without metals removal and 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 they 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 may be adjusted in line. Carbonate and bicarbonate ions act as oxidant scavengers and present an additional load to the treatment process. The only material handling associated with pH adjustment involves chemicals such as acids and bases; pH adjustment will not create any additional waste streams requiring disposal.

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 process operating conditions, treated water may require pH adjustment before discharge.

Personnel Requirements

Personnel requirements for the CAV-OX® process are minimal. Generally, one operator, trained by Magnum, conducts a weekly 30-minute process check. The operator should be able to: (1) fill the hydrogen peroxide feed tank and adjust flow rates to achieve desired doses, (2) operate the control panel, (3) collect liquid samples and perform simple physical and chemical analyses and measurements (for example, pH, hydrogen peroxide concentration, temperature, and flow rate), (4) troubleshoot minor operational problems or conduct monthly maintenance, and (5) collect samples for off-site analyses. Analytical work requiring more technical skills, such as VOC analyses and interpretation, can be performed by a local laboratory. The frequency of sample collection and analysis will depend on site-specific permit requirements.

Magnum reports that initial instruction to operate the CAV-OX® process requires about 8 hours of training and 8 hours of hands-on operation. The unit operator should also have completed an Occupational Safety and Health Administration (OSHA) initial 40-hour health and safety training course and an annual 8-hour refresher course, if applicable, before operating the CAV-OX® process at hazardous waste sites, and should participate in a medical monitoring program, as specified under OSHA requirements.

Potential Community Exposures

The CAV-OX® process generates no chemical or particulate air emissions. Therefore, the potential for on-site personnel or community exposure to airborne contaminants is very low. If the process malfunctions, alarms will sound, and all process components will shut off automatically. Contaminated-water pumps can be hard wired to the control panel so that alarms 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 process. However, when handled appropriately, the potential for exposure to hydrogen peroxide by on-site personnel is low. Hydrogen peroxide required for the CAV-OX® process is typically stored in polyethylene totes housed in metal frames or cages. The relatively small volumes of hydrogen peroxide that are used by the process and secure chemical storage practices result in a low potential threat of community exposure to hydrogen peroxide.

Potential Regulatory Requirements

This subsection discusses regulatory requirements pertinent to site remediation using the CAV-OX® process. Regulations applicable to a particular application of this process will depend on site-specific remediation logistics and the type of contaminated water to be treated. Table 3 summarizes the potentially applicable regulations that are discussed below.

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

Comprehensive Environmental Response, Compensation, and Liability Act

CERCLA, as amended by SARA, 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.

Table 3. *Regulations Summary*

Act	Applicability	Application to the CAV-OX® Process	Citation
Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)	Superfund sites	The Superfund program authorizes and regulates the cleanup of environmental contamination. It applies to all CERCLA site cleanups.	40 Code of Federal Regulations (CFR) Part 300
Resource Conservation and Recovery Act (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
Clean Water Act (CWA)	Discharges to surface water bodies	National Pollutant Discharge Elimination Sysem (NPDES) requirements of CWA apply to both Superfund and RCRA sites where treated water is discharged to surface water bodies. Pretreatment standards apply to discharge to publicly owned treatment works.	40 CFR Parts 122 to 125, Part 403
Safe Drinking Water Act (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 CERCLA and RCRA). 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
Toxic Substances Control Act (TSCA)	Polychlorinated biphenyl (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
Atomic Energy Act (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. Directives from the Office of Solid Waste and Emergency Response and the U.S. Department of Energy provide guidance for addressing mixed waste.	AEA and RCRA
Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA)	Pesticides	FIFRA regulates pesticide manufacturing and labeling. However, if pesticide-contaminated water is treated, RCRA regulations apply.	40 CFR Part 165
Occupational Safety and Health Act (OSHA)	All remedial actions	OSHA regulates on-site construction and the health and safety of workers at hazardous waste sites. Installation and operation of the process at Superfund or RCRA sites must meet OSHA requirements.	29 CFR Parts 1900 to 1926 20 CFR Part 1910.120 (hazardous waste operations and emergency response)

Contaminated water treatment using the CAV-OX® process will generally take place on site, while treated water may be discharged 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 using the CAV-OX® process are discussed below. No air emissions or residuals (such as sludge or spent filter media) are generated by the CAV-OX® process. Therefore, only regulations addressing contaminated water treatment and discharge are presented.

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 CAV-OX® process has been used to treat water contaminated with a variety of organic materials, including solvents, herbicides, polynuclear aromatic hydrocarbons, and petroleum hydrocarbons. Contaminated water treated by the CAV-OX® process 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 CAV-OX® process may include tank storage. Tank storage of contaminated and treated water (if the waters are hazardous under RCRA) must meet the tank storage requirements of 40 CFR Parts 264 or 265, Subpart J. Although air emissions are not associated with the CAV-OX® process, 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 standards for emissions from equipment leaks and system 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 CAV-OX® process 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 also will generally 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.

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 to the discharge. On-site discharges to surface water bodies must meet substantive National Pollutant Discharge Elimination System (NPDES) requirements, but do not require an NPDES permit. Off-site discharges to a surface water body require an NPDES permit and must meet NPDES permit limits. Discharge to a POTW is considered to be 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.

Safe Drinking Water Act

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

Under the SDWA, primary (or health-based) and secondary (or aesthetic) MCLs and used as cleanup standards for water that is, or may be, used for drinking water. 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 to establish ACLs (EPA 1987a).

Water discharge through injection wells is regulated by the underground injection control program. Injection wells are categorized as 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 CAV-OX® process, 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.

Toxic Substances Control Act

Testing, premanufacture notification, and recordkeeping requirements for toxic substances are regulated under the Toxic Substances Control Act (TSCA). TSCA also includes storage requirements for PCBs (40 CFR Part 761.65). The CAV-OX® process may be used to treat water contaminated with PCBs; PCB storage requirements would apply to pretreatment storage of PCB-contaminated water. The SDWA MCL for PCBs is 0.5 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 mg/L treated by incineration or an equivalent method must meet the requirements of 40 CFR Part 761.70.

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 CAV-OX® process 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 CAV-OX® process 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).

Federal Insecticide, Fungicide, and Rodenticide Act

The CAV-OX® process 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.

Occupational Safety and Health Administration

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 CAV-OX® process must comply with Part 1926, Subpart K, Electrical. Product chemicals used with the CAV-OX® process, such as hydrogen peroxide, 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 CAV-OX® process to treat groundwater containing VOCs. These cost estimates are based on data compiled during the SITE demonstration and provided by Magnum. Costs have been placed in 12 categories applicable to typical cleanup activities at Superfund and RCRA sites (Evans 1990). Costs are presented in October 1993 dollars and are considered to be order-of-magnitude estimates with an accuracy of plus 50 percent and minus 30 percent.

Table 4 lists the costs associated with operating the CAV-OX® I low-energy process. Table 5 lists the costs associated with operating the CAV-OX® II high-energy process. The tables present a breakdown of costs for the 12 cost categories and compare the costs between high-energy and low-energy configurations operating at flow rates of 10 and 25 gpm. Both tables show (in boldface type) the costs directly associated with using the CAV-OX® process. The tables also present total one-time costs and total annual O&M costs; the total costs for a hypothetical, 5-year groundwater remediation project; the net present values of the project; and the costs per 1,000 gallons of water treated. Each table concludes with a presentation of total CAV-OX® direct one-time and annual O&M costs and the direct costs per 1,000 gallons of water treated.

Basis of Economic Analysis

Several factors affect the estimated costs of treating groundwater with the CAV-OX® process, including flow rate, type and concentration of contaminants, groundwater chemistry, physical site conditions, geographical site location, contaminated groundwater plume size, and treatment goals.

The CAV-OX® process can treat several types of aqueous wastes, including contaminated groundwater 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. The following discussion presents the assumptions and conditions used in this analysis.

This analysis assumes that the CAV-OX® process will treat contaminated groundwater continuously, 24 hours per day, 7 days per week. Based on this assumption, during a 1-year period, the 10-gpm unit will treat about 5.3 million gallons, and the 25-gpm unit will treat about 13.1 million gallons. This analysis assumes that the treatment project will last 5 years for both flow rate scenarios. In both configurations, the 10-gpm flow rate will treat a total of 26.3 million gallons and the 25-gpm flow rate will treat 65.7 million gallons of water. While it is difficult in practice to determine both the volume of groundwater for treatment and the actual duration of a project, these figures are used in this economic analysis. In addition, a 5-year period was chosen for each flow rate scenario in order to highlight the operating parameters and costs specific to treating groundwater. It also shows the differences in the total volume of water treated by using each flow rate. Standardizing the time factor also standardizes all time-based costs (such as rental equipment).

The total costs for a groundwater remediation project are presented as future values. Using the period described above, this analysis assumes a 5 percent inflation rate when calculating annual O&M costs in order 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 per 1,000 gallons treated are derived from the net present values. Capital equipment is not depreciated in this economic analysis.

Assumptions about groundwater conditions and treatment for both configurations and flow rate scenarios include the following:

- Any suspended solids present in groundwater are removed prior to entering the CAV-OX® process.
- Hydrogen peroxide is the only feed chemical needed and is used at a rate of 30 mg/L.

Table 4. *Costs Associated with the CAV-OX® I Low-Energy Process*

Cost Categories	Estimated Costs (1993 $)			
	10 gpm (a)		25 gpm (a)	
Site Preparation (b)		$74,700		$77,100
Administrative	35,000		35,000	
Treatability Study	**2,000**		**2,000**	
System Design	33,700		36,100	
Mobilization	**4,000**		**4,000**	
Permitting and Regulatory Requirements (b)		15,725		17,125
Capital Equipment (b)		314,500		342,500
Extraction Wells	146,000		158,000	
Sheltered Concrete Pad	22,500		22,500	
Treatment Equipment	**48,000**		**64,000**	
Auxillary Equipment	98,000		98,000	
Startup (b)		**5,000**		**5,000**
Labor (c)		34,000		34,000
Operations Staff	**31,000**		**31,000**	
Health and Safety Refresher Course	3,000		3,000	
Consumables and Supplies (c)		4,760		8,760
Hydrogen Peroxide	**900**		**2,200**	
UV Lamps	**1,000**		**3,700**	
Cartridge Filters	200		200	
Carbon Columns	1,000		1,000	
Personal Protective Equipment	600		600	
Disposal Drums	60		60	
Sampling Supplies	1,000		1,000	
Utilities (c)		1,430		3,960
Treatment Process	**1,300**		**3,600**	
Auxillary Equipment	130		360	
Effluent Treatment and Disposal (d)		0		0
Residual and Waste Shipping and Handling (c)		4,000		4,000
Analytical Services (c)		24,000		24,000
Maintenance and Modifications (c)		2,920		3,240
Treatment Process	**960**		**1,280**	
Auxillary Equipment	1,960		1,960	
Demobilization (b)		40,000		40,000
Treatment Process	**10,000**		**10,000**	
All Other	30,000		30,000	
Total One-Time Costs		$449,925		$481,725
Total Annual O&M Costs		$71,110		$77,960
Groundwater Remediation:				
Total Costs (e,f,g)		$853,904		$923,555
Net Present Value (h)		$799,595		$864,014
Costs per 1,000 Gallons (g)		$30		$13
Total CAV-OX direct one-time costs		**$69,000**		**$85,000**
Total CAV-OX direct O&M costs (j)		**$35,160**		**$41,780**
Costs Per 1,000 Gallons--Direct Costs		**$10**		**$5**

NOTES:
Items in bold denote CAV-OX® process direct costs

a During a 1-year period, it is assumed the 10-gpm unit will treat about 5.3 million gallons, and the 25-gpm unit will treat about 13.1 million gallons
b One-time costs
c Annual operation and maintenance costs
d Not applicable
e Future value
f Total for a 5-year project
g To complete a project within 5 years, it is assumed that the 10-gpm flow rate will treat a total of 26.3 million gallons, and the 25-gpm flow rate will treat a total of 65.7 million gallons
h Annual discount rate of 5 percent
j Administrative, permitting, etc. are not considered a direct O&M cost for the process

Table 5. *Costs Associated with the CAV-OX® II High-Energy Process*

Cost Categories	Estimated Costs (1993 $)			
	10 gpm (a)		25 gpm (a)	
Site Preparation (b)		$74,700		$77,100
Administrative	35,000		35,000	
Treatability Study	**2,000**		**2,000**	
System Design	33,700		36,100	
Mobilization	**4,000**		**4,000**	
Permitting and Regulatory Requirements (b)		15,725		17,125
Capital Equipment (b)		314,500		342,500
Extraction Wells	146,000		158,000	
Sheltered Concrete Pad	22,500		22,500	
Treatment Equipment	**48,000**		**64,000**	
Auxillary Equipment	98,000		98,000	
Startup (b)		**5,000**		**5,000**
Labor (c)		34,000		34,000
Operations Staff	**31,000**		**31,000**	
Health and Safety Refresher Course	3,000		3,000	
Consumables and Supplies (c)		4,260		6,460
Hydrogen Peroxide	**900**		**2,200**	
UV Lamps	**500**		**1,400**	
Cartridge Filters	200		200	
Carbon Columns	1,000		1,000	
Personal Protective Equipment	600		600	
Disposal Drums	60		60	
Sampling Supplies	1,000		1,000	
Utilities (c)		6,050		14,500
Treatment Process	**5,500**		**13,200**	
Auxillary Equipment	550		1,300	
Effluent Treatment and Disposal (d)		0		0
Residual and Waste Shipping and Handling (c)		4,000		4,000
Analytical Services (c)		24,000		24,000
Maintenance and Modifications (c)		2,920		3,240
Treatment Process	**960**		**1,280**	
Auxillary Equipment	1,960		1,960	
Demobilization (b)		40,000		40,000
Treatment Process	**10,000**		**10,000**	
All Other	30,000		30,000	
Total One-Time Costs		$449,925		$481,725
Total Annual O&M Costs		$75,230		$86,200
Groundwater Remediation:				
Total Costs (e,f,g)		$876,670		$969,086
Net Present Value (h)		$819,214		$903,252
Costs per 1,000 Gallons (g)		$31		$14
Total CAV-OX direct one-time costs		**$69,000**		**$85,000**
Total CAV-OX direct O&M costs (j)		**$38,860**		**$49,080**
Costs per 1,000 Gallons--Direct Costs		**$11**		**$5**

NOTES:
Items in bold denote CAV-OX® process direct costs

a — *During a 1-year period, it is assumed the 10-gpm unit will treat about 5.3 million gallons, and the 25-gpm unit will treat about 13.1 million gallons*
b — *One-time costs*
c — *Annual operation and maintenance costs*
d — *Not applicable*
e — *Future value*
f — *Total for a 5-year project*
g — *To complete a project within 5 years, it is assumed that the 10-gpm flow rate will treat a total of 26.3 million gallons, and the 25-gpm flow rate will treat a total of 65.7 million gallons*
h — *Annual discount rate of 5 percent*
j — *Administrative, permitting, etc. are not considered a direct O&M cost for the process*

- Alkalinity is not a concern because scaling does not occur within the CAV-OX® process.

- The treated effluent has a pH between 6.5 and 8.5 and will not require posttreatment to meet discharge standards.

- The groundwater contains negligible amounts of iron and manganese and will not require pretreatment for metals.

This analysis assumes that treated water will be discharged to surface water, and that the MCLs specified in the SDWA are the treatment target levels. Based on results of the SITE demonstration, the CAV-OX® process should achieve these levels.

The following assumptions were also made in this analysis:

- The site is a Superfund site in a semirural area of California.

- Contaminated water is in an aquifer requiring 150-foot extraction wells.

- Suitable site access roads exist.

- All required utility lines (such as electricity and telephone) exist on site.

- A 900-square-foot concrete pad with an awning will be needed to site and shelter the treatment process and auxiliary equipment for both configurations and both flow rate scenarios.

- The treatment process operates automatically.

- One technician will be required to operate the equipment, collect all required samples, and maintain and repair equipment.

- Labor costs associated with major repairs are not included.

- Treated and untreated water samples will be collected monthly and analyzed off site for VOCs.

- Disposal costs for spent UV lamps from the CAV-OX® process are incurred by the customer.

Estimates of the chemical feed rates and the hydraulic retention time required to meet treatment goals, which are listed in Appendix B, are based on the CAV-OX® process's performance during pilot tests, and on discussions with Magnum. On the basis of the demonstration, VOCs in the groundwater are assumed to be TCE at 1,100 µg/L and benzene at 250 µg/L.

Cost Categories

Cost data associated with the CAV-OX® process 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. All direct costs associated with operating the CAV-OX® process are identified as CAV-OX® direct costs; all costs associated with the hypothetical remediation and auxiliary equipment are identified as groundwater remediation costs.

Site Preparation Costs

Site preparation costs include administrative, treatability study, process 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 be needed to determine the appropriate specifications of the CAV-OX® process for the site as well as the amounts of chemicals and reagents needed for optimal performance. Magnum, which will perform this study, estimates that a typical study will cost about $2,000.

Process design costs include those for the site layout and the treatment process operations, and are associated with a groundwater remediation project. Design costs are typically 20 percent of the total construction cost. Construction costs include constructing a concrete pad and shelter for the treatment and auxiliary equipment and installing extraction wells and piping (see Capital Equipment Costs). Construction costs are about $168,500 for the 10-gpm flow rate scenario and about $180,500 for the 25-gpm flow rate scenario for both configurations. Therefore, design costs would be about $34,000 for the 10-gpm flow rate and about $36,000 for the 25-gpm flow rate for both configurations.

Mobilization involves transporting all equipment to the site, assembling the equipment, performing optimization and shakedown activities, and training an operator. Transportation costs are site-specific and will depend on the location of the site in relation to all equipment vendors. The CAV-OX® process is delivered to each site in one semitrailer from El Segundo, California, and is estimated to cost $1,000. Magnum will position the process, but the customer is responsible for making all necessary connections and performing all optimization and shakedown activities. Initial operator training is needed to ensure

safe, economical, and efficient operation of the process. Magnum estimates that training will require about 1 day. Total mobilization costs are estimated to be about $4,000, and mobilization is estimated to take about 5 days to complete, regardless of flow rate or treatment process size.

For both configurations, total site preparation costs are estimated to be about $75,000 for the 10-gpm flow rate scenario and $77,000 for the 25-gpm flow rate scenario.

Permitting and Regulatory Requirements Costs

Permitting and regulatory costs depend on whether treatment is performed at a corrective action site regulated under Superfund or RCRA and disposal methods for treated effluent and solid waste. 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 associated with a groundwater remediation project 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 both configurations, permitting and regulatory costs are estimated to be $16,000 for the 10-gpm flow rate scenario and $17,000 for the 25-gpm flow rate scenario.

Capital Equipment Costs

Capital equipment costs include installing extraction wells; constructing a concrete pad and shelter for the treatment and auxiliary equipment; and purchasing all treatment and auxiliary 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 CAV-OX® process. 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 both configurations and flow rate scenarios will be about $90,000.

Pumps, piping, and valve connection costs are associated with a groundwater remediation project and will depend on the number of extraction wells needed, the flow rate, the distance of the extraction wells from the treatment process, and the climate of the area. This analysis assumes that four extraction wells are located about 200 feet from the CAV-OX® process. Four 2.5-gpm pumps will be required to maintain a 10-gpm flow rate. The total cost for four 2.5-gpm pumps is about $8,000. Four 6.25-gpm pumps will be required to maintain a 25-gpm flow rate; the total cost of four 6.25-gpm pumps is about $20,000. Piping and valve connection costs, including installation, are about $60 per foot. Therefore, total piping costs are estimated to be an additional $48,000.

The total cost of constructing extraction wells and all connections will be about $146,000 for the 10-gpm flow rate scenario and $158,000 for the 25-gpm flow rate scenario for both configurations.

A concrete pad with an awning will need to be constructed to shelter the CAV-OX® process and all auxiliary equipment. The concrete pad will measure about 900 square feet and will cost about $25 per square foot, including construction and materials, for a total cost of $22,500. Costs associated with designing the concrete pad are included in the process design costs (see Site Preparation Costs). Total construction costs for both configurations will be about $168,500 for the 10-gpm flow rate scenario and about $180,500 for the 25-gpm flow rate scenario for both configurations.

Treatment equipment typically consists of the CAV-OX® process and a 500-gallon hydrogen peroxide chemical feed module equipped with two feed pumps. The cost of the hydrogen peroxide module is included in the cost of the treatment process equipment. The cost of the CAV-OX® process will vary depending on the size of the required unit. Magnum identifies unit sizes by UV lamp kW demand. The wattage required depends on flow rates and the contaminants present in the water. For this analysis, the CAV-OX® I low-energy process operating at 10 gpm will require a unit with twelve 60-watt lamps available at a cost of $48,000. The CAV-OX® I process operating at 25 gpm will require a unit with forty-eight 60-watt lamps available at a cost of $64,000. The CAV-OX® II high-energy process operating at 10 gpm will require a unit with one 7.5-kW lamp available at a cost of $48,000. The CAV-OX® II process operating at 25 gpm will require a unit with one 20-kW lamp available at a cost of $64,000. Lamp wattage is estimated based on the flow through the process.

For this analysis, auxiliary equipment associated with a groundwater remediation project includes one sedimentation tank, two equalization tanks, two cartridge filters, and one filter press. This auxiliary equipment will be the same for both flow rate scenarios and treatment process configurations. 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 process that includes ductwork and carbon columns will be needed to eliminate fugitive emissions from the tanks. This venting process will cost about $25,000.

For this analysis, filtration will be required to remove any suspended solids from the sedimentation tank effluent. Two cartridge filters will be installed on the CAV-OX® feed line. Cartridges cost about $2,000 each for the 10- and 25-gpm flow rate scenarios, for a total cost of $4,000. 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.

Total auxiliary equipment costs, including venting ductwork, for both configurations and both flow rate scenarios will be about $98,000.

Startup Costs

Startup costs include the cost of developing a health and safety program, which will also include providing a 40-hour health and safety training course. The startup cost associated with a groundwater remediation project is estimated to be about $5,000 for both flow rate scenarios and both configurations.

Labor Costs

Labor costs include the total staff needed for operating and maintaining the CAV-OX® process, 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 process 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 adjustments, and perform routine maintenance, monitoring, and sample analysis. Magnum estimates that under normal operating conditions, an operator will be required to spend only 100 hours per year at the treatment site, excluding travel time. However, because finding a person willing to work for this short period may be difficult, this analysis assumes that the operator will work 8 hours during the weekdays. Annual labor costs for each treatment process and flow rate scenario are calculated using a 52-week year at a rate of $15 per hour for a total of about $31,000. An annual health and safety refresher course and medical monitoring are associated with a groundwater remediation project and will cost about $3,000 per person. Total annual labor costs will be about $34,000.

Consumables and Supplies Costs

Consumables and supplies costs fall into two major categories: (1) consumables and supplies associated with the operation of the CAV-OX® process (hydrogen peroxide, cartridge filters, activated carbon columns, and UV lamps) and (2) consumables and supplies associated with personal protective equipment (PPE), waste disposal, and sampling supplies.

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 500-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. The quantities of hydrogen peroxide consumed depend on the process flow rate and the waste characteristics. A 50 percent solution can be purchased for about $0.33 per pound including delivery. For this analysis, the hydrogen peroxide dose for both configurations and both flow rate scenarios will be 30 mg/L. This dosage requires 2,630 pounds of 50 percent hydrogen peroxide solution annually for the 10-gpm flow rate scenario for both configurations for a total cost of about $900. Annual hydrogen peroxide solution consumption for the 25-gpm flow rate scenario for both configurations would be 6,570 pounds for a total cost of about $2,200.

This analysis assumes that two cartridge filters capable of screening material larger than 3 microns will be installed upstream of the CAV-OX® unit and downstream of the sedimentation tank. The dual filter process allows one filter to be used while the other is replaced. These filters should remove any suspended solids prior to treatment. Replacement frequency depends on the quality of the groundwater to be treated and the flow rate. This analysis assumes that one replacement filter will be needed every 3 months. For both configurations and both flow rate scenarios, 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 require replacement every 6 months and are associated with a groundwater remediation project. 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.

Mercury-vapor UV lamps are used in the CAV-OX® process. Magnum recommends replacing UV lamps after every 7,500 hours of use in the CAV-OX® I low-energy process and every 2,000 hours of use in the CAV-OX® II high-energy process. At this rate, lamps in the CAV-OX® I process will need to be changed about every 10 months, and those in the CAV-OX® II process will need to be changed every 3 months. The CAV-OX® I process uses 12 UV lamps in the 10-gpm flow rate unit and 48 UV

lamps in the 25-gpm flow rate unit. Low-energy UV lamps cost $65 each. Therefore, the annual cost of UV lamps for the CAV-OX® I process will be about $1,000 for the 10-gpm flow rate scenario and $3,700 for the 25-gpm flow rate scenario. The CAV-OX® II process uses one 7.5-kW lamp in the 10-gpm flow rate unit, which costs $120, and one 20-kW lamp in the 25-gpm flow rate unit, which costs $350. Total lamp costs for the CAV-OX® II process will be about $500 for the 10-gpm flow rate scenario and $1,400 for the 25-gpm flow rate scenario.

PPE associated with a groundwater remediation project typically consists of nondisposable and disposable equipment. Nondisposable equipment consists of steel-toe boots and a full-face air respirator. Disposable PPE includes latex inner gloves, nitrile outer gloves, and safety glasses. Disposable PPE is assumed to cost about $600 per year for the operator, for both configurations and both flow rate scenarios.

Used UV lamps and disposable PPE are assumed to be hazardous and will need to be disposed of in 24-gallon drums. Any other potentially hazardous non-liquid wastes will also be disposed of in these drums. One drum is assumed to be filled every 3 months regardless of configuration or flow rate. Drums cost about $15 each, bringing the total annual drum cost to about $60.

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. For this analysis, the cost of sampling supplies is assumed to be $1,000 per year. Costs for laboratory analyses are presented in the Analytical Services Costs section.

Utilities Costs

Total utility costs are based on the electrical power used to operate the entire treatment process and all auxiliary equipment. The mercury-vapor UV lamps and pumps draw the majority of electricity used by the CAV-OX® process; that usage is presented in this analysis, which assumes that electricity costs about $0.07 per kW hour (kWh), inclusive of usage and demand charges. This analysis also assumes that all auxiliary equipment will draw an additional 10 percent of the total electrical power of the CAV-OX® process being used.

The CAV-OX® I low-energy process operating at 10 gpm draws about 2.2 kW, for a total annual cost of about $1,300. Operating at 25 gpm, it draws about 5.9 kW for a total annual cost of about $3,600. The CAV-OX® II high-energy process operating at 10 gpm draws about 9 kW, for a total annual cost of about $5,500. Operating at 25 gpm, it draws about 21.5 kW for a total annual cost of about $13,200.

Auxiliary equipment usage will cost an additional $130 for the 10-gpm CAV-OX® I process; $360 for the 25-gpm CAV-OX® I process; $550 for the 10-gpm CAV-OX® II process; and $1,300 for the 25-gpm CAV-OX® II process.

Electrical costs can vary by as much as 50 percent depending on the geographical location and local utility rates. A diesel-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.

Effluent Treatment and Disposal Costs

The CAV-OX® process does not generate sludge or spent carbon that requires further processing, handling, or disposal. Ideally, the products of the process are water, carbon dioxide, and sometimes organic acids. Effluent will be monitored routinely by the operator (see Labor Costs), and can be discharged directly to a nearby surface water body or POTW, assuming that the appropriate permits have been obtained (see Permitting and Regulatory Requirements Costs). This analysis assumes that no effluent treatment and disposal costs are incurred.

Residuals and Waste Shipping and Handling Costs

Spent cartridge filters, disposable PPE, and used UV lamps are generated from using the CAV-OX® process. These wastes are considered hazardous and will require disposal at a permitted facility. This analysis assumes that about four drums will be disposed of annually for both configurations, regardless of flow rate. 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 will be about $4,000.

In addition, filter cake from the filter press is considered a 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.

Analytical Services Costs

Analytical costs associated with a groundwater remediation project include laboratory analyses, data reduction and tabulation, quality assurance and quality control (QA/QC), and reporting. 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 are estimated to be about $24,000 for both configurations and both flow rate scenarios.

Maintenance and Modifications Costs

Annual repair and maintenance costs apply to all equipment involved in every aspect of groundwater remediation with the CAV-OX® process. No modification costs are assumed to be incurred. Magnum estimates that total annual maintenance costs will be about 2 percent of treatment process and auxiliary equipment costs. Maintenance costs are estimated at $3,000 for both configurations and both flow rate scenarios.

Demobilization Costs

This analysis assumes that site demobilization will include shutdown, disassembly, transportation, and disposal of CAV-OX® equipment and auxiliary equipment at a licensed hazardous waste disposal facility. This analysis also assumes that the CAV-OX® process will have no salvage value at the end of the project. Site clean up and restoration are also included in demobilization costs. This analysis assumes that the costs from shutdown to disposal for all activities associated with a groundwater remediation project will be about $30,000, including site clean up, restoration, and equipment decontamination. All disposal activities associated with operating the CAV-OX® process are estimated to cost an additional $10,000. Demobilization is estimated to take about 1 week to complete and to cost about $40,000.

The costs of demobilization, however, will be incurred at the end of the remediation project. This analysis assumes that the equipment will be used for 5 years, regardless of flow rate. Assuming an annual inflation rate of 5 percent, the net future value of this cost is estimated to be about $51,051. This figure was used to calculate the total costs presented in Tables 4 and 5.

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Appendix A
Vendor's Claims for the Technology

Note: This appendix to the report is provided entirely by Magnum Water Technology (Magnum). Claims and interpretations are made by Magnum and have not necessarily been substantiated by test data. This appendix has been edited only so that format is consistent with the document.

Introduction

Advanced oxidation systems have been used in various forms for many years to treat both industrial waste effluents and groundwater. A major benefit of advanced oxidation over conventional water treatment methods is its ability to reduce a variety of contaminants without producing by-products or transferring the contaminants to another medium requiring additional treatment or disposal.

In the past, ultraviolet (UV) radiation was combined with other oxidants, such as ozone, to achieve efficient reduction of contaminants at a more reasonable operating cost. The CAV-OX® process combines a patented cavitation chamber with hydrogen peroxide and UV radiation. The cavitation chamber is designed based on the principle of hydrodynamic cavitation, making the advanced oxidation process low maintenance and more cost-effective.

This appendix describes Magnum's experience in developing and applying the principles of hydrodynamic cavitation in combination with advanced oxidation for the treatment of industrial effluents and groundwater.

Hydrodynamic Cavitation

Physical Process

When a body of liquid is heated under constant pressure, or when its pressure is reduced at constant temperature by static or dynamic means, vapor-filled microbubbles (vapor and gas), or cavities, grow and ultimately become visible. This condition is called "boiling" if it is caused by temperature rise and "cavitation" if it is caused by dynamic pressure reduction at constant temperature. Cavitation involves the entire sequence of events beginning with bubble formation through cavity collapse.

Cavitation is very useful in the breakdown of organic chemicals and living organisms. In cavitated water, the heat from cavity implosion decomposes water into extremely reactive hydrogen atoms and hydroxyl radicals. During the immediate cooling phase, hydrogen atoms and hydroxyl radicals (OH•) recombine to form hydrogen peroxide, H_2O_2, and molecular hydrogen, H_2. If other compounds are added to the water, a wide range of secondary reactions can occur. Organic compounds are highly degraded in this environment, and inorganic compounds can be oxidized or reduced (Suslick 1989). Recent experiments have shown the temperature and pressure of the bubble collapse to be 5,000 degrees Kelvin (°K) and 1,000 atmospheres, respectively.

Cavitation is thus a result of pressure reductions in liquid and can be affected by controlling the pressure reduction. If the pressure is reduced and maintained long enough below a certain critical pressure, determined by the physical properties and conditions of the liquid, cavitation will result.

Dwell time is an integral part of cavitational flow, particularly for cavitation only operation. Dwell time is the period of time which the contaminant flow from the cavitation chamber is allowed to pause in dwell tanks, thereby enabling the micro bubble collapse process and the chemical dissociation mechanism to continue toward completion. After the dwell tank, the fluid stream is pumped back through the cavitation chamber for recycling, or is pumped forward into further processing. When the processing includes a UV reactor, then the process stream is pumped into the downstream UV reactor for further oxidation. Dwell tank time delay is a function of (1) the volume of the dwell tank, (2) the flow rate, and (3) the proportion of flow through the dwell tank.

The residence time of the process stream in the UV reactor is also a parameter in the management of the process stream. Residence time is the period required for a specific component of the contaminant stream to move into and out of the UV reactor. Residence time directly affects the amount of UV radiation received by each specific component of the contaminant stream. Residence time is allowed to vary from 1 minute to 20 minutes in the operating protocols. Generally, residence time is a direct function of the volume of the UV reactor divided by the flow in gallons per minute. Residence time can be directly affected by the amount of cavitation recycle being used, which is controlled by the recycle valve setting.

Chemical Process

The chemistry involved in the CAV-OX® process is based on the formation of hydroxyl radicals. The hydroxyl radical, OH•, one of the simplest diatomic radicals, is a powerful oxidizing agent as well as an excellent initiator for chain reactions. The standard oxidation electrode potential for the hydroxyl radical is 2.8 volts, while that of ozone is 2.18 volts, and that of chlorine is 1.68 volts. As a result, the hydroxyl radical more efficiently and rapidly oxidizes organics in water than either ozone or chlorine.

A hydroxyl radical initiates a chain reaction through many paths. The predominant route is the removal of an unstable hydrogen atom from an organic molecule. The attack on a glucose molecule by a hydroxyl radical is a typical example of these mechanics. The conversion of a glucose molecule into carbon dioxide and water begins when a hydroxyl radical removes a hydrogen atom from a glucose molecule. In the presence of air, the resulting glucose radical readily combines with an oxygen molecule to form a peroxy-glucose radical that in turn removes a hydrogen atom from another glucose molecule. This reaction results in a new glucose radical and a hydrogen peroxide molecule. The hydrogen peroxide molecule disassociates easily into an oxy-glucose radical, and a hydroxyl radical is regenerated. In the presence of oxygen, the oxy-glucose radical leads to the formation of a smaller organic radical, which continues to break down into oxalic acid and eventually to carbon dioxide and water.

With more complex molecules, competing reactions occur between the attack on the unstable hydrogen atom and the addition of the double bond. For example, minor amounts of intermediate molecules, such as catechol, hydroxyquinone, muconic acid, maleic acid, and oxalic acid are produced during the photo-oxidation of phenol. Reactions producing these molecules are typical of compounds that are difficult to oxidize.

The sonochemistry resulting from optimum cavitation is disclosed in the following articles: "Sonochemistry," K. S. Suslick, *Science*, March 23, 1990, Volume 247, pages 1439-1445, and an article entitled "The Temperature of Cavitation," E. B. Flint and K. S. Suslick, *Science*, September 20, 1991, Volume 253, pages 1397-1399.

Technology Description

The CAV-OX® process is a synergistic combination of hydrodynamic cavitation and UV radiation that oxidizes contaminants in water. It is a cost-effective method of removing organic contaminants from aqueous waste streams or groundwater without releasing volatile organic compounds (VOC) or producing material requiring further treatment. The process can reduce contaminant levels to meet discharge requirements for most aqueous solutions.

The complete CAV-OX® process consists of either the CAV-OX® I low-energy process or the CAV-OX® II high-energy process. The CAV-OX® I process effectively treats contaminants such as gasoline or trichloroethene, while more complex wastes, such as pentachlorophenol (PCP), require the use of the CAV-OX® II process.

The CAV-OX® process generally reduces contaminant levels by 95 to 99.99 percent. It cannot treat free product nor badly turbid waste streams because the UV reactors are less efficient because of lowered UV transfer to the waste stream; however, free product or turbid waste streams do not affect the cavitation chamber.

The CAV-OX® process oxidizes organic wastes into carbon dioxide through a free radical mechanism. Free radicals are generated and maintained by the combination of cavitation, seeding with hydrogen peroxide, metal catalysts, and ultraviolet light excitation. If required, reaction initiators are added to the water before entering the cavitation chamber. The oxidation process begins in the cavitation chamber; it continues in the UV reactor and persists long after the treated water leaves the process until there is no surplus of oxidants. Part or all of the waste streams can be recycled after cavitation, after UV oxidation, or after a combination of the two.

During oxidation, organic carbon is converted to carbon dioxide and sulfides are converted to sulfates. No solids are generated. The treated waste stream is low in organics and is disinfected by the UV light and carbon transition. It can be reused, discharged into local sewage facilities, or discharged directly into local waterways, depending on local discharge requirements and process design.

Operational parameters are varied during the treatment process to achieve desired treatment efficiencies. Such parameters include hydraulic retention time, hydrogen peroxide dose, UV lamp intensity, and influent pH. In general, increasing retention time increases treatment efficiency.

If present in excess, hydrogen peroxide can act as a free radical scavenger, decreasing the hydroxyl radical concentration. Therefore, the minimum dose of hydrogen peroxide that achieves the required treatment is preferred.

The CAV-OX® process tends to oxidize metallic salts; however, both the CAV-OX® I and CAV-OX® II UV lamps generate minimal heat and have shown no scaling tendencies.

Contaminants Treated by the CAV-OX® Process

The CAV-OX® process has been used to treat the following contaminants:

- Atrazine
- Chlorinated organics
- Halogenated organics
- Petroleum hydrocarbons
- Pesticides and herbicides
- Polychlorinated biphenyls (PCB)
- Polynuclear aromatic hydrocarbons (PAH)
- Benzene, toluene, ethylbenzene, and xylenes (BTEX)
- Cyanides
- Phenol
- Bacteria
- Viruses

The CAV-OX® process can treat the following contaminants in industrial wastewater:

- Amines
- Aniline
- Chlorinated solvents
- Chlorobenzene
- Complex cyanides
- Creosote
- Hydrazine compounds
- Isopropanol
- Methyl ethyl ketone (MEK)
- Methyl isobutyl ketone (MIBK)
- Methylene chloride
- PCBs
- PCP
- Pesticides
- Polynitrophenols
- Cyclonite
- 2,4,6-Trinitrotoluene
- Toluene
- Xylene

The CAV-OX® process can treat the following contaminants in groundwater:

- Bis(2-chloroethyl)ether
- Creosote
- 1,2-Dichloroethane
- Dichloroethene
- Dioxins
- Dioxanes
- Freon 113
- MEK
- MIBK
- Methylene chloride
- PCBs
- PCP
- Pesticides
- PAHs
- Tetrachloroethene
- 1,1,1-Trichloroethane
- Trichloroethene
- Tetrahydrofuran
- Vinyl chloride
- Triglycol dichloride ether

The cavitation process alone reduces contaminant concentrations by about 20 to 50 percent. The synergistic combination of cavitation and UV radiation can reduce contaminant concentrations from 95 to 99.99 percent.

Treatment By-Products

The CAV-OX® process produces no air emissions and generates no residue, sludge, or spent media that require further processing, handling, or disposal. If contaminants are reduced to nondetectable levels, the effluent consists of water with some dissolved carbon dioxide gas, halides (for example, chloride), and in some cases organic acids. No VOCs are released to the atmosphere. Any remaining contaminants remain in the effluent.

The CAV-OX® process can break down single- and multiple-bond organic compounds, aliphatics, aromatics, heterocyclics, and related chemicals. Pure benzene, for example, is transformed into carbon dioxide and water, while the breakdown of trichloroethane would probably result in residual chlorides.

The CAV-OX® process does not treat metals. It may, however, oxidize metallic ions or reduce metallic salts in the process of destroying organic contaminants.

Operating Modes

The CAV-OX® process can be operated in one of three modes:

- Cavitation chamber only
- Cavitation chamber with low-energy UV radiation and hydrogen peroxide
- Cavitation chamber with high-energy UV radiation and hydrogen peroxide

Applications

The CAV-OX® process has the following applications:

- Treatment of groundwater, wastewater, industrial process water, and drinking water, or generation of ultrapure water, either as a stand-alone process or as part of a treatment train
- Pretreatment of industrial effluent prior to discharge to a publicly owned treatment works
- Final polishing prior to reuse or discharge to a receiving water body

Treatment Capacity

Theoretically, a CAV-OX® process of any given size can be constructed and operated. The design is modular; for example, groups of 250-gpm units can be operated together in parallel.

The smallest CAV-OX® unit operated to date is a 1-gpm unit. This unit was built for a distributor to carry in the trunk of his car to demonstrate to customers. Several mid-size units (10- to 20-gpm capacity) are operational. A 50-gpm unit has been built and delivered to a major soft drink company.

Pretreatment Requirements

In general, advanced oxidation systems require influent characteristics that may necessitate some pretreatment. Table A-1 lists desirable influent characteristics for the CAV-OX® process.

The cavitation chamber is not affected by the quality of the influent or the type of contaminants. The specifications provided above are intended to limit suspended solids, which absorb UV energy and decrease effective UV energy.

Typically, the only pretreatment equipment required for the CAV-OX® process is a holding tank to ensure a constant stream flow to the process. In cases of high turbidity or other interfering agents, filtration equipment may also be required.

Transportation to Site

A CAV-OX® process is very compact and easily transported to the installation site. A skid-mounted 10-gpm CAV-OX® unit measures 5-foot by 4-foot by 7-foot and weighs about 600 pounds.

Table A-1. *Desirable Influent Characteristics*

Characteristic	Value
Turbidity	< 25 NTU
Iron salts	< 5 mg/L
Color	< 25 TCU
Suspended matter	< 10 microns
Free product	< 25 mg/L

Installation

A CAV-OX® unit is very easy to install and generally has a small footprint relative to the process flow rate. For example, a 20-gpm unit needs a 6-foot by 6-foot area and has a shipping weight of about 800 pounds. Each process is skid-mounted and transportable, and requires only the connection of 1-inch unions to complete the process flow. Construction materials are stainless steel and quartz glass with Viton™ rubber seals.

Power Requirements

The CAV-OX® I low-energy process requires a 230-volt, 3-phase, 30-ampere power supply. An internal transformer supplies 120-volt, single-phase, 10-ampere power for the chemical feed pump and control panel.

The CAV-OX® II high-energy process requires a 480-volt, single-phase, 30 ampere power supply, and a separate 120-volt, single-phase, 10-ampere power supply for the chemical feed pump and control panel.

Installation Time

A CAV-OX® unit can be placed on an existing concrete pad, wired to an existing disconnect box, and made operational in about 4 hours.

Permanent Installation

Permanent installation requires a concrete pad, security fence, open air metal roof, electric power, and inlet and outlet fluid lines. Additional requirements include a holding tank (about 250 to 500 gallons), located above the centrifugal pump inlet line to ensure adequate head, and a hydrogen peroxide subassembly. If a carbon polishing unit is used for post treatment, additional space for the carbon canisters must be provided. The CAV-OX® unit should be oriented so that hydrogen peroxide tanks can be easily exchanged as needed.

Portable Units

A CAV-OX® process is easily moved and can be mounted on either a truck bed or a trailer. One consulting firm has moved its 10-gpm CAV-OX® process to three different customer locations, obtaining rental fees many times the initial cost of the unit.

Hydrogen Peroxide Supply

A chemical pump for hydrogen peroxide is installed downstream of the cavitation chamber and before the UV reactors. The pump can be either hard wired to the control panel or operated with a utility power cord plugged into the 120-volt outlet on the side of the control panel. A circuit breaker inside the control panel provides a safety disconnect for the hydrogen peroxide supply.

The chemical pump is usually placed on top of the hydrogen peroxide tank so that the suction line is as short as possible for best pump performance.

As an alternative, hydrogen peroxide can be mixed with the influent in the holding tank. Suitable mixing and control methods must be provided.

Personnel Requirements

Training to operate the CAV-OX® equipment can be completed in about 8 hours. Personnel may also need the OSHA 40-hour health and safety training. Magnum recommends an additional 8 hours of "hands-on" operation tc enable any personnel to become proficient with the equipment.

The CAV-OX® process 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 divergent operating conditions in the CAV-OX® equipment. Remotely operated and monitored systems are hard-wired into centrally located control panels or computers through programmable logic controllers.

Comparison with Other Advanced Oxidation Technologies

The CAV-OX® process generates hydroxyl radicals at almost no cost. By comparison, ozone is not only expensive and hazardous, but must be added using a method that ensures no ozone is released to the atmosphere.

Other systems use multiple medium-energy UV lamps to photolyze hydrogen peroxide. Generally, UV tubes exposed to contaminants with this methodology become scaled, reducing UV transmission. To avoid this problem, a complicated wiper process is provided to clean the scale from the tubes. This, in turn, requires careful maintenance to monitor the output efficiency of the overall process.

The CAV-OX® process is free from such scaling problems. It generates hydroxyl radicals primarily from the cavitation process and secondarily from photolyzation of hydrogen peroxide. The hydroxyl radicals resulting from the cavitation process react with the dissolved gases, and the associated hysteresis effect reduces, if not eliminates, the scaling effect common to most UV systems. Furthermore, the gases and residual microbubbles dissolved in the fluid lower its density, thereby enhancing the ability of the process to oxidize organic contaminants. This effect also increases the synergistic effect between cavitated flow and UV radiation, improving the efficiency of the process.

Technical Data and Cost Comparisons

This section presents technical data collected by Magnum at Edwards Air Force Base (Edwards) independently of the Superfund Innovative Technology Evaluation (SITE) demonstration of the CAV-OX® process. This includes data for the use of cavitation alone, and economic comparisons with conventional groundwater treatment systems and carbon adsorption systems.

Figure A-1 is a photograph of the CAV-OX® process used at Edwards.

SITE Demonstration Results

During the SITE demonstration at Edwards, Magnum collected additional samples following Magnum's sampling matrix and sampling protocols. These additional samples were independent of samples collected for the SITE Program evaluation of the CAV-OX® technology. The results of these additional samples were not considered when developing conclusions for the SITE Program evaluation. Fifty- four samples were collected and analyzed on site in a mobile laboratory. The samples were analyzed using a Shimadzu GC-14A gas chromatograph and a modified EPA Method 8021. Results were available in 2 to 4 hours. Tables A-2 through A-7 present data from Magnum collected during the demonstration.

Cavitation Chamber Only

In a limited number of situations, a CAV-OX® cavitation chamber and ancillary equipment can be used as a stand-alone process to reduce contaminant concentrations by 50 to 80 percent. This operating mode is the least expensive; however, it normally is not effective for contaminants requiring high percentage reductions.

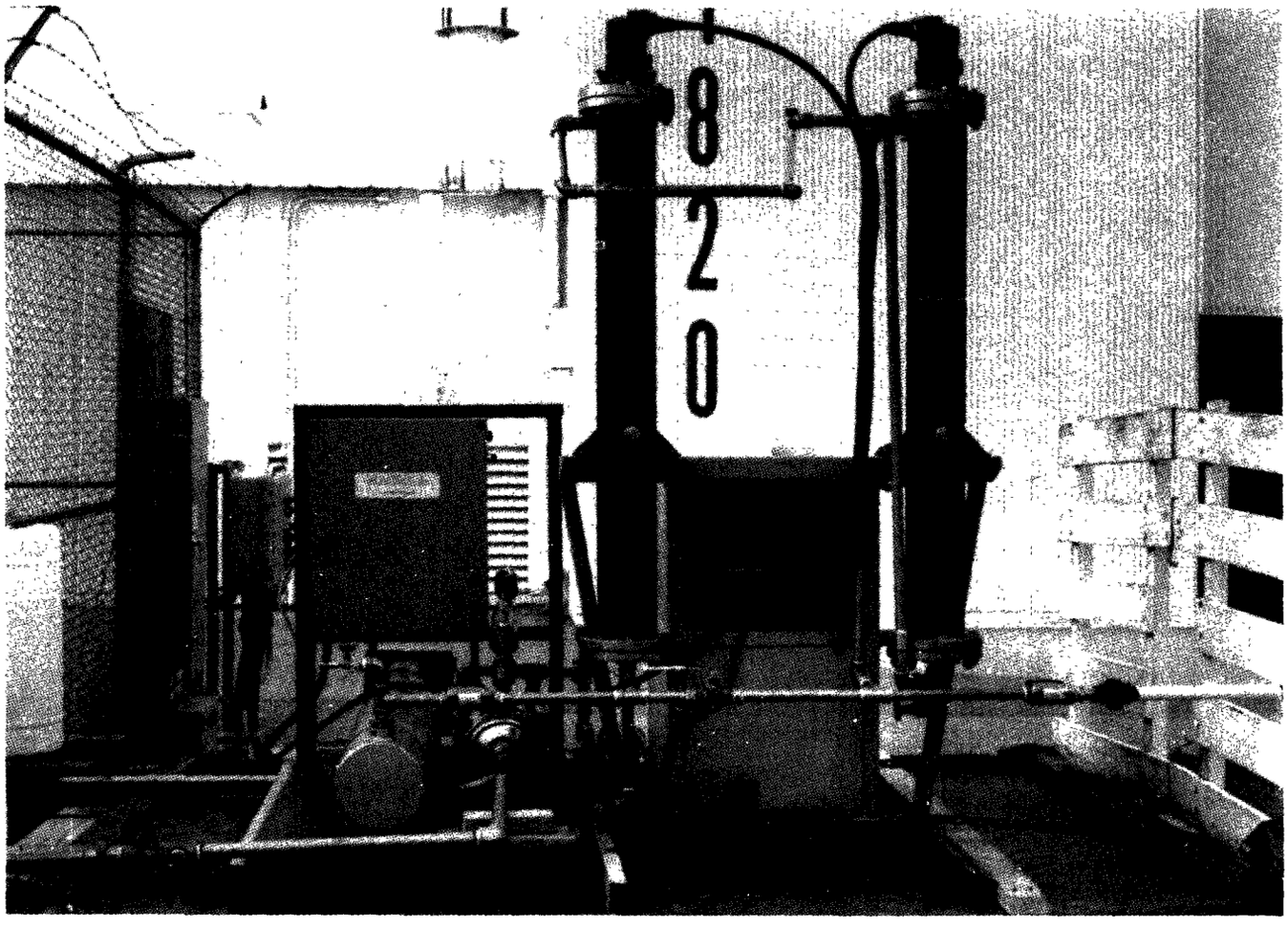


***Figure A-1**. CAV-OX® Process Used at Edwards Air Force Base*

Table A-2. Mobile Laboratory Results for Samples Collected 3/24/93 (μg/L)

Sample Description	Source	Benzene	TCE	Toluene	Ethylbenzene	Xylenes (total)	Hydrogen Peroxide
PQL	NA	1	0.40	1	1	3	NA
Influent	Process influent	226	2,010	35.63	3.5	86.47	0
0.36 kW/ 1.5 gpm 0 mg/L H_2O_2	High-energy process effluent	210	1,360	28.2	4.07	66.1	0
10 kW/ 1.5 gpm 0 mg/L H_2O_2	High-energy process effluent	87	15.4	6.63	1.15	8.84	0

Notes: PQL = Practical quantitation limit
NA = Not Applicable

Table A-3. Mobile Laboratory Results for Samples Collected 3/24/93 (μg/L)

Sample Description	Benzene	TCE	Toluene	Ethylbenzene	Xylenes (total)	Hydrogen Peroxide
PQL	1	0.40	1	1	3	NA
Influent	88.4	1,180	1.90	ND	ND[a]	0
5 kW/.5 gpm/0 mg/L H_2O_2 0 holding time	50.2	128	1.71	ND	ND	0
2.5 kW/.5 gpm/0 mg/L H_2O_2 0 holding time	67.5	155	2.91	1.00	3.90	0
0 kW/1.5 gpm/0 mg/L H_2O_2 0 holding time	250	1,670	7.16	1.03	3.06	0

Notes: [a] = Sample diluted to a ratio of 1:10. PQLs for ND compounds should be raised 1:10 to account for dilution.
NA = Not Applicable

Table A-4. *Mobile Laboratory Results for Samples Collected 3/24/93 (μg/L)*

Sample Description	Benzene	TCE	Toluene	Ethylbenzene	Xylenes (total)	Hydrogen Peroxide
PQL	1	0.40	1	1	3	NA
Influent	150	993	4.30	ND	ND	0
0 kW/1.5 gpm/0 mg/L H_2O_2 0 holding time	167	1,130	8.06	2.98	5.98	0
0 kW/1 gpm/0 mg/L H_2O_2 20 min. holding time	197	1,350	9.13	3.25	6.47	0
0 kW/1 gpm/0 mg/L H_2O_2 45 min. holding time	89.4	668	1.93	ND	ND	0
0 kW/1 gpm/0 mg/L H_2O_2 0 holding time	211	1,340	7.24	1.00	3.00	30.00
Verification of Process Influent						
Influent from bladder tank	177	1,010	6.36	ND	ND	NA
Influent from holding tank	202	1,140	7.12	ND	ND	NA

Notes: PQL = Practical quantitation limit
NA = Not applicable
ND = Not detected

Table A-5. *Mobile Laboratory Results for Samples Collected 3/24/93 (μg/L)*

Sample Description	Benzene	TCE	Toluene	Ethylbenzene	Xylenes (total)	Hydrogen Peroxide
PQL	1	0.4	1	1	3	NA
Influent	336	1,684	44.2	6.99	29	0
0 kW/1 gpm/0 mg/L H_2O_2 0 holding time	254	1,240	32.7	4.94	21.6	0
0 kW/1 gpm/0 mg/L H_2O_2 0 holding time	281	1,380	35.5	5.28	22.4	0
2.5 kW/1 gpm/0 mg/L H_2O_2 0 holding time	73.2	275	ND	1.19	ND	0
5.0 kW/1 gpm/0 mg/L H_2O_2 0 holding time	14.8	50.3	1.24	ND	ND	0
2.5 kW/4 gpm/0 mg/L H_2O_2 0 holding time	30.9	340	3.08	ND	ND	0
10.0 kW/4 gpm/0 mg/L H_2O_2 0 holding time	26.7	266	2.35	ND	ND	350
Influent/350 mg/L H_2O_2	320	1636	41.3	6.32	26.7	350
Influent/350 mg/L H_2O_2	316	1650	40 8	6.56	27	350
5.0 kW/4.0 gpm/350 mg/L H_2O_2 0 holding time	1.03	30.7	ND	ND	ND	350

Notes: PQL = Practical quantitation limit
NA = Not applicable
ND = Not detected

Table A-6. *Mobile Laboratory Results for Samples Collected 3/25/93 (μg/L)*

Sample Description	Benzene	TCE	Toluene	Ethylbenzene	Xylenes (total)	Hydrogen Peroxide
PQL	1	0.40	1	1	3	NA
0 kW/1 gpm/0 mg/L H_2O_2 24 hour holding time	229	986	25.1	8.37	ND	0
Influent	388	1,860	55	6.79	24	0
0 kW/1 gpm/0 mg/L H_2O_2 0 holding time	314	1,510	40.7	3.22	15.6	0
0 kW/10 gpm/0 mg/L H_2O_2 0 holding time	321	1,450	40.6	2.69	14	0
0 kW/1 gpm/0 mg/L H_2O_2 0 holding time/1 hour recycle through chamber	298	1,410	38.2	3.09	14.8	0
0 kW/1 gpm/0 mg/L H_2O_2 1 hour holding time	229	1,030	27.8	1.94	9.94	0
Influent with 90 mg/L H_2O_2 0 holding time	381	1,850	55.2	7.15	24.9	90
0 kW/1 gpm/90 mg/L H_2O_2 0 holding time	247	1,110	30.8	2.19	6.93	90
0 kW/1 gpm/90 mg/L H_2O_2 1 hour holding time	305	1,430	42.5	5.65	19.3	90
2.5 kW/5 gpm/90 mg/L H_2O_2 0 holding time	114	673	16.9	3.73	8.82	90
10.0 kW/2 gpm/90 mg/L H_2O_2 0 holding time	ND	11	ND	ND	ND	90
5.0 kW/5 gpm/90 mg/L H_2O_2 0 holding time	31.3	311	3.12	ND	ND	90
2.5 kW/0.5 gpm/90 mg/L H_2O_2 0 holding time	ND	14	ND	ND	ND	90
10.0 kW/8+ gpm/90 mg/L H_2O_2 0 holding time	3.89	66.30	ND	ND	ND	90
0 kW/0.25 gpm/0 mg/L H_2O_2 30 min. holding time	165	658	34.5	6.05	27.3	0

Notes: PQL = Practical quantitation limit
NA = Not applicable
ND = Not detected

Table A-7. *Mobile Laboratory Results for Samples Collected 3/26/93 (μg/L)*

Sample Description	Benzene	TCE	Toluene	Ethylbenzene	Xylenes (total)	Hydrogen Peroxide
PQL	1	0.40	1	1	3	NA
0 kW/1 gpm/0 mg/L H_2O_2/0 0 holding time/1hour recycle through cavitation chamber	154	668	21.3	4.22	14.2	0
Influent	381	1,350	109	8.78	68.1	0
0 kW/0.15 gpm/0 mg/L H_2O_2 0 holding time	357	1,280	104	10.9	63.8	0
10 kW/2 gpm/0 mg/L H_2O_2 0 holding time	81.5	34.6	12.5	1.19	3.3	0
5.0 kW/4 gpm/120 mg/L H_2O_2 0 holding time	26.4	179	5.25	ND	ND	120
10 kW/4 gpm/120 mg/L H_2O_2 0 holding time	14.9	113	283	ND	ND	120
10 kW/8 gpm/90 mg/L H_2O_2 0 holding time/pH 5.5	4.19	52.6	ND	ND	ND	90
0 kW/2.5 gpm /90 mg/L H_2O_2 0 holding time	29.01	70.6	6.02	ND	ND	90
0 kW/1 gpm/0 mg/L H_2O_2 10 min. holding time/pH 5.0	265	1,010	67.7	3	35.6	0
0 kW/2 gpm/0 mg/L H_2O_2 10 min. holding time/pH 5.0	267	1,020	69.4	3.02	36.3	0
Influent - pH 5.0	423	1,620	110	5.37	57.5	0
0.36 kW/1.5 gpm/90 mg/L H_2O_2 0 holding time	31.3	320	5.51	ND	ND	90
Influent - normal pH - 90 mg/L H_2O_2 0 holding time	418	1,610	102	3.43	44.3	90
10 kW/4.0 gpm/90 mg/L H_2O_2 0 holding time	16.2	126	2.4	ND	ND	90

Notes: PQL = Practical quantitation limit
NA = Not applicable
ND = Not detected

Case Study C-8 in Appendix C provides an example of using the CAV-OX® cavitation chamber only. In this case study, a CAV-OX® process capable of processing 3,900 gallons per hour was designed for Southern California Edison Company to treat 3 million gallons of contaminated seawater with a high biochemical oxygen demand (BOD). This section discusses procedures and results for using the cavitation chamber only, without UV radiation or hydrogen peroxide.

Procedure

The influent to the CAV-OX® process is drawn from a holding tank. A positive head from the holding tank is necessary for the centrifugal pump inlet.

The centrifugal pump releases fluid at about 70 pounds per square inch (psi). This 70-psi fluid flows directly into the cavitation chamber, where the pressure is made to drop suddenly to near vacuum. The sudden drop in pressure causes the aqueous molecules to dissociate, forming hydrogen atoms and hydroxyl radicals. Any organic contaminants in the fluid are likewise forced to undergo a sudden pressure drop, breaking weak bonds. These contaminants are also attacked by the atomic hydrogen and hydroxyl radicals from the dissociation of the fluid.

In certain applications, compounds in the fluid leaving the cavitation chamber not have time to react completely. In these cases, a dwell tank is used so that the fluid reaction can continue for as long as 15 minutes.

Results

Table A-8 presents selected results from the SITE demonstration for use of the cavitation chamber only.

Economic Analysis

Typical operating costs (presented in October 1993 dollars) for the CAV-OX® process are as follows:

- CAV-OX® cavitation chamber only — about $0.50 per 1,000 gallons of treated water
- CAV-OX® cavitation chamber with low-energy UV radiation and hydrogen peroxide — about $2 pee 1,000 gallons of treated water
- CAV-OX® cavitation chamber with high-energy UV radiation and hydrogen peroxide — about $4 per 1,000 gallons of treated water

Table A-9 presents cost data for three groundwater treatment methods: a filter carbon process, an air carbon process, and UV radiation plus hydrogen peroxide. The contaminant of concern was benzene, and the treatment goal was to reduce its concentration from 50,000 micrograms per liter (µg/L) to 50 µg/L. The results of this comparison were as follows: the filter carbon process cost $11.07 per 1,000 gallons; the air carbon process cost $14.07 per 1,000 gallons; and UV radiation plus hydrogen peroxide cost $8.22 per 1,000 gallons.

Table A-10 presents cost data for a 10-gpm CAV-OX® I low-energy process and a conventional carbon adsorption process to treat two sites contaminated with BTEX, trichloroethene (TCE), tetrachloroethene (PCE), and chloroform. The annual cost of operating the carbon adsorption process was $22,648 for the first site and $13,855 for the second site, while the annual cost of operating the CAV-OX® process was $10,964 for the first site and $7,468 for the second site.

References

Flint, E. B. and Suslick, K. S. 1991. "The Temperature of Cavitation." Science. Volume 253. September 20.

Suslick, K. S. 1989. "The Chemical Effects of Ultrasound." Scientific American. February.

Suslick, K. 1990. "Sonochemistry." Science. Volume 247. March 23.

Table A-8. *Developer-Generated SITE Demonstration Results, (Percent Reduction), CAV-OX® Cavitation Chamber Only*

Sample Description	Date	Benzene (%)	Ethylbenzene (%)	Toluene (%)	Xylene (%)	TCE (ug/L)	TCE (%)
Protocol A							
0 kW/0.25 gpm/0 mg/L H_2O_2 30 min. holding time	03/25/93	67	11	37	ND	1,850	65
0 kW/1 gpm/0 mg/L H_2O_2 0 holding time/1 hour cavitation chamber	03/24/93	54	40	53	51	1,680	60
0 kW/1 gpm/0 mg/L H_2O_2 1 hour holding time	03/25/93	41	71	49	59	1,860	45
0 kW/1 gpm/0 mg/L H_2O_2 24 hour holding time	03/24/93	32	20	43	ND	1,680	41
Protocol B							
0 kW/1 gpm/0 mg/L H_2O_2 10 min. holding time/pH 5	03/26/93	37	44	38	38	1,620	38
0 kW/1 gpm/0 mg/L H_2O_2 10 min. holding time/pH 5	03/26/93	37	43	37	37	1,620	37
0 kW/1 gpm /0 mg/L H_2O_2 45 min. holding time	03/23/93	40	ND	55	ND	993	33
Protocol C							
0 kW/1 gpm/0 mg/L H_2O_2 0 holding time/1 hour cavitation chamber	03/25/93	23	54	31	38	1,860	24
0 kW/10 gpm/0 mg/L H_2O_2 0 holding time	03/25/93	17	60	26	42	1,860	22
0 kW/1 gpm/0 mg/L H_2O_2 0 holding time	03/25/93	19	53	26	35	1,860	19
0 kW/1 gpm/0 mg/L H_2O_2 10 min. holding time	03/25/93	16	24	20	23	1,680	18

Notes: *Neither hydrogen peroxide nor UV radiation was used in these tests.*

ND = Not detected

Table A-9. *Economic Comparisons for Groundwater Treatment Process ($)* [a,b]

Item	Filter Carbon	Air Carbon	UV/Hydrogen Peroxide	CAV-OX® I Low-Energy Process
		Capital Cost		
Equipment	150,000	195,000	115,000	58,000
Installation	20,000	30,000	20,000	3,000
Total	170,000	225,000	135,000	61,000
		Annual Operating Costs		
Power ($0.08/kWh)	0	11,700	62,200	3,592
Carbon	108,000	108,000	0	0
Chemicals	0	0	12,100	1,741
Maintenance	7,500	11,250	6,750	5,114
Amortization (20% per year)	30,000	45,000	27,000	11,600
Labor (air monitoring)	0	9,000	0	0
Total	145,500	184,950	108,050	22,047
Cost per 1,000 gallons	11.07	14.07	8.22	1.67

Notes: [a] *All treatment processes had a flow rate of 25 gpm and were used to treat 50 mg/L benzene in groundwater to 50 µg/L.*
[b] *Cost data provided by Magnum*

Table A-10. *Economic Comparison Between a Carbon Adsorption System and CAV-OX® I Low-Energy Process ($)* [a]

Site	Cost Per 1,000 Gallons	Annual Cost
	Carbon Adsorption System	
1	4.3[b]	22,648
2	2.64[c]	13,855
	CAV-OX® I Low-Energy Process[d]	
1	2.08	10,964
2	1.46	7,468

Notes: [a] *This analysis assumes a flow rate of 10 gpm and the following contaminant concentrations (in µg/L):*
Site 1: benzene, 350; toluene, 340; ethylbenzene, 34; xylenes, 270; TCE, 33; PCE, 33; and chloroform, 10
Site 2: benzene, 2; toluene, 2; ethylbenzene, 40; xylenes, 82; TCE, 33; PCE, 10; and chloroform, 5
[b] *Assumes 42.5 pounds of carbon per day at $1.46 per pound*
[c] *Assumes 26 pounds of carbon per day at $1.46 per pound*
[d] *Includes all operating costs amortized over a 5-year period*

Appendix B
SITE Demonstration Results

In February 1992, Magnum Water Technology (Magnum) responded to the U.S. Environmental Protection Agency's (EPA) annual solicitation for proposals to participate in the Superfund Innovative Technology Evaluation (SITE) Program. At that time, Magnum discussed the possibility of demonstrating the CAV-OX® process's treatment of contaminated groundwater at Edwards Air Force Base (Edwards) under the SITE Program. EPA subsequently accepted the CAV-OX® process into the SITE Program. Through a cooperative effort among the EPA Office of Research and Development (ORD), EPA Region 9, State of California Department of Toxic Substance Control, State of California Regional Water Quality Control Board, and Edwards, the CAV-OX® process was demonstrated at Edwards Site 16 under the SITE Program. This appendix briefly describes Edwards Site 16 and summarizes the SITE demonstration activities and demonstration results.

Site Description

Edwards is a 300,000-acre U.S. Air Force base about 75 miles northeast of Los Angeles, California. The base is located on and adjacent to Rogers Dry Lake, a basin of internal drainage (Figure B-1) (Engineering-Science, 1988). Operations at the base began in the 1940s. Primary physical structures throughout the base include runways, buildings, and hangars housing aircraft, support equipment, and personnel.

The CAV-OX® process was demonstrated at Site 16, a military-grade jet fuel (JP-4) spill site located between Wolfe Avenue, Taxiway D, and Buildings 1810 and 1820 (Figure B-2). Site 16 occupies about 12 acres in an area that includes taxiways, hangars, office buildings, outside storage, and open fields. Other features at Site 16 include parking areas, a security station, equipment and supply storage yards, and sewer lines.

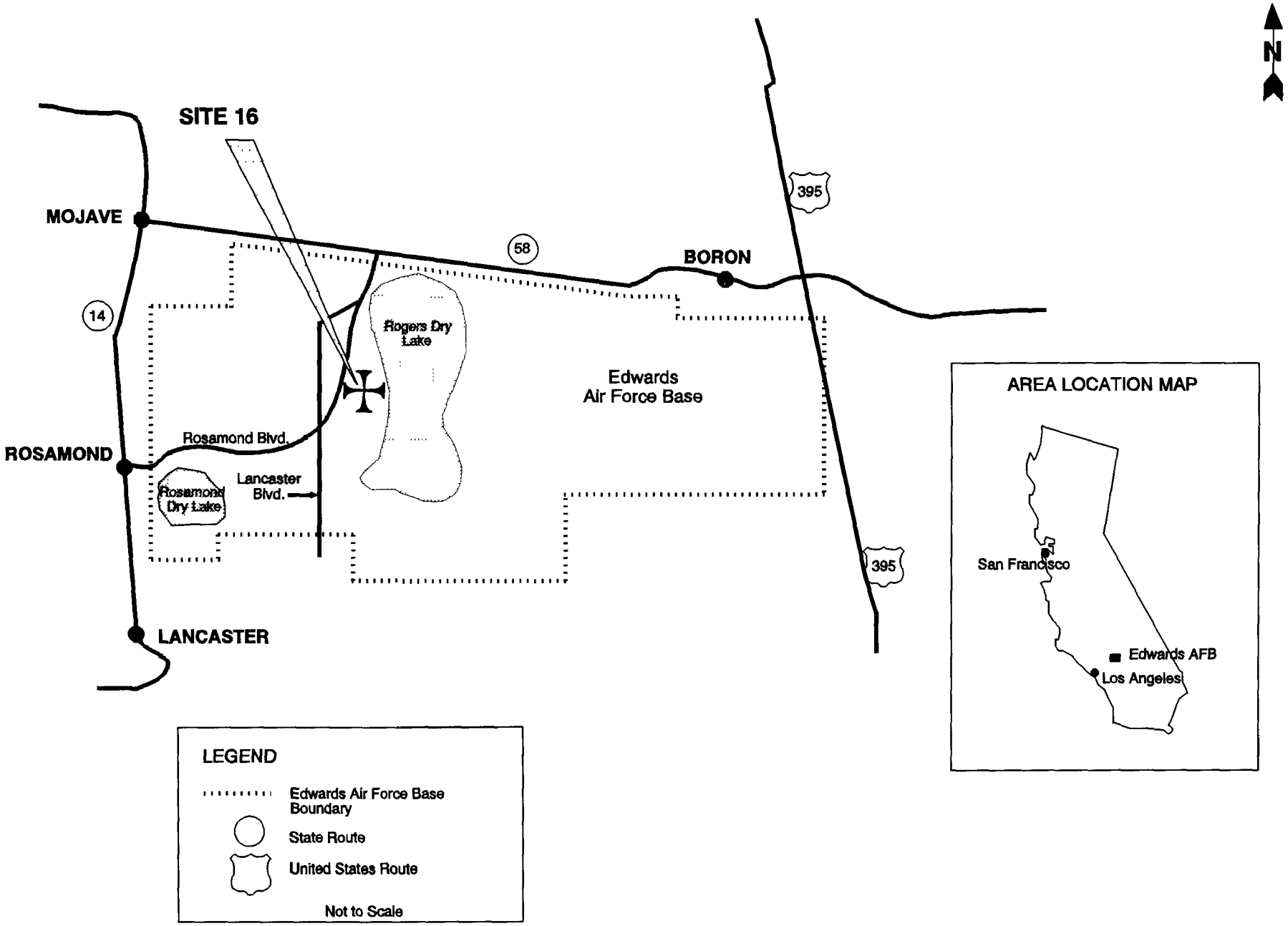
A shallow aquifer underlies Site 16. This aquifer is generally encountered between 8 and 20 feet below ground surface and occurs mainly in weathered granite, with some areas occurring in the overlying alluvium (Engineering-Science 1988). Groundwater flow in the shallow aquifer is to the east-northeast with a hydraulic gradient of less than 1.5×10^{-2}.

The JP-4 release was originally attributed to a leaking fuel transfer line that runs along the western boundary of Site 16. The leak began about September 1983 and contaminated about 12 acres. A measurable floating layer of fuel currently covers about 7 acres. The total quantity of free-floating fuel is estimated to be between 250,000 and 300,000 gallons (Engineering-Science 1988).

The State of California Regional Water Quality Control Board, Lahontan Region issued a Clean-Up and Abatement Order (No. 84-10) for Site 16 on November 13, 1984. This order was followed by remedial actions including pipeline replacement and monitoring well installation. Further investigation included a feasibility study and remedial design for cleanup of the fuel spill. The remedial action combined a recovery well process, a recovery fuel storage process, and a fuel-water separator process. Discharge water from the process was routed to the base sanitary sewer process, and the fuel was collected for reuse. However, dissolved trichloroethene (TCE) was later detected in the water above discharge limits. Because TCE could not be discharged to the sanitary sewer process, the recovery well process ceased operation in December 1987 (Engineering-Science 1988).

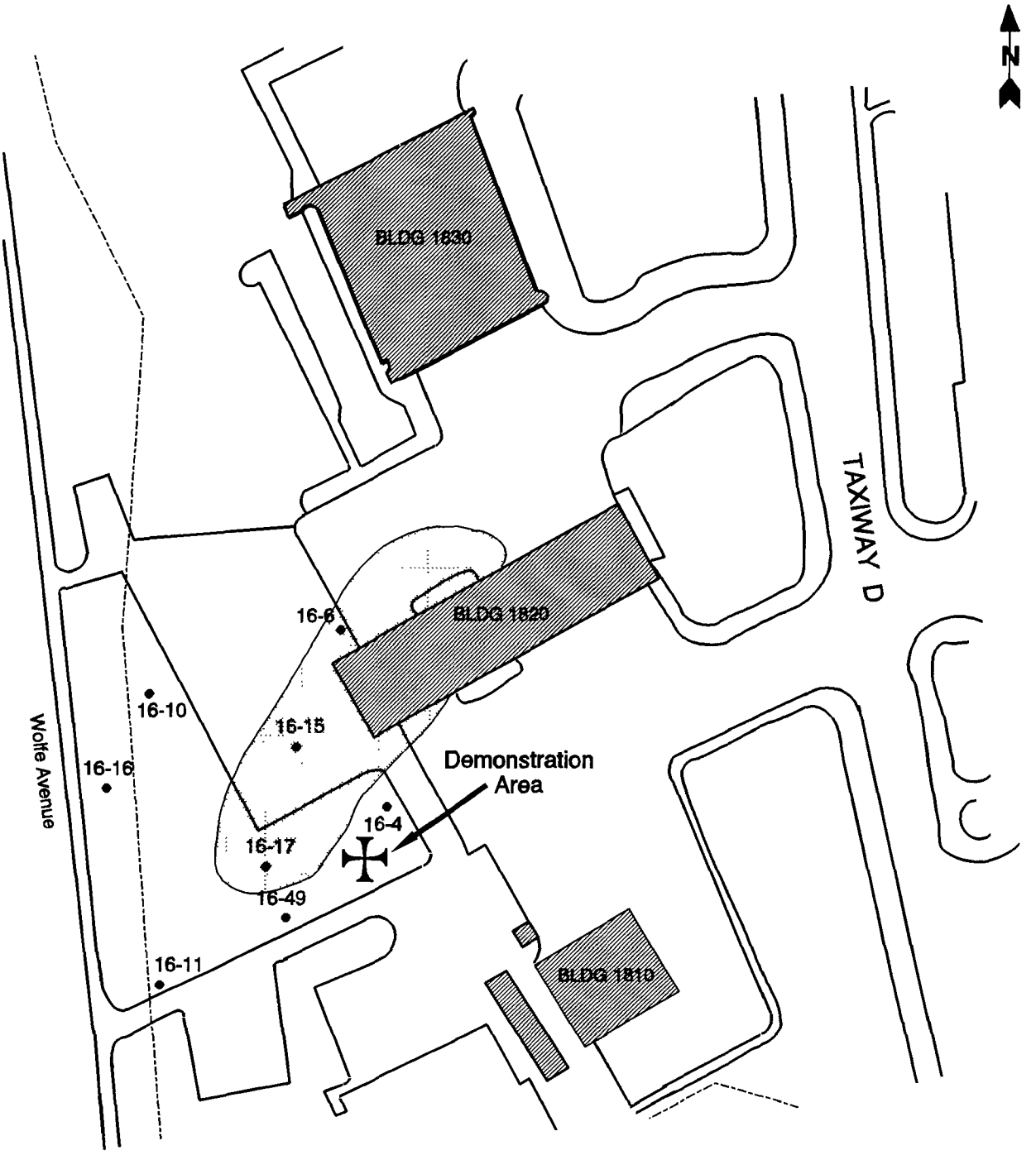
Contaminated groundwater for the demonstration was obtained from Site 16. The contaminated groundwater contains volatile organic compounds (VOC), primarily TCE; benzene, toluene, ethylbenzene, and xylene (BTEX); and low levels of carbon tetrachloride; chloroform; 1,1-dichloroethane; 1,2-dichloroethane; 1,1-dichloroethene; trans-1,2-dichloroethene; tetrachloroethene (PCE); 1,1,1-trichloroethane; and 1,1,2-trichloroethane.

A site assessment was completed in June 1989 through the Department of Defense Installation Restoration Program. A pilot plant study was completed for the site in May 1990. This study proposed a treatment process that included an ultraviolet-oxidation unit and air stripping to treat contaminated groundwater from recovery wells at Site 16.



Source: The Earth Technology Corporation 1992

Figure B-1. Edwards Site Location



LEGEND

- ● Monitoring Well Location and Designation
- ------ Underground JP-4 Fuel Line
- ⬭ Approximate Location of Floating Fuel Layer

Source: Engineering-Science 1988

1" = 350'
APPROXIMATE SCALE

Figure B-2. Site 16 Layout

Site Contamination Characteristics

In October and November 1991, Edwards sampled monitoring wells at Site 16 and analyzed the samples for VOCs, semivolatile organic compounds (SVOC), metals, and a variety of other parameters including pH and alkalinity.

VOCs present in high concentrations included TCE (nondetectable [ND] to 3,100 micrograms per liter [µg/L]), benzene (ND to 1,800 µg/L), toluene (ND to 3,100 µg/L), ethylbenzene (ND to 1,300 µg/L), and p- and m-xylene (ND to 3,300 µg/L). Other contaminants with concentrations above detection limits were 1,1-dichloroethane (ND to 154 µg/L); 1,2-dichloroethane (ND to 7 µg/L); trans-1,2-dichloroethene (ND to 1.7 µg/L); PCE (ND to 3.3 µg/L); 1,1,1-trichloroethane (ND to 270 µg/L); and dichloromethane (ND to 230 µg/L). Other sampling parameters included pH of 7.4 and alkalinity (as calcium carbonate) at 450 milligrams per liter (mg/L).

Review of SITE Demonstration

Three configurations of the CAV-OX® process were demonstrated: the CAV-OX® I low-energy process operating at 360 watts and the CAV-OX® II high-energy process operating at either 5 kilowatts (kW) or 10 kW. The CAV-OX® I process contains six 60-watt lamps per reactor. The CAV-OX® II process contains two ultraviolet (UV) reactors with one UV lamp each; it can operate at 2.5, 5, 7.5, or 10 kW. Flow capacity is estimated to be less than 3 gallons per minute (gpm) for the CAV-OX® I process and less than 5 gpm for the CAV-OX® II process as demonstrated. Groundwater from monitoring wells 16-4, 16-17, and 16-49 was used for the demonstration. The demonstration consisted of 15 planned runs for each configuration of the CAV-OX® process over a 4-week period. The following sections describe the demonstration and review the CAV-OX® process's performance during the demonstration.

Site Preparation

A 2,000 square-foot area was used for both CAV-OX® configurations, support facilities, nonhazardous and hazardous waste storage containers, and the office and field laboratory trailer. Site preparation included setting up major support equipment, on-site support services, and utilities. A schematic of the process is shown in Figure B-3.

Major Support Equipment

Support equipment for the CAV-OX® process demonstration included storage tanks for untreated and treated groundwater, a solid waste dumpster for disposal of nonhazardous wastes, 55-gallon drums for storage of decontamination rinse water, a forklift for unloading and loading support equipment, three submersible positive displacement pumps with gasoline-powered generators, sampling and analytical equipment, and health and safety equipment.

On-Site Support Services

A 10-foot by 40-foot air-conditioned office trailer containing furniture and filing cabinets was used to complete and file daily oversight and data collection reports, house laboratory equipment for field analyses, and store small equipment and supplies. Rooms within the trailer were used to separate administrative and laboratory activities. Edwards provided access to restrooms in Building 1820 for use by demonstration personnel.

Utilities

Utilities required for the demonstration included water, electricity, and telephone service. Water was required for equipment and personnel decontamination. Edwards provided about 20 to 50 gallons per day of potable water for decontamination. Drinking water was available inside the office and laboratory trailer in 1-gallon containers.

Operation of the CAV-OX® process requires electricity. At Edwards, the CAV-OX® I process used a 220-volt, 3-phase, 30-ampere electrical service. The CAV-OX® II process used a 480-volt, single-phase, 20-ampere electrical service. Additional 110-volt, single-phase, 10-ampere electrical service was needed for UV power supply controls and chemical feed pumps. The office and laboratory trailer required 220-volt, 3-phase, 50-ampere electrical service.

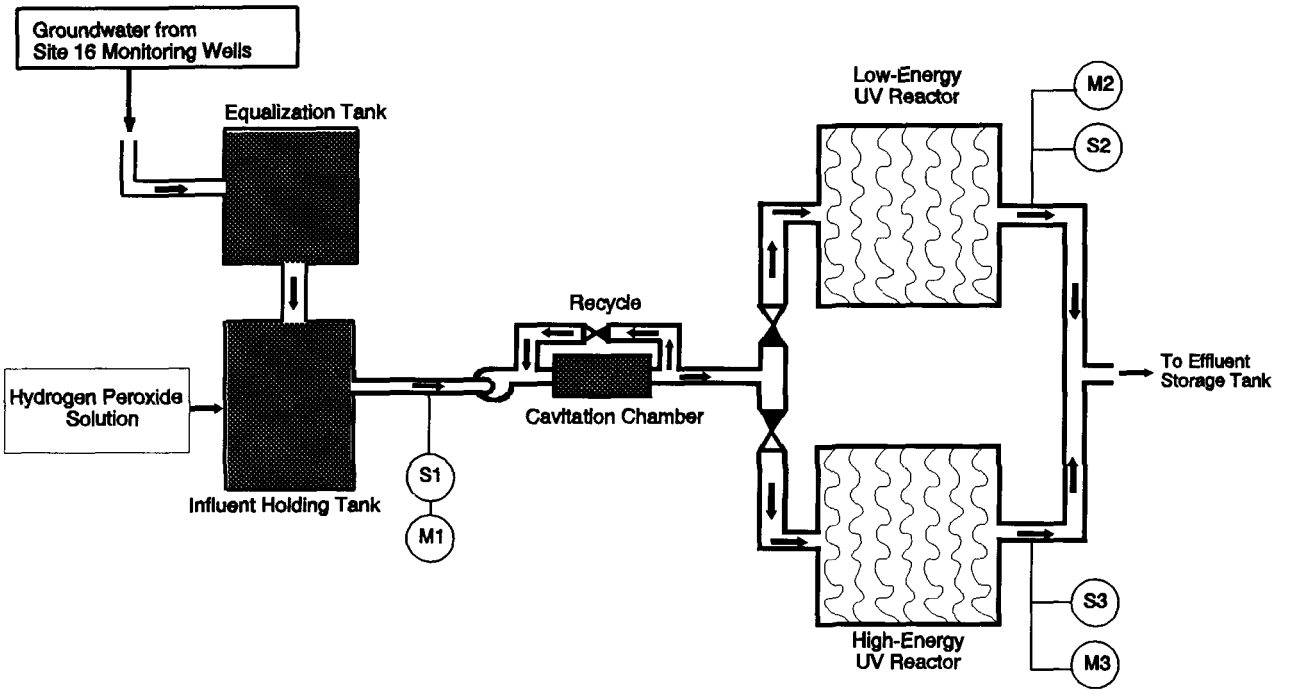
Two cellular telephones in the office and laboratory trailer were used for ordering equipment, parts, reagents, and other chemical supplies, and for scheduling deliveries.

Technology Demonstration

This section discusses (1) operational and equipment problems, (2) health and safety considerations, and (3) site demobilization associated with the SITE demonstration.

Operational and Equipment Problems

Hydrogen peroxide is usually injected in-line with a small chemical feed pump; however, for the demonstration it was added directly to the influent holding tank. In normal field operations, treatability studies would be conducted to determine preferred operating conditions; the CAV-OX® process would then be adjusted until preferred conditions were achieved. Because the chemical feed pump is highly influenced by the pressure of the CAV-OX® process, optimization of the process often requires numerous chemical feed pump adjustments, with hydrogen peroxide analyses following each adjustment. Usually, this optimization process would be done only one time for the desired flow rate at the preferred hydrogen peroxide injection level. However, during the demonstration three hydrogen peroxide concentrations were examined at three flow rates, and operating conditions changed several times each day. Therefore, adding hydrogen peroxide in-line would have required continuous



SAMPLE COLLECTION (S) OR MEASUREMENT (M) LOCATION	LOCATION IDENTIFIER	PARAMETERS	
		SAMPLE	MEASUREMENT
MAIN FEED LINE FROM INFLUENT HOLDING TANK	S1 M1	TCE, BTEX, HYDROGEN PEROXIDE, TOC, TC, POC, METALS, ALKALINITY, HARDNESS, TRPH, VOCS (GC/MS), SVOC, TURBIDITY, BIOASSAY	pH, TEMPERATURE, FLOW RATE, SPECIFIC CONDUCTANCE
EFFLUENT LINE FROM CAV-OX® I UV REACTOR	S2 M2		
EFFLUENT LINE FROM CAV-OX® II UV REACTOR	S3 M3		

(S) = Sample Location

(M) = Measurement Location

Figure B-3. *CAV-OX® Process Sample and Measurement Locations*

adjustment of the chemical feed injection rate. Because of the time required with in-line adjustment, hydrogen peroxide was added directly to the influent holding tank until the desired concentration was reached.

Health and Safety Considerations

In general, potential health hazards resulted from possible exposure to contaminated groundwater and hydrogen peroxide solution. Although the treatment process was entirely closed, potential routes of exposure during the demonstration included inhalation, ingestion, and skin and eye contact from 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, in compliance with federal OSHA regulation 29 CFR 1910.120. Appropriate personal protective equipment (PPE) was used for each 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.

Site Demobilization

After the demonstration was completed and on-site equipment was disassembled and decontaminated, equipment and site demobilization began. Equipment demobilization included loading the support equipment, transporting it off site, returning rented support equipment, and disconnecting utilities. The CAV-OX® configurations remained mounted on a flat-bed truck so that they could be transported off site after the influent line, effluent line, and electricity were disconnected.

Decontamination was necessary for the bladder tank, effluent storage tank, sampling equipment, pumps, mixers, valves, and nondisposable PPE. Magnum was responsible for decontaminating the CAV-OX® equipment and its health and safety equipment.

The effluent was disposed of off site, in accordance with Edwards base regulations. Total liquid wastes were about 8,500 gallons. The demonstration evaluated runs with numerous operating conditions, not all of which resulted in an effluent that met discharge limits; also, untreated groundwater was used for daily calibrations of flow meters with the UV reactor off. Therefore, the discharge water collected during the demonstration did not meet State of California drinking water action levels and federal drinking water maximum contaminant levels (MCL) for TCE and BTEX. The collected water could not be discharged to the sanitary sewer and was disposed of off site in accordance with arrangements made among EPA, Edwards, EPA Region 9, and the State of California.

Other liquid and solid wastes generated during the demonstration included (1) washwater from decontaminating personnel and equipment; (2) disposable PPE, such as Tyvek® suits, gloves, and boot covers; and (3) disposable laboratory supplies, such as spent vials, empty reagent containers, and paper towels. Solid wastes were collected in plastic bags, 55-gallon drums, and dumpsters. All liquid and solid wastes were disposed of in accordance with disposal arrangements made among EPA, Edwards, EPA Region 9, and the State of California.

Experimental Design

The demonstration's objectives were to: (1) determine TCE and BTEX removal efficiencies in the treatment process under various operating conditions, (2) determine whether TCE and BTEX levels in treated groundwater met applicable discharge limits to the base sanitary sewer at the 95 percent confidence level, and (3) compare TCE and BTEX removal efficiencies among the three treatment process configurations. Secondary objectives for the technology demonstration were to (1) collect information, including process chemical dosage and utility requirements, needed to estimate treatment costs, (2) assess the presence of degradation by-products in the treated water, and (3) collect characterization data for both the influent and effluent streams. The sections that follow describe the testing approach and sampling and analytical procedures used to accomplish these objectives.

Testing Approach

Water from monitoring wells 16-4, 16-17, and 16-49 was pumped through a common manifold into a 7,500-gallon equalization (bladder) tank. The combined flow from the three wells was about 4 gpm. An equalization tank was used to minimize any variability in the influent characteristics (primarily VOCs), and to provide a steady water supply to the CAV-OX® process. The bladder tank was made of heavy duty, polyurethane-coated nylon fabric and was rated for potable water. Before the demonstration began, approximately 7,500 gallons of water were collected in the equalization tank. Water was collected simultaneously from the wells to obtain a representative mix of the contaminant plume. To minimize volatilization of VOCs, water in the equalization tank was not mixed by any other means. A separate pump transferred water from the equalization tank to an influent holding tank, mounted on Magnum's truck.

Operations followed the schedule shown in Table B-1. The CAV-OX® I low-energy process was operated simultaneously with the CAV-OX® II high-energy process. The CAV-OX® II high-energy process operated with the UV reactor at 5 kW and then at 10 kW. From the equalization tank, the water was transferred to an influent holding tank, where hydrogen peroxide was added. The influent holding tank maintained a positive head for the centrifugal pump. The water was then pumped through

Table B-1. Experimental Conditions

Run	Influent pH	Hydrogen Peroxide (mg/L)	Process Flow Rate (gpm)		
			CAV-OX® I	5-kW CAV-OX® II	10-kW CAV-OX® II
Low Hydrogen Peroxide Dose					
1	7.2	0	0.6	2	2
2	7.2	0.4	1.5	1.6	1.6
3	7.2	0.4	1.5	3.9	4
Medium Hydrogen Peroxide Dose					
4	7.2	4.9	1.5	4	3.9
5	7.2	4.9	1.5	3.9	3.4
6	7.2	5.9	0.5	1.5	1.4
7	7.2	5.9	0.7	1.9	2
8	7.2	6	0.7	1.9	1.9
9	7	6.1	1.5	4	4
High Hydrogen Peroxide Dose					
10	7	23.4	0.6	2	2.1
11	6.9	33.1	0.5	1.6	1.5
12	7.1	48.3	0.6	1.4	1.4
Vendor-Preferred Conditions					
13	7.1	1.8	NA [b]	1.9	1.9
14 [a]	5	9.1	NA [b]	NA [b]	7.9
15 [a]	5.5	1	NA [b]	NA [b]	0.8 [c]

Notes:
[a] Influent pH adjusted
[b] CAV-OX® I and 5-kW CAV-OX® II not considered a preferred condition in this case
[c] CAV-OX® II operated at 2.5 kW

NA = not applicable
mg/L = milligrams per liter
gpm = gallons per minute
kW = kilowatts

the cavitation chamber. After exiting the cavitation chamber, the water flowed to either the UV reactors, or back to the cavitation chamber through a recycle line. The water flowing to the UV reactors was split between the CAV-OX® I and the CAV-OX® II reactors. Treated groundwater was stored in an effluent storage tank for off-site disposal.

The CAV-OX® I process was operated unchanged while the CAV-OX® II process was operated first at 5 kW and then at 10 kW. Sampling of all three CAV-OX® configurations was completed for one run before the next run began.

Operating parameters, including hydrogen peroxide dose, hydraulic retention time (flow rate), and UV output were varied to observe how the process performed under different operating conditions. The initial flow rate was based on known groundwater contaminant concentrations and Magnum's professional judgment and experience. Preferred operating conditions were then determined by Magnum as those that reduced effluent VOCs to below target levels. Table B-2 shows VOC target levels for the demonstration.

Table B-2. *Target Levels for Critical Analytes in Effluent Samples*

Contaminant	Concentration (ug/L)
Trichloroethene (TCE)	5
Benzene	1
Toluene	20
Ethylbenzene	680
Total Xylene	1,750

The first test run was preceded by a preliminary run. Operating parameters for the preliminary run were identical to those of the first test run, including the use of contaminated groundwater. The purpose of the preliminary run was to identify and resolve any problems in the sampling and field analysis protocols and to remove any residual contaminants from previous use. Only field analyses (such as temperature and flow rate) were performed during the preliminary run. Steady state conditions (a stable flow rate) were achieved for the preliminary run after approximately three hydraulic retention times.

Sampling and Analytical Procedures

Figure B-3 shows the three locations where samples were collected and measurements taken during the demonstration. Treated water was sampled and measured only after steady state was attained (after three hydraulic retention times).

Before each run, hydrogen peroxide in the influent was measured to determine concentrations. In addition, the influent flow rate was adjusted before each run to provide the desired hydraulic retention time.

VOC concentrations and flow rate were considered critical parameters for evaluating the technology. 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 providing data on degradation products or other contaminants.

Because the CAV-OX® process was developed to treat organics, and because VOCs were the principal contaminants in groundwater, four replicate samples were collected for GC analysis of VOCs to increase accuracy and precision. For other analytes, the number of samples was based on the (1) intended use of the data, (2) analytical costs, (3) sampling time, and (4) analytical laboratory discretion. EPA-approved sampling, analytical, and quality assurance and quality control (QA/QC) procedures were followed to obtain reliable data. QA/QC procedures are detailed in the Technology Evaluation Report.

Review of Treatment Results

This section summarizes the results of both critical and noncritical parameters for the CAV-OX® demonstration, and 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 replicate sample had concentrations at nondetectable levels, using one-half the detection limit as the estimated concentration for all such replicable samples would significantly reduce the standard deviation of the mean and would 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 the demonstration only two contaminants, TCE and benzene, were detected in the influent at levels well above target levels. Figure B-4 shows the influent concentrations of benzene and TCE. Figure B-5 shows the influent concentrations of ethylbenzene, toluene, and xylene. Toluene, ethylbenzene, and xylene were present in the influent; however, because these VOCs were present in relatively low levels compared to TCE and benzene, the discussion of the CAV-OX® technology's effectiveness pertains only to TCE and benzene.

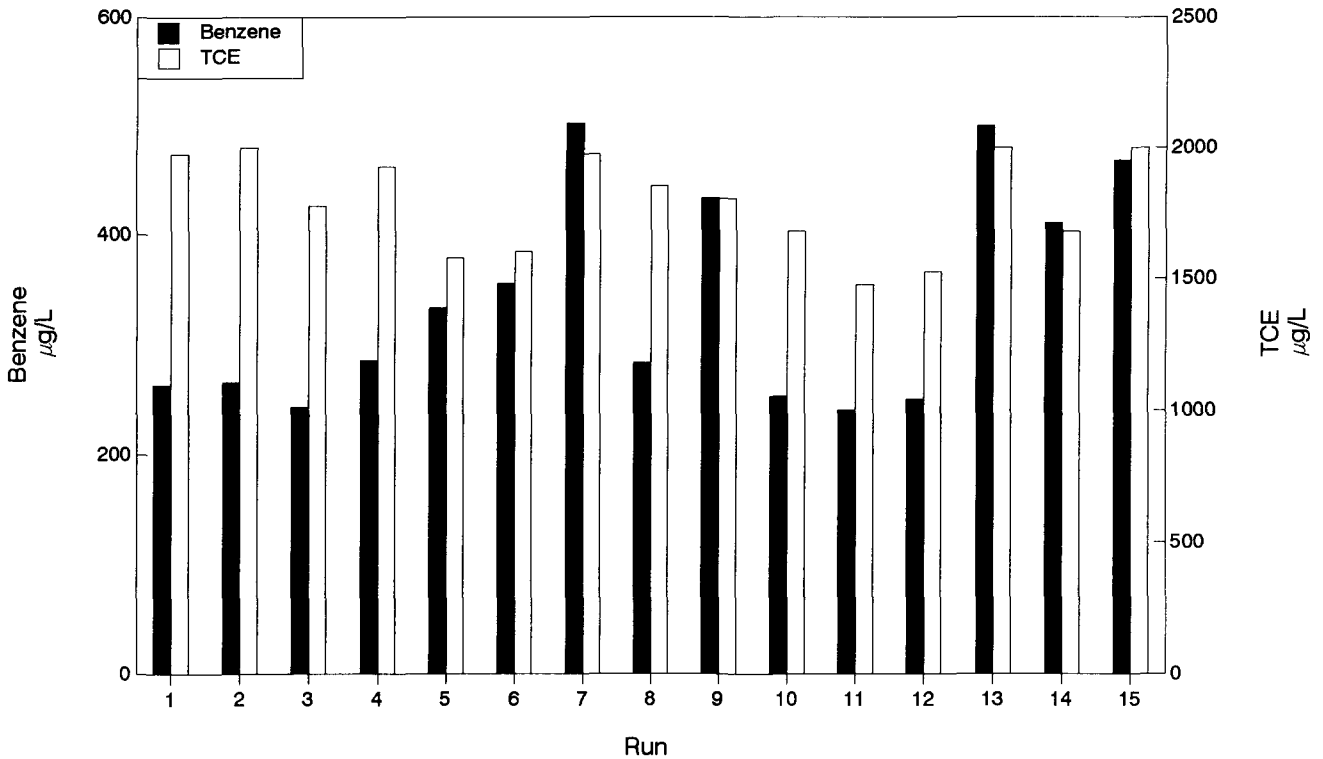


Figure B-4. *Influent Concentrations - Primary Contaminants*

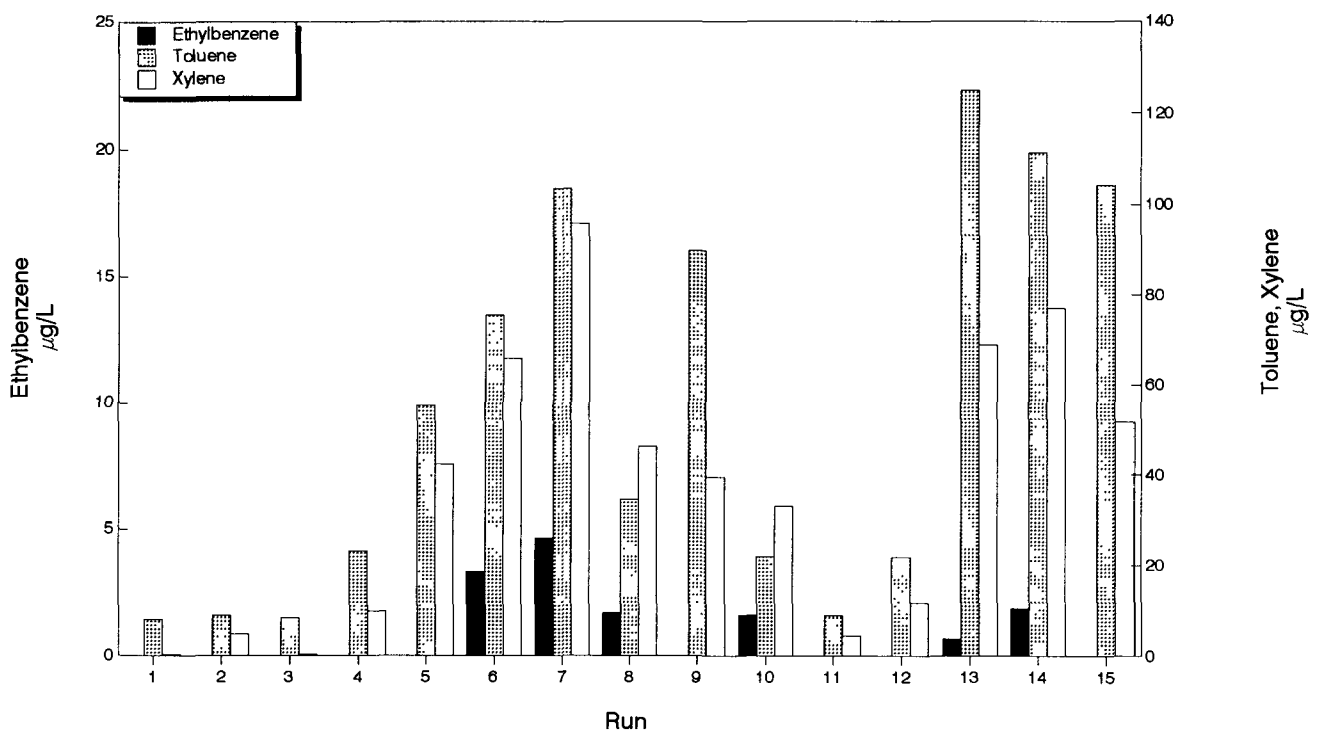


Figure B-5. *Influent Concentrations - Secondary Contaminants*

Summary of Results for Critical Parameters

Critical parameters are those used to meet primary project objectives. Table B-3 compares TCE and benzene removals among the three treatment process configurations. Table B-4 compares TCE and benzene removal efficiencies among the three treatment process configurations. Figure B-6 compares the TCE removal efficiency of the three configurations. Figure B-7 compares the benzene removal efficiency of the three configurations. The major differences among the three configurations involve UV output and flow rate. In general, contaminant removal increased with UV output and with decreased flow rates. However, the choice of a process depends on site specific characteristics. For the conditions at Edwards, the CAV-OX® I low-energy process would be adequate for a desired flow rate of 0.6 gpm. Likewise, if a greater flow rate is required, a 5-kW or 10-kW process may be preferable.

While operating under the preferred conditions, all CAV-OX® process effluents met State of California drinking water action levels and federal drinking water MCLs for BTEX at the 95 percent confidence level. Effluent from one configuration of the CAV-OX® I process met State of California drinking water action levels and federal drinking water MCLs for TCE at the 95 percent confidence level. In addition, average effluent contaminant values from the CAV-OX® II process, while operating under the preferred conditions, met State of California drinking water action levels and federal drinking water MCLs for TCE. However, because of data variability, the effluent did not meet the 95 percent confidence level for TCE. The demonstration evaluated numerous operating conditions; not all conditions meet these discharge limits. Figure B-8 summarizes these results.

Figure B-9 shows the effects of flow rate variations on the CAV-OX® I process for TCE removals. Figure B-10 shows the effects of flow rate variations on the CAV-OX® I process for benzene removals. Figure B-11 shows the effects of flow rate variations on the CAV-OX® II process for TCE removals. Figure B-12 shows the effects of flow rate variations on the CAV-OX® II process for benzene removals. Overall contaminant removal efficiency increased with a decrease in flow rate. However, the choice of a CAV-OX® configuration depends on site specific characteristics.

Summary of Results for Noncritical Parameters

The technology demonstration also evaluated analytical results for several noncritical parameters, which are those used to meet secondary project objectives. These results are summarized below.

Hydrogen Peroxide Effects

A secondary objective of the demonstration was to examine the effects of different hydrogen peroxide doses on the efficiency of the treatment process. To meet this goal, hydrogen peroxide was added to the influent holding tank to achieve concentrations of 0, 30, 60, and 90 mg/L. For runs 10, 11, and 12, Magnum added a calculated hydrogen peroxide dose to the holding tank. The hydrogen peroxide concentration was then measured using a titanium complexary method (Boltz and Howell 1979). Magnum then added more hydrogen peroxide or water to the holding tank as necessary to reach the desired concentration. However, because Magnum distrusted titanium complexary method results, Magnum purchased a test kit based on a ferric reaction and used it for runs 4, 5, 6, 7, 8, 9, and 14. Hydrogen peroxide was not added for runs 1, 2, 3, 13, and 15.

Results obtained using the Boltz and Howell method better reflect the actual available hydrogen peroxide in each sample for two reasons. First, the Boltz and Howell method is straightforward. Titanium and peroxide ion form stable peroxo complexes with a typical structure of $[Ti(O_2)OH(H_2O)]^+$. The overall ferric reaction is also simple:

$$H_2O_2 + 2Fe^{2+} \rightarrow 2OH^- + 2Fe^{3+}$$

The mechanism of this reaction is not simple, however, because it involves free radicals. Therefore many other reactions may occur. One well known reaction occurs in the presence of oxygen and organics. The oxygen reacts with the organic free radical to create organic peroxide radicals (RO·); these radicals oxidize ferrous iron to make a hydroperoxide (ROOH), which will react with more ferrous iron. The overall reaction, which results in a falsely high analysis result, is shown below.

$$O_2 + 4Fe^{2+} + 4H^+ \rightarrow 4Fe^{3+} + 2H_2O$$

Second, hydrogen peroxide was added to the influent holding tank during the demonstration. The water in the tank not only contained organic matter and some metal ions, but also was exposed to air. Therefore, the actual hydrogen peroxide content of the influent began declining upon contact. The rate of decline of hydrogen peroxide depends on the rate of the free radical generation, which is influenced by many factors. Therefore, the possibilities for side reactions in the ferric reaction are much greater than those with the Boltz and Howell method.

Also, the chemistry involved in the CAV-OX® process is not at equilibrium. The composition of the water in the process continuously changes; therefore, peroxide measurements taken at different times, and possibly from different places within the tank, will differ. There is no direct correlation of the time and location of samples analyzed by the two methods.

Table B-3. *Contaminant Removal*

Run	Influent		Hydrogen Peroxide Level (mg/L)	CAV-OX® I			CAV-OX® II					
	TCE (µg/L)	Benzene (µg/L)		Flow (gpm)	Effluent		Flow (gpm)		Effluent			
					TCE (µg/L)	Benzene (µg/L)			TCE (µg/L)		Benzene (µg/L)	
							5-kW	10-kW	5-kW	10-kW	5-kW	10-kW
Low Hydrogen Peroxide Dose												
1	1,975	263	0	0.6	1,450	280	2.0	2.0	235	28.0	160	95.3
2	2,000	265	0.4	1.5	1,400	285	1.6	1.6	119	16.8	135	84.5
3	1,775	243	0.4	1.5	1,550	268	3.9	4.0	608	248	223	163
Medium Hydrogen Peroxide Dose												
4	1,925	285	4.9	1.5	550	32.5	4.0	3.9	235	35.8	29.3	3.8
5	1,575	333	4.9	1.5	603	61.3	3.9	3.4	235	46.3	34.8	7.23
6	1,600	355	5.9	0.5	57.5	2.28	1.5	1.4	6.55	10.1	1.72	2.06
7	1,975	503	5.9	0.7	255	17.5	1.9	2.0	43.0	15.6	3.1	2.4
8	1,850	283	6.0	0.7	225	8.7	1.9	1.9	29.0	13.5	3.3	2.08
9	1,800	433	6.1	1.5	710	60.3	4.0	4.0	248	20.3	28.3	2.38
High Hydrogen Peroxide Dose												
10	1,675	252	23.4	0.6	1.64	ND	2.0	2.1	5.3	5.23	1.24	1.12
11	1,475	240	33.1	0.5	1.95	ND	1.6	1.5	6.01	11.9	1.4	2.78
12	1,525	250	48.3	0.6	4.77	ND	1.4	1.4	2.88	5.0	ND	ND
Vendor Selected Condiitons												
13	2,000	500	1.8	NA[b]	NA[b]	NA[b]	1.9	1.9	388	47.8	308	198
14[a]	1,675	410	9.1	NA[b]	NA[b]	NA[b]	NA[b]	7.9	NA[b]	141	NA[b]	17.3
15[a,c]	2,000	468	1.0	NA[b]	NA[b]	NA[b]	NA[b]	0.8	2,025[b,d]	73.1	468[b,d]	21.4

Notes:
[a] *Influent pH adjusted*
[b] *CAV-OX® I and 5-kW CAV-OX® II not operated*
[c] *CAV-OX® II operated at 2.5 kW*
[d] *Sample collected after the cavitation chamber prior to UV reactor*

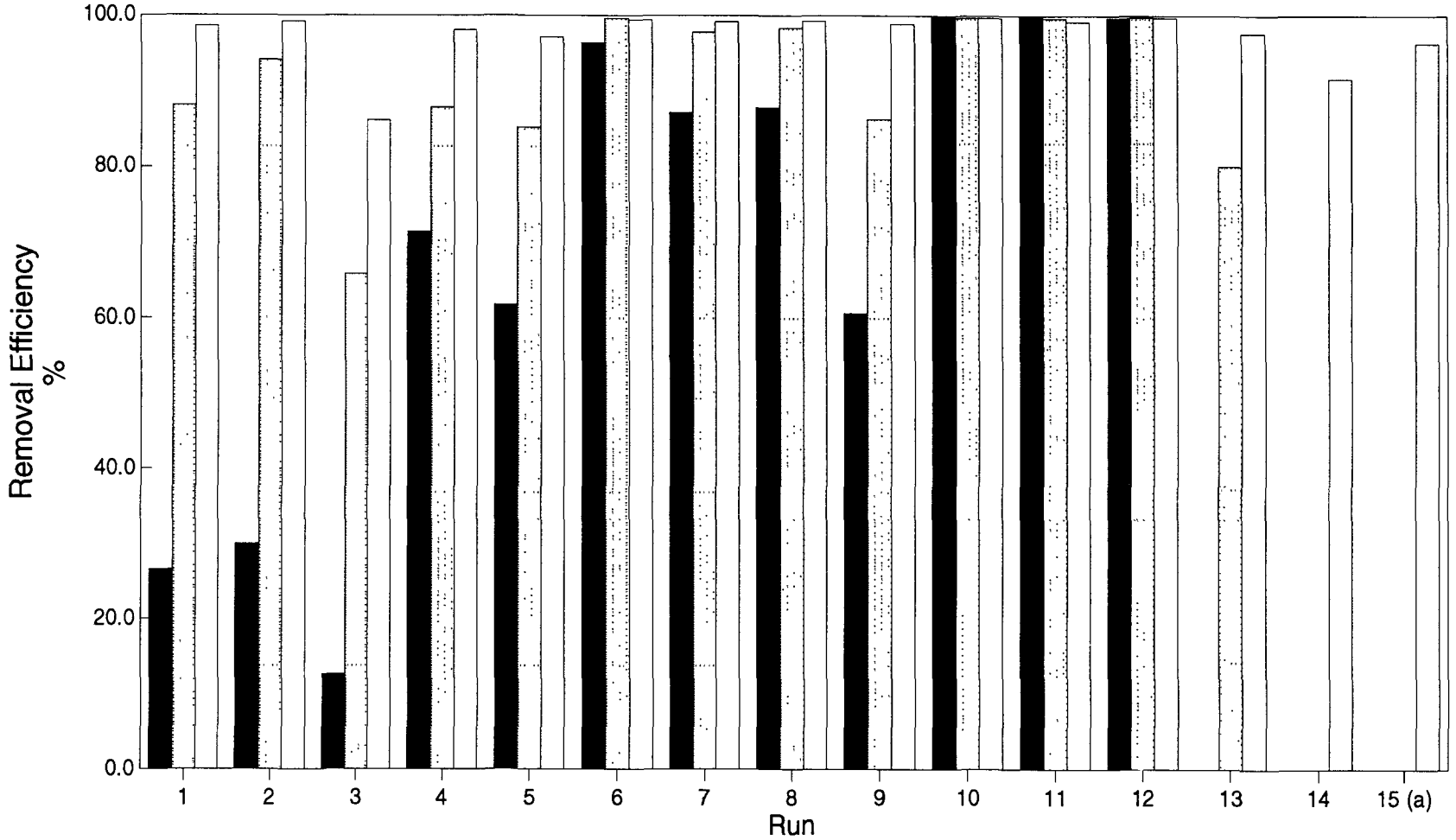
NA = not applicable *mg/L = milligrams per liter*
ND = not detected *µg/L = micrograms per liter*
gpm = gallons per minute *kW = kilowatts*

Table B-4. *Contaminant Removal Efficiency*

Run	Hydrogen Peroxide Level (mg/L)	CAV-OX® I			CAV-OX® II					
		Flow (gpm)	Removal Effficiency (%)		Flow (gpm)		Removal Efficiency (%)			
			TCE	Benzene			TCE		Benzene	
					5-kW	10-kW	5-kW	10-kW	5-kW	10-kW
Low Hydrogen Peroxide Dose										
1	0	0.6	26.6	0	2.0	2.0	88.1	98.6	39.0	63.7
2	0.4	1.5	30.0	0	1.6	1.6	94.1	99.2	49.1	68.1
3	0.4	1.5	12.7	0	3.9	4.0	65.8	86.1	8.2	33.0
Medium Hydrogen Peroxide Dose										
4	4.9	1.5	71.4	88.6	4.0	3.9	87.8	98.1	89.7	98.7
5	4.9	1.5	61.7	81.6	3.9	3.4	85.1	97.1	89.5	97.8
6	5.9	0.5	96.4	99.4	1.5	1.4	99.6	99.4	99.5	99.4
7	5.9	0.7	87.1	96.5	1.9	2.0	97.8	99.2	99.4	99.5
8	6.0	0.7	87.8	96.9	1.9	1.9	98.4	99.3	98.8	99.3
9	6.1	1.5	60.6	86.1	4.0	4.0	86.2	98.9	93.5	99.5
High Hydrogen Peroxide Dose										
10	23.4	0.6	99.9	99.9	2.0	2 1	99.7	99.7	99.5	99.5
11	33.1	0.5	99.9	>99,9	1.6	1.5	99.6	99.2	99.4	98.8
12	48.3	0.6	99.7	>99.9	1.4	1.4	99.8	99.7	99.8	99.8
Vendor Selected Condiitons										
13	1.8	NA [b]	NA [b]	NA [b]	1.9	1.9	80.1	97.6	38.5	60.5
14 [a]	9.1	NA [b]	NA [b]	NA [b]	NA [b]	7.9	NA [b]	91.6	NA [b]	95.8
15 [a,c]	1.0	NA [b]	NA [b]	NA [b]	NA [b]	0.8	NA [b,d]	96.3	NA [b,d]	95.4

Notes:
- [a] *Influent pH adjusted*
- [b] *CAV-OX® I and 5-kW CAV-OX® II not operated*
- [c] *CAV-OX® II operated at 2.5 kW*
- [d] *Sample collected after the cavitation chamber prior to UV reactor*

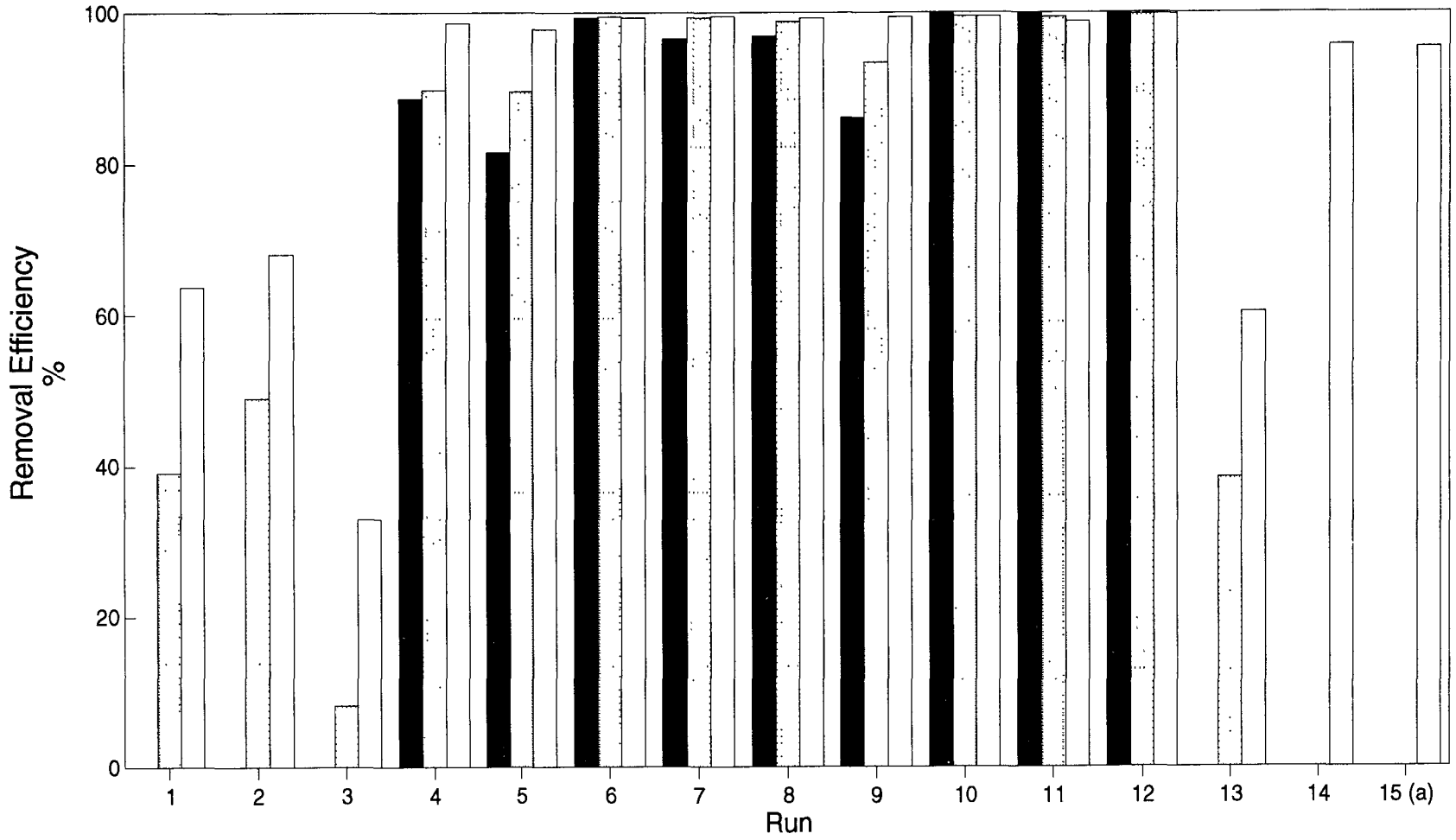
NA = not applicable *mg/L = milligrams per liter*
gpm = gallons per minute *kW = kilowatts*



■ CAV-OX® I	26.6	30.0	12.7	71.4	61.7	96.4	87.1	87.8	60.6	99.9	99.9	99.7	NA	NA	NA
▨ 5-kW CAV-OX ® II	88.1	94.1	65.8	87.8	85.1	99.6	97.8	98.4	86.2	99.7	99.6	99.8	80.1	NA	0 (b)
□ 10-kW CAV-OX ® II	98.6	99.2	86.1	98.1	97.1	99.4	99.2	99.3	98.9	99.7	99.2	99.7	97.6	91.6	96.3

Notes: [a] CAV-OX® II high-energy process operated at 2.5 kW
[b] Sample collected after cavitation chamber prior to UV reactor
NA = Not Applicable

Figure B-6. *Trichloroethene Removal Efficiency Comparison*



■ CAV-OX® I	0	0	0	88.6	81.6	99.4	96.5	96.9	86.1	99.9	99.9	99.9	NA	NA	NA
▨ 5-kW CAV-OX ® II	39.0	49.1	8.2	89.7	89.5	99.5	99.4	98.8	93.5	99.5	99.4	99.8	38.5	NA	0 (b)
□ 10-kW CAV-OX ® II	63.7	68.1	33.0	98.7	97.8	99.4	99.5	99.3	99.5	99.5	98.8	99.8	60.5	95.8	95.4

Notes: [a] CAV-OX® II high-energy process operated at 2.5 kW
[b] Sample collected after cavitation chamber prior to UV reactor

NA = Not Applicable

Figure B-7. *Benzene Removal Efficiency Comparison*

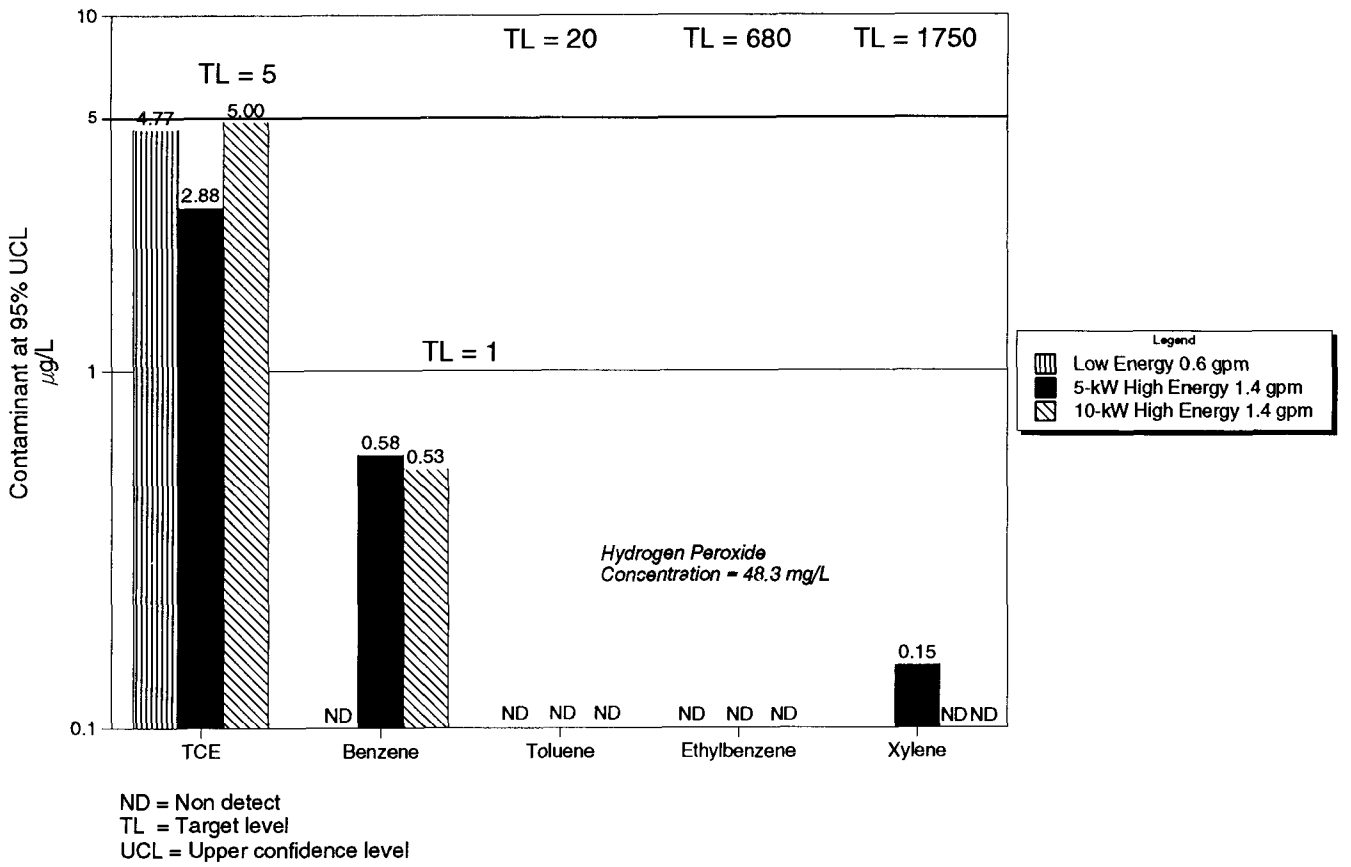


Figure B-8. *Comparison of 95 Percent UCLs for Effluent VOC Concentrations with Demonstration Target Levels (Run 12)*

The demonstration results show that removal efficiency increased with the addition of hydrogen peroxide. However, Magnum reports that this increase in efficiency is limited and that efficiency decreases beyond some level of hydrogen peroxide addition. The demonstration did not fully evaluate enough hydrogen peroxide levels to determine the concentration at which efficiency decreases with additional hydrogen peroxide. Table B-4 shows the increase in removal efficiencies with increased hydrogen peroxide dose.

pH Effects

For runs 14 and 15 (in which pH was varied) only acid addition is considered because of the high bicarbonate levels in the groundwater. Because carbonate and bicarbonate scavenge hydroxyl radicals, acid addition may improve process performance by shifting the carbonate equilibrium to carbonic acid. However, during the two runs in which pH was varied, other parameters were also varied; therefore, definitive conclusions cannot be drawn about the effects of pH.

Vendor-Selected Conditions

Runs 13, 14, and 15 were conducted under conditions chosen by Magnum. For these runs Magnum chose not to operate the CAV-OX® I low-energy process.

Run 13 repeated the conditions of Run 1 (a previous run with no hydrogen peroxide added). The results of these runs agree and show that although some contaminants are removed, hydrogen peroxide is vital to achieve high removal efficiencies.

For Run 14, Magnum chose to operate with a hydrogen peroxide concentration of 9.1 mg/L and a flow rate of 8 gpm. Results of this run showed that the increased hydrogen peroxide levels did not compensate for the increased flow rate (and therefore decreased retention time) in the process. Also, since the pH of the influent was lowered, definitive conclusions cannot be based on this run.

For Run 15, Magnum chose to operate the CAV-OX® II reactor at 2.5 kW with no added hydrogen peroxide and a flow rate of 1 gpm. The purpose of performing this run under these operating conditions was to examine the effects of the cavitation chamber. Samples were collected from three locations: (1) at the intake to the process, (2) after the cavitation chamber but before the UV reactor, and (3) after the UV reactor. Run 15 results indicated no immediate decrease in contamination in the water exiting the cavitation chamber. Magnum reports that a holding time of about 1 hour after the water exits the cavitation chamber is optimal for removal of contaminants in the cavitation chamber. However, the equipment demonstrated at Edwards

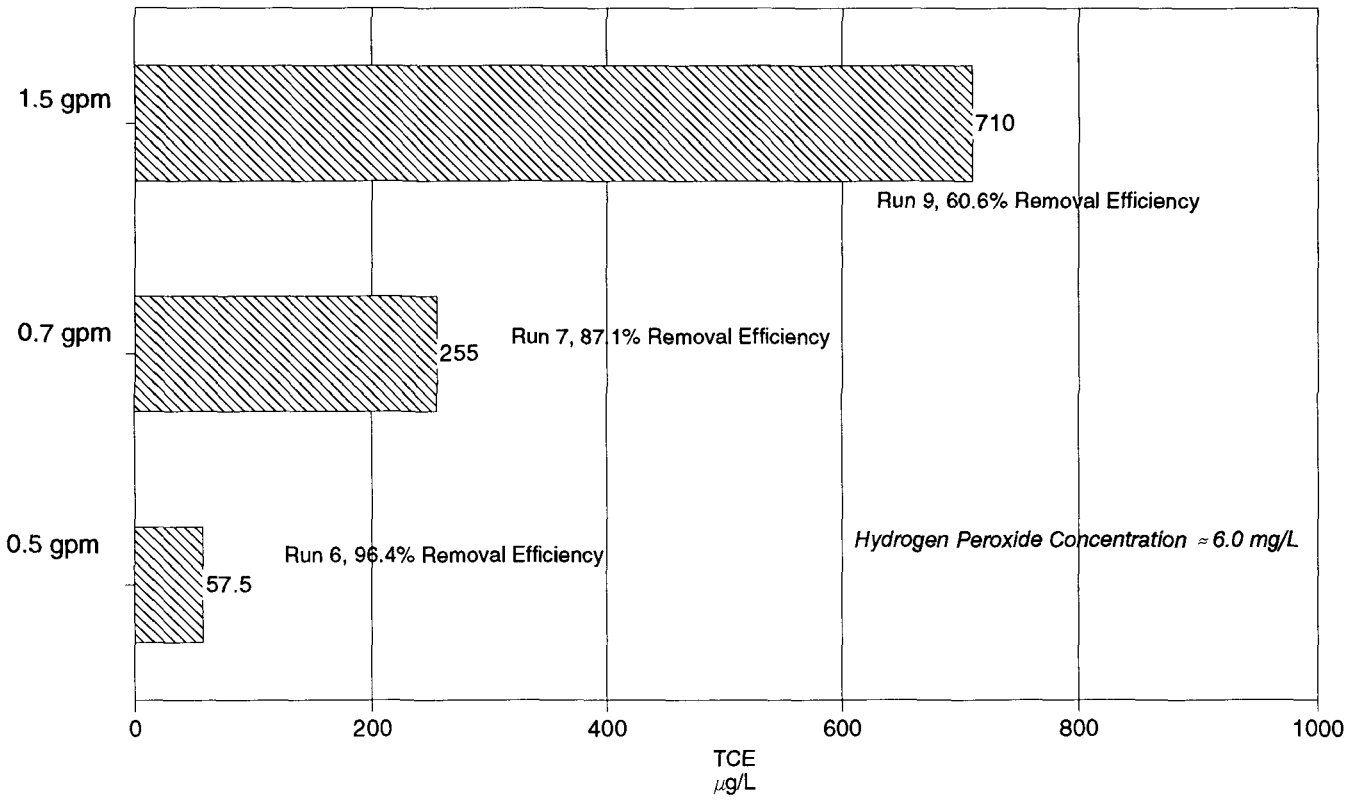


Figure B-9. *CAV-OX® I Flow Variations on Trichloroethene Removals*

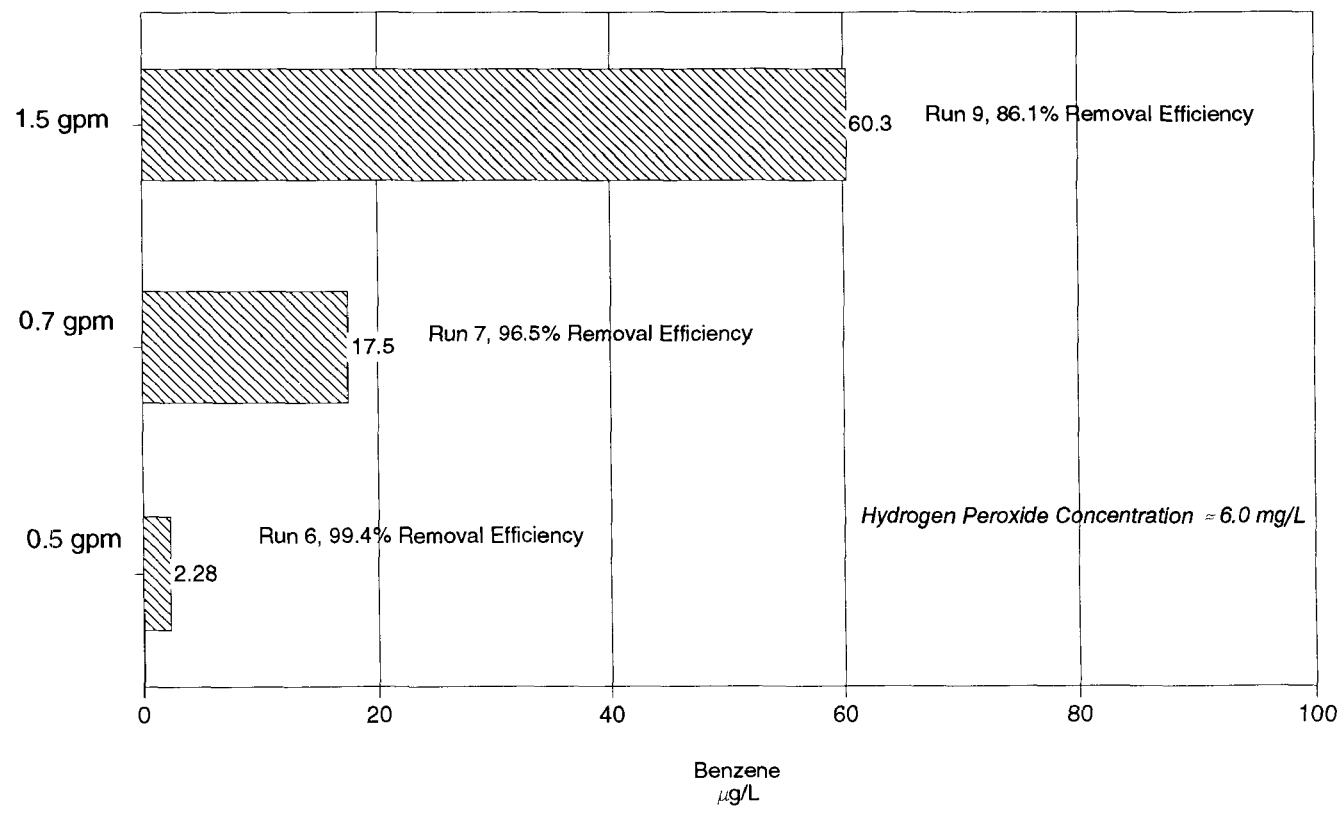


Figure B-10. *CAV-OX® I Flow Variations on Benzene Removals*

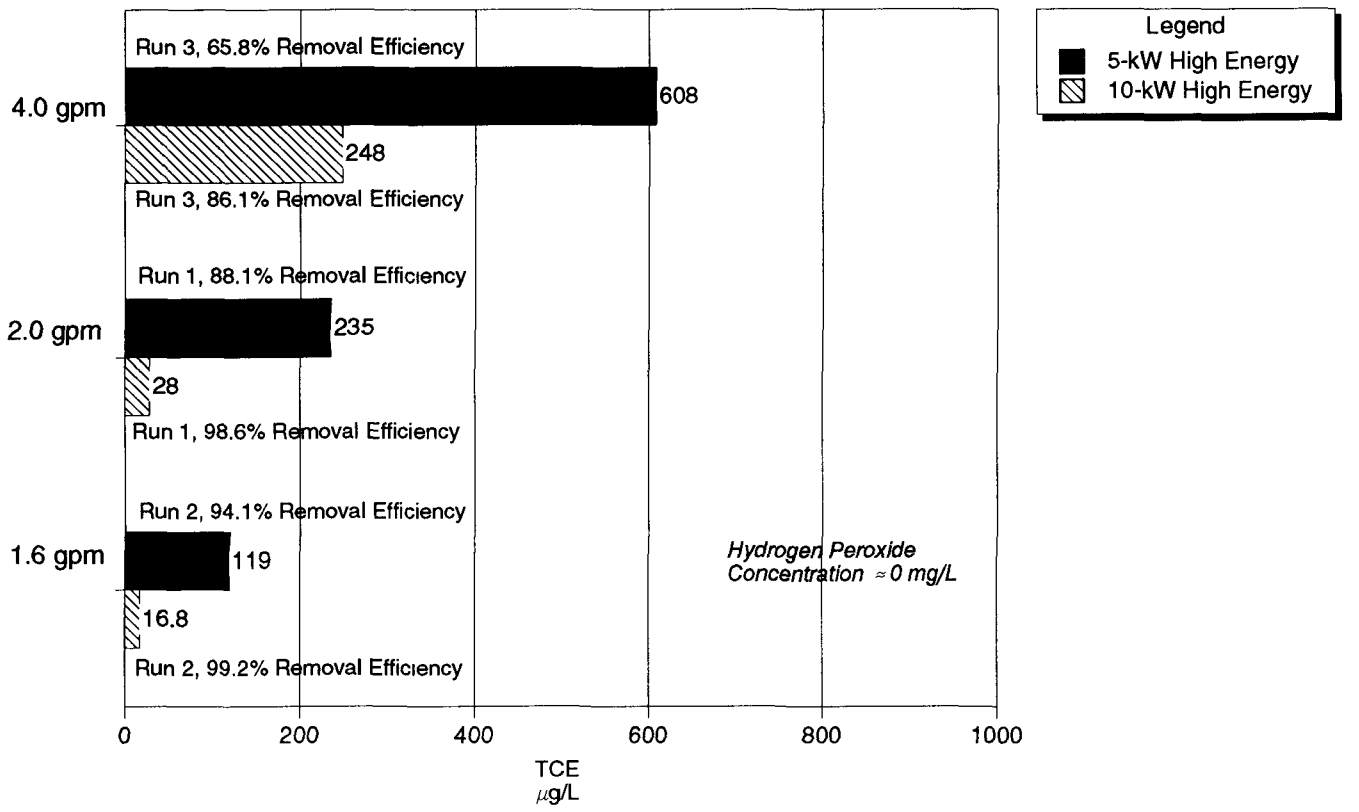


Figure B-11. *CAV-OX® II Flow Variations on Trichloroethene Removals*

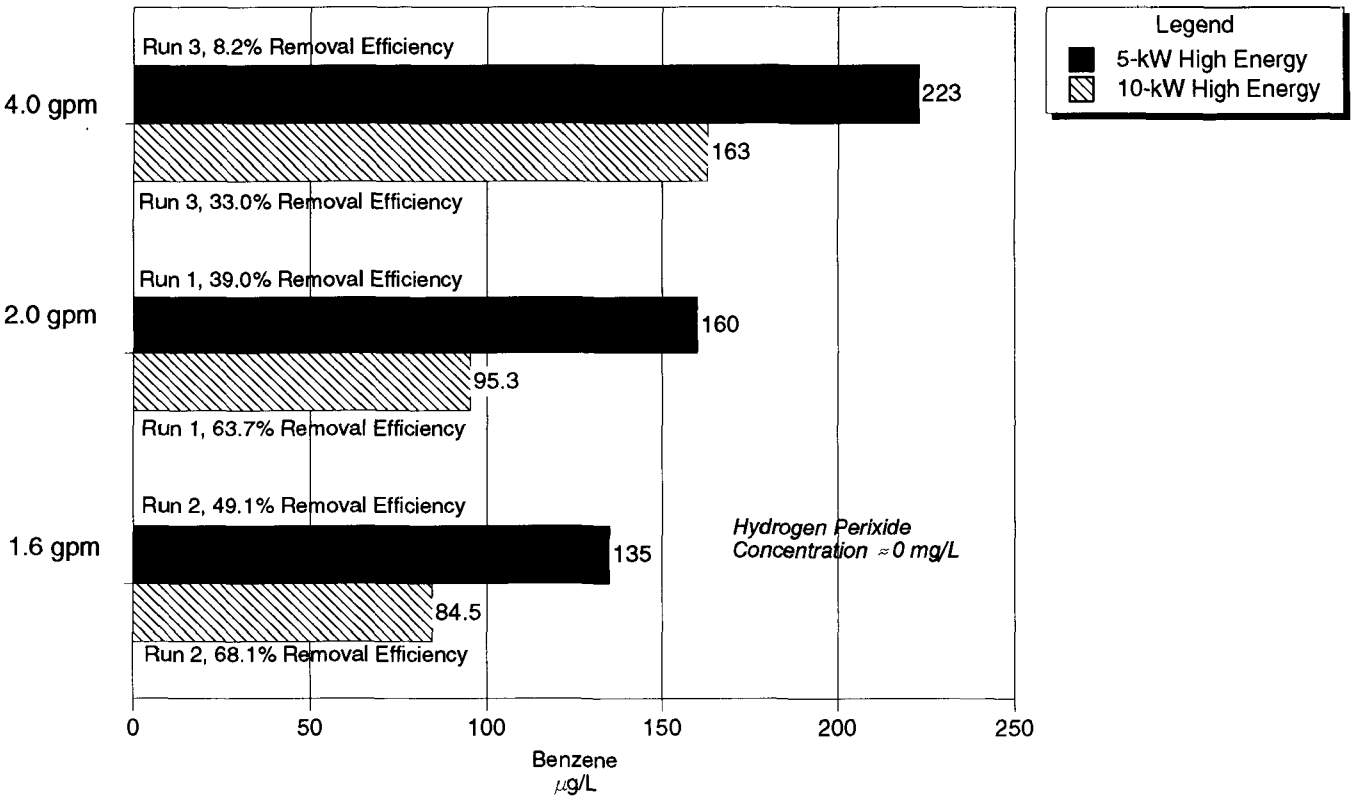


Figure B-12. *CAV-OX® II Flow Variations on Benzene Removals*

The focus of a SITE demonstration is to examine a technology in its entirety, not to study its individual components. The effects of cavitation alone, therefore, were not fully evaluated during the CAV-OX® demonstration. Results of other studies conducted by Magnum concerning the effects of cavitation alone, independent of the SITE demonstration, are included in Appendix A and Appendix C.

Additional Noncritical Parameters

Additional analytical results for several noncritical parameters are summarized below.

In general, GC/MS analysis of influent and effluent samples for VOCs indicated that several new target compounds or tentatively identified compounds (TIC) were formed during the treatment. Acetone and 2-butanone concentrations were generally higher in the effluent than in the influent. Also, several unknown TICs were identified in both the influent and effluent samples. However, vinyl chloride and 1,1-dichloroethane were not formed during treatment.

GC/MS analysis of influent and effluent samples for SVOCs revealed only phenol, 2-methylphenol, and bis(2-ethylhexyl)phthalate. The highest concentration found was 11 µg/L, and these compounds were found in both the influent and effluent samples in similar concentrations. As with the VOC analysis, several unknown TICs were identified in both the influent and effluent samples.

During Runs 13, 14, and 15, bioassay tests were performed to evaluate the acute toxicity of influent and effluent samples. 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 was expressed as the percent of effluent (or influent) in the test water. One influent and one effluent sample was tested in each run. Bioassay analyses showed influent and effluent from Run 13 to be nontoxic to the fathead minnow and moderately toxic to the water flea. Bioassay analyses also showed influent and effluent from Run 14 to be toxic to both the fathead minnow and the water flea, and that influent from Run 15 was nontoxic to the fathead minnow and toxic to the water flea. Effluent from Run 15 was toxic to both the fathead minnow and the water flea. Bioassay analyses of water from runs with low levels of hydrogen peroxide (Run 13) showed that the CAV-OX® process effluent was nontoxic to the fathead minnow but moderately toxic to the water flea, while bioassay analyses of water from runs with hydrogen peroxide (Run 14) showed that the CAV-OX® process effluent was toxic to both the fathead minnow and the water flea. Comparison of effluent toxicity data with that of hydrogen peroxide in the effluent (10 mg/L) indicates that effluent toxicity may be due partially to hydrogen peroxide rather than CAV-OX® treatment by-products. Additional studies are needed to draw any conclusion on any effluent toxicity related to hydrogen peroxide.

Samples were also analyzed for iron and manganese. Iron concentrations in the influent ranged from 180 to 462 µg/L, while concentrations in the effluent ranged from 217 to 512 µg/L. Manganese concentrations in the influent ranged from 662 to 694 µg/L, while concentrations in the effluent ranged from 686 to 740 µg/L. These results indicate that the CAV-OX® process did not remove iron or manganese because these metals were present at similar levels in the influent and the effluent.

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

Total recoverable petroleum hydrocarbons (TRPH) were found in the influent at concentrations of 0.64 to 1.15 mg/L. TRPH concentrations in the effluent ranged from below detection limits to 0.78 mg/L.

Turbidity readings for the influent samples ranged from 2.97 to 3.58 nephelometric turbidity units (NTU). Readings for the effluent samples ranged from 2.07 to 3.38 NTUs.

In the CAV-OX® I process, the water temperature increased at a rate of about 0.26 °F per minute of UV exposure. In the 5-kW CAV-OX® II process, the water temperature increased at a rate of about 2.36 °F per minute of UV exposure. In the 10-kW CAV-OX® II process, the water temperature increased at a rate of 4.29 °F per minute of UV exposure. Since the equipment was exposed to the surrounding environment, the temperature increase may vary depending upon the ambient temperature or other atmospheric conditions.

Electricity is the only utility required for the CAV-OX® process. The electricity demand was 2.2 kW for the CAV-OX® I process, 6.4 kW for the 5-kW CAV-OX® II process, and 13 kW for the 10-kW CAV-OX® II process.

Hydrogen peroxide, the only process chemical used in the CAV-OX® process, was used at a rate of between 0 and 48.3 mg/L.

After operating about 2 weeks, no scaling was observed on any of the UV tubes at the end of the demonstration. Magnum reports that scaling is not a concern for the CAV-OX® process.

Conclusions

The following preferred operating conditions were determined for the CAV-OX® I low-energy process: (1) an influent hydrogen peroxide level of 23.4 mg/L and (2) a flow rate of 0.6 gpm. At these conditions, TCE and benzene levels in the effluent were generally below target levels (5 µg/L and 1 µg/L, respectively). The average removal efficiencies for TCE and benzene were both greater than 99.7 percent.

The following preferred operating conditions were determined for both the 5-kW and 10-kW CAV-OX® II configurations: (1) an influent hydrogen peroxide level of 48.3 mg/L and (2) a flow rate of 1.4 gpm. At these conditions, TCE and benzene levels in the effluent were generally below the target level. The average removal efficiencies for TCE and benzene were about 99.7 and 99.8 percent, respectively.

While operating under the preferred conditions, all CAV-OX® process effluents met State of California drinking water action levels and federal drinking water MCLs for BTEX at the 95 percent confidence level. One configuration of the CAV-OX® I process effluents met State of California drinking water action levels and federal drinking water maximum contaminant levels for TCE at the 95 percent confidence level.

In the CAV-OX® I low-energy process, the 5-kW CAV-OX® II high-energy process, and the 10-kW CAV-OX® II high-energy process, water temperature increased at an average rate of about 0.26 °F, 2.36 °F, and 4.29 °F per minute of UV exposure, respectively. Since the equipment was exposed to the surrounding environment, the temperature increase may vary depending upon the ambient temperature or other atmospheric conditions.

After operating about 2 weeks, no scaling was observed on any of the tubes at the end of the demonstration.

References

Boltz, D.F., and J.A. Howell. 1979. *Colorimetric Determination of Non-Metals.* John Wiley & Sons, New York, New York.

The Earth Technology Corporation. 1992. "Benzene Plumes, Fall 1991". Prepared for Edwards Air Force Base, California. October.

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Appendix C
Case Studies

Note: This appendix presents nine case studies provided by Magnum Water Technology (Magnum) on the application of the CAV-OX® process to contaminant streams. Claims and interpretations of results in this appendix are made by Magnum and may not be substantiated by test or cost data. This appendix has been edited only so that format is consistent with the document.

Introduction

Table C-1 summarizes the results of nine case studies provided by Magnum involving both pilot- and full-scale units treating contaminated groundwater and industrial wastewaters. Magnum provided all case studies as additional performance data for the CAV-OX® process. Contaminants of concern included pentachlorophenol (PCP), total petroleum hydrocarbons (TPH), benzene, toluene, ethylbenzene, and xylenes (BTEX), biochemical oxygen demand (BOD), total organic carbon (TOC), atrazine, cyanide, phenol, and the bacterium *Salmonella*.

In case studies involving PCP, TPH, and BTEX, the CAV-OX® process reduced the levels of these contaminants in various aqueous phases by 96 to 99.94 percent.

Two case studies investigated BOD removal. In the first of these, the CAV-OX® process reduced BOD in resin plant effluent by 94.1 percent. In the second, BOD in contaminated seawater was reduced by 83.3 to 88.4 percent. In the first case study hydrogen peroxide was added; in the second hydrogen peroxide was not added and ultraviolet (UV) treatment was not used.

One case study involved groundwater contaminated with the herbicide atrazine. The CAV-OX® process reduced atrazine levels from 1,000 micrograms per liter (µg/L) to 200 µg/L, a reduction of 80 percent. Although atrazine could have been reduced further, the customer in this case determined that 200 µg/L was acceptable.

The CAV-OX® process has also been used to treat wastewater contaminated with potassium cyanide. In this case study, the process consistently oxidized potassium cyanide to nondetectable levels with retention times of less than 4 minutes and hydrogen peroxide levels as low as 20 milligrams per liter (mg/L). Using cavitation and UV radiation only, without adding hydrogen peroxide, potassium cyanide levels were reduced by 46 percent.

In another case study, the CAV-OX® process reduced levels of *Salmonella* in city water from 2,000,000 colony-forming units per milliliter (CFU/mL) to 0.8 CFU/mL without hydrogen peroxide addition. After injecting the water with 80 mg/L hydrogen peroxide, *Salmonella* levels were reduced from 1,900,000 CFU/mL to 0.01 CFU/mL.

In the final case study phenol was reduced from 20 parts per million (ppm) (with 60 ppm hydrogen peroxide) to nondetectable levels at a flow rate of 2 gallons per minute (gpm) and to 0.8 ppm at a flow rate of 6 gpm.

Some case studies identify the cost (in October 1993 dollars) to treat 1,000 gallons of influent, an industry-standard method of presentation. Magnum's method accounts for the following operating costs:

- Operating chemical usage
- Power consumption by ultraviolet (UV) lamps and centrifugal pump
- Maintenance allowance costs
- Amortization of capital equipment over 5 years

The cost per 1,000 gallons is the total of these costs. Costs from the case studies ranged from $1.62 to $1.93 per 1,000 gallons of water containing organic contaminants. For one case study, the cost to reduce BOD using only the cavitation chamber (no UV and no hydrogen peroxide) was $0.13 per 1,000 gallons.

Table C-1. Case Study Summary

Case Study	Facility	Contaminants	Results
C-1	Wood-treating Superfund site, Pensacola, Florida	Pentachlorophenol (PCP), polynuclear aromatic hydrocarbons (PAH)	PCP reduced by 96 percent
C-2	Chevron service station, Long Beach, California	Total petroleum hydrocarbons (TPH); benzene, toluene, ethylbenzene, and xylenes (BTEX)	TPH reduced by 99.94 percent
C-3	Presidio Army Base, San Francisco, California	TPH, BTEX	Ethylbenzene and TPH reduced to nondetectable levels
C-4	Chemical plant, East Coast U.S.	Biochemical oxygen demand (BOD)	BOD reduced by 94.1 percent
C-5	Mannesmann Anlagenbau, Salzburg, Austria	Atrazine	Atrazine reduced from 1,000 micrograms per liter (ug/L) to 200 ug/L
C-6	Steel mill, South Korea	Cyanide, phenol	Cyanide reduced by 55 percent using cavitation only and greater than 99.9 percent using cavitation and UV radiation
C-7	Chicken farm, Virginia	Salmonella	Samonella reduced from 2,000,000 colony forming units per milliliter (CFU/mL) to 0.8 CFU/mL without hydrogen peroxide addition; reduced to 0.01 CFU/mL after hydrogen peroxide addition
C-8	Southern California Edison, Los Angeles, California	BOD	BOD reduced by 83.3 to 88.4 percent using cavitation only
C-9	Corporacion Mexicana de Investigacion en Materials, S.A. de C.V. (CMIMSA)	Phenol, pharmaceuticals	At high flow rates phenol was reduced to nondetectable levels

CASE STUDY C-1: Wood Treating Superfund Site, Pensacola, Florida

Introduction

In mid-1992, Magnum was asked to supply a CAV-OX® process to reduce PCP in a leachate discharged from a soil washing process. The soil washing process was part of a demonstration sponsored by the U.S. Environmental Protection Agency (EPA) to evaluate the remediation of this site, which had been in operation for more than 40 years before it was designated a Superfund site.

Equipment

Magnum delivered both a CAV-OX® I low-energy unit and a CAV-OX® II high-energy unit. The units could be run in series, parallel, or independently through suitable valving.

The CAV-OX® I low-energy unit consisted of a 2-horsepower centrifugal pump, cavitation chamber, recycle loop, six 60-watt lamps in a 6-foot stainless steel reactor and associated controls, UV ballasts, function lamps, and circuit breakers. The CAV-OX® II high-energy unit used the same centrifugal pump, cavitation chamber, and recycle loop but had an independent power supply for the 5-foot high-energy reactor with its 2.5- or 5-kilowatt (kW) lamp.

The equipment was shipped using a common carrier and delivered to the site over a weekend. It was installed and tested the following Monday. The next 5 days were full test days lasting from 8 to 12 hours. The CAV-OX® equipment was operable 100 percent of the time and had no failures of any kind.

Methodology

The customer decided that the leachate would receive minimal pretreatment, to develop a worst-case scenario for evaluating the technology. Because the leachate was a thin slurry instead of a contaminated water stream, it was treated with high levels of hydrogen peroxide (2,000 to 4,000 mg/L), followed by treatment in the CAV-OX® II high-energy process. Minimum pretreatment on future test runs, if needed, would consist only of pH adjustment, followed by minimal cartridge filtration using swimming pool filters.

A 500-gallon polyethylene holding tank was used to collect leachate from the soil washing process (without pretreatment) and served as a recycle vessel for the batch process test. Preliminary tests were run to evaluate process efficiency in reducing PCP and to determine optimal operating parameters.

The initial runs showed that little UV was being transmitted and that most PCP destruction was taking place in the cavitation chamber, aided by hydrogen peroxide addition. PCP was generally reduced by 22 to 50 percent in the initial runs.

However, for runs in which flow-through was reduced or recycling increased, increasing the UV intensity raised the effluent temperature from 100 °F to 150 °F and above. The temperature rise caused the PCP concentration in the effluent to increase dramatically, often doubling or tripling in the influent. The higher concentrations resulted from the slurry releasing additional contaminants as the temperature rose.

A series of tests on the process stream, without pretreatment, was made with recycle times of 30 minutes, 60 minutes, and 90 minutes. On the basis of these tests, it was decided that adjusting the pH of the process stream from 9 to 5.5 would cause flocculation and sedimentation in the holding tank, resulting in a clearer influent to the CAV-OX® process.

Results

After adjusting the pH of the process stream, one subsequent test run showed a 96 percent reduction in PCP levels. It is important to note that while PCP levels in the influent varied from 900 to 15,000 µg/L, an additional load of polynuclear aromatic hydrocarbons (PAH) ranging from 16,000 to 128,000 µg/L was also present in the influent.

CASE STUDY C-2: Chevron Service Station, Long Beach, California

Introduction

In late 1990, a CAV-OX® I low-energy process was installed at a former Chevron service station to remediate groundwater at the site. Gasoline storage tanks at the site had leaked for several years, resulting in a groundwater contaminant plume that was migrating toward adjoining commercial property.

Since the plume had spread over a large area, 12 wells were drilled at its periphery to feed the overall treatment process and prevent the plume from spreading further. The CAV-OX® I process was to operate at 10 gpm, in order to reduce TPH from 200 mg/L to a level that met local regulations.

Equipment

The CAV-OX® I low-energy process used for this project was rated at 10 gpm and included a cavitation chamber, a centrifugal pump, a hydrogen peroxide injection process, and twelve 60-watt UV lamps housed in two stainless steel reaction chambers. A control panel housed the necessary wiring, UV ballasts, circuit breakers, and control switches. Figure C-1 is a photograph of the process.

Magnum worked closely with the site consultant and the client to design the pretreatment process. The final pretreatment process system consisted of a closed, pressurized design, preventing volatile organic compounds (VOC) from being released to the environment. The entire unit was housed in a 15-foot-by-12-foot enclosure at the corner of the property.

Methodology

Influent was drawn from the 12 wells using bladder pumps driven by an on-site compressor, which also supplied air to maintain 4 pounds per square inch (psi) of pressure on the sealed holding tank. Influent was pumped through two 3.5-cubic-foot media filters and forwarded to the holding tank. The liquid level in the holding tank was maintained by a level-control process, which was coordinated with an on-off control valve to the centrifugal pump. This centrifugal pressure pump developed 64 psi in the cavitation chamber. Groundwater was fed from the cavitation chamber at about 8 psi to the UV reactors. A recycle process allowed the groundwater to be returned upstream for additional treatment and functioned as a flow control for process throughput.

Figure C-1. *Photograph of CAV-OX ® Process*

Operations

During the 2 years required to remediate the site, the CAV-OX® I low-energy process was maintained by the site consultant's technical staff. After process start up, a trained technician collected effluent samples and serviced the process every 20 to 30 days. The CAV-OX® I low-energy process was operational 99.9 percent of the time over the 2-year period.

Initial problems with components in the air pressure process prevented the process from maintaining consistent operating conditions during the first few months. These problems were eventually solved.

Because of potential variations in influent quality, 400 pounds of activated carbon was included in the process to handle free product that might pass through the CAV-OX® I low-energy process. The carbon was replaced once during the 2-year period.

The UV lamps were replaced twice during the 2-year period. In addition, one quartz tube was broken when it was removed to be examined for exterior fouling, and was replaced. The quartz tubes never showed any indication of scaling, although the influent quality varied widely and appeared black at times because of apparent biological activity.

In early 1992, the 20 mg/L hydrogen peroxide injection before the centrifugal pump inlet was discontinued because tests indicated that it was unnecessary.

Results

As of late 1992, when the CAV-OX® I low-energy process was shut down, the influent TPH level had been reduced from 190,000 µg/L to 120 µg/L, a reduction of 99.94 percent. The overall cost was $1.62 for every 1,000 gallons of groundwater treated.

CASE STUDY C-3: Presidio Army Base, San Francisco, California

Introduction

A 20-gpm CAV-OX® I low-energy process was installed to remove VOCs from groundwater at a service station on the Presidio Army Base in San Francisco, California.

Equipment

The Model 2662.5 CAV-OX® I low-energy process installed at the site consisted of the cavitation chamber, a centrifugal pump, a hydrogen peroxide injection process, thirty-six 60-watt UV lamps housed in six stainless-steel reactors, a control panel with UV ballasts, and necessary switches, relays, and indicator lamps.

The CAV-OX® I low-energy process was combined with other equipment, including a vacuum extraction process for soil remediation, groundwater pumps and manifold, an influent holding tank with level controls, and the necessary electrical process and interlocks.

Table C-2. *Groundwater Sampling Results, August 20, 1990 (µg/L)*

Sample Point	Benzene	Toluene	Xylenes	Ethyl-benzene	TPH
Influent	*450*	*44*	*100*	*25*	*80*
Effluent	*6*	*1.9*	*1.5*	*ND*	*ND*

Notes: ND = Not detected

Results

Results of samples collected after installation, start up, and training are shown in Table C-2.

Tests performed in 1993 show that contaminants in groundwater at the site have been reduced dramatically. However, contaminant levels in soil require further remediation using the vacuum extraction process in conjunction with the CAV-OX® I low-energy process. The CAV-OX® I low-energy process may need to be operated intermittently if contaminants in the soil are further released into the groundwater.

The CAV-OX® I low-energy process was not installed under a protective cover at this site and has been exposed to the elements for the last 3 years. The UV components and parts not made of stainless steel have deteriorated somewhat; however, a protective cover will prevent this deterioration.

The overall cost was $1.75 for every 1,000 gallons of groundwater treated.

CASE STUDY C-4: Chemical Plant, East Coast U.S.

Introduction

In 1992, a major U.S. resin manufacturer contracted with Magnum to conduct a pilot study for remediating its plant effluent. This waste stream was common to several of the manufacturer's facilities on the east coast of the United States. Plant procedures required that the effluent be shipped off site for treatment, resulting in high costs and potential liabilities.

The customer agreed that the effluent was not suitable for treatment by standard advanced oxidation systems because of the type of contaminants and the high contaminant levels. The purpose of the pilot study was to determine how the CAV-OX® process could reduce contaminant levels in order to reduce overall disposal costs.

Equipment

A CAV-OX® II high-energy pilot unit was used for this study because of the types and concentrations of contaminants in the effluent. The unit consisted of a double reactor with a total UV output of 10 kW. Each 5-foot reactor had a 2.5- or 5-kW UV lamp and an independent power supply. The unit also included a 2-horsepower centrifugal pump, a cavitation chamber, a recycle loop, and a control panel with associated switches, indicator lamps, and circuit breakers.

Because the CAV-OX® II high-energy pilot unit consists of full-scale modules operating at 3 gpm, results from this study can be directly extrapolated to full-scale 10-gpm or 25-gpm industrial processes.

Methodology

First, 250 gallons of effluent was placed in a holding tank. The effluent was clear, somewhat viscous, and irritating to mucous membranes, with a strong odor. Next, hydrogen peroxide was added to the holding tank to achieve a concentration of 100 mg/L, resulting in an opaque, beige colored solution. Because this would decrease transmission of the UV radiation, most of the contaminant destruction would have to occur in the cavitation chamber. The test procedure was altered to allow maximum flow through the cavitation chamber; the flow was then directed through the UV reactors at 0.75 gpm.

Results

BOD was the primary parameter of concern; however, the CAV-OX® II high-energy process treated all constituents in the influent. Although nontargeted contaminants absorbed a significant amount of energy from the cavitation chamber and UV lamps, BOD in the treated effluent was reduced by 94.1 percent.

CASE STUDY C-5: Mannesmann Anlagenbau, Salzburg, Austria

Introduction

Mannesmann Anlagenbau (Mannesmann) of Salzburg, Austria, contracted with Magnum to treat groundwater contaminated with the herbicide atrazine. Atrazine is manufactured and sold worldwide by Ciba-Geigy Corporation (Ciba). Tests were conducted at Magnum's El Segundo, California, facility using atrazine samples supplied by Ciba. Ciba also provided technical support.

Equipment

A CAV-OX® I low-energy process with a 3-gpm flow was used for these tests. The process consisted of nine 45-watt lamps contained in three stainless steel reactors, a hydrogen peroxide injection unit, a centrifugal pump, and the cavitation chamber.

Methodology

The atrazine solution was mixed according to Ciba's recommendations and to Mannesmann's recommended level of 1 mg/L. The mixture was fed to the CAV-OX® I low-energy process from a 150-gallon holding tank.

The solution was processed using various protocols. Different flow rates and treatment levels were tested to determine an ideal protocol. However, the cost of laboratory analyses limited further optimization.

Results

Samples were sent to a local certified laboratory chosen by Mannesmann. Although atrazine could have been reduced to nondetectable levels, Mannesmann decided that the 200 µg/L achieved in the first test, a reduction of 80 percent, was acceptable.

CASE STUDY C-6: Steel Mill, South Korea

Introduction

A major steel mill in South Korea had been disposing of wastewater contaminated with phenol and cyanide by discharging it to holding ponds. South Korean government regulations now prohibit this disposal method. Tests were conducted at Magnum's El Segundo, California, facility to demonstrate the CAV-OX® process's ability to remove these contaminants. In addition, a pilot-scale CAV-OX® unit was purchased and installed at the steel mill to demonstrate the technology on site.

Equipment

Three configurations of CAV-OX® equipment were tested:

- A CAV-OX® I low-energy laboratory-scale unit
- A CAV-OX® I low-energy pilot-scale unit
- A CAV-OX® II high-energy unit

The laboratory-scale unit consisted of a 55-gallon, stainless steel holding tank, a 1.5-horsepower centrifugal pump, and plumbing and bypass lines into three UV reactors. Each reactor was 3 feet long with three 45-watt lamps, for a total UV output of 405 watts. The reactors were plumbed in series. Effluent from the reactors flowed through the discharge lines.

The Model 3162 pilot-scale unit, with a rated capacity of 3 gpm, consisted of the same holding tank, a 2-horsepower centrifugal pump, and one 6-foot, low-pressure UV reactor with six 60-watt lamps, for a total UV output of 360 watts. The unit also included a control panel with the necessary electrical and electronic circuits and electronic ballasts. Effluent from the reactors was either directed to the discharge lines or to the CAV-OX® II high-energy unit.

The CAV-OX® II high-energy unit was operated either in series with the output from the CAV-OX® I units or independently. In the latter case, it consisted of a cavitation chamber, centrifugal pump, and control panel. It also had an independent power supply for operating the high-energy lamps. Its UV reactor held one UV lamp rated at 2.5 or 5 kW.

Methodology

Wastewater from the steel mill was stored in the holding tank prior to entering the CAV-OX® unit. Potassium cyanide powder was added to the holding tank to introduce the desired concentration of cyanide. Three concentrations of potassium cyanide were used: 0.65 mg/L, 1 mg/L, and 50 mg/L. Phenol was also added to the holding tank, resulting in an influent concentration of 11 mg/L. One test treated 20 mg/L phenol, while other tests treated 200 mg/L phenol.

Finally, hydrogen peroxide was added to the holding tank. The tank contents were then thoroughly mixed with a motor-powered propeller.

Samples were collected at three points: the influent, the first effluent sample from each unit, and the last effluent sample from each unit. A Chemetrics K-8012 test kit was used to measure phenol, and a Chemetrics K-3810 test kit was used to measure cyanide. Tests for cyanide were run first, followed by tests for phenol and then by tests for cyanide and phenol combined. In addition, pH was measured using an EXTECH pH meter, and flow rate was measured with a GPI electronic digital flow meter. The first cyanide tests were conducted with the CAV-OX® I low-energy unit.

Results

Cyanide, phenol, and combined cyanide/phenol tests were run to determine the effectiveness of the CAV-OX® process in destroying each contaminant.

Cyanide Tests

The CAV-OX® II high-energy process consistently oxidized potassium cyanide to nondetectable levels with retention times of less than 4 minutes and hydrogen peroxide levels as low as 20 mg/L. Using only cavitation and UV radiation, without hydrogen peroxide, potassium cyanide levels were reduced by 46 percent. The effluent met discharge standards.

The CAV-OX® I low-energy pilot-scale unit oxidized 1 mg/L potassium cyanide to nondetectable levels under the following conditions: 40 mg/L hydrogen peroxide, 0.75 gpm flow rate, and 13 minutes retention time. Using 50 mg/L hydrogen peroxide, a flow rate of 1 gpm, and a retention time of 10 minutes, 1 mg/L of cyanide was reduced by 70 percent.

Table C-3 lists additional representative results for the CAV-OX® II high-energy and CAV-OX® I low-energy units.

The CAV-OX® I low-energy laboratory-scale unit showed similar results. The total UV output of the laboratory unit was 360 watts instead of 405 watts.

Previous tests for another foreign customer, using the CAV-OX® I low-energy pilot-scale unit but with sodium cyanide as the contaminant, had similar results.

Phenol Tests

Table C-4 lists representative results of the phenol tests.

Combined Cyanide and Phenol Tests

Table C-5 lists representative results of the combined cyanide and phenol tests.

Operating costs for the CAV-OX® I low-energy pilot-scale unit are estimated at $1.93 per 1,000 gallons.

CASE STUDY C-7: Perdue Farms, Bridgewater, Virginia

Introduction

Chickens contaminated with the bacterium *Salmonella* are a serious problem at U.S. chicken farms. Magnum conducted tests in cooperation with Silliker Laboratories, a national microbiology company, to demonstrate the CAV-OX® process's ability to eliminate pathogens associated with chicken farming. The test results were presented to several of the nation's largest chicken farms.

Table C-3. *Cyanide Removals*

Test	Flow (gpm)	UV (Watts)	Hydrogen Peroxide (mg/L)	Cyanide in Influent (mg/L)	Cyanide in Effluent (mg/L)	Percent Reduction
CAV-OX®II High-Energy Process						
1	2.5	2,860	0	0.65	0.35	46
2	0.75	2,860	20	0.65	ND	>99.9
3	1	5,360	60	50	0.5	99
4	2.5	5,360	60	50	0.5	99
5	2	5,360	60	2	ND	>99.9
CAV-OX®I Low-Energy Pilot-Scale Unit						
1	2.5	360	0	0.65	0.5	23
2	1	360	60	50	15	70
3	2.5	360	60	11	4.95	55
4	0.75	360	40	1	ND	>99.9
5	0.75	0	40	1	0.45	55
6	1	360	60	11	0.6	95

Notes: ND = Not detected

Table C-4. *Phenol Removals*

Phenol (mg/L)	Hydrogen Peroxide (mg/L)	UV Output	Percent Reduction
11	0	0.36 kW	18.2
11	0	5 kW	32
11	60	5 kW (no cavitation)	77
11	60	5 kW	95.5
11	60	cavitation only	9
12	60	0.36 kW	87

Table C-5. *Combined Cyanide /Phenol Removals*

Cyanide (mg/L)	Phenol (mg/L)	Hydrogen Peroxide (mg/L)	UV Output	Percent Reduction
10	12	0	0.36 kW	50
10	10	60	0.36 kW + 5 kW	ND
13.5	12	60	0.36 kW	70
20	20	0	2.5 kW	97

Notes: ND = Not detected

Equipment

The tests were conducted using a CAV-OX® I low-energy pilot-scale unit in parallel with a CAV-OX® II high-energy pilot-scale unit. The CAV-OX® I low-energy unit consisted of a 2-horsepower centrifugal pump, a cavitation chamber, a recycle loop, a low-energy UV reactor with six 60-watt lamps, and a control panel with the necessary electronics, UV ballasts, switches, indicator lamps, and circuit breakers. The CAV-OX® II high-energy unit used the same pump, cavitation chamber, recycle loop, and control equipment. It also included an independent power supply and a 5-foot UV reactor with a 2.5- or 5-kW lamp.

Methodology

Several strains of *Salmonella* were grown at 35 °C for 24 hours on Standard Methods agar and harvested using a sterile Butterfield's buffer. Each strain was then held at 4 °C for 1 hour and inoculated into a purged and rinsed 55-gallon drum filled with city water. The initial concentration was adjusted to obtain a final concentration in the drum of about 1 million cfu/mL. The influent was also injected with 220 mL of 10 percent sodium thiosulfate. An electric mixer thoroughly homogenized the mixture in the drum. A flow rate of 1 gpm was used.

Next, the inoculated water was injected with 80 mg/L hydrogen peroxide and processed through the CAV-OX® units. Seven samples were collected as shown in Table C-6.

All *Salmonella* enumeration was performed using Hektoen Enteric agar. A 0.45-micron Millipore filter was used for all filtration analysis. Serial 10-fold dilutions were carried out to six orders of magnitude (10^6) using sterile Butterfield's buffer dilution blanks.

Results

Salmonella concentration was cumulatively reduced a total of eight orders of magnitude by the CAV-OX® process. Table C-6 lists the results of this study.

Table C-6. Salmonella Study Results

Sample No.	Location	Concentration (CFU/mL)
1	Untreated water from the 55-gallon drum	2,000,000
2	Water exiting the cavitation chamber at 1 gpm	1,600,000
3	Water exiting the high-energy, 5-kW reactor	0.8
4	Hydrogen peroxide-treated water from the 55-gallon drum	3,000,000
5	Hydrogen peroxide-treated water exiting the cavitation chamber	1,900,000
6	Hydrogen peroxide-treated water exiting the CAV-OX® I UV reactor	500
7	Hydrogen peroxide-treated water exiting the CAV-OX® II UV reactor	0.01

CASE STUDY C-8: Southern California Edison, Los Angeles, California

Introduction

Southern California Edison, a major U.S. utility company, contracted with Magnum to conduct a treatability study using the CAV-OX® process to treat 3 million gallons of seawater contaminated with fluorescent dyes, lubricating oil, and detergent emulsions. The water consisted of reverse osmosis reject water and hydrotest discharge water that was methylene blue-reactive, indicating the presence of detergent compounds. The water also contained oxidized iron, which caused scaling at the liquid surface.

Southern California Edison preferred not to use UV radiation or hydrogen peroxide injection, since these were considered treatment systems under existing regulations. Transferring the water with a pump through a cavitation chamber was not considered a treatment process.

Equipment

The seawater was fed into a high-volume cavitation chamber using a 2-horsepower centrifugal pump.

Methodology

The centrifugal pump transferred the process seawater into the cavitation chamber at 65 psi. The cavitation chamber vacuum was maintained at 27 inches of mercury, and effluent line pressure at 6 psi. The flow rate varied between 2 and 4 gpm. A 15-to-1 ratio was recycled to the cavitation chamber for further treatment. Discharge from the cavitation chamber flowed to a holding tank. Samples were collected from the holding tank and sent to a laboratory for analysis.

Results

Treatment in the cavitation chamber reduced BOD in effluent samples by 83.3 to 88.4 percent. The average cost to treat 1,000 gallons of seawater was $0.13.

CASE STUDY C-9: Corporacion Mexicana de Investigacion en Materials, S.A. de C.V. (CMIMSA)

Introduction

In the spring of 1993, CMIMSA contacted Magnum about process effluents from a pharmaceutical plant and a petroleum plant. Magnum conducted a pilot-scale study of the pharmaceutical plant effluent.

Equipment

Six different process lines generated the pharmaceutical plant effluent. To accomplish the desired contaminant reduction, Magnum modified and increased the efficiency of the CAV-OX® II process. Two changes were made to the equipment design used for the SITE demonstration:

1. UV window ports allowed UV output to be monitored with an optical monitor 31 inches from the top of the reactor

2. Engineering modifications substantially improved the UV lamp efficiency

Methodology

Phenol was selected as a test contaminant. Phenol is an excellent test chemical for advanced oxidation systems since it is stable, difficult to break down, and accurate phenol test kits are readily available.

Results

Table C-7 shows the results of the pilot-scale study. Data from previous pilot studies (Case Study C-6) are also shown for comparison. For both studies, influent contained 20 µg/L phenol, and the process was operated with the addition of 60 mg/L hydrogen peroxide.

Based on these and other results, the CAV-OX® IIA modifications increase the reduction efficiency two to four times. The CAV-OX® IIA modifications allow the measurement and comparison of UV flux over different operating protocols.

Table C-7. Phenol Removal Comparison

Test No.	Flow (gpm)	Percent Reduction	Method
	CAV-OX® II (Case Study C-6)		
1	1	95	Protocol A
2	2	55	Protocol B
3	4	45	Protocol C
4	6	39	Protocol D
	CAV-OX® II A (Modified CAV-OX® Process, Case Study C-9)		
1	2	100	Protocol B
2	4	99	Protocol C
3	6	96	Protocol D