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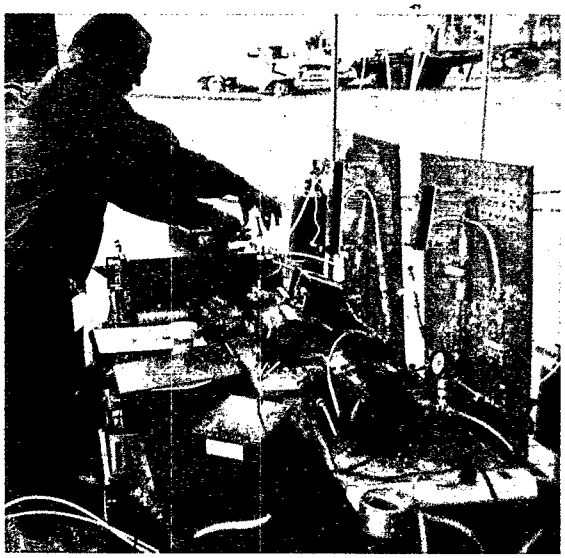
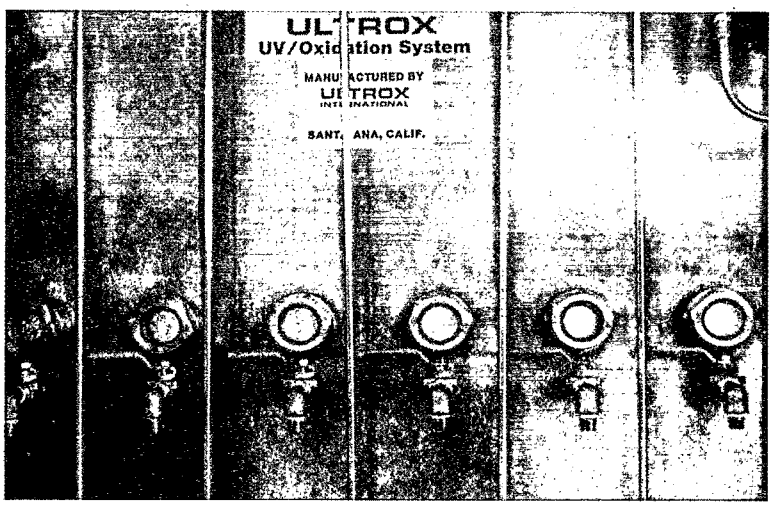
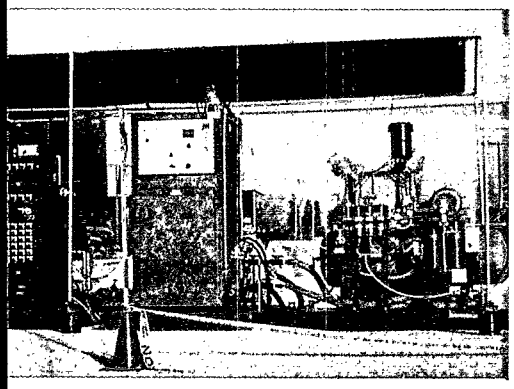
Ultrox International Ultraviolet Radiation/Oxidation Technology

Applications Analysis Report







SITE
SUPERFUND INNOVATIVE
TECHNOLOGY EVALUATION

EPA/540/A5-89/012
September 1990

Ultrox International Ultraviolet Radiation/Oxidation Technology

Applications Analysis Report

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

Notice

The information in this document has been funded by the U.S. Environmental Protection Agency under the auspices of the Superfund Innovative Technology Evaluation (SITE) program (Contract No. 68-03-3484). It has been subjected to the Agency's peer and administrative review and it has been approved for publication. Mention of trade names or commercial products does not constitute an endorsement or recommendation for use.

Foreword

The Superfund Innovative Technology Evaluation (SITE) Program was authorized in the 1986 Superfund Amendments and Reauthorization Act (SARA). The program is a joint effort between EPA's Office of Research and Development (ORD) and Office of Solid Waste and Emergency Response (OSWER). The purpose of the program is to assist the development of hazardous waste treatment technologies necessary to implement new cleanup standards which require greater reliance on permanent remedies. This is accomplished through technology demonstrations which are designed to provide engineering and cost data on selected technologies.

This project is a field demonstration under the SITE Program and is designed to analyze Ultrox International's ultraviolet radiation/oxidation technology. The technology demonstration took place at a former drum recycling facility in San Jose, California. The demonstration effort was directed to obtain information on the performance and cost of the technology and to assess its use at this and other uncontrolled hazardous waste sites. Documentation consists of two reports: (1) a Technology Evaluation Report that describes the field activities and laboratory results; and (2) this Applications Analysis Report that provides an interpretation of 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 Martin Luther King Drive, Cincinnati, Ohio 45268. Requests should include the EPA document number found on the report's cover. When the limited 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. You can also call the SITE Clearinghouse hotline at (800) 424-9346 or (202) 382-3000 in Washington, D.C., to inquire about the availability of other reports.

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

Abstract

In support of the U.S. Environmental Protection Agency's (EPA) Superfund Innovative Technology Evaluation (SITE) Program, this report evaluates the Ultrox International technology and its applicability as an on-site treatment method for contaminated groundwater. The ULTROX® technology (a registered trademark of Ultrox International) simultaneously uses ultraviolet (UV) radiation, ozone, and hydrogen peroxide to oxidize dissolved organic contaminants (subject of a U.S. patent), including chlorinated hydrocarbons and aromatic compounds, found in groundwater or wastewater. This report evaluates both treatment efficiency and economic data from the SITE demonstration and seven case studies.

Under the SITE Program, the ULTROX® technology demonstration was conducted at the Lorentz Barrel and Drum (LB&D) site, San Jose, California, in February and March of 1989. During this demonstration, the Ultrox system achieved volatile organic compound (VOC) removals greater than 90 percent. The majority of VOCs were removed through chemical oxidation. However, stripping also contributed toward removal of a few VOCs, such as 1,1,1- trichloroethane (1,1,1-TCA) and 1,1-dichloroethane (1,1-DCA). The treated groundwater met the applicable National Pollutant Discharge Elimination System (NPDES) standards for discharge into a local waterway. In addition, there were no harmful air emissions to the atmosphere from the Ultrox system, which is equipped with an off-gas treatment unit.

The results from seven case studies are also summarized in this report. Six of the seven case studies involved facilities that were primarily contaminated with VOCs and polychlorinated biphenyls, in the ppm and ppb concentration ranges. The other case study involved a wood treatment facility contaminated with phenol at 150 to 200 mg/L and pentachlorophenol at 1 mg/L. In all the case studies, effluent from the Ultrox system met the applicable discharge standards. Pretreatment was required for influent that contained high levels of manganese, oil and grease, and suspended solids.

Potential sites for applying this technology to contaminated groundwater include facilities with sources of petroleum, wood treatment facilities, and facilities with sources of chlorinated or nonchlorinated solvents. Economic data indicate that the capital costs for the reactor and ozone generator would range between $70,000 to approximately $260,000. Operation and maintenance costs can be as low as $0.25 per 1,000 gallons treated, considering only oxidant and electrical costs, or exceed $17 per 1,000 gallons treated, if extensive pretreatment is required.

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Acknowledgments

This report was prepared under the direction and coordination of Norma Lewis, U.S. Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) Project Manager in the Risk Reduction Engineering Laboratory, Cincinnati, Ohio. Mr. David Fletcher, Ultrox International, contributed greatly to this report. Many other individuals provided information useful in summarizing the case studies.

Dr. Gary Welshans, Dr. Kirankumar Topudurti, Barbara Sootkoos, and Sharon Weinberg of PRC Environmental Management, Inc., prepared this report for EPA's SITE Program under Contract No. 68-03-3484.

Section 1
Executive Summary

Introduction

The Ultrox International ultraviolet (UV) radiation/oxidation technology (ULTROX®, a registered trademark of Ultrox International) was evaluated under the U. S. Environmental Protection Agency's (EPA) Superfund Innovative Technology Evaluation (SITE) Program. The Ultrox technology demonstration was conducted at the Lorentz Barrel and Drum (LB&D) site in San Jose, California, during February and March of 1989. The Ultrox treatment process (U.S. Patent No. 4,792,407) uses a combination of UV radiation, ozone, and hydrogen peroxide to oxidize organic compounds in water. The developer claims that the final reaction products are salts, water, carbon dioxide, and possibly some organic acids.

The technology demonstration had the following four objectives:

1. Evaluate the technology's ability to treat organic contaminants in the groundwater at the site
2. Evaluate the effects of major process parameters on the technology's performance
3. Evaluate the efficiency of the ozone decomposer (Decompozon) unit in treating ozone in the off-gas from the Ultrox reactor
4. Develop information useful for evaluating whether this technology is suitable for other hazardous waste sites with similar conditions

The purpose of this report is to provide information, based on the results from the SITE demonstration and other case studies, necessary for implementing the Ultrox technology at Superfund and Resource Conservation and Recovery Act (RCRA) hazardous waste sites. Section 2 presents an overview of the SITE Program and a description of the Ultrox technology. Information relevant to the technology's application, including pre- and post-treatment requirements, operation and maintenance requirements, potential community exposures, and environmental regulations are presented in Section 3. Section 4 summarizes the costs associated with implementing the technology. A list of contacts familiar with the demonstration, the vendor's claims regarding the technology's performance, a summary of the SITE demonstration results, and seven case studies are included in Appendices A through D, respectively.

Overview of the Site Demonstration

The shallow groundwater at the LB&D site was selected as the waste stream to be used for evaluating the Ultrox treatment process. This groundwater was primarily contaminated with volatile organic compounds (VOC) such as trichloroethylene (TCE) and vinyl chloride, at levels of 100 and 40 µg/L, respectively. Other VOCs present at relatively low concentrations (in the range of 5 to 15 µg/L) included 1,1-dichloroethane (1,1-DCA), 1,1,1- trichloroethane (1,1,1-TCA), 1,2-dichloroethane (1,2-DCA), benzene, chloroform, and tetrachloroethylene. Semivolatiles and polychlorinated biphenyls (PCB)/pesticides were not detected.

The total organic carbon (TOC) concentration of the groundwater was approximately 25 mg/L. However, the concentration of priority pollutants (VOCs and semivolatiles) was only 2 percent of the TOC concentration.

The pH and alkalinity of the groundwater were about 7.2 and 950 mg/L as $CaCO_3$, respectively. These measurements indicated that the bicarbonate ion (HCO_3^-), which acts as an oxidant scavenger, was present at high levels. Other oxidant scavengers such as bromide, cyanide, and sulfide were not detected.

The experimental demonstration program evaluated the performance of the Ultrox technology in removing VOCs from the groundwater under various operating conditions. During the demonstration program, hydraulic retention times, oxidant doses and ratios, UV radiation intensities, and influent pH levels were varied for each test. The Ultrox system was shut down at the end of each test and was not started up until the next test.

Results from the Site Demonstration

The groundwater treated by the Ultrox system met the applicable National Pollutant Discharge

Elimination System (NPDES) standards for discharge into a local waterway under certain operating conditions. The Ultrox system achieved removal efficiencies as high as 90 percent for the total VOCs present in the groundwater. The removal efficiencies for TCE were greater than 99 percent. The maximum removal efficiencies for 1,1-DCA and 1,1,1-TCA under optimal operating conditions were about 65 and 85 percent, respectively.

One set of operating conditions included a hydraulic retention time of 40 minutes, ozone dose of 110 mg/L, hydrogen peroxide dose of 13 mg/L, all 24 UV lamps (at 65 watts each) operating, and influent pH of 7.2 (unadjusted). These "preferred" parameters were selected for verification of subsequent runs during the demonstration based on achieving acceptable effluent at the lowest operating cost.

Within the treatment system, the removals of 1,1-DCA and 1,1,1-TCA appear to be due to both chemical oxidation and stripping. Specifically, stripping accounted for 12 to 75 percent of the total removals for 1,1,1-TCA, and for 5 to 44 percent of the total removals for 1,1-DCA. However, stripping accounted for less than 10 percent of the total removals for TCE and vinyl chloride. For other VOCs such as 1,1-dichloroethylene, 1,2-dichloroethylene, benzene, acetone, and 1,1,2,2-tetrachloroethane, stripping was negligible. Volatile organics present in the gas phase within the reactor at levels of approximately 0.1 to 0.5 ppm were removed to below detection levels in the Decompozon unit.

The Decompozon unit destroyed ozone in the Ultrox reactor off-gas to levels less than 0.1 ppm (Occupational Safety and Health Act (OSHA) standards). The ozone destruction efficiencies were observed to be greater than 99.99 percent.

Based on the gas chromatography (GC) and GC and mass spectrometry (MS) analyses performed for VOCs, semivolatile organics, and PCBs/pesticides, no new compounds were detected in the effluent. In addition, very low TOC removal occurred. Since VOCs made up less than 2 percent of the TOC, complete conversion of VOCs to carbon dioxide and water could not be verified.

The Ultrox system's average electrical energy consumption was about 11 kilowatt-hours/hour of operation.

Results from the Case Studies

Information on the Ultrox technology's performance at seven facilities was evaluated to provide additional performance data. These facilities were:

1. The Department of Energy, Kansas City, Missouri
2. Hewlett Packard, Palo Alto, California
3. FEI Microwave, Sunnyvale, California
4. Golf Course, City of South Gate, California
5. Xerox, Webster, New York
6. General Electric Company, Lanesboro, Massachusetts
7. Koppers Industries, Denver, Colorado

Groundwater treated by the Ultrox system at Facilities 1 through 6 was generally contaminated with several VOCs, including vinyl chloride, TCE, benzene, toluene, xylene, tetrachloroethylene, methylene chloride, 1,1-DCA, and 1,1,1-TCA, and PCBs. The contaminant concentrations in the influent were in both the ppb and ppm ranges. The effluent from the Ultrox system was able to meet the discharge standards in all cases, with treatment efficiencies ranging from 90 to 99.99 percent in most of the cases. The removal efficiencies for 1,1-DCA and 1,1,1-TCA were less than 40 percent.

At Facility 7, wood treatment wastewater contaminated with phenols, pentachlorophenols (PCP), and oil and grease was treated by the Ultrox system. Phenol was present at 150 to 200 mg/L, PCPs at 1 mg/L, and oil and grease at 3 percent in the influent. The effluent from the Ultrox unit met the applicable discharge standards.

Pretreatment was required for cases where the influent contained high levels of iron, manganese, oil and grease, or suspended solids. Pretreatment included precipitation of iron and manganese followed by filtration, breaking of the oil-water emulsion, and removal of suspended solids by filtration.

Operational problems were encountered at Facility 1, which resulted in frequent shutdowns of the Ultrox system. Some operational problems included frequent cleaning of UV lamps and ozone spargers, and the ultimate replacement of ozone spargers. These problems were due to the precipitation of iron and manganese within the reactor. The facility also reported the following additional operational problems: (1) air compressor systems do not yield air that is adequately dry; (2) ozone generator has a highly variable ozone output; and (3) the unit suffers from poor transfer of ozone from the gas to liquid phase.

Waste Applicability

This technology can be applied to groundwater and industrial wastewater contaminated with VOCs, semivolatiles, and PCBs/pesticides. Potential sites for applying this technology to contaminated groundwater include facilities with sources of petroleum, wood treatment facilities, semiconductor

manufacturing facilities, and other facilities with sources of chlorinated or nonchlorinated solvents.

Economics

An economic analysis was performed which examined 12 separate cost categories for three treatment flow rates (20, 100, and 250 gpm). This analysis assumed that the system would operate in a continuous mode (24 hours a day, 7 days a week) for one year. The economic analysis was carried out for one year to provide a reliable estimate of annual operation and maintenance (O&M) costs. Annual O&M costs were estimated to be $63,100, $135,100, and $240,400 for the 20-, 100-, and 250-gpm units, respectively. Capital costs for these reactors ranged from $70,000 for the smallest unit to $260,000 for the largest. O&M costs are presented in the appendices for several operating or demonstration systems. The costs from the case studies presented in Appendix D ranged from approximately $0.25 per 1,000 gallons of treated wastewater, considering only oxidant and energy costs, to more than $17 per 1,000 gallons of treated water, if the influent required extensive pretreatment.

Section 2
Introduction

This section provides background information about the SITE Program, discusses the purpose of this Applications Analysis Report, and describes the Ultrox technology. A list of key contacts is provided in Appendix A for additional information.

Purpose, History, and Goals of the Site Program

In response to the Superfund Amendments and Reauthorization Act of 1986 (SARA), EPA's Office of Research and Development (ORD) and Office of Solid Waste and Emergency Response (OSWER) established a formal program to accelerate the development, demonstration, and use of new or innovative technologies to clean up Superfund sites across the country. A second program fosters the further investigation and development of treatment technologies that are still at the laboratory scale. ORD has also established a program to demonstrate and evaluate new, innovative measurement and monitoring technologies. These three program areas are components of 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. Major goals of the SITE Program are to:

- Identify and remove impediments to the development and commercial use of alternative technologies
- Demonstrate the more promising innovative technologies in order to establish reliable performance and cost information for site characterization and cleanup decision making
- Develop procedures and policies that encourage selection of available alternative treatment remedies at Superfund sites
- Structure a development program that nurtures emerging technologies

EPA recognizes that a number of forces inhibit the expanded use of alternative technologies at Superfund sites. One of the objectives of the program is to identify these impediments and remove them or design methods to promote the expanded use of alternative technologies.

Another objective of the SITE Program is to demonstrate and evaluate selected technologies. This is a significant ongoing effort involving ORD, OSWER, EPA Regions, and the private sector. The demonstration program serves to test field-ready technologies and provide Superfund decision makers with the information necessary to evaluate the use of these technologies for future cleanup actions.

Another aspect of the SITE Program includes developing procedures and policies that match available technologies with wastes, media, and sites for actual remediation.

The SITE Program also provides assistance in nurturing the development of emerging innovative technologies from the laboratory- or bench-scale to the full-scale stage.

Technologies chosen for a SITE demonstration must be pilot- or full- scale applications, innovative, and offer some advantage over existing technologies. Mobile technologies are of particular interest. Each selected round of demonstrations includes at least 10 technologies.

Documentation of the Site Demonstration Results

The results of each SITE demonstration are incorporated in two documents: the Technology Evaluation Report and the Applications Analysis Report. The Technology Evaluation Report provides a comprehensive description of the demonstration and its results. A likely audience for the Technology Evaluation Report is engineers responsible for performing a detailed evaluation of the technology for a specific site and waste situation. These technical evaluators seek to understand, in detail, the performance of the technology during the demonstration and the advantages, risks, and costs of the technology for the given application. This information is used to produce conceptual designs in

sufficient detail to enable preliminary cost estimates for the demonstrated technology.

The Applications Analysis Report is intended for decision makers responsible for implementing specific remedial actions. The basic use of the Applications Analysis Report is to assist in determining whether the specific technology should be considered further as an option for a particular cleanup situation. The report discusses the advantages, disadvantages, and limitations of the technology. Costs of the technology for different applications are estimated based on available data for pilot- and full-scale applications. The report discusses the factors, such as site and waste characteristics, that have a major impact on cost and performance. If the candidate technology appears to meet the needs of the site engineers, a more thorough analysis will be conducted, based on the Technology Evaluation Report and the Applications Analysis Report and information from remedial investigations for the specific site.

Purpose of the Applications Analysis Report

To encourage the general use of demonstrated technologies, EPA will provide information on the applicability of each technology to certain sites and wastes, other than those already tested, and will study the costs of these applications. Available information and data are presented through the Applications Analysis Reports. These reports attempt to synthesize available information on the technology and draw reasonable conclusions as to its broad range applicability. The Applications Analysis Report is very useful to those considering the technology for Superfund cleanups and represents a critical step in the development and commercialization of the treatment technology.

Each SITE demonstration will evaluate the performance of a technology in treating a particular waste found at the demonstration site. To obtain data with broad applications, attempts will be made to select waste frequently found at other Superfund sites. In many cases, however, the waste at other sites will differ in some way from the waste tested. Thus, the successful demonstration of a technology at one site does not ensure that it will work equally well at other sites. Data obtained from the demonstration may have to be extrapolated to estimate the total operating range over which the technology performs satisfactorily. This extrapolation should be based upon both demonstration data and other information available 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 at pilot- or full-scale treatment systems. In addition, there are limits to conclusions regarding Superfund applications that can be drawn from a single field demonstration. A successful field demonstration does not necessarily ensure that a technology will be widely applicable or fully developed to a commercial scale.

Technology Description

The Ultrox UV radiation/oxidation technology is suitable for destroying dissolved organic contaminants, including chlorinated hydrocarbons and aromatic compounds, in water with low suspended solids levels. This technology uses UV radiation, ozone, and hydrogen peroxide to oxidize organics. The Ultrox treatment system can be skid-mounted for easy transport on either a flatbed truck or in an enclosed trailer. The treatment system can be used either as a stand-alone unit or in combination with other treatment units.

Principal Treatment Operations

The major components of the Ultrox system are the UV radiation/oxidation reactor module, the air compressor/ozone generator module, the hydrogen peroxide feed system, and the ozone decomposer (Decompozon) unit. An isometric view of the Ultrox system is shown in Figure 2-1.

The UV radiation/oxidation reactor used in the demonstration (Model PM-150) has a volume of 150 gallons and is 3 feet long by 1.5 feet wide by 5.5 feet high. The reactor is divided by five vertical baffles into six chambers to create a serpentine flow through the unit. The reactor contains 24 UV lamps (65 watts each) in quartz sheaths. The UV lamps are installed vertically and are evenly distributed throughout the reactor (four lamps per chamber). Each chamber also has one stainless steel sparger that extends along the width of the reactor. These spargers uniformly diffuse ozone gas from the base of the reactor into the water. Hydrogen peroxide is introduced in the influent to the reactor from a storage tank. An in-line static mixer is used to disperse the hydrogen peroxide into the contaminated water in the influent feed line. Acids can be added to the influent in a fashion similar to that of the hydrogen peroxide feed.

During the Ultrox system operation, contaminated water first comes in contact with hydrogen peroxide as it flows through the influent line to the reactor. The water then comes in contact with the UV radiation and ozone as it flows through the reactor at a specified rate chosen to achieve the desired hydraulic retention time. The hydroxyl radicals (OH°) are formed from ozone and catalyzed by UV radiation and hydrogen peroxide. The hydroxyl radicals, in general, are known to react with organics more rapidly than ozone, hydrogen peroxide, and UV

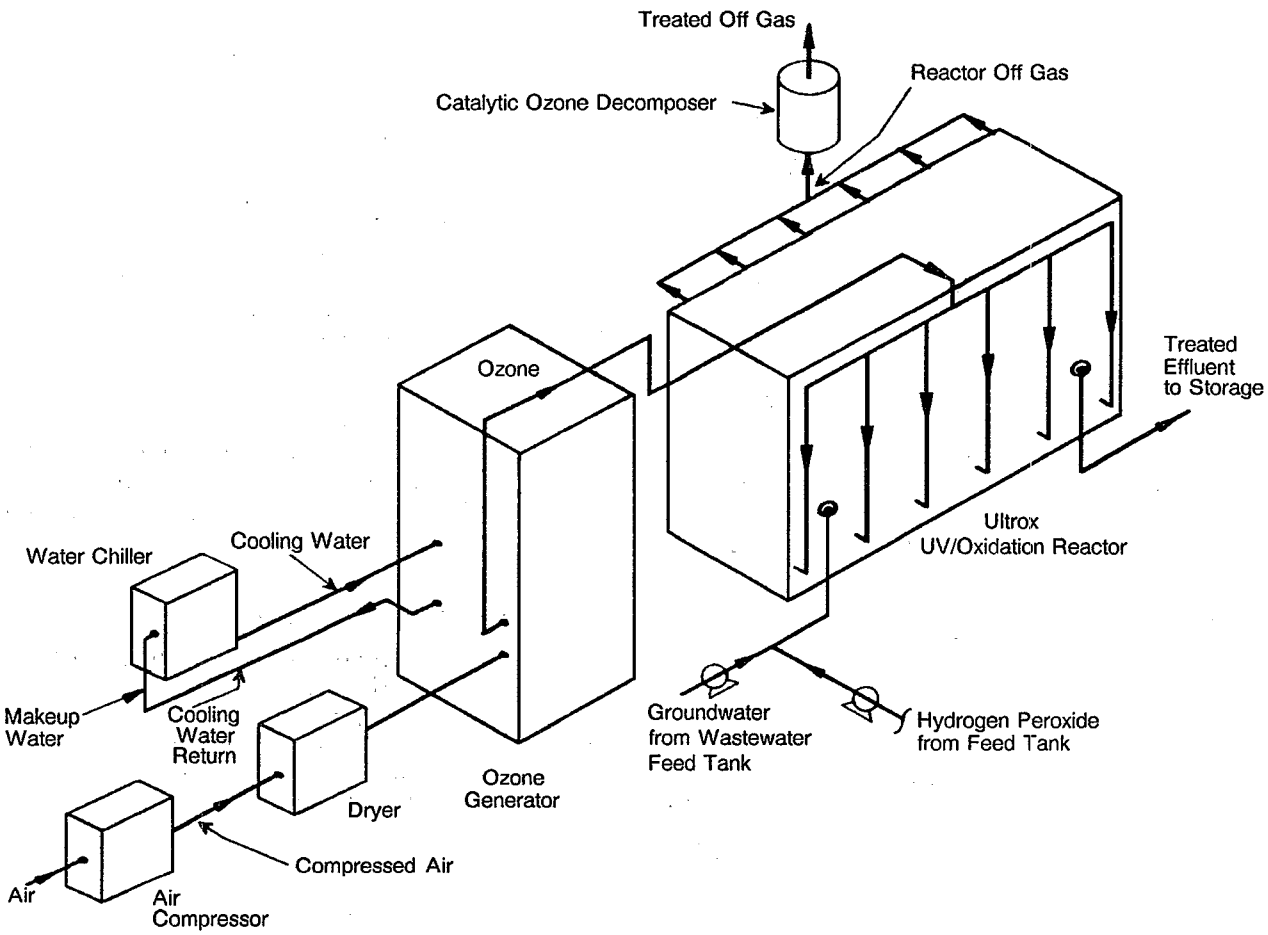


Figure 2-1. Isometric view of the Ultrox System.

radiation. The hydroxyl radicals are also much less selective in oxidation reactions than the three other oxidants.

Ozone that does not go into solution with the contaminated water will be present in the reactor off-gas. This ozone is subsequently destroyed by the Decompozon unit (which contains proprietary catalysts and is operated at about 140°F) before being vented to the atmosphere. The treated water flows from the reactor for appropriate discharge.

The flow rates at which the Ultrox system can be operated depend on the influent waste characteristics and the hydraulic retention time required to achieve the target effluent concentrations. At the demonstration site with all 24 lamps operating, a hydraulic retention time of 40 minutes, an ozone dose of 110 mg/L, and a hydrogen peroxide dose of 13 mg/L were determined to be adequate for the treatment of contaminated groundwater. Since a 150-gallon reactor was used during the demonstration, 3.75 gallons of groundwater were treated per minute (flow rate). However, if higher flow rates are desired, the volume of the reactor will have to be increased proportionally. For example, assuming that the groundwater characteristics and operating conditions are the same as those used in the demonstration, a flow rate of 130 gallons per minute could be achieved using a larger Ultrox reactor (5,200 gallons). The actual treatment capacity at another site will likely be different, however, depending on the waste characteristics and the operating conditions.

Innovative Features of the Technology

The use of oxidants such as ozone, hydrogen peroxide, and UV radiation to destroy organic contaminants present in groundwater is gaining considerable attention. However, the oxidation of organics by ozone, hydrogen peroxide, or UV radiation alone is known to have kinetic limitations and, therefore, has yet to become a competitive treatment option.

Several studies indicated that the kinetic limitations could be overcome by using two oxidants simultaneously (Glaze and others, 1980; Glaze, 1987; Weir and others, 1987; Aieta and others, 1988; and Glaze and Kang, 1988). However, these studies did not address the relative performance of various oxidant combinations or the simultaneous use of three oxidants.

The chemistry of the oxidation processes in which two or three oxidants are used simultaneously is not well understood. However, according to Ultrox International, the simultaneous use of these three oxidants has a definite advantage over the simultaneous use of two oxidants on waters containing compounds such as methylene chloride. In general, processes in which ozone is used in combination with hydrogen peroxide or UV radiation may be categorized as catalytic ozonation processes. These processes accelerate ozone decomposition, thereby increasing the hydroxyl radical (OH°) concentration and promoting the oxidation rate of organics.

Oxidation treatment of volatile organics has advantages over conventional wastewater treatment methods, such as air stripping, steam stripping, carbon adsorption, and biological treatment processes. Although effective, these processes have certain limitations. For example, stripping and adsorption merely transfer the contaminants from one medium (water) to another (air or carbon), whereas biological treatment processes generate sludge which requires further treatment and disposal. In addition, biological treatment processes have slow reaction rates. Table 2-1 compares several treatment options for VOC-contaminated waters. Similar comparisons can be made for semivolatiles, PCB, and pesticides, although air stripping is not generally applicable to these types of contaminants.

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

Technology	Advantages	Disadvantages
Air stripping	Effective at high concentrations; mechanically simple; relatively inexpensive	Inefficient at low concentrations; VOCs discharged to air
Steam stripping	Effective at all concentrations	VOCs discharged to air; high energy consumption
Air stripping with carbon adsorption of vapors	Effective at high concentrations	Inefficient at low concentrations; requires disposal or regeneration of spent carbon
Air stripping with carbon adsorption of vapors and spent carbon regeneration	Air Effective at high concentrations; no carbon disposal costs; can reclaim the product	Inefficient at low concentrations; high energy consumption
Carbon adsorption	Low air emissions; effective at high concentrations	Inefficient at low concentrations; requires spent carbon disposal or regeneration; relatively expensive
Biological treatment	Low air emissions relatively inexpensive	Inefficient at high concentrations; slow rates of removal; sludge treatment and disposal required
UV/ozone/hydrogen peroxide oxidation (Ultrox International)	No air emissions; effective at all concentrations; VOCs destroyed; readily available	High energy consumption; process mechanisms not well understood

Note: Based on Garland II, 1989.

Section 3
Technology Applications Analysis

Introduction

This section addresses the applicability of the Ultrox UV radiation/oxidation technology to treat hazardous wastes. Its applicability is based on the Ultrox SITE demonstration and other Ultrox applications test data. Since the results of the SITE demonstration provided an extensive data base, evaluation of the technology's effectiveness and its applicability to other potential cleanup operations is mainly based on these results, which are presented in detail in the Technology Evaluation Report (EPA, 1989). The developer's claims regarding the applicability and performance of the Ultrox technology are included in Appendix B.

Technology Evaluation

The objectives of the Ultrox technology demonstration performed under the SITE Program were to:

- Evaluate the ability of the Ultrox system to treat VOCs present in the groundwater at the LB&D site
- Evaluate the efficiency of the Decompozon unit in treating ozone in the reactor off-gas
- Develop capital and operating costs for the Ultrox system that can be used in Superfund decision-making processes at other sites
- Develop information useful to EPA Region IX for site remediation

With these objectives in mind, a total of 13 test runs were performed to evaluate the effectiveness of the technology. A summary of the SITE demonstration results, including site characteristics, waste characteristics, and a review of the Ultrox system's performance, is presented in Appendix C.

The effectiveness of the Ultrox technology is summarized below. The technology's effectiveness based on the SITE demonstration is presented first, followed by a discussion of the results from other case studies. A fuller discussion of performance, maintenance requirements, and costs at seven case studies is presented in Appendix D.

Effectiveness of the Ultrox Technology

The SITE demonstration was conducted at a former drum recycling facility in San Jose, California, over a 2-week period in February and March of 1989. Approximately 13,000 gallons of groundwater contaminated with several VOCs were treated by the Ultrox system during the 13 test runs. During the first 11 runs, 5 operating parameters were adjusted to evaluate the system: hydraulic retention time, ozone dose, hydrogen peroxide dose, UV radiation intensity, and influent pH level. The last 2 runs were conducted to verify the reproducibility of the system's performance at Run 9's operating conditions, which had been found to be successful at treating the contaminated groundwater.

To complete the demonstration within a 2-week period, the concentrations of indicator VOCs in the treated and untreated groundwater were analyzed overnight. Only 3 of the 44 VOCs identified in the groundwater at the site were selected as indicator VOCs for analysis to evaluate the performance of each run. These performance indicator VOCs were trichloroethylene (TCE); 1,1- dichloroethane (1,1-DCA); and 1,1,1-trichloroethane (1,1,1-TCA). TCE was selected because it is a major volatile contaminant at the site, and the latter two VOCs were selected because they are relatively difficult to oxidize.

The pH and alkalinity of the groundwater were 7.2 and 950 mg/L as $CaCO_3$, respectively. These measurements indicated that bicarbonate ion (HCO_3^-), which acts as an oxidant scavenger, was present at high levels. Other oxidant scavengers such as bromide, cyanide, and sulfide were not detected. Organic contaminants such as semivolatiles, PCBs, and pesticides were also not detected.

Key findings of the SITE demonstration are summarized as follows:

- Under certain operating conditions, the groundwater treated by the Ultrox system met

the applicable NPDES standards, at the 95 percent confidence level, for discharge into Coyote Creek, a nearby waterway. The Ultrox system achieved removal efficiencies as high as 90 percent for the total VOCs present in the groundwater. The removal efficiencies for TCE were greater than 99 percent. The maximum removal efficiencies for 1,1-DCA and 1,1,1-TCA under optimal operating conditions were about 65 and 85 percent, respectively.

- One set of operating conditions that met discharge standards was selected as the "preferred", or optimal, set of operating conditions. These "preferred" parameters were selected for verification of subsequent runs during the demonstration based on achieving acceptable effluent at the lowest operating costs. These conditions included a hydraulic retention time of 40 minutes, ozone dose of 110 mg/L, hydrogen peroxide dose of 13 mg/L, all 24 UV lamps (65 watts each) operating, and influent pH at 7.2 (unadjusted).

- Within the treatment system, the removals of 1,1-DCA and 1,1,1-TCA appear to be due to both chemical oxidation and stripping. Specifically, stripping accounted for 12 to 75 percent of the total removals for 1,1,1-TCA, and 5 to 44 percent of the total removals for 1,1-DCA. However, stripping accounted for less than 10 percent of the total removals for TCE and vinyl chloride. Stripping was negligible for other VOCs, such as 1,1-dichloroethylene, 1,2- dichloroethylene, benzene, acetone, and 1,1,2,2-tetrachloroethane. VOCs present in the gas phase within the reactor at levels approximately 0.1 to 0.5 ppm were removed to below detection levels in the Decompozon unit.

- The Decompozon unit destroyed ozone in the reactor off-gas to levels less than 0.1 ppm (OSHA standards). The ozone destruction efficiencies were observed to be greater than 99.99 percent. There were no VOCs detected in the exhaust from the Decompozon unit.

- Based on the gas chromatography (GC), and GC and mass spectrometry (MS) analyses performed for VOCs, semivolatile organics, and PCBs/pesticides, no new compounds were detected in the effluent. In addition, very low TOC removal occurred. Since VOCs made up less than 2 percent of the TOC, complete conversion of VOCs to carbon dioxide and water could not be verified.

- The Ultrox system's average electrical energy consumption was about 11 kilowatt-hours per hour of operation.

Several other studies on the performance of the Ultrox system have been carried out. The results of these case studies at seven facilities are summarized in Appendix D. A brief summary of the effectiveness of Ultrox technology at three of those facilities is presented below.

The Environmental Sciences Division of the Oak Ridge National Laboratory performed a study that focused on the removal of VOCs from groundwater at the Department of Energy Kansas City Plant (Garland II, 1989). A 725-gallon unit is being used to treat the contaminated groundwater at the site. In addition to VOCs, the groundwater also had bacteria, total suspended solids (TSS), iron, manganese, and oil and grease at levels that would reduce the effectiveness of the operation. Therefore, the groundwater was filtered prior to treatment. The data indicated that: the effluent from the Ultrox system met the applicable discharge standards for VOCs; nitrogen (as ammonia and nitrite) was oxidized to nitrate; about 98 percent of bacterial removal was achieved within the Ultrox system; but, very little oil and grease was removed by the system. Plugging of ozone spargers and coating of UV lamps was observed over a 3-month operation, due to the precipitation of iron and manganese within the Ultrox system. This required shutting down the Ultrox unit for a short time, which indicates that an effective pretreatment unit is also important for the proper functioning of the Ultrox system.

Ultrox International performed a study at the Hewlett Packard facility in Palo Alto, California. A 150-gallon unit was used at this facility. This study focused on the removal of toxic organic compounds such as benzene, toluene, ethylbenzene, and xylene present in groundwater at approximate levels of 4,400, 3,300, 175, and 3,100 µg/L, respectively. The study demonstrated that the Ultrox system could achieve removal levels of 98 to 99.9 percent and also that the treated effluent could meet discharge standards. No data were reported on operation and maintenance problems.

A 650-gallon unit was used by Ultrox International at FEI Microwave in Sunnyvale, California, to remove TCE present in the groundwater at levels as high as 6,000 µg/L. Removals as high as 99.99 percent were achieved at this facility.

In summary, Ultrox International's UV radiation/ oxidation technology has been demonstrated to be effective in removing chlorinated and nonchlorinated organics. Although the removal of certain compounds which are difficult to oxidize occurs significantly due to stripping, no harmful air emissions were observed. This is because VOCs present in the reactor off-gas were destroyed by the Decompozon unit before the reactor off-gas was emitted to the atmosphere.

Factors Influencing Performance

Several factors influence the performance of the Ultrox UV radiation/oxidation technology. These factors can be grouped into three categories: (1) waste characteristics, (2) operating parameters, and (3) maintenance requirements. Each of these is discussed below.

Waste Characteristics

If, under a given set of operating conditions, the influent contaminant levels are higher than the contaminant levels for which the operating conditions were established, the effluent levels will also increase, which might result in noncompliance. However, treatment efficiency can be increased by modifying the operating conditions to accommodate increased influent contaminant levels. These conditions are discussed in this section under Operating Parameters. If the influent contaminant levels are anticipated to fluctuate, an equalization tank should be provided prior to treatment in order to minimize fluctuations. Based on the studies performed, no maximum limit on the influent contaminant levels can be specified. Also, under a given set of operating conditions, the removal efficiencies will depend upon the characteristics of the contaminants. Key contaminant characteristics are as follows:

- Organics with double bonds, such as TCE, tetrachloroethylene (PCE), and vinyl chloride, and aromatic compounds, such as phenol, toluene, benzene, and xylene, are easily removed because they are readily oxidized.
- Organics without double bonds and with high Henry's law constants, such as 1,1-DCA and 1,1,1-TCA, are also removed. Removal of these compounds is primarily due to stripping because they are difficult to oxidize. (Henry's law constants for 1,1-DCA and 1,1,1-TCA are 0.0043 atm-m^3/mol, and 0.014 atm-m^3/mol, respectively.)
- Organics without double bonds and with low Henry's law constants, such as diethylamine and 1,4-dioxane, would be difficult to remove because they are not easily oxidized or stripped. (Henry's law constants for diethylamine and 1,4-dioxane are 0.00009 atm-m^3/mol and 0.00001 atm-m^3/mol, respectively.)

Since the Ultrox technology is an oxidation process and is intended for the destruction of organic contaminants, any other species that consume oxidants are considered an additional load for the system. These species are called scavengers and include anions such as bicarbonates, carbonates, sulfides, nitrites, bromides, and cyanides. Also, metals present in their reduced states, such as trivalent chromium, ferrous iron, manganous ion, and several others, are likely to be oxidized. These reduced metals, in addition to acting as scavengers, cause additional concerns. For example, trivalent chromium, when oxidized, will be converted to hexavalent chromium, which is more toxic. Ferrous iron and manganous ion are converted to less soluble forms, which precipitate in the reactor and can cause UV lamp scaling and suspended solids formation. Organics (TOC) which are likely to be oxidized could act as potential scavengers in this treatment technology. Other parameters such as TSS, oil, and grease reduce UV transmission and thereby decrease the treatment efficiency.

Operating Parameters

Operating parameters are those parameters which are varied during the treatment process to achieve desired treatment efficiencies. Such parameters include hydraulic retention time, ozone dose, hydrogen peroxide dose, UV lamp intensity, influent pH level, and gas-to-liquid flow rate ratio.

In general, increasing the hydraulic retention time will increase treatment efficiency up to a certain point. At this point, the system tends to proceed toward equilibrium and increasing the hydraulic retention time no longer plays an important role.

The higher the oxidants' doses (ozone and hydrogen peroxide), the better the treatment rate. However, systems which use ozone and hydrogen peroxide together are affected by the molar ratio of the oxidants' doses used. For example, the expected stoichiometry for hydroxyl radical (highly reactive oxidant) formation from ozone and hydrogen peroxide is two, as shown by the following equation:

$$H_2O_2 + 2O_3 \leftrightarrows 2OH^\circ + 3O_2$$

In the treatment of water containing TCE and PCE, researchers observed maximum removals at a molar ratio of 2 or a 2.86 weight ratio of ozone to hydrogen peroxide, which agrees with the expected stoichiometry (the removals were significantly less when the molar ratio was not 2). Although, in this case the expected stoichiometry for pure water agreed with the molar ratio at which optimum removal was observed, several factors may influence the molar ratio (Aieta and others, 1988). These factors are summarized below:

- Hydrogen peroxide can act as a free radical scavenger itself, thereby decreasing the hydroxyl radical concentration if it is present in excess.
- Ozone can react directly with hydroxyl radicals, consuming both ozone and hydroxyl radicals.

- Ozone and hydroxyl radicals may be consumed by other constituents, known as scavengers, in the water being treated (see Waste Characteristics).

The optimum proportion of the oxidants for maximum removals cannot be predetermined. Instead, the proportion needs to be determined for the waste under consideration using pilot-scale or treatability tests.

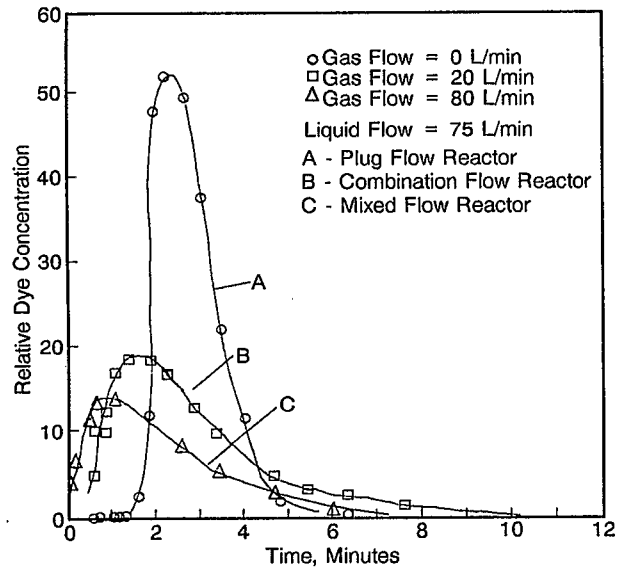
UV photolysis of ozone in water yields hydrogen peroxide, which in turn reacts with ozone to form hydroxyl radicals. In addition, UV radiation photolyzes compounds such as PCE, aromatic halides, and pesticides to increase their removal (Glaze and others, 1987).

The pH of water to be treated has a significant effect on the treatment efficiency. If water has significant bicarbonate and carbonate alkalinity (>400 mg/L as $CaCO_3$), lowering the pH to a range of 4 to 6 should, in general, improve the treatment efficiency. This is because carbonate and bicarbonate ions act as scavengers for the oxidants. The concentration of these scavengers is decreased by shifting the equilibrium toward carbonic acid at low pH values. If the carbonate and bicarbonate alkalinity is low, then a high pH, in general, should improve the treatment efficiency. This is because, at a high pH, hydroxyl radical formation is increased due to the reaction between ozone and the hydroxyl ion.

The ozone gas flow rate can also significantly influence the treatment efficiency. In practice, once the ozone dose is selected, it can be applied at several combinations of ozone gas phase concentration and ozone gas flow rate. According to Venosa and Opatken (1979), the ratio of gas flow rate to liquid flow rate will dictate the hydraulic characteristics of the reactor, as shown in Figure 3-1. This figure shows that, at low gas-to-liquid flow rate ratios, the mixing regime in a reactor is close to that of a plug flow reactor (shown as Curve A), whereas at high ratios, the reactor mixing regime is close to that of a mixed reactor (shown as Curve C). It is advantageous to operate the reactor with plug flow mixing characteristics rather than with mixed reactor mixing characteristics because a higher treatment efficiency is achieved for reactions with a positive reaction order (Levenspiel, 1972). Since most reactions have a positive reaction order, low gas-to-liquid flow rate ratios should be considered in actual operation of the unit. In addition to increasing the treatment efficiency, stripping of volatile organics can be reduced by choosing low gas-to-liquid flow rate ratios.

Maintenance Requirements

The maintenance requirements for the Ultrox system summarized here are based on a literature review



Source: Venosa and Opatken, 1979.

Figure 3-1. Dye tests showing effects of gas flow rates on the mixing characteristics of a bubble diffuser ozone contact basin.

(Cheremisinoff and others, 1981; WPCF, 1986; Tucker, 1986; Robson, 1987). Regular maintenance by trained personnel is essential for the successful operation of the Ultrox system. The following components require maintenance: (1) ozonation system, (2) UV lamp assembly, (3) ozone decomposer unit, and (4) miscellaneous components. A brief summary of the maintenance requirements for each of these components is presented below.

Ozonation System

The main components of the ozonation system are the air preparation system, the ozone generator, and the ozone contacting and associated equipment.

The air preparation system consists of process equipment that includes an air filter, an air compressor, an optional water chiller, and a desiccant drier. Replacement cycles for the air filter are site-specific, depending on air purity and flow. However, inspection intervals for the filter should not exceed 3 months. Air compressors should be checked as recommended by the manufacturer to minimize any feed air contamination by the compressor components.

A water chiller can be used to recirculate cooling water required for the ozone generator. Tap water (potable, suitable process water, or groundwater) can also be used as a cooling water source. If a water chiller is used, inspections of refrigerant dryers should be carried out at 3-month maximum intervals by personnel skilled in the operation and

maintenance of refrigeration equipment. Minimum checks should include compressor belt tension and refrigerant pressure measurement. The water lines require annual inspection for scaling or deterioration resulting from the passage of the cooling water through the heat exchanger.

Desiccant dryers should be inspected weekly to ensure proper operation of the unit. Maintenance of the dryers is important to keep the unit in operation and to prevent damage to the unit by fires, which can occur if a desiccant tower runs for a prolonged period in the regeneration mode. Ultrox uses heatless adsorption dryers in most air systems. These heatless adsorption dryers are reliable and do not cause fires. Annual maintenance should include disassembly of the unit and inspection of the desiccant. The media normally lasts approximately 10 years, but may have to be replaced sooner if the dryer has been overloaded or poorly maintained.

The ozone generator is typically an unfamiliar unit to maintenance personnel and may justify, at least initially, having a maintenance contract with the generator supplier for emergency assistance and annual service. Specific personnel should be assigned to generator maintenance to enable them to gain sufficient familiarity and skills to perform tasks such as fuse replacement and dielectric tube cleaning, which will result in lower energy costs for a given ozone output. Dielectric tube cleaning necessitates manpower and inevitable breakage or damage to the tubes during the cleaning process. Therefore, it is necessary to carefully evaluate the frequency of cleaning. It is recommended that the first cleaning period of the dielectric tubes not exceed 12 months after unit start-up. Depending on the condition of the tubes at that time, the next period of cleaning can be projected.

Inspection of the ozone contacting equipment should address the functional as well as the structural integrity of the components of the contactor. Pipings, valves, fittings, supports, brackets, and spargers should be checked at least once every 3 months for the deterioration which results from exposure to a highly oxidizing environment. Deteriorated material should be replaced. Good records, including photographs, of the conditions observed during the inspection should be maintained. The gas spargers should be checked for plugging due to solids accumulation once changes in the gas bubble diffusion pattern are noted. The spargers must be immediately cleaned to minimize cracking of joints and excessive power costs.

The instrumentation and controls of the ozonation system must be maintained regularly. Flow meters, temperature and pressure sensors, and ozone analyzers must be kept in working order to enable the operator to measure various parameters required for efficient operation.

UV Lamp Assembly

The maintenance of the UV lamp assembly requires periodic cleaning and eventual replacement of the lamps. The frequency at which the lamps should be cleaned depends on the type and concentration of suspended solids present in the influent or formed during treatment. The frequency may range from once every month to once every 3 months. Several cleaning procedures include the use of chemicals, mechanical wipers, or ultrasonics.

The life of low-pressure UV lamps normally cited by most manufacturers is 7,500 hours, based on a use cycle of 8 hours. A number of factors combine to effectively age the lamps, which limits their useful life and requires their replacement. These factors include failure of the electrodes, plating of the mercury to the interior lamp walls (blackening), and solarization of the lamp enclosure material (reducing its transmissibility). These all cause steady deterioration in the lamp's output at the effective wavelength (253.7 μm), such that its output at the end of the lamp's life can be only 40 to 60 percent of its normal output. This reduction in the output may require more frequent replacement of the UV lamps

Ozone Decomposer (Decompozon) Unit

The Decompozon unit, including enclosure catalyst and heating elements, should be inspected thoroughly to ensure efficient operation. Replacing the catalyst is a considerable expenditure that can be deferred by following the manufacturer's maintenance program.

Miscellaneous Components

Other components of the system, such as valves, flow meters, pipelines, hydrogen peroxide feed tank, and acid feed tank should be checked for leaks once a month. In addition, the influent, hydrogen peroxide, and acid feed pumps should be checked once a month for proper operation and maintenance.

Site Characteristics

Site characteristics, in addition to influent characteristics and effluent discharge requirements, are important issues when considering using the Ultrox technology. Site-specific factors have both positive and negative impacts on the implementation of the Ultrox technology and should be considered before selecting this technology. These factors include site preparation, site access, hydrogeology, climate, utilities, and services and supplies.

Site Preparation

Ultrox systems are available in several volumetric sizes ranging in capacity from 60 to 5,200 gallons. During the SITE demonstration, a 150-gallon unit was used. A 20- by 20-foot area was adequate for the Ultrox system and associated equipment. Larger units would require slightly larger areas. For example, for the 5,200-gallon unit, an area about 30 by 50 feet should be provided. Areas required for influent and effluent storage tanks, if needed, may vary depending on the flow rate, effluent requirements, and turn-around time for any effluent analysis required prior to its disposal.

The area containing the Ultrox unit and tanks should be relatively level. It can be paved or covered with compacted soil or gravel. A tent or some type of shelter is needed for the Ultrox system to protect it from inclement weather.

A 20- by 20-foot area is required for indoor office space and any on- site laboratory work.

Site Access

Site access requirements for the 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 Ultrox unit and tanks.

Hydrogeology

At sites that require remediation of contaminated groundwater, extraction wells will be needed to collect the contaminated groundwater. Since the Ultrox system would be operated as a flow-through system on a continuous basis during site remediation, installation of several extraction wells may be required to provide a continuous supply of groundwater. When installing a groundwater collection and storage system, preventative measures should be considered that would reduce volatile contaminant losses.

Climate

Below-freezing temperatures and heavy precipitation could have an impact on the operation of the Ultrox system. If below-freezing temperatures are expected for a long period of time, the Ultrox system and influent storage tanks should be insulated or kept in a well-heated shelter, such as a building or shed. The Ultrox unit, and particularly the ozone generator which requires a high-voltage power supply, should also be protected from heavy precipitation.

Utilities

The Ultrox system requires tap water and electricity. Tap water is required for equipment cleanup and personnel decontamination. In some cases, the Ultrox system uses tap water as a source of cooling water for its ozone generator.

A 480-volt, 3-phase electrical service is required for the efficient operation of the Ultrox system. An additional 110-volt power line will also be required for other on-site uses.

A telephone connection is required to contact emergency services and to provide normal communications.

Services and Supplies

A number of services and supplies are required for the Ultrox technology. Most of these services and supplies can be readily obtained.

Tanks will likely be required for influent and effluent storage. Extensive piping connections will be required to assemble the groundwater collection system.

In case any pumps or UV lamps malfunction, or any flow meters, gas spargers, or lines crack, an adequate on-site supply of spare parts or access to a nearby industrial supply center is an important consideration.

Chemicals such as hydrogen peroxide and sulfuric acid are used in this process. An adequate supply or proximity to a supply center carrying these chemicals is essential.

Since the Ultrox technology is designed to treat organics, including volatiles, semivolatiles, and PCBs/pesticides, entering into a contract with a local analytical laboratory would be prudent for an ongoing monitoring program.

Materials Handling Required by the Technology

Materials handling for the Ultrox Technology can be divided into the pretreatment processing of the influent before it enters the reactor unit and the residuals handling of the air and liquid waste streams as well as miscellaneous wastes generated during the operation.

Pretreatment Processing

In general, the pretreatment requirements for this technology are minimal. Depending on the waste characteristics, pretreatment processing involves one or more of the following: oil and grease removal,

suspended solids removal, or pH adjustment to reduce carbonate and bicarbonate levels.

Wastes containing emulsified oil and grease require pretreatment to break down and remove emulsions. If not treated, the emulsified oil and grease will coat the UV lamps and reduce the UV transmission in the Ultrox system, thereby making the process less effective.

Pretreatment of wastes containing suspended solids at levels greater than 30 mg/L may need to be considered, as the suspended solids would also reduce the UV transmission. In addition, pretreatment may be necessary for wastes containing dissolved metals, such as iron and manganese, which have lower solubilities at higher oxidation states. The removal of such metals is required because they will be oxidized and precipitated in the Ultrox system, resulting in the formation of suspended solids and, also, scaling of the UV lamps.

pH adjustments may need to be considered for wastes having bicarbonate and carbonate ions at levels greater than 400 mg/L as $CaCO_3$. These ions act as oxidant scavengers and cause additional load to the treatment system. If required, pH adjustments can be performed in-line.

Even if no pretreatment is needed, the aqueous organic wastes may still need to be pumped to an equalization tank (such as bladder tanks to minimize VOC losses) to reduce flow and concentration fluctuations. If so, plumbing connections will be needed.

Residuals Handling

Two major types of residuals are generated from the Ultrox treatment system: (1) air emissions and (2) treated effluent. The Ultrox system did not generate any harmful air emissions during the demonstration. The ozone decomposer unit in the Ultrox system removed the ozone and VOCs present in the reactor off-gas to environmentally safe levels. Therefore, no special residual handling procedures were required for the air emissions at the demonstration site. However, periodic monitoring of air emissions for ozone and VOCs is recommended.

Air emissions are treated by the Decompozon unit (Model 3014 FF), which uses a nickel-based proprietary catalyst and operates at about 140°F to decompose reactor off-gas ozone to oxygen. The Decompozon unit can accommodate flows of up to 10 standard cubic feet per minute and can destroy ozone concentrations in ranges of 1 to 20,000 ppm (by weight) to less than 0.1 ppm.

The treated water could be disposed of either on- or off-site. Examples of on-site disposal options for the effluent include groundwater recharge and temporary storage on-site for sanitary usage. Examples of off-site disposal options are discharge into rivers, creeks, storm sewers, and sanitary sewers. Bioassay tests may be required in addition to routine chemical and physical analyses before the effluent is disposed of. During the demonstration, the treated water was stored in a 20,000-gallon metal tank until laboratory analyses indicated that the water met NPDES standards. Subsequently, the effluent was discharged into Coyote Creek, a nearby waterway.

In addition to these principal residuals, the operation of the Ultrox system also requires the handling and replacement of miscellaneous items related to the operation. These items include UV lamps, spargers, and filters which may be required to treat the influent. To avoid excessive analytical costs to determine whether or not these items are nonhazardous, disposal of these items as hazardous wastes seems warranted.

Personnel Requirements

Personnel trained to operate the Ultrox system are needed to ensure a reliable operation. Operating personnel requirements depend on the size of the Ultrox system purchased, as well as the features included on the unit. For example, the Ultrox system (Model F-4000), which has been in operation at the Sealed Power Corporation in Muskegon, Michigan, is totally automated and, therefore, requires minimal attention. This system has alarms to indicate power failure, high ambient ozone levels, and any malfunctioning of the system components, such as the Decompozon unit and the air compressor. These alarms can be connected to the control/security room, where the facility operator or security personnel is stationed. At the sound of an alarm, all system components and the wastewater flow will be shut off, and the problem area will be indicated on the control unit for proper action. Typically with this type of unit, a 15-minute routine inspection at the beginning and end of each day by an operator with basic mechanical skills is adequate. Typically, no operator attention is needed in the evenings or on weekends.

A person capable of collecting samples from taps and performing wet chemistry analysis (measuring pH, oxidant concentrations, etc.) is required to monitor the Ultrox system operation once a day. These analyses may take about an hour. Samples for organic analyses can be sent to a contract laboratory.

A project supervisor is required to provide general technical guidance. This person should have an understanding of the treatment process and be capable of reviewing data to evaluate the system's performance. About 2 hours per week of the project supervisor's time should be adequate.

The operating personnel are subject to OSHA regulations. According to OSHA, the maximum allowable ozone exposure for an 8-hour period is 0.1 ppm. When functioning properly, the Decompozon unit reduces ozone levels in the reactor off-gas to about 0.001 ppm and, therefore, alleviates this concern. However, other health and safety issues due to the contaminants present in the untreated aqueous waste will be site-specific. Therefore, a site-specific Health and Safety Plan should be prepared. This plan should include the facility description, a list of chemicals of concern and their concentrations, health and safety zones, personnel protective clothing and equipment, contaminant monitoring procedures, hospital routes, and the personnel to contact in the event of an emergency.

Potential Community Exposures

Contaminant emissions from the Ultrox system are minimal. The Ultrox system, equipped with its Decompozon air treatment system, destroys ozone present in the reactor off-gas to nondetectable levels. The SITE demonstration data indicated that the Decompozon unit also reduced the VOC levels present in the reactor off-gas to nondetectable levels when the Decompozon unit functioned properly. Therefore, no major potential for on- site personnel or community exposure to air-borne contaminants is anticipated. In case of any malfunctioning, all components of the system and unit will shut off automatically, leaving no threat to the community.

Regulatory Requirements

This subsection discusses the regulatory requirements for the Ultrox system as they relate to conducting a hazardous waste site remediation.

Comprehensive Environmental Response, Compensation, and Liability Act

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, authorizes the Federal government to respond to releases or potential releases of any hazardous substance into the environment, as well as to releases of pollutants or contaminants that may present an imminent or significant danger to public health and welfare or the environment.

The Superfund Amendments and Reauthorization Act of 1986 (SARA) amended CERCLA, and directed EPA to:

- Use remedial alternatives that permanently and significantly reduce the volume, toxicity, or mobility of hazardous substances, pollutants, or contaminants
- Select remedial actions that protect human health and the environment, are cost-effective, and involve permanent solutions and alternative treatment or resource recovery technologies to the maximum extent practicable
- Avoid off-site transport and disposal of untreated hazardous substances or contaminated materials when practicable treatment technologies exist (Section 121 (b))

As part of the requirements of CERCLA, EPA has prepared the National Contingency Plan (NCP) to address responses to releases of hazardous substances. The NCP (codified in 40 CFR Part 300) delineates the methods and criteria used to determine the appropriate extent of removal and cleanup for hazardous waste contamination. The NCP includes chemical oxidation as a direct waste treatment method that can be considered a long-term, permanent solution for remediating contaminated groundwater at CERCLA sites (Part 300.70(B)(5)).

In general, there are two types of responses possible under CERCLA: removal and remedial actions. Chemical oxidation technologies can be part of a CERCLA removal action. However, if the removal action is part of a remedial action, the removal action will be limited in the amount of time and money spent to implement the response. Superfund-financed removal actions cannot exceed 12 months in duration or $2 million in cost in most cases (Section 104(c) (1)).

Remedial actions are governed by SARA amendments to CERCLA. As stated above, these amendments promote remedies that permanently reduce the volume, toxicity, and mobility of hazardous substances, pollutants, or contaminants. Section 121(c), of CERCLA as amended by SARA, requires EPA to review any remedial action in which hazardous substances, pollutants, or contaminants remain at the site.

Because each hazardous waste site is unique and has specific contamination characteristics, a discussion of all potential applicable or relevant and appropriate requirements (ARAR) for a given remedial action involving chemical oxidation cannot be covered in this regulatory analysis. On-site remedial actions must comply with Federal and more stringent state ARARs that are determined on a site-by-site basis. ARARs will dictate the degree of cleanup necessary at CERCLA sites, and CERCLA provides only six waivers to meeting ARARs during a remedial action (Section 121(d)(4)). If chemical oxidation is chosen as the sole technology for a remedial action, then the chemical oxidation process must meet ARARs for cleanup at the site.

Section 121(e)(1) specifies that no Federal, state, or local permit is required for the portion of any removal or remedial action conducted entirely on-site. However, the remediation must comply with all substantive regulatory requirements.

Resource Conservation and Recovery Act

RCRA, an amendment to the Solid Waste Disposal Act, was passed in 1976 to address the problem of how to safely manage and dispose of municipal and industrial solid wastes. RCRA specifically addresses the identification and management of hazardous wastes. The Hazardous and Solid Waste Amendments of 1984 (HSWA) significantly expanded the scope and requirements of RCRA, including prohibiting the land disposal of hazardous wastes that do not meet promulgated treatment standards.

RCRA regulations concerning hazardous waste identification and management are specified in 40 CFR Parts 124, 260-272. EPA and RCRA- authorized states implement and enforce RCRA and state regulations.

The key to determining whether RCRA regulations apply to the Ultrox process is whether the contaminated media is a hazardous waste. EPA defines hazardous waste in 40 CFR Part 261. If hazardous wastes are treated by chemical oxidation, the owner/operator of the treatment or disposal facility must obtain a RCRA permit from EPA or RCRA-authorized state. RCRA requirements for permits are specified in 40 CFR Part 260. Requirements for hazardous waste generators are specified in 40 CFR Part 262, and include obtaining an EPA identification number prior to treating hazardous wastes. The requirements for a hazardous waste generator will be applicable if contaminated groundwater is determined to be a hazardous waste, and is extracted for treatment, storage, or disposal.

In some situations, chemical oxidation may be used as part of a pump and treat remediation method. In these cases, the owner or operator of the treatment system will have to comply with 40 CFR Part 265, Subparts B (General Requirements) and Q (Chemical, Physical, and Biological Treatment).

If hazardous wastes are generated in batches and must be stored on-site prior to treatment, other RCRA regulations may apply. These regulations may include complying with 90-day accumulation limits for facilities without hazardous waste storage permits (40 CFR Section 262.34), complying with 40 CFR Part 264 or 265, Subpart I, if hazardous wastes are stored in containers, and complying with 40 CFR Part 264 or 265, Subpart J, if hazardous wastes are stored in tanks. In addition, small quantity generators cannot store more than 6,000 kg of hazardous waste on-site without a permit (40 CFR Section 262.34(D)).

Once hazardous wastes are treated by chemical oxidation, the treated waste must be analyzed to determine if it still contains any hazardous properties or constituents. As such, subsequent management of the treated waste may also be subject to the above RCRA requirements, until these analyses are performed. Other applicable RCRA requirements could include the use of a Uniform Hazardous Waste Manifest if the waste is transported off-site and restrictions as to where the treated waste can be discharged.

Currently, air emissions from hazardous waste treatment operations are not addressed by RCRA regulations. However, Section 3004(n) of RCRA directs EPA to issue regulations concerning air emissions from hazardous waste treatment, storage, and disposal facilities.

RCRA Corrective Action

RCRA regulations (Sections 264.100 - 264.101) require that a corrective action program be instituted as necessary to protect human health and the environment from all releases of hazardous waste or its constituents from any solid waste management unit. The corrective action program must be in compliance with groundwater protection standards and must begin within a reasonable amount of time after the groundwater protection standard has been exceeded. The contaminated water must be treated to the levels determined in the corrective action order. These levels can vary, depending on state and local requirements (e.g., NPDES, publicly-owned treatment works (POTW), or maximum contaminant levels (MCL)).

Additionally, a groundwater monitoring program must be implemented to prove that the corrective action program has been effective. Corrective action must be completed during the compliance period to the extent necessary to ensure that the groundwater protection standard is met. However, if corrective action is being performed at the end of a compliance period, that corrective action must continue for as long as necessary to achieve compliance with the groundwater protection standard.

Clean Air Act

The Clean Air Act requires that treatment, storage, and disposal facilities comply with primary and secondary ambient air quality standards. Since volatile organic air emissions are possible during the extraction or transfer of the contaminated water to the treatment unit, steps need to be taken to prevent or minimize the potential impact from organic vapors. Preventative measures could include storing

the contaminated water in an enclosed tank or container.

During treatment, steps must be taken to minimize the release of ozone into the atmosphere. Furthermore, any release of ozone must be no more than 0.12 ppm, in accordance with 40 CFR Section 50.9 (national primary and secondary ambient air quality standards for ozone). Ultrox's Decompozon unit is specifically used to destroy ozone in the reactor off-gas.

State air quality standards may require additional measures to prevent volatile organic air emissions, including the release of ozone.

Clean Water Act

The Clean Water Act (CWA), as amended by the Water Quality Act of 1987, describes standards and enforcement for discharges, including toxic and pretreatment effluent standards which are applied primarily to protect surface water quality. The CWA established the National Pollutant Discharge Elimination System (NPDES), which requires that (1) EPA publish water quality criteria for pollutants and (2) each state set water quality standards, using the EPA criteria, for every significant body of surface water within its borders. States then issue permits for discharges into these bodies of surface water.

NPDES requirements are specified in 40 CFR Part 122. Part 122 requires that contaminated water be treated to appropriate levels prior to discharging into a storm sewer or surface waterbody. If chemical oxidation is used as part of an industrial process or as a RCRA-corrective action and the treated water is discharged to a surface waterbody, a NPDES discharge permit must be obtained.

Safe Drinking Water Act

The Safe Drinking Water Act (SDWA) of 1974, as most recently amended by the Safe Drinking Water Amendments of 1986, requires EPA to establish regulations to protect human health from contaminants in drinking water. The legislation authorized national drinking water standards and a joint Federal- state system for ensuring compliance with these standards.

The National Primary Drinking Water Standards are found in 40 CFR Part 141. Under SDWA, maximum contaminant levels (MCL), which are enforceable standards for chemicals in public drinking water supply systems, were established. MCLs consider both health factors and the economic and technical feasibility of removing a contaminant from a water supply system. Treated water injected into groundwater used as a public drinking water source must meet the MCLs.

Toxic Substances Control Act

The Toxic Substances Control Act (TSCA) of 1976, as codified in 40 CFR Parts 700 through 799, established requirements and authorities for identifying and controlling toxic chemical hazards to human health and the environment. The disposal of PCBs is specifically regulated under Section 6(e) of TSCA, with PCB treatment and disposal regulations specified in 40 CFR Section 761.60.

Soil contaminated with PCBs may be encountered when boring groundwater extraction and monitoring wells. PCBs in concentrations between 50 and 500 ppm may be disposed of in either a TSCA-permitted landfill or destroyed at a TSCA-approved incinerator (40 CFR Section 761.70).

TSCA does not regulate treatment or disposal of water contaminated with PCBs at concentrations less than 50 ppm, which is typically found during groundwater remedial actions.

Occupational Safety and Health Act

Superfund remedial actions and RCRA-corrective actions must be performed in accordance with the Occupational Safety and Health Act (OSHA) requirements codified in 29 CFR Parts 1900 through 1926. During site preparation, a pad, made of compacted gravel or concrete, will likely have to be constructed to place the Ultrox unit on. The construction of this pad must be performed in accordance with Part 1926 of OSHA (Safety and Health Regulations for Construction).

A weather shelter to provide protection for the Ultrox system from inclement weather and to provide suitable work environment for on-site personnel needs to be constructed. The complexity of this shelter will depend on the climate where the site is located and the duration of treatment. For the Ultrox demonstration in San Jose, California, a large awning proved sufficient. However, in areas without year-round, mild climates, it may be necessary to build a sturdy and durable enclosure.

Since the Ultrox unit operates on electricity, utility hookups are needed. Construction of these hookups must be performed in accordance with Part 1926, Subpart K (Electrical) of OSHA. If the utility lines are placed underground, the excavation performed must follow the requirements specified in Part 1926, Subpart P of OSHA.

Although the Ultrox system requires little personnel involvement once it is operating under desired conditions, technicians performing daily and weekly monitoring and sampling must wear personnel protective equipment, such as rubber gloves and eye guards (Part 1910, Subpart I). Additional personnel

protective equipment may be needed when handling untreated waste.

State occupational safety and health requirements may be significantly stricter than Federal standards.

Section 4
Economic Analysis

Introduction

The costs associated with the Ultrox technology are defined by 12 cost categories that reflect typical cleanup activities at Superfund and RCRA-corrective action sites. Each of these categories is defined and discussed, thereby forming the basis for the estimated cost analysis presented in Table 4-1 for an Ultrox UV technology operation. Annual operating and maintenance costs and one-time costs are presented in Table 4-1 for three treatment flow rates: 20, 100, and 250 gpm. The costs presented in this analysis are order-of-magnitude (-30 to +50 percent) estimates, as defined by the American Association of Cost Engineers.

Site-Specific Factors Affecting Cost

Several factors affecting the cost of the Ultrox system are highly site-specific, and are difficult to calculate without the benefit of data from an accurate site-remedial investigation report. The factors most affecting cost include: volume of aqueous waste to be treated; extent of contamination; site condition (in terms of necessary site preparation, such as constructing access roads and regrading for a treatment pad, etc.); treatment goals to meet discharge requirements; and frequency of equipment repair and replacement.

Basis of Economic Analysis

The Ultrox technology can be operated in a batch or continuous mode depending upon treatment requirements. For the purpose of this economic analysis, it is assumed that the system will be operated in a continuous mode, 24 hours a day, 7 days a week, for one year. During this period the unit should treat approximately 10.5 million gallons in the 20-gpm unit, 52.5 million gallons in the 100-gpm unit, and 131.5 million gallons in the 250-gpm unit. One year was chosen as the period of time for this

Table 4-1. Estimated Costs Associated with Three Ultrox System Units

Item	Estimated Costs (1990 $)		
	20 gpm	100 gpm	250 gpm
Site Preparation Costs[a]	36,000	55,000	75,000
Permitting and Regulatory Costs[a]	3,500	7,500	13,000
Capital Equipment Costs[a]	70,000	150,000	260,000
Startup and Fixed Costs[a]	32,000	32,000	32,000
Labor Costs[b]	6,600	6,600	6,600
Supply and Consumable Costs[b]	10,500	16,500	20,800
Utility Costs[b]	12,000	58,000	145,000
Effluent Monitoring and Disposal Costs[b]	3,000	3,000	3,000
Residuals and Waste Shipping, Handling, and Transporting Costs[b]	1,000	5,000	7,000
Analytical Costs[b]	24,000	24,000	24,000
Equipment Repair and Replacement Costs[b]	4,000	22,000	33,000
Site Demobilization Costs[a]	2,000	3,000	4,000
Total One-Time Costs	143,500	247,500	384,000
Total Annual Operation and Maintenance Costs	61,100	135,100	239,400

[a] One-time costs
[b] Annual operation and maintenance costs

analysis so that reliable annual operating and maintenance costs could be determined. However, it should be noted that most groundwater remedial actions require a significant amount of time (e.g., 5 to 30 years).

In addition, it is assumed that the groundwater is contaminated with VOCs such as TCE and vinyl chloride, at levels of 100 and 40 µg/L, respectively. The operating conditions assumed for this analysis are as follows: a hydrogen peroxide dose of 16 mg/L; an hydraulic retention time of 60 minutes; an ozone requirement of 14 lbs/day at 2 percent weight in air; and all UV lamps operating at 100 percent efficiency. The contaminants were assumed to be treated to meet NPDES standards for discharge into a storm drain or nearby waterway.

The following is a list of assumptions used for this analysis:

- Utility connections will be overhead
- Suitable access roads exist
- Contaminated water is in a shallow aquifer
- Installation of the Ultrox system at the site is not included in the capital equipment cost
- One technician, one hour per day, seven days a week will check and maintain the system
- One supervisor, two hours per week, will supervise the technician
- Labor costs associated with major repairs are not included
- Spent UV lamps from the treatment process are considered a hazardous waste
- One treated water sample will be taken each month and tested for organic compounds
- UV lamps will be replaced annually
- Site demobilization only includes transporting the Ultrox unit off-site
- Decommissioning equipment and disposal costs are not included.

A detailed discussion of each of the 12 cost categories in Table 4-1 is provided below.

Site Preparation Costs

The costs associated with site preparation include planning and management, system design, auxiliary and temporary equipment and facilities, legal searches, access rights, preparation for support facilities, minor cleaning of the site, emergency and safety equipment, utility connections, constructing foundations, installing monitoring and extraction wells if groundwater is the aqueous waste, startup, and site support staff.

Site preparation costs will vary depending on the type of site where the treatment operation takes place and the condition of the site. Sites that require major cleaning and regrading for the foundation will significantly increase site preparation costs. Utility connections can be either overhead or buried; however, the latter option will require more design, planning, and construction. For this analysis, it is assumed that utility connections will be overhead. In addition, some sites may require the construction of access roads; however, this analysis, assumes that suitable access roads already exist.

Installing monitoring and extraction wells are a significant portion of site preparation costs, depending on the depth of the groundwater to be monitored and extracted. The Ultrox system can also be used to treat contaminated surface water. In such a case, a pump system may need to be installed, including a filtration system to screen out debris and any other solids. It is assumed for this analysis that contamination is present in a shallow aquifer. Site preparation costs are estimated to be approximately the following: $36,000 for a 20-gpm unit; $55,000 for a 100-gpm unit; and $75,000 for a 250-gpm unit.

Permitting and Regulatory Costs

Permitting and regulatory costs will vary depending on whether treatment is performed on a Superfund or a RCRA-corrective action site and on how the effluent is disposed. Section 121(d) of CERCLA as amended by SARA requires that remedial actions be consistent with ARARs for environmental laws, ordinances, regulations, and statutes. ARARs include Federal standards and criteria as well as more stringent standards or criteria promulgated under state or local jurisdictions. Applicable requirements are those for which the jurisdictional prerequisites of the underlying statute are satisfied. Relevant and appropriate requirements do not legally apply to the situation or action planned, but are none the less suitable because of the characteristics of the remedial action, the pollutants in question, or the physical circumstances at the site. ARARs must be determined on a site-specific basis.

At RCRA-corrective action sites, analytical protocols and annual monitoring records will have to be kept, which will increase the regulatory costs. For these situations, an additional 5 percent should be added to the estimate rendered for this category. Contaminated soil removed during the installation of monitoring and extraction wells will have to be stored in compliance with RCRA or state requirements. Soil that will be disposed of at a permitted landfill will have to meet Federal or state

land disposal restriction requirements. This may be very difficult and costly for PCB- contaminated soil.

Permitting and regulatory costs are assumed to be approximately 5 percent of the capital equipment costs for a treatment operation that is part of a Superfund remedial action. This estimate does not include annual discharge permit costs which may vary significantly depending on state and local requirements.

Capital Equipment Costs

Capital equipment costs include the cost of an Ultrox reactor, an air compressor, an ozone generator, and a hydrogen peroxide feed system. Based on information provided by Ultrox International, these costs are $70,000 for a 20-gpm unit, $150,000 for a 100-gpm unit, and $260,000 for a 250-gpm unit. Installation costs are not included in these estimates but are assumed to be approximately 5 to 7 percent of the capital equipment costs.

Startup and Fixed Costs

Startup costs include those required to establish operating procedures, train operators, perform an initial shakedown of the equipment and analysis, construct a shelter to protect the system, and initiate an environmental monitoring program.

To ensure safe, economical, and efficient operation of the unit, a program to train operators is necessary. The costs associated with this training program include developing a health and safety program and associated manuals, providing health and safety training, and providing training for operating and maintaining the system. At least three persons (i.e., two technicians and one supervisor) will need health and safety training, with the supervisor receiving health and safety supervisory training in addition. These individuals will be responsible for daily monitoring and will have to be instructed by Ultrox personnel about operating and maintaining the system. Startup training costs are estimated to be approximately $7,500. This estimate is based on three 40-hour health and safety training courses, one health and safety supervisory training course, and three weeks of instruction for the three individuals from Ultrox's staff.

Mobilization and shakedown costs include the transportation of the unit to the site, initial setup, on-site checkout, construction of a weather shelter, construction supervision, working capital, and analysis to determine the proper operating parameters for treatment. These costs are site-specific and will vary depending on the location of the site. Personnel travel costs to the site are not included. For this analysis, equipment shakedown and analysis are assumed to be $20,000. Total startup and fixed costs are estimated to be approximately $32,000.

Labor Costs

Once the Ultrox UV radiation/oxidation system is assembled and shakedown has been completed, the system requires very little labor for operation. Based on information provided by the developer, from case studies, and from the operation of other similar groundwater treatment systems, it is assumed that a skilled technician will be needed for one hour a day, seven days a week, to check and maintain the equipment and take routine water and air samples. This analysis assumes that two individuals will split this job (one during the week and one during the weekend) and that they will be working on other remediation efforts the remaining seven hours in their workshift. In addition, a supervisor will be needed for two hours per week, to oversee the work performed by the technicians. It is assumed that the technician will be paid $10 per hour and the supervisor will be paid $20 per hour (fringe benefits are not included). The annual operating labor costs will be approximately $3,600 for the technician and $2,100 for the supervisor. The two technicians and the supervisor will require an annual health and safety refresher course and it is estimated that this will cost $900 annually. Total annual labor costs are assumed to be $6,600. This estimate does not include labor costs associated with major equipment repairs.

Supply and Consumable Costs

Supplies and consumables for the Ultrox UV radiation/oxidation system include hydrogen peroxide, acids for pH adjustment, and other miscellaneous supplies. The quantities of hydrogen peroxide and acid used depend upon the size of the system employed and the level of organic contamination in the waste stream. These costs are assumed to be approximately 15 percent annually of capital equipment costs for the 20-gpm unit, 11 percent for the 100-gpm unit, and 8 percent for the 250-gpm unit. These estimates represent the average costs of these items incurred during implementation of the Ultrox system at other sites. The cost of the supplies is expected to significantly decrease with the larger volume units, due to economies of scale.

Utility Costs

The Ultrox system runs on commercial electricity. Utility costs reflect the amount of electricity needed to operate the ozone generator, the UV radiation/oxidation reactor with its lamps, and site support facilities. The quantity of electricity used depends on the quantity of groundwater treated, the amount of ozone needed, the level of contamination, and the retention time. It is estimated that the electrical cost will be $1.10 per 1,000 gallons treated,

based on averages from other case studies and estimates from several utility companies.

Effluent Monitoring and Disposal Costs

This cost category consists of effluent monitoring and a supply and storage or source of clean water for personnel and equipment decontamination. Effluent monitoring will be performed routinely by the technician. The effluent will be discharged to a nearby storm drain or reinjected into the groundwater. The cost estimate for this category is based on discharge to a storm drain and is approximately $3,000 per year.

Residuals and Waste Shipping, Handling, and Transportation Costs

The Ultrox UV radiation/oxidation process produces very few residuals that require special handling. Filters and UV lamps may need to be disposed of following treatment due to a buildup of residuals and corresponding reduction in effectiveness and efficiency. Spent UV lamps are considered hazardous because they contain mercury and will therefore require disposal at a permitted facility. Residuals shipping, handling, and transporting costs to a hazardous waste disposal facility are assumed to be between $1,000 and $7,000 per year for the 3 Ultrox units, based on disposal costs of $500 per drum.

Analytical Costs

Analytical costs include laboratory analyses, data reduction and tabulation, quality assurance/quality control (QA/QC), and reporting. Monthly laboratory analyses will cost approximately $1,250, while data reduction and tabulation, QA/QC, and reporting should cost $500 to $750 dollars per month. This analysis assumes that one organic treated water sample, will be taken each month. Total estimated analytical costs are, therefore, approximately $24,000 per year.

Equipment Repair and Replacement Costs

During the course of operation, certain parts of the Ultrox system will need to be replaced. The most common parts needing replacement are the UV lamps, spargers, and influent feed line filters. The 20-gpm unit contains 36 lamps, the 100-gpm unit has 288 lamps, and the 250-gpm unit has 432 lamps. UV lamps will have to be replaced annually, at a cost of $60 per lamp installed. Annual equipment repair and replacement costs are estimated to be approximately 5.7 percent of the capital costs for the 20-gpm unit; 14.7 percent of the capital costs for the 100-gpm unit; and 16 percent of the capital costs for the 250-gpm unit. It is assumed for this analysis that the cost of filters and spargers will decrease due to economies of scale.

Site Demobilization Costs

Site demobilization will include operation shutdown, site cleanup and restoration, permanent storage costs, and site security. Site demobilization costs will vary depending on whether the treatment operation occurs at a Superfund site or at a RCRA-corrective action site. Demobilization at the latter type of site will require detailed closure and post-closure plans and permits. Demobilization at a Superfund site does not require as extensive post-closure care; for example, 30-year monitoring is not required. This analysis assumes site demobilization costs cover only those items involved with transporting the Ultrox units and are assumed to vary between $2,000 and $4,000 for the different treatment units. Decommissioning equipment and disposal costs are not included in this estimate.

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Appendix A
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Appendix A
Key Contacts for the SITE Demonstration

Additional information on the Ultrox technology, the SITE Program, and the demonstration site can be obtained from the following sources.

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Appendix B
Vendor's Claims for the Technology

Note: This appendix to the report is based upon claims made by Ultrox International either in conversations or in written or published materials. These claims and interpretations of the regulations are those made by the vendor and are not necessarily able to be substantiated by test data. Many of Ultrox's claims are compared in Appendix C with the available test data.

Introduction

The removal of low levels of organic contaminants from groundwaters and industrial wastewaters presents a challenge to environmental professionals. The ULTROX® (a registered trademark of Ultrox International) ultraviolet (UV) radiation/oxidation process is a cost effective treatment technique which is applicable to the destruction of a wide range of soluble organic contaminants in water. Other well-known and commonly used treatment processes such as granular activated carbon (GAC) and air stripping transfer pollutants from one medium to another. With increasing public and regulatory concern over the fate of pollutants, such transferential technologies are not optimal.

Conventional chemical oxidation has been used in the treatment of various waters polluted by organic chemicals for a number of years. Potassium permanganate, chlorine, and chlorine dioxide have been used for treating organics such as phenol and its homologs in wastewaters. Hydrogen peroxide, with a catalyst such as ferrous sulfate, has been used for oxidizing phenol and other benzene derivatives. Processes utilizing iron-catalyzed peroxides and chlorine compounds are attractive because they use relative low-cost treatment equipment. The disadvantages of these processes are that they can attack only a limited number of refractory organics, and that they produce iron sludges or chlorinated organics. Ozone alone has been used to treat phenolic wastes, cyanides, and certain pesticides. Ozone treatment is a very clean process but is limited in the number of compounds which it can effectively treat.

The use of UV radiation-catalyzed ozone plus hydrogen peroxide (UV radiation/oxidation) as a water treatment technique is rapidly expanding. It offers a means of solving many of the problems created by the water soluble, toxic organic chemicals that are found today in groundwater, wastewater, leachate, and drinking water supplies without many of the disadvantages of more conventional techniques.

UV radiation/oxidation, when used as a stand-alone treatment process or in tandem with a few of the above mentioned processes, can cost-effectively destroy the organic chemicals on EPA's priority pollutant list or render the organics non-toxic.

This appendix describes the experience of Ultrox International in developing and applying the ULTROX® UV radiation/oxidation process to the full-scale treatment of organics in wastewaters, drinking waters, leachates, and groundwaters. Ultrox International was issued a process-patent in 1988 covering the application of UV radiation, ozone, and hydrogen peroxide to the treatment of a broad range of organic compounds in water.

Description of the ULTROX® Process

The ULTROX® UV radiation/oxidation process was developed over a 15-year period. UV radiation, when combined with ozone and/or hydrogen peroxide, produces a highly oxidative environment significantly more destructive than that created with ozone or hydrogen peroxide by themselves or in combination.

UV radiation significantly enhances ozone and hydrogen peroxide reactivity by:

- Transformation of ozone and hydrogen peroxide to highly reactive OH° radicals
- Excitation of the target organic solute to a higher energy level
- Initial attack of the target organic compound by UV radiation

The importance of the conversion of the ozone and hydrogen peroxide to OH° can be more easily

understood after studying the relative oxidation power of oxidizing species. Hydroxyl radicals have significantly higher oxidation power than either hydrogen peroxide or ozone. The oxidation potentials and relative oxidation powers of several oxidants are as follows:

Species	Oxidation Potential Value	Relative Oxidation Power (Cl = 1.00)
Fluorine	3.06	2.25
Hydroxyl radical (OH°)	2.80	2.05
Atomic Oxygen	2.42	1.78
Ozone (O_3)	2.07	1.52
Chlorine dioxide	1.96	1.44
Hydrogen peroxide (H_2O_2)	1.77	1.30
Perhydroxyl radicals	1.70	1.25
Hypochlorous acid	1.49	1.10
Chlorine	1.36	1.00

The effect of UV-enhanced oxidation is illustrated in Table B-1.

ULTROX® Equipment

ULTROX® UV radiation/oxidation equipment treatment systems have very few moving parts, operate at low pressure, require minimum maintenance, operate full-time or intermittently in either a continuous or batch-treatment mode, utilize efficient, low-temperature, long-life UV lamps, and can employ the use of a microprocessor to control and automate the treatment process.

The ULTROX® UV radiation/oxidation system consists of a UV radiation/oxidation treatment tank and an oxidation source which can be either an ozone generator with an air preparation system or a hydrogen peroxide feed system. Figures 2-1 (see Section 2), B-1, and B-2 are an isometric assembly view, a drawing, and a photograph, respectively, of a model F-150 system, which accommodates flow rates up to 10 gpm or batches of 150 gallons.

The treatment tank is made of stainless steel. The UV lamps are enclosed within quartz tubes for easy replacement and are mounted vertically within the tank. Depending upon the size of the tank and the type of wastewater to be treated, the tank can have four to eight chambers separated by baffles. Lamps are installed either in all chambers or in designated chambers, depending on the treatment specified. When ozone is used as the oxidant, it is introduced at the base of the chamber. The ozone is dispersed through porous stainless steel diffusers. The number of diffusers needed will depend upon the type of organics being oxidized and the degree of removal required.

Ozone is produced from either compressed air, dried to a -60°F dewpoint by desiccant columns, or produced from compressed or liquid oxygen. Up to 2 percent (by weight) ozone is generated from air, and up to 5 percent (by weight) ozone can be produced economically from oxygen.

Commercial-grade hydrogen peroxide used in the process, is directly metered into the influent line to the reactor.

Water pumped into the treatment tank flows from chamber to chamber in a sinusoidal path. When the reactor uses ozone, the residual ozone in the off- gas is decomposed back to oxygen by the use of a fixed-bed catalytic unit operating at 150°F. The air is then vented to the atmosphere.

Ozone generators with varying capacities are used with the Model F-150 reactor. The size of the generator depends upon the ozone dosage requirements. Present installations use 28 to 140 pounds per day capacities.

Applications of the ULTROX® System

The UV radiation/oxidation equipment developed by Ultrox in recent years has been used to treat a wide variety of waste streams. Table B-2 lists toxic compounds found in wastewaters and groundwaters that have been successfully treated with the ULTROX® system. Specific case histories of treatability and design studies for private industries and military installations are presented in Table B-3. Contaminants oxidized included pesticides, petroleum compounds, munitions waste, and chlorinated solvents. In each of these cases, pilot treatment plants were operated on-site to develop treatment design and cost data.

Table B-4 illustrates projects where the treatability and design studies were converted into permanent on-site UV radiation/oxidation installations. Full-scale ULTROX® units are currently treating contaminated groundwater, wastewater, and process water. Contaminants in these waters include phenols, chlorinated solvents, hydrazine, dimethylnitrosamine, tetrahydrofuran, and formaldehyde. Commercial systems have been designed, built, and installed to treat flows varying from 10,000 to 300,000 gallons per day. A system to treat 1.3 million gallons per day is under construction.

Standard equipment designs are used in all of these installations. Reactor size varies from 300 to 4,800 gallons. Ozone generators range from 21 to 140 pounds per day. In several cases, hydrogen peroxide is used in place of, or with, ozone.

Specific design parameters are developed through performance of treatability studies, pilot tests, and

Table B-1. Oxidations of Methylene Chloride and Methanol

Contact Time (min.)	Control	UV	UV/H_2O_2	O_3/H_2O_2	UV/O_3	$UV/O_3/H_2O_2$
Methylene Chloride						
0	100	100	100	100	100	100
15	100	59	46	32	36	19
25	100	42	17	21	16	7.6
Methanol						
0	75	75	75	NDA	75	75
30	75	75	75	NDA	31	1.2

Notes: 1. All concentrations reported in mg/L.
2. NDA = No data available.

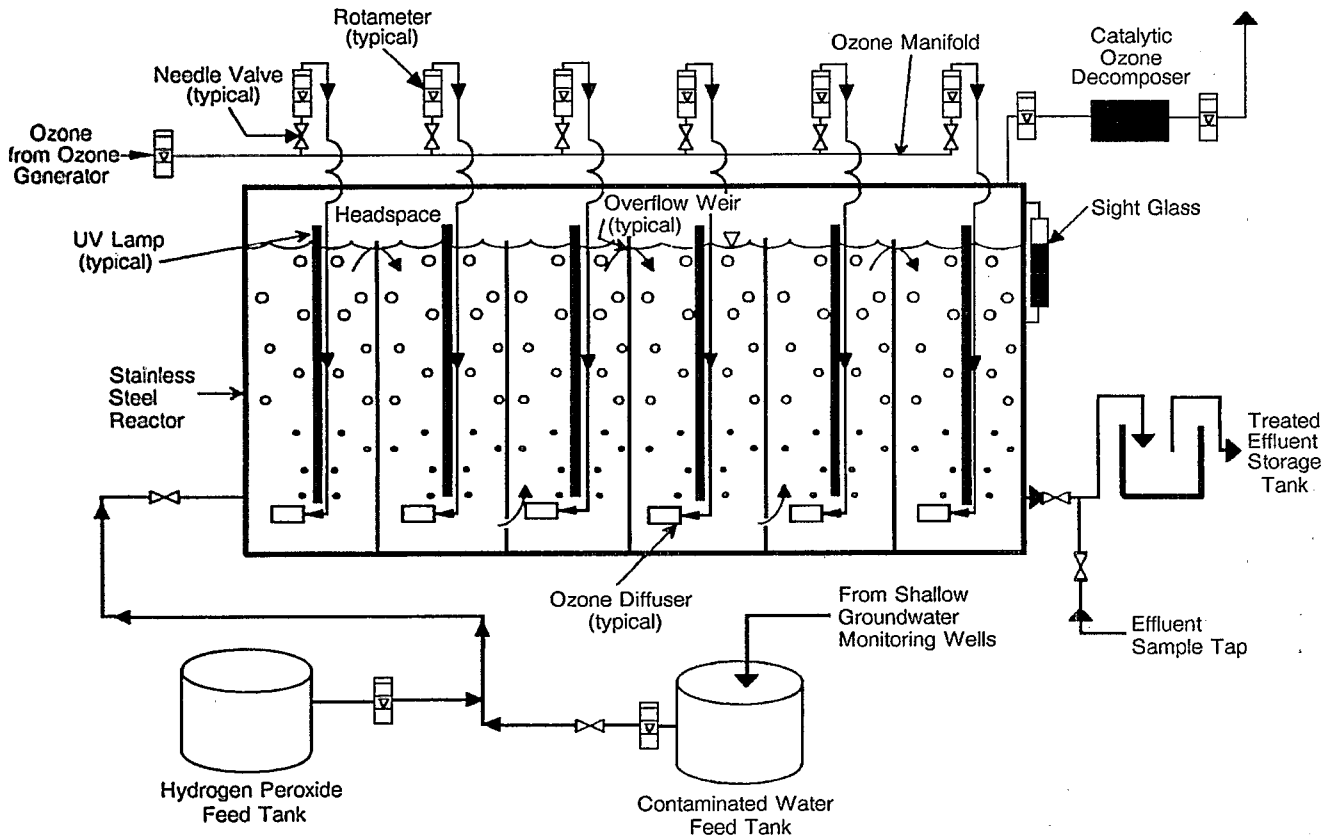

Figure B-1. ULTROX® system flow diagram.

full-scale shakedowns. Treatability studies are carried out first in the laboratory using bench-scale equipment to evaluate the feasibility of treating the water with UV radiation/ozone, UV radiation/hydrogen peroxide, or UV radiation/ozone/hydrogen peroxide. If the results are encouraging, the next step in the study involves the installation of a skid-mounted, pilot-scale unit on-site. Sufficient design and cost data normally are collected within 2 weeks. Specifications for the full-scale system are then

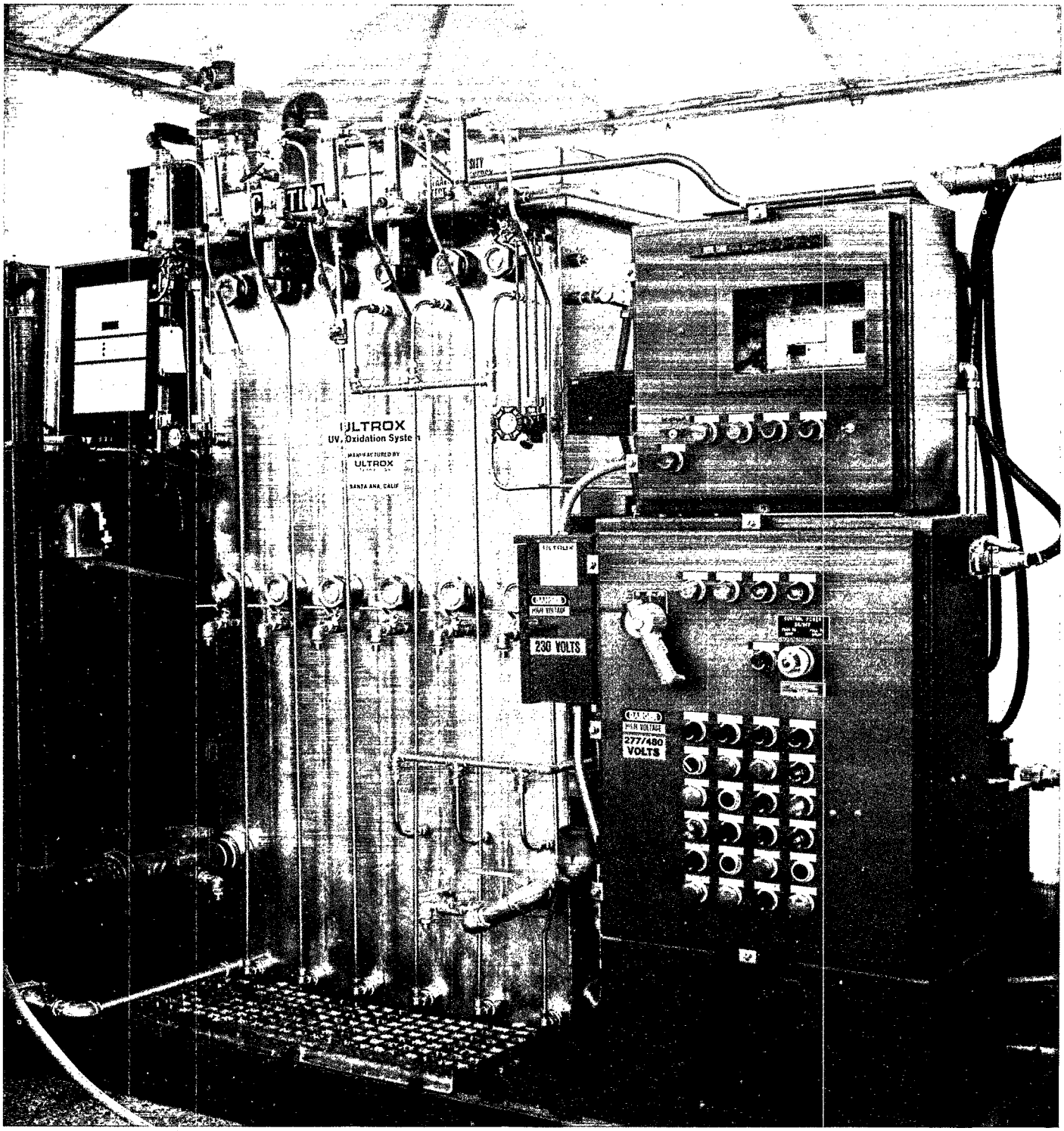

Figure B-2. Photograph of the ULTROX® unit.

Table B-2. Contaminants Treated by the ULTROX® System

Industrial Effluent Contaminants	Groundwater Contaminants
Amines	Benzene, toluene, and xylene (BTX)
Analine	Bis (2-chloroethyl) ether
Benzene	Creosote
Chlorinated solvents	1,2-Dichloroethane (1,2-DCA)
Chlorobenzene	Dichloroethylene (DCE)
Complex cyanides	Dioxins
Creosote	Dioxanes
Hydrazine compounds	Freon 113
Isopropanol	Methylene chloride
Methyl ethyl ketone (MEK)	Methyl isobutyl ketone (MIBK)
Methyl isobutyl ketone (MIBK)	Polychlorinated biphenyl (PCB)
Methylene chloride	Tetrachloroethylene (PCE)
Polychlorinated biphenyl (PCB)	Pentachlorophenol
Pentachlorophenol	Pesticides
Pesticides	Polynuclear aromatic hydrocarbons (PAH)
Phenol	1,1,1-Trichloroethane (1,1,1-TCA)
Cyclonite (RDX)	Trichloroethylene (TCE)
2,4,6-Trinitrotoluene (TNT)	Tetrahydrofuran (THF)
Toluene	Vinyl chloride
Xylene	Triglycol dichloride ether
Polynitrophenols	

Table B-3. Treatability and Design Study Results Using Pilot Plants On-Site

Customer	Application	Contaminants	Results
Bulk Chemical Transfer Depot	Contaminated groundwater	TCE, PCE, methylene chloride	Water treated and reinjected
Municipal Water Producers	Contaminated drinking water supply	TCE, PCE, color	VOCs and color reduced to below state action levels
Aerospace Co.	Paint stripping wastewater	Methylene chloride	Methylene chloride reduced from 4,000 ppm to less than 100 ppb
Chemical Co.	Wastewater	Misc. pesticides (including DBCP)	DBCP and other pesticides reduced to less than 1 ppb
Automotive Co.	Contaminated groundwater	TCE, Methylene chloride	Reduced 10 ppm to 5.0 ppb
Electronics Co.	Wastewater/runoff, groundwater	PCBs, VC, DCA, and other VOCs	Reduced PCBs to less than 1 ppb; VOCs reduced to below state action levels
Munition Plants	Wastewater	TNT, RDX	TNT and RDX reduced from 100 ppm to less than 1 ppm
Army Bases	Contaminated groundwater	DIMP, DBCP, VOCs	DIMP and DBCP reduced to less than 10 ppb; VOCs reduced to below state action levels
Semiconductor Co.	Wastewater	EDTA	Reduced EDTA from 6,000 ppm to 100 ppm (acceptable discharge standard)
Petrochemical Mfr.	Wastewater	Benzene	Reduced benzene from 10 ppm to 50 ppb
Semiconductor Mfr.	Contaminated groundwater	Benzene, toluene, ethylbenzene, xylene	Reduced contaminants from 14.0 ppm to 4.0 ppb

Notes:

DCA: dichloroethane; DBCP: dibromochloropropane; DIMP: diisopropyl methyl phosphonate; EDTA: ethylenediamine tetraacetic acid; PCB: polychlorinated biphenyl; PCE: tetrachloroethylene; RDX: cyclonite; TCE: trichloroethylene; TNT: 2,4,6-trinitrotoluene; VC: vinyl chloride; VOC: volatile organic compound.

prepared. Standard reactors, ozone generators, and hydrogen peroxide feed systems are utilized. Systems are assembled and tested at Ultrox's facilities and then shipped to the job site. The systems are then installed, inspected, and turned over to the customer. Full-service maintenance contracts are available.

Table B-4. Applications of Full-Scale ULTROX® Systems

Customer	Application	Contaminants	Results
Wood Treatment Plants (2)	Wood treatment wastewater	Phenol, pentachlorophenol	Treated water discharged to POTW
Closed Wood Treating Plant	Contaminated groundwater	Phenol, pentachlorophenol	Treated water discharged to POTW
Chemical Plant	Fume scrubber waste	Hydrazine, monomethyl hydrazine, unsymmetrical dimethyl hydrazine	Destroyed parent compounds to not detected levels and dimethyl nitrosoamine below 10 ppb
Automotive Foundry	Contaminated groundwater	TCE, 1,2-trans-DCE	Treated water discharged to lake
Aerospace Co.	Contaminated groundwater	TCE, TCA, DCA, PCE, methylene chloride	Treated water dsicharged to POTW
Chemical Plant	Wastewater	Phenol, formaldehyde	Treated water discharged to POTW
Semiconductor Co.	Contaminated groundwater	THF	Replaced a GAC system to reduce THF from 1,000 ppb to less than 5 ppb

Notes:

DCA: dichloroethane; DCE: dichloroethylene; GAC: granular activated carbon; PCE: tetrachloroethylene; POTW: publicly-owned treatment works; TCA: trichloroethane; TCE: trichloroethylene; THF: tetrahydrofuran.

Full-scale systems, in most cases, are automated using microprocessor control. The system usually requires periodic monitoring (once per shift or once per day). The systems are designed to operate in a batch or continuous mode depending on treatment requirements.

In a number of cases, UV radiation/oxidation is used as part of a treatment train. For example, at wood treatment sites, the wastewater or groundwater requires breaking of oil/water emulsions, removal of suspended matter, and adjustment of pH prior to the UV radiation/oxidation treatment.

Selected Case Studies

Automotive Parts Manufacturer

Testing of groundwater at a Michigan automotive parts manufacturing site revealed significant VOC contamination. TCE levels of 5,000 to 10,000 µg/L were recorded, as well as trace levels of other chlorinated solvents. The Michigan Department of Natural Resources required that the manufacturer pump and treat the groundwater.

The manufacturer investigated air stripping with GAC off-gas treatment, aqueous phase GAC, and ULTROX® UV radiation/oxidation as possible treatment alternatives. Bench-scale studies were conducted at a GAC supplier and at Ultrox's laboratory. While all treatment techniques could provide the required removal levels, UV radiation/oxidation was the most economical. Testing of an ULTROX® P-75 pilot-scale treatment system over a 2-week period confirmed the data obtained in the laboratory. An ULTROX® F-3900 treatment system was ordered and installed in May 1989. The system is currently operating and achieving the following results, which exceed Michigan requirements:

Flow Rate:	210 gpm
Influent Concentration:	5,500 µg/L TCE
Effluent Concentration:	1 µg/L TCE
Treatment Costs:	$/1,000 gallons
Ozone (@ 0.06/kWh)	$0.119
H_2O_2 (@ $0.75/lb)	0.188
UV (incl. power and annual lamp replacement)	0.133
O&M Cost	0.44
Capital Amortization (16%/year)	0.29
Total Treatment Cost:	$0.73

Semiconductor Manufacturer

In 1982, groundwater contamination was detected beneath a Hewlett Packard facility in Palo Alto, California. The contamination was due to leaks in underground chemical storage tanks. Benzene, toluene, ethylbenzene, and xylene (BTEX) levels of 4,000 to 15,000 µg/L were recorded.

In 1988, granular activated carbon (GAC) treatment of groundwater was initiated as an interim measure. In early 1989, under the sponsorship of the California Department of Health Services Hazardous Waste Reduction Grant Program, Ultrox brought a mobile P-150 UV radiation/oxidation system to the site. During 3 weeks of testing, Ultrox demonstrated the treatment equipment's ability to treat the

groundwater to publicly-owned treatment works (POTW) or NPDES standards. Treatment costs for a 5 gpm flow were $60,000 per year with the GAC system. Based on the field studies, projected operation and maintenance (O&M) costs for an ULTROX® system are less than $5,000 per year. The treatment costs, scaled up to 50 gpm, to meet either the POTW and NPDES standards are as follows:

Flow Rate:	50 gpm
Influent Concentration:	11,000 ppb BTEX
Effluent Concentration:	<5 ppb BTEX

Treatment Costs:	$/1,000 gallons	
	98.66% Removal BTEX	99.96% Removal BTEX
Ozone (@ 0.06/kWh)	$0.31	$0.38
H_2O_2 (@ $0.75/lb)	0.28	0.38
UV (incl. power and annual lamp replacement)	0.32	0.64
O&M Cost	0.91	1.40
Capital Amortization (16%/year)	0.75	0.91
Total Treatment Cost:	$1.66	$2.31

Wood Treatment Facility

The groundwater under a closed wood treatment facility in Nashua, New Hampshire, had widespread contamination due to leaking storage tanks and past disposal practices. Contaminants included phenol and PCP. After extensive bench testing, the selected treatment processes were filtration followed by oil/water separation followed by UV radiation/oxidation. An ULTROX®F-650 treatment system was installed in April 1986 and has been operating on a 24 hour per day basis since then. Operating conditions and treatment costs are as follows:

Flow Rate:	40 gpm
Influent Concentration:	5 ppm phenol, 100 ppb PCP
Effluent Concentration:	<0.1 ppm phenol, <0.1 ppb PCP

Treatment Costs:	$/1,000 gallons
Ozone (@ 0.06/kWh)	$0.50
UV (incl. power and annual lamp replacement)	0.35
O&M Cost	0.85
Capital Amortization (16%/year)	0.75
Total Treatment Cost:	$1.60

Cost Information

Table B-5 represents the direct O&M costs for treatment of contaminants in groundwater at water supply sites. The costs are based upon pilot plant studies at four different sites in Southern California. At three of the sites, PCE and TCE were the contaminants with concentrations ranging from 20 to 200 ppb.

Table B-6 presents costs for treatment of wastewater and groundwater at various permanent industrial installations. Costs are presented as dollars per 1,000 gallons treated. For hydrazines, a small volume of water is treated per day on a batch basis and a comparatively long reaction time is needed. UV radiation/oxidation was found to be the most cost-effective method of destroying the three types of hydrazines and the nitrosamine that is formed as a by-product of the oxidation. The UV radiation/oxidation system replaced a chlorination unit, which produced chlorinated organic by-products.

The price range of UV radiation/oxidation equipment is presented in Table B-7. Capital costs for various installations vary from $45,000 to $300,000 (uninstalled). Costs depend on the oxidants required, their estimated dosages, the chemical structure of the organic compounds treated, the number of UV lamps required, and the retention time required to achieve an acceptable discharge.

Summary

Over the last 15 years, UV radiation/oxidation has progressed from research and development to commercial operation. During these years, Ultrox International has advanced its treatment system design through applied bench testing, pilot studies, and full-scale systems to remove contaminants from a wide variety of wastewaters and groundwaters. UV radiation/oxidation technology is not suitable for every organic contamination problem. It can, however, effectively address a wide range of cleanup needs. This form of on-site chemical oxidation can offer real advantages over conventional treatment techniques and should be considered when evaluating water treatment alternatives.

Table B-5. Direct Operation and Maintenance Costs Using UV Radiation/Oxidation for Water Supplies

Type of Water	Contaminants	Contaminant Concentration	Discharge to	Direct O&M Cost Range ($/1,000 gal)
Contaminated potable drinking groundwater	TCE, PCE	less than 20 ppb	Drinking water supply	0.10 to 0.20
Contaminated potable drinking groundwater	TCE, PCE	200 ppb	Drinking water supply	0.20 to 0.30
Contaminated potable drinking groundwater	Color	70 color units	Drinking water supply	0.10 to 0.15

Notes: 1. Assumes cost of electrical energy is $0.06/kWh.
2. PCE: tetrachloroethylene; TCE: trichloroethylene

Table B-6. Direct Operation and Maintenance Costs Using UV Radiation/Oxidation at Industrial Installations

Type of Waste	Contaminants	Total Contaminant Concentration	Discharge to	Daily Volume Treated (gpd)	Direct O&M Cost Range ($/1,000 gal)
Wood treatment wastewater	Pentachlorophenol and phenol	50 ppm	POTW	30,000	1.25-1.35
Contaminated groundwater	Pentachlorophenol and phenol	5 ppm	POTW	86,400	0.90-1.00
Scrubber wastes	Hydrazine, monomethyl-hydrazinee, unsymmetrical-dimethylhydrazine	5,000 ppm	Biotreatment plant on-site	600 to 1,500	86.
Contaminated groundwater	TCE, trans-DCE, methylene chloride	5 ppm	Surface Water	300,000	0.47
Contaminated groundwater	TCE, TCA, DCA, PCE, methylene chloride, VC	600 ppb	POTW	72,000	0.33
Contaminated groundwater	THF	1 ppm	Ground	216,000	0.39
Wastewater	Phenol	90 ppm	POTW	4,300	6.48

Notes: 1. Assumes cost of electrical energy is $0.06/kWh.
2. DCA: dichloroethane; PCE: tetrachloroethylene; POTW: publicly-owned treatment works; TCA: trichloroethane; TCE: trichloroethylene; THF: tetrahydrofuran; trans-DCE: trans-dichloroethylene; VC: vinyl chloride.

Table B-7. Typical Capital Costs for UV Radiation/Oxidation Systems

Type of Waste	Contaminants	Total Contaminant Concentration	Water Flow Rate (gpd)	Price Range (uninstalled) ($)
Wood treatment wastewater	Pentachlorophenol, phenol	150 ppm	30,000	125,000-150,000
Contaminated groundwater	Pentachlorophenol, phenol	5 ppm	86,400	175,000-200,000
Scrubber wastes	Hydrazines	5,000 ppm	600-1,500	125,000-150,000
Contaminated groundwater	TCE, trans-DCE, methylene chloride	5 ppm	300,000	225,000-275,000
Contaminated groundwater	TCE, TCA, DCA, PCE, methylene chloride, VC	600 ppb	72,000	130,000-150,000
Contaminated groundwater	THF	1 ppm	216,000	250,000-300,000
Wastewater	Phenol	90 ppm	4,300	45,000-55,000

Notes: 1. Assumes cost of electrical energy is $0.06/kWh.
2. DCA: dichloroethane; PCE: tetrachloroethylene; TCA: trichloroethane; TCE: trichloroethylene; THF: tetrahydrofuran; Trans-DCE: trans-dichloroethylene; VC: vinyl chloride.

Appendix C
Site Demonstration Results

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Appendix C
Site Demonstration Results

Introduction

In 1947, Lorentz Barrel and Drum (LB&D) began recycling drums at its facility in San Jose, Santa Clara County, California. Other industrial uses at the site included auto wrecking, roofing and construction, sandblasting, and auto junkyard. Drums for recycling were received from over 800 private companies, as well as military bases, research laboratories, and county agencies in California and Nevada. These drums generally contained residual aqueous wastes, organic solvents, acids, metal oxides, and oils.

As part of normal operations at the site, residual wastes from drums and wastewaters from cleaning drums were disposed of in an on-site drainage ditch. From the ditch, these wastes were routed to a large sump located in the northeast corner of the site. Prior to 1968, wastewater from the sump was discharged to the storm drain system. Sometime between 1968 and 1971, the discharge was diverted to the sanitary sewer. This practice was discontinued between 1983 and 1984; subsequently, liquid wastes were reportedly reduced in volume by evaporation and then drummed and disposed of off-site as hazardous waste (Ebasco, 1988).

In 1987, LB&D ceased operation at the site due to a temporary restraining order from the Santa Clara County District Attorney's Office. Later, the U.S. EPA (Region IX) assumed lead agency responsibility for site remediation and initiated a remedial investigation/feasibility study.

The material presented in this appendix briefly summarizes the work performed during the SITE demonstration and the results presented in the Technology Evaluation Report (EPA, 1989).

Ultrox Technology Evaluation and the SITE Program

The Ultrox UV radiation/oxidation technology was evaluated by Region IX as part of the engineering evaluation/cost analysis of remedial alternatives and through a treatability study. The treatability study was successful in demonstrating that the technology could treat the contaminated groundwater at the LB&D site (Ebasco, 1988).

Ultrox International submitted a proposal under EPA's SITE Program to demonstrate the Ultrox technology at the LB&D facility. Because of the promising results of the treatability study, and because Region IX needed additional data to complete its decision-making for Phase I remediation of groundwater at the site, the Ultrox technology demonstration was put on an accelerated schedule. The field demonstration was conducted from February 24 through March 9, 1989.

Site Characteristics

When LB&D began operating, the site comprised 10.5 acres (Figure C-1). Since then, half of the original property has been sold, resulting in the current L-shaped site which covers 5.25 acres. This area is suspected to contain the highest levels of contamination. The site is surrounded by a chain-link fence to prevent unauthorized access.

The site slopes gently from the southwest to the northeast corner. The highest elevation at the southwest corner is 106 feet, and the lowest point at the northeast corner is 102 feet above mean sea level.

The water table at the site is approximately 20 feet below ground surface (Figure C-2). The actual aquifer thickness, seasonal water table fluctuations, and the hydraulic characteristics of the clay aquitard are unknown. As is typical with water table aquifers, the shallow groundwater flow appears to follow the ground surface topography, flowing northeast toward Coyote Creek, a local watercourse, less than 1/2 mile east of the site.

The climate in the area is characterized by warm, dry summers and cool, wet winters. Annual minimum temperatures are generally a few degrees below freezing, while maximum temperatures in excess of 100°F are common. Normal January and July daily average temperatures are 49.5°F and 68.8°F, respectively. The temperature at the site during the demonstration varied from the upper 50°F to upper 60°F range. Normally, average annual rainfall in the

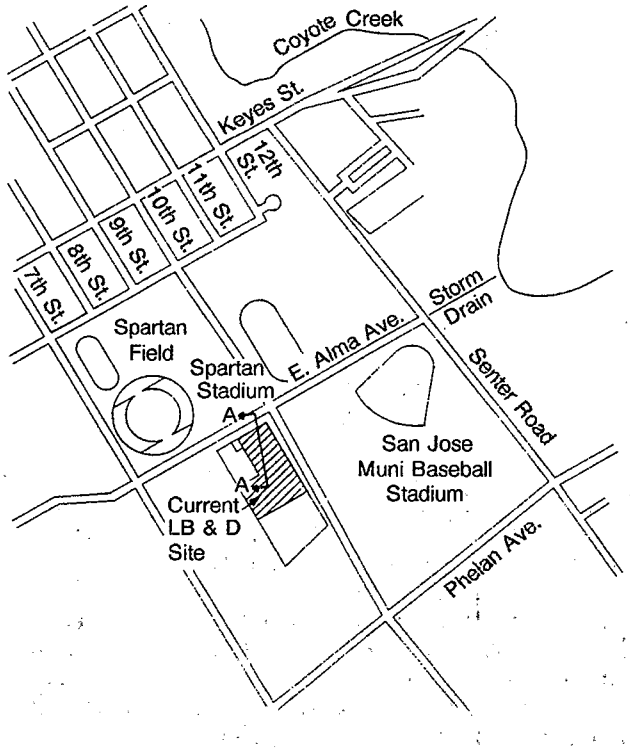

Figure C-1. Lorentz barrel and drum site location.

area is 13.9 inches, most of which occurs from November through April. During the last few days of the demonstration, there was intermittent rainfall at the site.

The LB&D site is located in an area zoned for manufacturing, at the southwest corner of East Alma Avenue and South Tenth Street. The site is located just south of land zoned as residential. This residential zone includes San Jose State University's (SJSU) football stadium (Spartan Field and Spartan Stadium) and recreation fields, as well as the San Jose Municipal Baseball Stadium. SJSU University student housing (the closest residential area) is located about a quarter mile north of the site.

Surface water runoff from the LB&D site is routed to Coyote Creek via a 60-inch diameter storm drain at the corner of East Alma Avenue and South Tenth Street. This drain flows to Coyote Creek under Alma Avenue. A secondary 18-inch storm drain runs northwest under South Tenth Street and connects with the 60-inch diameter storm drain.

Coyote Creek flow rates are regulated by the Coyote and Anderson reservoirs. An average flow rate of 45 cubic feet per second (cfs) has been recorded between 1970 and 1983. A maximum flow rate of 5,000 cfs was recorded in March 1983. Zero flow rate has been recorded for short durations in the fall.

Waste Characteristics

The drum recycling operations over a 40-year period are the principal causes for the site's contaminated groundwater. Remedial investigations carried out by state and Federal agencies from 1983 to 1987 have indicated that the soils and the shallow groundwater at the LB&D site are contaminated with VOCs, pesticides, PCBs, and metals. These investigations have also indicated that groundwater downgradient of the site is contaminated with VOCs (Ebasco, 1988). The organic contaminants measured in the on-site groundwater from 1983 to 1987 range in concentration from 0.2 ppb for chlordane, a pesticide, to 2,108 ppb for TCE, a VOC. Organic contaminants measured in the off-site groundwater range from 0.5 ppb for chloroform to 311 ppb for TCE (Ebasco, 1988).

Remedial activities at the site addressing soil contamination have involved the excavation of four major "hot spot" drainage and sump areas. Activated carbon adsorption and UV radiation/oxidation treatment technologies were evaluated to clean up the groundwater. Since the Ultrox technology is best suited for destroying dissolved organic contaminants, such as chlorinated hydrocarbons and aromatic compounds, found in groundwater or wastewater with low levels of suspended solids, the shallow groundwater at the LB&D site was selected as the waste stream to demonstrate the Ultrox technology.

Groundwater Sampling for the SITE Demonstration

In anticipation of the SITE demonstration, groundwater samples were collected in December 1988 from wells at and near the LB&D site. Samples were collected from three off-site wells and two on-site wells near the location of the technology demonstration. Several VOCs detected at relatively high levels included acetone (160 ppb); 1,1-dichloroethylene (180 ppb); 1,2-trans-dichloroethylene (200 ppb); TCE (920 ppb); and vinyl chloride (240 ppb). VOCs detected in all five wells included 1,1-dichloroethylene; 1,2-trans-dichloroethylene; 1,1,1-trichloroethane (1,1,1-TCA); and TCE. No semivolatiles, PCBs, or uncharacterized pollutants were detected. Based on these results, four extraction wells were installed in the northeastern corner of the site to collect contaminated groundwater for the SITE demonstration.

During the demonstration, influent samples collected during the test runs were analyzed to characterize groundwater contamination and measure removal efficiencies. Laboratory analytical parameters measured during the test runs included the following: VOCs, TOC, metals, semivolatiles, PCBs, and pesticides. Field testing parameters included pH, alkalinity, conductivity, temperature, and turbidity.

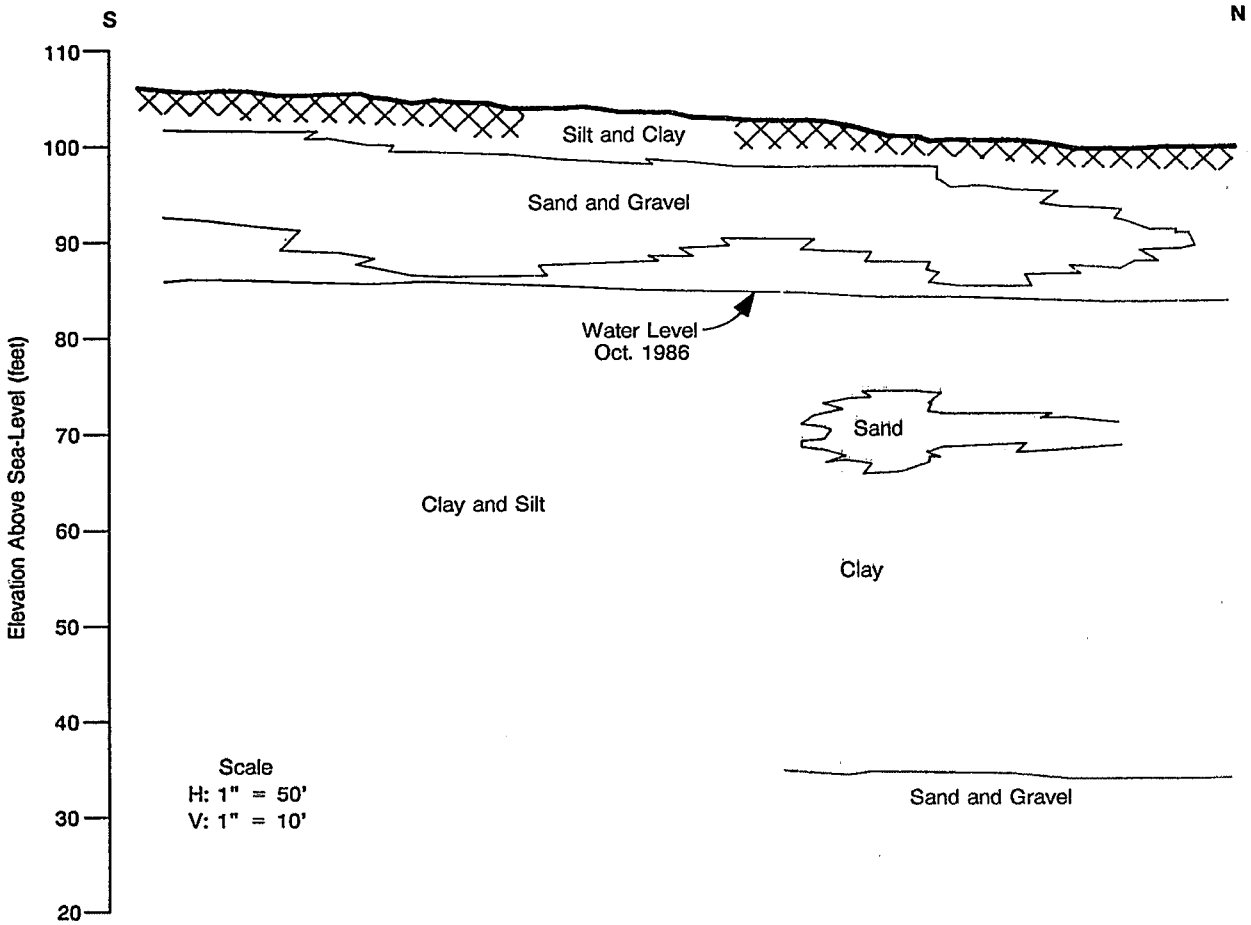

Figure C-2. General geologic cross-section.

The groundwater was contaminated primarily with VOCs such as TCE and vinyl chloride, at levels of 100 and 40 µg/L, respectively. Other VOCs present at relatively low concentrations (in the range of 5 to 15 µg/L) included 1,1-dichloroethane (1,1-DCA), 1,1,1-TCA, 1,2,-dichloroethane (1,2-DCA), benzene, chloroform, and tetrachloroethylene. No PCBs, semivolatiles, or pesticides were detected in the influent. During the demonstration period, there was a 30 to 50 percent decrease in the influent VOC concentrations. This decrease was probably due to VOC volatilization, although bladder tanks were used to minimize the VOC losses.

The TOC concentration of the groundwater was about 25 mg/L. However, the concentration of priority pollutants (VOCs and semivolatiles) was only about 2 percent of the TOC concentration.

During the demonstration, the pH and alkalinity of the groundwater were about 7.2 and 950 mg/L as $CaCO_3$, respectively. These measurements indicated that the bicarbonate ion ($HCO3^-$), which acts as an oxidant scavenger, was present at high levels. Other oxidant scavengers such as bromide, cyanide, and sulfide were not detected. Since the Ultrox technology is based on an oxidation process, any other species present in the contaminated water which consume oxidants were viewed as an additional load for the system.

Review of Technology and Equipment Performance

The technology demonstration was divided into three phases: (1) site preparation (approximately 3 weeks), (2) technology demonstration (approximately 2 weeks), and (3) site demobilization (approximately 3 weeks). The activities and a review of technology and equipment performance during these phases are described below.

Site Preparation

Site preparation included setting up major support equipment, on-site support services, and utilities.

These activities and equipment requirements are described as follows.

To accommodate the demonstration program schedule, Region IX installed four groundwater extraction wells at the LB&D site in January 1989. The wells were necessary to obtain sufficient groundwater from the most contaminated area of the LB&D site for the technology demonstration test runs. Once installed and developed, the four wells were pumped to estimate groundwater yields.

From February 20 to 23, 1989, approximately 13,000 gallons of contaminated groundwater from the LB&D site were collected from the extraction wells. Only three of the four wells installed were needed to obtain the necessary groundwater for the demonstration.

Major Support Equipment

Two 7,500-gallon bladder tanks were used to hold the groundwater collected from the site. These tanks were flexible and made of a synthetic material suitable for potable water storage. The bladder tanks were selected to minimize VOC losses during the test period.

Three dedicated, submersible pumps were used to pump the groundwater into the bladder tanks. The maximum and average pumping rates were approximately 5 and 1 gpm per pump, respectively. The bladder tanks and pumps were connected using piping manifolds so that both tanks could be filled simultaneously. From the bladder tanks, the groundwater was pumped to the Ultrox unit.

A commercial-size (150-gallon) Ultrox unit, Model PM-150, was delivered by truck van. This unit has four skid-mounted modules designed for transport with either a flatbed truck or in an enclosed trailer. The unit was unloaded using a fork lift on February 21, 1989.

A 21,000-gallon storage tank was used to store effluent from the Ultrox system. The tank was steam cleaned prior to delivery to the site. In addition, several 55-gallon, open-top drums were used to store wastewater generated during the sample collection activities, laboratory analyses, and decontamination procedures.

On-Site Support Services

On-site laboratory analyses were conducted in a field trailer. The field trailer also served as an office for field personnel, provided shelter and storage for small equipment and supplies, and acted as a base for site security personnel. Two chemical toilets were located near the trailer.

Although the LB&D site perimeter is enclosed by a fence, a commercial security service was hired to provide additional protection from equipment vandalism during evening hours and weekends.

Utilities

Utilities required for the Ultrox system demonstration included telephone, water, and electricity service. A single telephone line was installed in the trailer. Telephone service was required to order supplies, coordinate site activities, and provide communication. Tap water was required for equipment and personnel decontamination. Water used for equipment and personnel decontamination was provided using existing site pipelines.

Electrical service was connected to the site from a public utility. Electricity was required to operate the Ultrox system, the office trailer, and the laboratory equipment. The Ultrox system required 480-volt, 3-phase electrical service, which was provided through a 100-amp service using a dedicated meter and a transformer. An additional 110-volt, 100-amp service was connected to another dedicated meter to provide power to the office and laboratory trailer.

Technology Demonstration

Approximately 13,000 gallons of contaminated groundwater were treated by the Ultrox system in 13 test runs over a 2-week period, with 1 or 2 test runs performed each day. During this period, there were no significant variations from the proposed demonstration schedule. This section discusses operational and equipment problems and health and safety issues associated with the SITE demonstration.

Operational Problems

During the course of the field demonstration, two operational problems with the electrical power supply were encountered. These problems were a wiring problem discovered during Run 2 which affected electricity measurements and an electrical power shutdown at the end of Run 9, which was caused by a minor accident at the site.

During Run 2, it was discovered that both the trailer and the Ultrox system were inadvertently wired to a common meter. As a result, separate watt-hour meters and service panels were installed for the Ultrox system and the on-site trailer. An electrical subcontractor rewired and set each meter properly, and the electrical energy consumption for the first two runs was estimated by analyzing the power consumed on subsequent runs. Based on the electrical energy consumption observed in Runs 3 to

13, the electrical energy consumption by the trailer appeared to be negligible.

At the end of Run 9, a trailer truck entered the site and accidentally broke the wooden power pole that supported the electric power lines by catching the sagging lines with the trailer. Although the accident did not cause any injury to the people working on-site or damage any equipment, as a precautionary measure, the power was shut off, and the electrical subcontractor was contacted to install a new power pole. A stronger pole was installed and power restored the following morning.

To circumvent this accident, electrical lines could have been buried at the site. Although the cost of the demonstration would have increased, a safer work atmosphere would have been provided. As an alternative, the lines could have been placed clear of any possible transportation routes or elevated to a height necessary to accommodate truck clearance. Portable electrical generators could also have been provided as a backup.

Equipment Problems

During normal operations, the Decompozon unit, which is equipped with a heater, is designed to destroy ozone in the reactor off-gas. After Run 8, however, the heater malfunctioned. As a result, the temperature in the unit, which should normally be 140°F for the unit to function properly, was about 80°F. The effect of this heater failure is reflected in the ozone concentrations in the Decompozon unit exhaust. For Runs 1 through 8 there was greater than 99.9 percent ozone destruction, and ozone concentrations in the exhaust were quite low (<0.1 ppm). However, ozone concentrations in the exhaust were approximately 1 ppm for Runs 9 and 10, and greater than 10 ppm for Runs 11, 12, and 13.

At its permanent installations, Ultrox incorporates interlocks for emergency automatic shut-off of the treatment unit if the heater fails so that operating personnel will not be exposed to ozone even for short periods. This feature should be incorporated at other similar demonstrations.

Health and Safety Considerations

Work zones were established to minimize the transfer of hazardous materials and contaminated debris from potentially contaminated areas to "clean" areas at the site. For the demonstration, the contaminant reduction zone was combined with the exclusion zone. The work zone contained the Ultrox system and associated equipment, power connections, 55-gallon drums used to separately store wastewater and contaminated debris, the two 7,500-gallon bladder tanks, and the 21,000-gallon steel storage tank used for effluent wastewater storage.

In general, health hazards associated with the demonstration resulted from exposure to the contaminated groundwater. Although the treatment system was entirely closed, the potential routes of exposure during the demonstration were inhalation, ingestion, and skin and eye contact from possible splashes or spills during sample collection.

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

Equipment Demobilization

Groundwater remaining in the bladder tanks after the final test run was treated by the Ultrox system and pumped to the effluent storage tank. Similarly, miscellaneous liquid wastes which had been stored in 55-gallon drums during the test period were treated by the Ultrox system and pumped to the storage tank. These miscellaneous liquids consisted of well development water, excess sample volumes generated during sampling operations, and spent chemical reagent wastes produced from on-site laboratory analyses.

All effluent was temporarily stored in the tank prior to discharge. After the effluent was analyzed to ensure that it met the applicable NPDES standards, it was discharged into a storm drain which emptied into Coyote Creek, a nearby waterway. All collected effluent was held for approximately 2 weeks before discharge, awaiting laboratory test results.

Contaminated materials, such as empty sample containers, laboratory wastes, and disposable protective equipment generated during the demonstration, were placed in a 55-gallon, open-top drum. These materials contained only residual contamination. During the demobilization phase, the wastes were packaged and stored before being disposed of off-site by Region IX.

The Ultrox unit was loaded on a trailer truck and transported to another site to treat contaminated groundwater.

Review of Treatment Results

The demonstration was designed to evaluate the Ultrox technology by controlling the system's five operating parameters: hydraulic retention time, ozone dose, hydrogen peroxide dose, UV radiation intensity, and influent pH level. During the test runs, these operating parameters were varied and the system's performance was evaluated under each resulting set of operating conditions.

VOCs were selected as the critical parameters for evaluating the effectiveness of the Ultrox technology, because the Ultrox technology was developed primarily to treat organics (such as VOCs, semivolatiles, and PCBs/pesticides). Of these organics, only VOCs were found in the groundwater samples collected in December 1988. As such, the performance of the Ultrox system for each test run was evaluated based on its effectiveness at removing indicator VOCs.

The three indicator VOCs selected were TCE, 1,1-DCA, and 1,1,1-TCA. TCE was selected because it is a major volatile contaminant at the site, and the latter two VOCs were selected because, from Ultrox's experience, they are relatively difficult to oxidize. Only three indicator VOCs were selected because of analytical time constraints to perform the tests over the 2-week period. Full VOC analyses were also performed for all test runs following completion of the demonstration.

To assess the effectiveness of the technology performance, the concentration of total VOCs was estimated by adding the concentration of each VOC. Since this study only uses the total VOC data for qualitative interpretation, this approach is considered practical and useful from an engineering perspective.

"Preferred" Operating Conditions

As part of the technology demonstration, the system's performance during Runs 1 through 11 was evaluated to determine "preferred" operating conditions, given the nature of contaminated groundwater at the site. For the Ultrox technology demonstration, the "preferred" operating conditions were defined as the set of operating parameters where the effluent concentrations of indicator VOCs were below their respective NPDES limits and the relative operating costs were the lowest.

The initial operating conditions selected for Run 1 were expected to approximate optimum operating conditions, based on the results of the groundwater treatability study. From Run 1, the selection of operating conditions for Runs 2 to 11 proceeded in an interactive manner, with the results of previous runs setting operating conditions for subsequent runs.

To set operating conditions for subsequent runs, the results from the overnight analysis of one-third of the previous run's samples were evaluated. Specifically, only two of the six replicate samples collected at each of the three liquid sampling locations (influent, midpoint, and effluent of the reactor) were analyzed overnight by gas chromatography (GC), for the three indicator VOCs. Only one-third of the samples could be analyzed overnight, due to analytical time constraints.

Based on the analyses of two replicate VOC samples for each of the first 11 runs, only Runs 8 and 9 had average effluent concentrations of indicator VOCs that were below their respective NPDES limits. Of Runs 8 and 9, a lower hydrogen peroxide dose was used in Run 9. As a result, the operating conditions for Run 9 were determined to be the "preferred" operating conditions. These conditions included a hydraulic retention time of 40 minutes, ozone dose of 110 mg/L, hydrogen peroxide dose of 13 mg/L, all 24 UV lamps (at 65 watts each) operating, and influent pH of 7.2 (unadjusted).

Subsequently, Runs 12 and 13 were performed using the "preferred" operating conditions determined from Run 9. The results from these latter two test runs were used to evaluate if performance levels were reproducible. A summary of the results for reproducible runs is presented in Table C-1.

Table C-1. Performance Data for Reproducible Runs

	Mean Influent (µg/L)	Mean Effluent (µg/L)	Percent Removal
Run 9			
TCE	65	1.2	98
1,1-DCA	11	5.3	54
1,1,1-TCA	4.3	0.75	83
Total VOCs	170	16	91
Run 12			
TCE	52	0.55	99
1,1-DCA	11	3.8	65
1,1,1-TCA	3.3	0.43	87
Total VOCs	150	12	92
Run 13			
TCE	49	0.63	99
1,1-DCA	10	4.2	60
1,1,1-TCA	3.2	0.49	85
Total VOCs	120	20	83

After the demonstration, complete analyses of all replicate samples from the 13 test runs were performed. From these results, the mean concentration of 1,1-DCA in the effluent of Run 9 was actually found to be slightly higher than 5 µg/L, the discharge standard for the compound. However, these

results were not available until after the demonstration. Operating conditions for Run 9 are still considered to be "preferred" since the mean effluent concentration was quite close to the discharge standard.

Quantifiable Results

The Ultrox process achieved removal efficiencies (RE) as high as 90 percent for the total VOCs present in the groundwater at the LB&D site. Based on the data for individual VOCs, REs for TCE were greater than 99 percent, and REs for 1,1-DCA and 1,1,1-TCA were as high as 65 and 85 percent, respectively.

The REs for the three indicator VOCs were dependent on the operating conditions. For example, the REs for the three indicator VOCs generally decreased considerably in Run 7. This decrease was most likely due to the decreased ozone dose in that run.

In Runs 9, 12, and 13, which were all run at the "preferred" operating conditions, the REs for each indicator VOC did not differ. That is, the technology performance levels were reproducible under the same operating conditions. In general, the REs for TCE were higher than those for 1,1-DCA and 1,1,1-TCA. This is expected, since 1,1-DCA and 1,1,1-TCA were selected intentionally because they are relatively difficult to oxidize.

A comparison of the 95 percent upper confidence limit (UCL) values for effluent VOC concentrations in Runs 12 and 13 with the discharge standards indicated that the effluent met the discharge standards for all regulated VOCs. However, in Run 9, the effluent did not meet the discharge standards for 1,1-DCA and 1,2-DCA. This difference in performance among Runs 9, 12, and 13 is negligible and may be attributed to the higher influent VOC concentrations in Run 9 than in Runs 12 and 13. Since the mean effluent VOC concentrations of 1,1-DCA and 1,2-DCA are higher than the discharge standard, statistical inferences at other confidence levels (such as 90 percent) will not be different.

VOC Removal Due to Stripping

The potential for VOC removal due to stripping was evaluated since ozone gas was bubbled through the groundwater treated by the Ultrox system. The VOC air sampling data indicated that stripping contributed significantly to the total removal, (chemical oxidation plus stripping) of 1,1,1-TCA and 1,1-DCA. Specifically, stripping accounted for 12 to 75 percent of the total removals for 1,1,1-TCA, and for 5 to 44 percent of the total removals for 1,1-DCA.

For compounds such as TCE and vinyl chloride, stripping accounted for less than 10 percent of the total removal, as oxidation was found to be the major removal mechanism. For other VOCs such as 1,1-dichloroethylene, 1,2-dichloroethylene, benzene, acetone, and 1,1,2,2-tetrachloroethane, stripping was negligible since only occasional traces of these compounds were detected in the off-gas.

Final Products of the Treatment Process

The developer claims that the final products of the oxidation of organic compounds in water are salts, water, carbon dioxide, and possibly some organic products. However, during the demonstration, no significant TOC removals were achieved in the treatment system, which implies that only partial oxidation occurred; as such, the predominant final products were not carbon dioxide and water. In addition, since no new VOCs were found by GC and GC/mass spectrometry (MS) analysis of the effluent, the final oxidation products do not appear to be new VOCs. Instead, the final products may be organic acids, which were analyzed as TOC in the TOC analysis. Neither semivolatiles nor PCBs/pesticides were detected in the effluent. Consequently, the Ultrox unit did not generate any of these compounds.

Metals such as iron and manganese were detected in the influent at low concentrations. After treatment, no significant metal removal was observed.

Field Parameters

Field parameters measured during the test runs included pH, alkalinity, conductivity, temperature, and turbidity. The effect of the treatment process on field parameters are described below.

The pH increased by 0.5 to 0.8 units after treatment. The pH increase indicates that partial oxidation of organics occurred to produce organic acids and that complete oxidation to CO_2 did not occur, which would result in a pH decrease. However, the pH increase is not surprising because the groundwater had high alkalinity and an initial pH of about 7.2, at which the predominant form of alkalinity was bicarbonate. The reaction of hydroxyl radicals with bicarbonate or carbonate ion yields hydroxyl ions (Hoigne and Bader, 1975). The production of hydroxyl ions due to this reaction would have caused an increase in pH. No change in alkalinity was observed after the treatment.

The temperature increased by approximately 2 to 3 degrees Celsius after the treatment. This increase was mainly due to the heat from the UV lamps and not the oxidation of organics, because the temperature increase was higher than usual when the hydraulic retention time was increased from 40 minutes to 1 hour (Run 5), and the increase was not observed in Runs 10 and 11 when the UV lamps were used in only three chambers.

Turbidity usually increased by 1 to 4 units (NTU) after the treatment. This slight increase in turbidity may be due to the limited removal of metals by metal oxidation and precipitation. No change in conductivity was observed after the treatment.

Performance of the Decompozon Unit

The Decompozon unit destroyed ozone in the Ultrox reactor off-gas to levels less than 0.1 ppm (OSHA standards). The ozone destruction efficiencies were observed to be greater than 99.99 percent.

Although the primary function of the Decompozon unit is to remove ozone, significant VOC removals occurred in the Decompozon unit when it functioned as designed (Runs 1 through 8). Specifically, volatile organics present in reactor off-gas at levels of approximately 0.1 to 0.5 ppm were reduced to below detection levels in the Decompozon unit before air was discharged to the atmosphere.

Electrical Energy Consumption

The average electrical energy consumption during the demonstration was about 11 kWh/hour of operation. It was noted that the electrical energy consumption was higher in Run 7 (38 mg/L ozone dose) than that in Run 6 (110 mg/L ozone dose), which is contrary to what would be expected. This result cannot be explained.

Accomplishing the Goals of the Technology Demonstration

In addition to meeting the general objectives of the SITE Program during the Ultrox technology demonstration, four specific goals were identified to serve the needs of both the SITE Program and Region IX. These four goals, and an evaluation of how they were met, are discussed as follows.

1. Demonstrate the ability of the Ultrox system to treat VOCs present in the groundwater at the LB&D site.

   The Ultrox system successfully treated VOCs present in the groundwater at the LB&D site to meet regulatory discharge standards. REs as high as 90 percent were achieved for the total VOCs present in the groundwater at the LB&D site. Specifically, for the three indicator VOCs, REs for TCE were greater than 99 percent, and REs for 1,1-DCA and 1,1,1-TCA were as high as 65 and 85 percent, respectively.

2. Evaluate the efficiency of the ozone decomposer unit in treating ozone in the reactor off-gas.

   The Decompozon unit destroyed ozone in the Ultrox reactor off-gas to levels less than 0.1 ppm (OSHA standards). The ozone destruction efficiencies were observed to be greater than 99.99 percent.

3. Develop capital and operating costs for the Ultrox system that can be used in Superfund decision-making processes at other sites.

   The cost of conducting the Ultrox technology demonstration was approximately $633,000. This cost includes site characterization and preparation, demonstration planning and field work, chemical analyses, and report preparation. The developer's portion of this cost was $23,000 and the balance of $610,000 was allocated to the SITE Program. The cost of the Ultrox unit used in the demonstration was approximately $140,000.

4. Develop information useful to Region IX for site remediation.

   The SITE demonstration provided additional data that will assist Region IX in completing its decision-making for Phase I remediation of groundwater at the LB&D site. Specifically, as a result of the demonstration, the contaminated groundwater was further characterized, and actual information regarding the "preferred" operating parameters for the Ultrox system was obtained.

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Appendix D
Case Studies

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Appendix D
Case Studies

Introduction

This appendix summarizes several case studies on the use of the Ultrox UV radiation/oxidation process. These cases involve pilot-scale units as well as full-scale operating units treating contaminated groundwater and industrial wastewaters. No data on VOC stripping are available from any of these case studies. The information provided for these studies varied widely with scant data available for some operations and comprehensive analytical and economic information for others. This appendix summarizes the following case studies:

Case Study	Facility and Location
D-1	Department of Energy, Kansas City Plant, Missouri
D-2	Hewlett Packard Facility, Palo Alto, California
D-3	FEI Microwave, Sunnyvale, California
D-4	Golf Course, City of South Gate, California
D-5	Xerox Facility, Webster, New York
D-6	Koppers Industries, Denver, Colorado
D-7	General Electric Company, Lanesboro, Massachusetts

Case Study D-1, Department of Energy, Kansas City Plant, Missouri

Introduction

This case study presents the results of full-scale testing of an Ultrox unit at the Allied-Signal facility in Kansas City, Missouri. The testing is currently being performed under contract by the U.S. Department of Energy. Over the years, the operation of the facility has resulted in the contamination of groundwater by total organic halogens (TOX), including trichloroethylene (TCE). One of the contaminated groundwater plumes, the tank farm plume, was selected for remediation using UV radiation, ozone, and hydrogen peroxide. Since this process is new and information on its performance, costs, and operating experience is not documented, the Oak Ridge National Laboratory was requested to evaluate the treatment process.

Testing began during 1988, and the project is scheduled to continue into 1990. Data from the first year's effort are presented in a report prepared by the Oak Ridge National Laboratory (Garland II, 1989). The report discusses the mechanisms involved in the treatment process, describes the treatment plant, presents the testing methodology, evaluates the results, and offers recommendations. Portions of this appendix are taken directly from the report.

Plant Description

Based on results of bench-scale studies conducted by Ultrox, a 725- gallon reactor, divided by baffles into 6 stages, was selected to treat the site groundwater at a flow rate of 25 gpm. Ozone is supplied by a generator capable of producing 21 lb per day at 2 percent ozone by weight. The air dryer provides clean, dry air to the ozone generator at 12-15 psig.

The reactor is equipped with 72 quartz-sheathed, low-pressure, 65-watt UV lamps located throughout the reactor chamber. The lamps are arranged in rows of 6, with 12 lamps in each stage. In addition, each stage is equipped with a sight glass and a sample port.

Up to 50 pounds per day of hydrogen peroxide can be supplied from either of two 55-gallon storage drums. The hydrogen peroxide is mixed with the influent groundwater with an in-line static mixer.

Three wells are used to extract contaminated groundwater from the tank farm plume at a rate of approximately 6 gpm. To enhance performance by reducing loads on the equipment, one in-line cartridge filter is located on the influent line. Following treatment, the plant effluent is discharged into Kansas City's municipal sewer system.

Methodology

The performance evaluation tests were conducted in accordance with a study plan that included monitoring the plant performance, determining the operation and maintenance costs for the plant, comparing the costs with other technologies, evaluating contaminant removal mechanisms, and assisting in optimization of the process. Initially, the treatment plant was operated in a batch mode so that all of the effluent could be contained and analyzed prior to discharge. Four batch tests were performed to demonstrate that the effluent criteria could be met. The parameters monitored during these tests included pH, biochemical oxygen demand, total suspended solids, oil and grease, 13 inorganics, 34 organics, and total organic halogens.

Following the batch tests, the treatment plant was operated in a continuous, flow-through mode with different samples collected at various frequencies. The monitoring plan for the flow-through mode showing the frequencies, parameters, and sample locations is shown on Table D-1-1.

Table D-1-1. Groundwater Treatment Plant Monitoring Plan, Flow-Through Mode

Frequency	Parameter[a]	Sample Locations[b]
Continuous	pH	E
	Flow	IBF
Daily	BOD	IBF, IAF, E
	TSS	IBF, IAF, E
Weekly	Sulfate	IBF, IAF, E
	Sulfite	IBF, IAF, E
	Sulfides	IBF, IAF, E
	Nitrate	IBF, IAF, E
	Nitrite	IBF, IAF, E
	Ammonia	IBF, IAF, E
	Ferrous ion	IBF, IAF, E
	Manganous ion	IBF, IAF, E
	TOX	IBF, IAF, E, RC
	VOC	IBF, IAF, E, RC
	TOC	IBF, IAF, E, RC
	Iron	IBF, IAF, E
	Manganese	IBF, IAF, E
Monthly	Cadmium	IBF, IAF, E
	Chromium	IBF, IAF, E
	Copper	IBF, IAF, E
	Lead	IBF, IAF, E
	Nickel	IBF, IAF, E
	Zinc	IBF, IAF, E
	Boron	IBF, IAF, E
	Arsenic	IBF, IAF, E
	Oil and grease	IBF, IAF, E
	Total cyanide	IBF, IAF, E
	Total plate count	IBF, IAF, E
	Off-gas TOX	Tap
One Time	Calcium	IBF, IAF, E
	Magnesium	IBF, IAF, E
	Sodium	IBF, IAF, E
	Potassium	IBF, IAF, E
	Chloride	IBF, IAF, E
	Fluoride	IBF, IAF, E
	Phosphate	IBF, IAF, E
	Carbonate	IBF, IAF, E
	Bicarbonate	IBF, IAF, E

Notes: [a] Parameters: BOD—biochemical oxygen demand; TSS—total suspended solids; TOX—total organic halogens; VOC—volatile organic compounds; TOC—total organic carbon.
[b] Sample Locations: E—effluent; IBF—influent before filter; IAF—influent after filter; Tap—gas vent from reaction chamber; RC—all six stages in reaction chamber.

Results

Batch Operations

The results of the batch operations for TOX indicate that the influent had been adequately treated to meet the discharge standard after passing the first chamber. Most of the VOCs in the effluent were reported at concentrations below detection limits. The process of filtering the influent reduced all measured VOCs to less than reportable values in three of the four batch runs. Table D-1-2 contains the average results from all four batch runs for a variety of parameters that are listed in the plant's discharge permit.

Flow-Through Operations

Although the test protocol examined numerous parameters, only a few of the results are presented in this discussion. The flow data for the treatment plant are presented in Table D-1-3. Tables D-1-4 and D-1-5 contain the TOX and VOC results, respectively. Samples were collected of the influent, before and after the filter, of the effluent, and at all six sample ports. The values are monthly averages of weekly grab samples except for the single 24- hour composite effluent sample collected once a month for TOX.

Costs

In general, cost data only reflect the period of time that the plant was treating groundwater in the flow-through mode of operations. During this period, the costs totaled approximately $8,600 for routine sampling and analysis, electricity, filters, and hydrogen peroxide. An additional $65,500 was spent during the entire testing program for sampling and evaluation. The capital costs for the bench scale study, pilot plant study, and construction of the treatment plant were $304,000. Considering only the operation and maintenance costs of $8,600 and the total volume of 586,000 gallons of groundwater treated during the 5-month flow-through mode, the cost per volume treated is approximately $15 per 1,000 gallons.

Operations

When the plant was operating in the flow-through mode, several shutdowns occurred. From May through September the plant was shut down nearly 50 days primarily due to excessive ozone in the exhaust or due to the necessity of cleaning or

Table D-1-2. Groundwater Treatment Plant, Batch Results[a]

Parameter	Unfiltered Influent (mg/L)	Effluent Stage 1 (mg/L)	Effluent Stage 6 (mg/L)	Standard (mg/L)
BOD[b]	6	3	2.5	--
Chloride	45	--	8.0	--
pH	6.9	8.3	8.1	6-10
TSS[b]	230	382	71	--
Sulfide	0.3	<0.1	<0.1	10.0
Arsenic	0.006	0.048	0.015	0.25
Barium	--	0.23	--	--
Boron	2.11	0.30	0.19	1.0
Cadmium	0.007	0.004	0.009	0.69
Chromium	0.016	0.065	0.047	2.77
Copper	0.67	0.067	0.12	3.38
Iron	47.6	32.5	15.3	100
Lead	0.63	0.05	0.042	0.69
Manganese	5.07	13.6	6.8	20.00
Nickel	0.022	0.043	0.023	3.98
Zinc	3.81	0.49	0.34	2.61
Cyanide	<0.001	<0.001	<0.001	2.0
Oil and grease	6.5	0.7	0.6	10

Notes: [a] These are average values for the four batch tests.
[b] BOD—biochemical oxygen demand; TSS—total suspended solids.

Table D-1-3. Groundwater Treatment Plant Flow Data

Month	Flow (gal)	Flow Rate (gpm)	Percentage of Design Flow[a]
May	145,760	5.9	24
June	133,041	5.4	22
July	92,929	5.4	22
August	157,080	7.3	29
September	57,652	10.0	40
Average	117,292	6.8	27

Note: [a] The design flow rate is 25 gpm.

replacing the spargers. On the average, an operator at the plant spent an hour a day on monitoring and maintenance.

Conclusions and Recommendations

The effluent standards were met consistently, and the VOCs were eliminated in the reaction chamber. However, the TOX concentrations in the plant effluent were higher than those in the sixth stage of the reaction chamber, and the TOX removal was not as high as expected. Since the flow rate was approximately 27 percent of the design flow rate, while the operating parameters varied from 50 percent to full treatment capacity, higher removals of TOX were anticipated.

A demand on the treatment chemicals was exerted by ammonia, ferrous ion, manganous ion, and bacteria as well as by the VOCs.

A pretreatment system is an important aspect of the treatment plant to reduce ozone demand by removing scavengers and to minimize the downtime caused by clogged ozone diffusers. Precipitation in the reaction chamber, coating of the UV lamps, and frequent replacement of the prefilter increased the operation and maintenance time over that expected. The plant was out of operation 30 percent of the time, primarily due to excessive ozone in the exhaust or for maintenance and repair.

Operation and maintenance costs are much higher than those predicted. The report also suggests that the economic analysis should include costs associated with personnel maintenance and monitoring as well as those costs incurred by regulatory compliance monitoring.

Case Study D-2, Hewlett Packard Facility, Palo Alto, California

Introduction

This case study describes Ultrox's UV radiation/oxidation project that took place at the Hewlett Packard facility in Palo Alto, California, in the fall of 1988. The pilot study project was part of the state's Department of Health Services grant to demonstrate the removal of toxic organic compounds such as benzene, toluene, xylene (BTX), and ethylbenzene from the groundwater. Organic compounds such as these are solvents typically used in electronic and other manufacturing facilities.

Groundwater contamination at the Hewlett Packard facility was discovered in 1982 and was traced to leaking underground chemical storage tanks. In 1988, a GAC filter system was installed to treat groundwater from three wells.

Plant Description

To accommodate the existing GAC treatment system, the Ultrox unit was installed upstream of the carbon filters so that the usual treatment system could operate when the Ultrox unit, was not being tested. A security fence was erected to protect the equipment from tampering, and a tent was provided to shelter the equipment from inclement weather.

Prior to treatment, groundwater was stored in a 450-gallon tank where some volatilization could have occurred. After the water was treated by the Ultrox reactor, it was pumped through the GAC system and discharged into a sewer.

Methodology

The main objective of this pilot demonstration was to meet the same discharge limitations as specified by regulatory agencies. These requirements were to reduce the level of total toxic organics (TTO) to less than 1,000 µg/L with no specific constituent greater than 750 µg/L and to reduce the BTX, 1,1,1-TCA, and 1,2-DCA contaminants to less than 5 µg/L.

Table D-1-4. Groundwater Treatment Plant Total Inorganic Halogen Results

	Total Inorganic Halogens (mg/L)[a]											
			Reaction Chamber Stages						Effluent		% Removal[b]	
Month	IBF[c]	IAF[c]	1	2	3	4	5	6	Grab	Comp.	Grab	Comp.
May	0.351	0.304	0.159	0.087	0.134	0.094	0.063	0.067	0.073	0.090	76	70
June	0.383	0.218	0.107	0.064	0.061	0.052	0.042	0.028	0.064	0.085	71	61
July	0.186	0.173	0.110	0.100	0.087	0.110	0.061	0.051	0.040	0.048	77	72
August	0.296	0.340	0.188	0.141	0.069	0.062	0.059	0.053	0.081	0.147	76	60
September	0.318	0.268	0.177	0.145	0.110	0.114	0.103	0.095	0.120	--	55	--
Average	0.307	0.261	0.148	0.107	0.092	0.086	0.066	0.059	0.076	0.09	71	66
Standard	NA[c]	NA	NA	NA	NA	NA	NA	NA	0.16	0.16	NA	NA

Notes: [a] All samples are weekly grab samples (averaged monthly) except for the composite effluent sample, which is a single 24-hour composite sample.
[b] Percent removal values use the IAF values for initial concentrations.
[c] IBF = influent before filter; IAF = influent after filter; NA = not applicable.

Table D-1-5. Groundwater Treatment Plant VOC Results

	Volatile Organic Compounds (mg/L)[a]								
			Reaction Chamber Stages						
Parameter	IBF[b]	IAF[b]	1	2	3	4	5	6	EFF[b]
Chloromethane	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010
Bromomethane	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010
Vinyl Chloride	0.015	0.010	0.010	<0.010	0.010	0.010	0.010	0.010	0.010
Chloroethane	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010
Methylene Chloride	0.021	0.007	0.016	0.014	<0.005	<0.005	<0.005	<0.005	<0.005
Acetone	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Carbon Disulfide	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
1,1-Dichloroethylene	0.014	0.017	0.005	0.005	<0.005	<0.005	<0.005	<0.005	<0.005
1,1-Dichloroethane	0.019	0.020	0.010	0.007	0.006	<0.005	<0.005	<0.005	<0.005
1,2-Dichloroethylene (Total)	0.714	0.856	0.113	0.034	0.011	0.008	<0.005	<0.005	<0.005
Chloroform	0.007	0.006	0.005	0.006	0.005	<0.005	<0.005	<0.005	<0.005
1,2-Dichloroethane	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
2-Butanone	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
1,1,1-Trichloroethane	0.014	0.013	0.008	0.006	<0.005	<0.005	<0.005	<0.005	<0.005
Carbon Tetrachloride	<0.005[c]	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Vinyl Acetate	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Bromodichloromethane	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
1,2-Dichloropropane	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
cis-1,3-Dichloropropene	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Trichloroethylene	0.520	0.573	0.088	0.025	0.008	0.006	<0.005	<0.005	<0.005
Dibromochloromethane	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
1,1,2-Trichloroethane	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Benzene	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
trans-1,3-Dichloropropene	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Bromoform	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
4-Methyl-2-pentanone	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
2-Hexanone	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Tetrachloroethylene	0.042	0.050	0.011	0.005	<0.005	<0.005	<0.005	<0.005	<0.005
7,1,2,2-Tetrachloroethane	<0.005	<0.005	<0.005	0.005	0.005	0.005	0.005	0.005	0.005
Toluene	0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Chlorobenzene	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Ethylbenzene	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Styrene	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Xylene (Total)	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005

Notes: [a] Values are averages for all analyses performed from May through August 1988. No analyses were performed in September. All samples were weekly grab samples.
[b] BF—influent before filter; IAF—influent after filter; EFF—effluent.
[c] Carbon tetrachloride was below detectable limits in all analyses except one, in which it was at the detectable limit (0.005 mg/L).

The results of analytical testing on the three extraction wells used to collect the groundwater are shown on Table D-2-1. From this list of compounds, benzene, ethylbenzene, xylene, and toluene were selected for further examination in the pilot study because they had higher concentrations than 1,2-

Table D-2-1. Groundwater Quality Results for Extraction Well Sampling

Sample Location	Date	Acetone[a]	1,2-DCA[a]	TCE[a]	Benzene[a]	Toluene[a]	Xylenes[a]	Ethyl-benzene[a]	TPH[a]
EW-1	1-19-88	34,000	510	260	7,800	1,200	2,300	ND[b]	NA[c]
	1-20-88	27,000	440	ND	6,900	1,100	2,000	ND	NA
	1-21-88	28,000	380	ND	6,100	830	1,800	ND	NA
	2-19-88	43,000	310	ND	4,400	730	1,100	ND	NA
EW-2	1-19-88	28,000	870	890	8,100	1,800	2,200	ND	NA
	1-20-88	15,000	820	890	7,900	1,900	1,900	ND	NA
	1-21-88	19,000	830	980	8,000	1,700	1,900	ND	NA
	2-19-88	62,000	480	1,500	5,800	1,400	1,200	ND	NA
Well No. 29	1-19-88	ND	350	ND	7,400	7,500	4,000	ND	NA
	1-20-88	5,100	350	ND	6,900	7,700	3,300	580	NA
	1-21-88	44,000	450	ND	7,800	8,700	3,600	640	NA
	2-19-88	23,000	710	ND	12,000	11,000	4,600	720	NA
Combined Influent	2-19-88[d]	43,,000	420	460	6,100	2,800	1,800	140	NA
	3-22-88	61,000	ND[e]	ND[e]	5,000	ND[e]	ND[e]	ND[e]	NA
	4-07-88	35,000	ND[e]	ND[e]	4,100	2,000	ND[e]	ND[e]	3,000
	4-19-88	51,000	290	460	3,800	1,900	1,300	ND	6,000
	5-24-88	36,000	ND[e]	ND[e]	3,200	ND[e]	ND[e]	ND[e]	NA

Notes: [a] Concentrations reported in ppb.
[b] Not detected above reporting limit.
[c] Not analyzed.
[d] Weighted average based on individual extraction well flow rates and concentrations.
[e] Reporting limit greater than 1,000 ppb due to sample dilution.

DCA and 1,1,1-TCA, and because they oxidize faster than acetone and total petroleum hydrocarbon (TPH). Also, neither acetone nor TPH were being regulated.

Twelve tests were conducted over a 2½-week period with 2 or 3 test runs each day. The samples were analyzed the day after the test runs. The initial test was conducted with the Ultrox unit operating in a batch mode to determine the retention time and oxidant dosage required. Based on these results, subsequent runs were performed in a continuous, flow-through operation.

Results

Batch Operations

The operating conditions and analytical results of the initial batch test are shown on Table D-2-2. The contaminants were easily oxidized in the first 15 minutes with contaminant removals exceeding 99 percent. The concentration of the influent TTO was 3,935 ppb while the treated effluent concentration was 14 ppb after 15 minutes. Thus, the upper discharge limit of 1,000 ppb could be achieved in under 15 minutes; the lower discharge limit of 5 ppb would require about 30 minutes of treatment.

Flow-Through Operations

The operating conditions for test runs 2 through 12 are presented on Table D-2-3. The analytical results for these test runs are shown on Table D-2-4. The tests were conducted to examine removal efficiencies with the Ultrox reactor operating with various oxidant dosages. For instance, Tests 2 and 3 demonstrate differences between UV radiation/ozone and UV radiation/ozone/hydrogen peroxide when using approximately the same total dosage of oxidant. Tests 5 and 6 distinguish the difference between UV radiation/ozone and UV radiation/hydrogen peroxide oxidation. Test 7 retained the same oxidant dosages as in Test 6 but reduced the UV lamps by 50 percent. Tests 6, 8, and 10 examined the effects of various oxidants and Tests 8 through 11 examined the effects of different retention times. Finally, Test 12 was performed to demonstrate that the Ultrox UV radiation/oxidation system was capable of reducing the volatile TTO level to less than 5 µg/L for each constituent from the initial concentration of nearly 11,000 µg/L. Test 3 also achieved this performance but the influent concentration was approximately 4,000 µg/L.

Costs

The direct operating and maintenance costs for oxidants were estimated for Tests 2 through 12 with the Ultrox unit operating in the continuous mode. The costs per 1,000 gallons of groundwater treated are shown on Table D-2-5. These costs do not include costs associated with any operator who oversees the equipment nor do they include such items as amortization costs of the equipment or replacement of filters or spargers, or analytical testing. The budgetary capital costs for the Ultrox UV radiation/oxidation equipment to treat groundwater at this facility are between $105,000 (5 gpm) and $120,000 (20 gpm) (not installed).

Table D-2-2. Operating Conditions and Analytical Results for Test Run 1 (Batch)

Operating Conditions					
Contact Time (min)	0	15	30	45	60
Reactor Volume (gal)	--	150	150	150	150
Gas Flow Rate (scfh) (Ozone 2%)	--	115	115	115	115
Ozone Dosage (mg/L)	--	116	233	349	466
Percent UV Lamps	--	100	100	100	100
Laboratory Analysis					
Benzene (µg/L)	2,250	8	0	0	0
Toluene (µg/L)	540	2	2	2	2
Ethylbenzene (µg/L)	69.5	2	2	0	0
Xylene (g/L)	1,075	2	2	0	0
Total	3,934.5	14	6	2	2
Total Removal (%)	--	99.64	99.85	99.95	99.95

Table D-2-3. Operating Conditions for Test Runs 2 through 12 (Continuous)

Test Number	2	3	4	5	6	7	8	9	10	11	12
Flow Rate (gpm)	5	5	5	5	5	5	5	7.5	6	4	5
Retention Time (min)	30	30	30	30	30	30	30	20	25	37.5	30
Ozone Flow Rate (scfh)	90	45	68	45	45	45	40	60	50	30	60
Ozone (wt %)	2.16	2.16	2	0	2.16	2.15	2.05	2.01	2.04	2.05	2.02
Ozone Dosage (mg/L)	98.29	49.14	68.76	0.00	49.14	48.92	41.46	40.65	42.98	38.87	61.28
H_2O_2 Rate (mL/min)	0.00	2.00	0.0	4.00	2.00	2.00	1.70	2.70	2.14	1.47	2.76
H_2O_2 Dosage (mg/L)	0.00	44.39	0.00	88.77	44.39	44.39	37.73	39.95	39.58	40.78	61.25
Total Oxidants (mg/L)	98.29	93.53	68.76	88.77	93.53	93.30	79.19	80.60	82.55	79.65	122.53
Percent UV Lamps On	100	100	100	100	100	50	100	100	100	100	100

Table D-2-4. Analytical Results for Test Runs 2 through 12 (Continuous)

Test Number		2	3	4	5	6	7	8	9	10	11	12
Benzene	- Influent	2,250	2,250	2,250	4,400	4,400	4,400	4,400	4,400	4,400	4,400	4,400
	- Effluent	0	0	6	137.5	23	80	44	143.2	115	85	0
Toluene	- Influent	500	520	520	3,800	3,800	3,550	3,550	3,550	3,550	3,300	3,300
	- Effluent	2	1	2	88.5	8.5	52	23	87.5	7.5	51	2
Ethylbenzene	- Influent	75	68	70	185	185	183.5	183.5	183.5	183.5	175	175
	- Effluent	0	0	2	72.5	2	13.5	7.8	19.8	61	31.2	1
Xylene	- Influent	1,190	1,100	1,115	3,200	3,200	3,137.5	3,137.5	3,137.5	3,137.5	3,100	3,100
	- Effluent	31	0	2	82.2	2	5	21.8	84.8	67	46	1
Total	- Influent	4,265	3,888	3,955	11,585	11,585	11,271	11,171	11,271	11,271	10,975	10,975
	- Effluent	33	1	12	380.7	35.5	150.5	96.6	335.3	250.5	213.2	4
% Removed		99.23	99.97	99.70	96.71	99.69	98.66	99.14	97.03	97.78	98.06	99.96

Notes: 1. Influent and effluent concentrations are reported in µg/L.
2. For the purpose of calculating, zero value was entered for the analysis of samples that were non-detectable. Also, a <5 µg/L sample was approximated as 2 µg/L.
3. On a few selected samples, duplicates were taken and therefore average values were entered.

Case Study D-3, FEI Microwave, Sunnyvale, California

Introduction

This case study describes Ultrox's demonstration at the FEI Microwave site in Sunnyvale, California in the spring of 1989. The pilot study was part of the California Hazardous Waste Reduction Program administered by the state's Department of Health Services grant to demonstrate the removal of groundwater contaminants such as trichloroethylene (TCE).

Table D-2-5. O&M Cost Estimates for Test Runs 2 through 12 (Continuous)

Test Number	2	3	4	5	6	7	8	9	10	11	12
Ozone	0.492	0.246	0.344	0.000	0.246	0.245	0.207	0.203	0.215	0.194	0.307
H_2O_2	0.00	0.241	0.000	0.481	0.241	0.241	0.204	0.216	0.214	0.221	0.332
UV	0.955	0.955	0.955	0.955	0.955	0.478	0.955	0.637	0.796	1.194	0.955
Total	1.45	1.45	1.30	1.44	1.44	0.96	1.37	1.06	1.23	1.61	1.59

Note: Cost estimates are reported in $/1,000 gallons.

The contamination of groundwater on the FEI Microwave site resulted from a leaking underground storage tank holding chemicals used in manufacturing electronic components. Contamination of the site was discovered when FEI acquired the property. After a site characteristics study, a groundwater extraction system was installed to prevent the contaminated groundwater plume from leaving the property. The existing groundwater contamination and treatment system consists of nine extraction wells of varying depth and an air stripping unit to reduce the toxic contaminant concentrations to the regulatory discharge limit of 0.5 µg/L for TCE or any other toxic organic compounds.

Plant Description

The Ultrox UV radiation/oxidation system was installed avoiding interference with the existing air stripping process. A fence was erected around the equipment to prevent tampering, and a tent was provided to protect the equipment from the elements.

Prior to treatment, the groundwater was stored in a 6,500-gallon temporary storage tank in quantities of no greater than required for each test (2,000 gallons). After treatment the effluent was pumped to another 6,500-gallon tank. Following each day of testing, the effluent was piped to the air stripper for additional treatment prior to discharge.

Methodology

The principal goals of this pilot demonstration were to reduce TCE below detectable limits and other constituents to concentrations less than 5 µg/L. These criteria were prescribed by the local California Regional Water Quality Control Board for discharges to sewers. The results of analytical testing of the groundwater samples from the influent and effluent ports on the air stripper are presented in Table D-3-1.From this list of compounds, TCE was selected for further examination in the pilot study. This compound was targeted because it was a major contaminant in the groundwater and because it had been a standard component of the chemicals used for the manufacture of electronic hardware on the site.

Thirteen tests were performed over a two-week period with one or two tests run each day. The samples were analyzed the day following the test runs. All tests were conducted while the unit was operating in a continuous mode with the flow rate varying between 22 and 37 gpm.

Results

Test Operations

The operating conditions and analytical results of the 13 tests are shown on Table D-3-2. The influent concentration of TCE varied from 150 to 7,750 µg/L. The removal efficiencies varied from 77.3 to 100 percent.

The first three test results showed that TCE was oxidized to a nondetectable level (<5 µg/L). Tests 4, 5, 7, and 13 were run with less than all of the UV lamps operating to assess this aspect of the treatment. Tests 4, 5, and 13 were run with 50 percent of the UV lamps operating while varying ozone and hydrogen peroxide. Test 7 was conducted without any UV lamps operating and achieved the lowest removal of TCE (77.3 percent and 500 µg/L). Tests 8 and 10 were run without any ozone to measure the effect of different hydrogen peroxide dosages. The higher hydrogen peroxide dosage in Test 8 resulted in TCE concentrations in the effluent below the detection level. Overall, 7 of the 13 test runs achieved acceptable effluents where TCE was less than the analytical detection limit of 5 µg/L.

Costs

The costs for oxidants were estimated for all test runs with the Ultrox unit operating with various oxidant dosages. The costs per 1,000 gallons of groundwater treated are shown in Table D-3-3. Test 9 has the lowest total cost for any test run which achieved acceptable discharge limits. These costs do not include costs associated with any operator who oversees the equipment nor do they include such items as amortization costs of the equipment, or replacement of filters or spargers, or analytical testing. The budgetary capital cost for the Ultrox UV radiation/oxidation equipment to treat groundwater at this facility at 40 gpm is $120,000 (not installed).

Table D-3-1. Groundwater Treatment Results During the Air Stripper Study

Sample Location	Date	TCE[a]	1,1-DCA[a]	1,1-DCE[a]	1,2-DCE[a]	PCE[a]	1,1,1-TCA[a]	1,2-DCB[a]	Vinyl Chloride[a]	Freon[a]	Methyl Chloride[a]	Total VOCs[a]
Dw.Str.	01/28/88	2,000	<10	<10	320	20	<10	<10	10	19	<10	2,373
	02/12/88	15	<0.5	<0.5	0.7	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	15.7
	06/02/88	3.8	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	4.3
	08/30/88	3.2	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	2.2
	11/15/88	1.2	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	0.8	2.0
Outlet	01/20/88	150	<1.0	<1.0	21	<1.0	<1.0	<1.1	<1.0	<1.5	<1.0	173.6
	02/08/88	39	<0.5	<0.5	3.0	<0.5	<0.5	<0.5	<0.5	<0.9	<0.5	42.9
	02/12/88	17	<0.5	<0.5	0.7	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	17.7
	03/07/88	8.8	<0.5	<0.5	<0.5	0.6	<0.5	<0.5	<0.5	<0.5	<0.5	9.4
	04/12/88	6.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	6.5
	06/01/88	4.4	<0.5	<0.5	<0.5	<0.5	<0.8	<0.5	<0.5	0.8	<0.5	6.0
	06/02/88	5.3	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	5.3
	07/05/88	3.6	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	3.6
	08/30/88	3.7	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	3.7
	09/30/88	6.6	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	6.6
	10/25/88	1.1	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	1.1
	11/15/88	1.9	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	0.7	2.6
	11/15/88	1.8	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<1	<5	1.8
	12/07/88	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Inlet	01/28/88	5,400	<100	<100	210	<100	<100	<100	<100	<100	<100	5,610
	02/08/88	4,500	<50	<50	190	78	<50	<50	<50	<50	<50	4,768
	03/07/88	4,900	<50	<50	170	58	<50	<50	<50	180	<50	5,308
	06/02/88	6,200	<50	<50	90	<50	<50	<50	<50	260	150	6,700
	08/30/88	11,000	<200	<200	<200	<200	<200	<200	<200	<200	<200	11,000
	11/15/88	3,700	<50	<50	<50	<50	<50	<50	<50	200	<50	3,900
Dw.Str.	01/10/89	2.4	0.5	<0.5	<0.5	<0.5	<0.5	--	<1.0	<1.0	<5.0	2.4
Outlet	01/10/89	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	--	<5.0	--	<25	<25
	01/10/89	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	--	<5.0	--	<25	<25
	02/16/89	2.5	0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	2.5
	03/14/89	3.8	0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	
Inlet	01/10/89	2,900	<250	<250	<250	<250	<100	--	<100	--	1,200	2,900
	02/16/89	2,000	<250	<250	<250	<250	<250	<250	<250	<250	<250	2,900

Notes: Concentrations reported in ppb.

1,1-DCA: 1,1-dichloroethane; 1,2-DCB: 1,2-dichlorobenzene; 1,1-DCE: 1,1-dichloroethylene; 1,2-DCE: 1,2-dichloroethylene; Dw.Str.: down stream; PCE: tetrachloroethylene; 1,1,1-TCA: 1,1,1-trichloroethane; and TCE: trichloroethylene.

Case Study D-4, Golf Course, City of South Gate, California

Introduction

This case study describes Ultrox's UV radiation/oxidation project conducted at a par-3 golf course in the City of South Gate, California, at the end of 1987. This demonstration, supported by the California Department of Health Services, consisted of a series of tests to treat groundwater contaminated with PCE and TCA. A 675-gallon Ultrox Model P-675 reactor was operated in the continuous, flow-through mode at 50 gpm during the test runs. The test program was conducted over a 6-day period to define operating, maintenance, and equipment costs for full-scale equipment. This is the only case study presented in this report with estimated costs for

Table D-3-2. Operating Conditions and Analytical Results for the Ultrox System

Test Number	1	2	3	4	5	6	7	8	9	10	11	12	13
Operating Conditions													
Flow Rate (gpm)	37	30	33	37	37	37	37	37	37	37	37	37	22
Retention Time (min)	16	20	18	16	16	16	16	16	16	16	16	16	27
Gas Flow Rate (scfh)	150	120	150	150	150	150	150	0	150	150	150	150	150
(Ozone)	1.97	0.86	2.33	1.97	1.39	0.73	1.57	0	1.97	0	2.94	1.7	1.62
Ozone (wt %)													
Ozone Dosage (mg/L)	18.3	7.9	24.3	18.3	12.9	6.78	14.6	0	18.3	0	27.3	15.8	25.3
H_2O_2 Rate (ml/min)	16	13	14	16	11.5	17	3.3	16	6	8.3	8.3	5	8.3
H_2O_2 Dosage (mg/L)	48	48	47	48	34.5	51	9.9	48	18	25	25	15	25
Total Oxidants (mg/L)	66.3	55.9	71.3	66.3	47.4	57.8	24.5	48	36.3	25	52.3	30.8	50.3
Percent UV Lamps On	100	100	100	50	50	100	0	100	100	100	100	100	50
Laboratory Analysis													
Inf. TCE Conc. (mg/L)	6.375	6.75	5.75	7.75	7.5	1.5	2.2	1.3	3.3	0.15	0.229	0.625	2.25
Eff. TCE Conc. (mg/L)	ND	ND	ND	0.06	0.052	ND	0.5	ND	ND	0.02	ND	0.049	0.054
Removal (%)	100	100	100	99.2	99.3	100	77.3	100	100	86.7	100	99.2	97.6

Note: ND : Not detected.

Table D-3-3. Oxidant Cost Estimates

Test Number	TCE Effluent Conc. (mg/L)	Ozone[a]	H_2O_2[a]	UV[a]	Total[a]
1	ND[b]	0.09	0.29	0.39	0.76
2	ND	0.04	0.28	0.48	0.80
3	ND	0.12	0.27	0.44	0.83
4	0.06	0.09	0.28	0.19	0.56
5	0.052	0.06	0.20	0.19	0.46
6	ND	0.03	0.30	0.39	0.72
7	0.50	0.07	0.06	0.00	0.13
8	ND	0.00	0.28	0.30	0.58
9	ND	0.09	0.10	0.30	0.50
10	0.02	0.00	0.14	0.31	0.45
11	ND	0.14	0.14	0.30	0.58
12	0.049	0.08	0.09	0.42	0.58
13	0.054	0.13	0.14	0.14	0.41

Note: [a] Cost estimates reported in $/1,000 gallons
[b] ND: Not detected.

pressurized and nonpressurized systems. Twelve tests were run in which the oxidant doses were varied while attempting to achieve the desired treatment standard of 2 µg/L for PCE. The untreated concentration of TCA, ranging from nondetectable to 3 µg/L, was less than the level of concern.

Results

Operations

A description of the operating conditions and the analytical results are presented in Table D-4-1. As shown, the influent water PCE concentrations varied between 14 and 18 ppb with the average being 17 ppb. Six tests (Nos. 2, 3, 5, 7, 9, and 11) produced water with a PCE concentration of less than 2 ppb, which was the desired treatment standard.

TCA was also detected in the water at concentrations of nondetectable to 3 ppb, which is below present drinking water standards. The various operating conditions did not significantly reduce the TCA with the exception of Test No. 9, which used UV-hydrogen peroxide.

Costs

The projected O&M costs per day for a continuously operating system at 1,250 gpm for the successful test runs are presented on Table D-4-2. Test No. 11, run without UV or hydrogen peroxide, shows the lowest O&M costs. Tables D-4-3 and D-4-4 present capital costs estimated for pressurized (80 psig) and nonpressurized systems. The lowest capital costs for both systems are those associated with Test No. 11. Test No. 7 had the next least expensive capital costs.

Case Study D-5 Xerox Facility, Webster, New York

Introduction

This case study describes Ultrox's UV radiation/oxidation testing of an approximately one-quarter scale unit on contaminated groundwater at the Xerox Corporation, Salt Road site. The contaminants include TCE and vinyl chloride with total volatile organics ranging in concentrations from 1 to 10 mg/L. The information contained in this appendix is based on a draft, interim report by Xerox

Table D-4-1. Operating Conditions and Analytical Results

Test No.	Ozone Dosage	H_2O_2 Dosage	Operating UV Lamps	PCE Influent	PCE Effluent	TCA Influent	TCA Effluent
1	Med.	0	All	14	4	3	2.4
2	High	0	All	20	0.2	ND	ND
3	High	Med.	0	17	0.4	ND	ND
4	0	High	0	17	14	ND	ND
5	0	Med.	1/3	17	0.1	ND	ND
6	0	0	All	17.5	4	0.4	0.5
7	Med.	Med.	0	18	0.2	0.5	0.4
8	0	Med.	1/4	16	13	1.3	1.3
9	0	Med.	1/2	16	1.3	1.2	0.3
10	Low	Low	0	18	2.2	ND	ND
11	Med.	0	0	--	0.32	ND	ND
12	Low	0	0	18	4.4	ND	ND

Note: 1. All tests run at 50 gpm.
2. ND: Not detected.
3. Concentrations reported in ppb.

Table D-4-2. Daily O&M Cost Estimates for 1,250-gpm System

Test No.	Ozone	H_2O_2	UV Power	UV Maint.	Total
2	164	0	235	80	479
3	164	54	0	0	218
5	0	54	78	27	159
7	110	51	0	0	161
9	0	54	118	40	212
11	110	0	0	0	110

Note: 1. All values reported in dollars.
2. Assumes cost of electrical energy is at $0.085/kWh.
3. An additional $21/day O&M costs is required for 80-psig pressurized systems.

Table D-4-3. Capital Cost Estimates for 1,250-gpm Pressurized System

Test No.	Ozone Generator	H_2O_2 Supply	Reactor	Total
2	162,000	0	400,000	562,000
3	162,000	10,000	85,000	257,000
5	0	10,000	300,000	310,000
7	125,000	10,000	85,000	220,000
9	0	10,500	350,000	360,000
11	125,000	0	85,000	210,000

Note: All values reported in dollars.

Table D-4-4. Capital Cost Estimates for 1,250-gpm Nonpressurized System

Test No.	Ozone Generator	H_2O_2 Supply	Reactor	Total
2	122,000	0	360,000	482,000
3	122,000	10,000	50,000	182,000
5	0	10,000	260,000	270,000
7	100,000	10,000	50,000	160,000
9	0	10,000	315,000	325,000
11	100,000	0	50,000	150,000

Note: All values reported in dollars.

and personal communication. No cost data were provided.

Plant Description

A 650-gallon Ultrox reactor was installed at the site in March 1989 for a series of pilot tests. Recovery well pumps provide the hydraulic pressure necessary for process flows. A 5-micron fiber bag filters the groundwater prior to treatment. During the pilot tests, effluent from the Ultrox system was sent to a storage tank and subsequently pumped to an air stripper to guarantee effluent discharge requirements. The effluent, currently discharged to a sanitary sewer, will later be sent to a surface stream from the air stripper during full-scale operation.

Methodology

During the test period, the groundwater flow rate varied from 30 to 50 gpm, with an additional 10 gpm acting as cooling water for the air compressor and ozone generator. A 50 percent solution of hydrogen peroxide was added to the influent at a dose of 30 mg/L. The ozone dosage was set at 58 mg/L with a constant pressure of 15 psig. The feed mixture was calibrated to deliver 2 percent ozone in the reactor. All 72 UV lamps were operating during the test runs.

Twenty-four sampling events were conducted during the test period, with daily samples collected during the first week of operation and twice weekly thereafter. Influent was sampled prior to the hydrogen peroxide injection; effluent was sampled from the sixth cell sampling port of the reactor.

Results

Analytical

For the test runs, the average contaminant concentration for total volatile organics was 3,048 µg/L. The removal efficiency averaged 93 percent with 3 constituents below 90 percent and 21 compounds above 90 percent. The removal efficiencies for specific compounds were as follows:

Compound	Removal Efficiency (%)
Vinyl Chloride	100
Toluene	100
Tetrachloroethylene	100
1,2-Dichloroethylene	98.6
Trichloroethylene	92.2
1,1,1-Trichloroethane	36
1,1-Dichloroethane	0.0

Maintenance

Daily inspection during the test period revealed that periodic adjustments are required to maintain peak operating efficiency. The groundwater at the site contains relatively high concentrations of iron which affected the UV lamps. Based on the tests, inspections would be prudent to replace lamps and clean the quartz sleeves. Additional maintenance would be required to check and change the compressor oil and filter as well as inspect and change the ozone decomposer catalyst.

Case Study D-6 Koppers Industries, Denver, Colorado

Introduction

This case study briefly presents treatment results of an Ultrox system employed by Koppers Industries, Inc., on wastewater from a wood processing facility. An Ultrox unit, operating since December 1985 with UV and ozone, is used to treat the organic contaminants, phenol and pentachlorophenol (PCP), from the plant's wastewater. A pretreatment system consists of pH adjustment, oil removal, and flocculation and settling of heavy metals.

The organic concentrations of the influent typically range between 150 to 200 mg/L for phenol and are about 1 mg/L for PCP. Oil and grease are measured at about 3 percent in the raw wastewater.

Results

Analytical

The results of effluent testing from several months of operation based on 1-day composites are presented as follows:

Constituent	5/88	8/88	11/88	3/89
pH	7.2	7.0	11.6	12.2
PCP (mg/L)	0.18	0.5	0.44	0.15
Phenol (mg/L)	145.0	65.0	38.0	45.0
Oil (mg/L)	15.0	78.0	<1.0	24.0

The flows in March 1989 were reported to be 5,211 gpd on an average daily basis, with a maximum daily flow of 16,047 gpd.

Costs

The operating and maintenance costs per 1,000 gallons of treated wastewater for the entire system are presented in Table D-6-1. The capital cost of the

Table D-6-1. O&M Cost Estimate

Item	$/1,000 gal
Flocculating agents	5.79
Sulfuric acid	.39
Caustic soda	.81
Defoamer	.42
Electricity	2.11
Labor	1.40
Analysis	1.83
Effluent disposal	4.64
Total	$17.39/1,000 gal

entire treatment system installed was $550,000, of which $200,000 was for the Ultrox UV radiation/oxidation portion.

Case Study D-7 General Electric Company, Lanesboro, Massachusetts

Introduction

This case study describes the Ultrox technology's performance in a treatability study that took place at General Electric Company's Rose Site, Lanesboro, Massachusetts in the fall of 1987. In addition to UV radiation/oxidation, the project evaluated the effective use of air stripping and carbon adsorption in treating groundwater contaminated with several volatile compounds including vinyl chloride and trans-1,2-dichloroethylene, and trace concentrations of PCBs.

Plant Description

An Ultrox Model P-75 pilot system, with a wet volume of 75 gallons, 6 cells, and 30 UV lamps, was used in the study. The unit was supplied with groundwater from a single well that passed through a 10-micron cartridge filter prior to treatment.

Methodology

Tests were performed on the Ultrox system to evaluate the use of UV-ozone and UV-hydrogen peroxide. All UV lamps remained operating while the hydraulic retention times and oxidant dosages were varied. UV-ozone test conditions had flow rates between 1.5 and 2 gpm with ozone dosages between 160 and 600 mg/L at concentrations of approximately 3 percent. UV-hydrogen peroxide test conditions had flow rates between 0.75 and 1 gpm with hydrogen peroxide dosages between 53 and 580 mg/L. Batch tests preceded continuous-flow operations for each phase of study.

Results

Both treatment combinations, UV-ozone and UV-hydrogen peroxide, were able to reduce the two principal VOCs and PCBs to levels below the analytical detection limits. Both oxidants, in conjunction with UV radiation, achieved VOC reductions greater than 99.9 percent. These tests also indicated that hydrogen peroxide alone could achieve substantial VOC and PCB removals. Trans-1,2-dichloroethylene, the VOC with the highest influent concentration, was more difficult to treat than vinyl chloride. Another VOC, 1,1,2-TCA, present in low concentrations in the influent, appeared to be resistant to oxidation, or a product of degradation.

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Case Study

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