



**US Army Corps  
of Engineers**  
Waterways Experiment  
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*Installation Restoration Research Program*

# **Treatment of Low-Level Contaminated Landfill Leachate Using Advanced Oxidation Processes**

*by Mark E. Zappi, Evelyn Toro, Robert Jones, Jeff Talley, WES  
Mona Data, Baltimore District*

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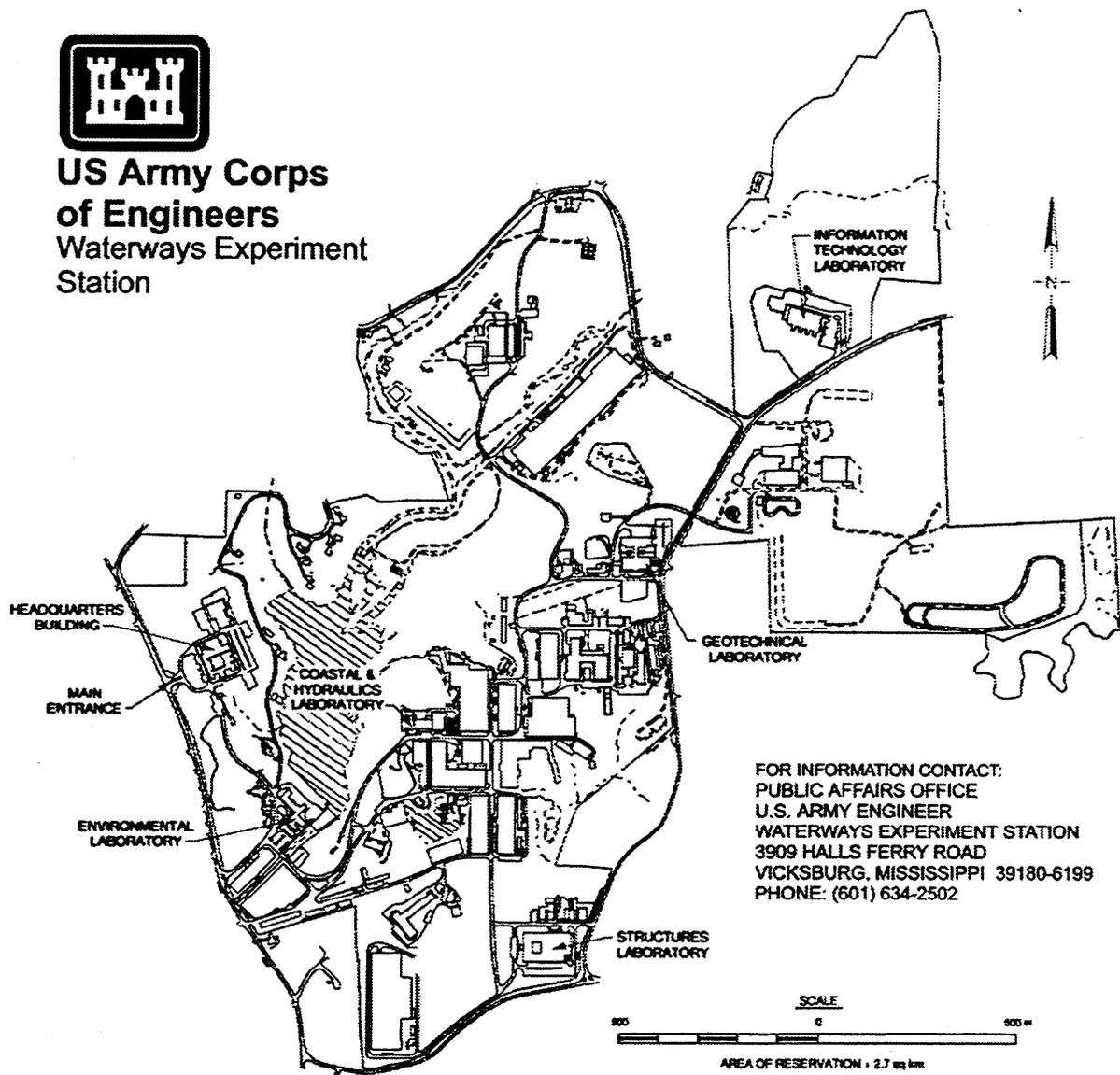
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**Final report**

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# Preface

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The study herein was conducted by the U.S. Army Engineer Waterways Experiment Station (WES) in support of the U.S. Army Engineer District, Baltimore, and as part of the Installation Restoration Research Program (IRRP) and the U.S. Army Environmental Quality Technology Research Program.

Dr. Clem Meyer was the IRRP Coordinator at the Directorate of Research and Development, Headquarters, U.S. Army Corps of Engineers (HQUSACE). Dr. Bob York of the U.S. Army Environmental Restoration Division, Directorate of Military Programs, HQUSACE, served as the IRRP Overview Committee. Dr. M. John Cullinane, WES, was the IRRP Program Manager.

The study was conducted and the report prepared by Dr. Mark E. Zappi, Ms. Evelyn Toro, and Mr. Jeff Talley, Environmental Restoration Branch (ERB), Environmental Engineering Division (EED), Environmental Laboratory (EL), WES; Mr. Robert Jones, Environmental Chemistry Branch, EED; and Ms. Mona Data, Baltimore District.

The study was conducted under the general supervision of Mr. Daniel E. Averett, Chief, ERB; Mr. Norman R. Francingues, Jr., Chief, EED; and Dr. John Harrison, Director, EL.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin.

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# 1 Introduction

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## Site Background

The Strasburg Landfill Superfund Site is located in Newlin and Bradford townships, Chester County, Pennsylvania. The site operated as a landfill for both municipal and industrial waste from 1979 through 1983; however, the site was barred from accepting industrial wastes in 1980 by the Pennsylvania Department of Environmental Resources (PADER). The landfill was later covered with a 20-mm polyvinyl chloride membrane and soil. Shortly after closing, leachate runoff from the landfill into a nearby creek was observed. The site was placed on the U.S. Environmental Protection Agency's (USEPA) National Priorities List on October 15, 1988, based on detection of contaminants in local groundwater, nearby home wells, and surface waters. Chemical analysis of the groundwater and local seeps indicated that low levels of contaminants have apparently migrated from the landfill into environment. The most prominent of these contaminants are chlorinated solvents and simple aromatics. The U.S. Army Engineer District, Baltimore, is currently evaluating a variety of options for prevention of the continued, uncontrolled release of contaminants into the environment. Also under evaluation by the Baltimore District are a variety of options for treatment of contaminated groundwater and/or leachate collected during proposed containment activities.

At this time, leachate and contaminated groundwater collected from the site are stored and treated using a system of surge tanks and an air stripper located at the site. Operation of this system has been somewhat difficult due to the oxidation of reduced iron found in the groundwater within both the surge tanks and air stripping unit. Trimetaphosphate is currently being added to the air stripper influent as an attempt to control iron oxidation within the stripper packing. The Baltimore District reports that, to date, this system is functioning properly in terms of organics removal by meeting the volatile organics effluent requirements currently imposed on the site by both the USEPA and PADER. The Record of Decision requires that an advanced oxidation process (AOP) be considered as a potential replacement for the air stripping unit due to concerns over potential future increases in volatile and semivolatile organic levels in the system influent.

The U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, under the direction of the Baltimore District evaluated several AOPs for treatment of leachate and groundwater collected from the Strasburg site. This report summarizes the results of these efforts. Candidate AOPs that were evaluated were irradiation of hydrogen peroxide with ultraviolet (UV) light emitted from low-pressure mercury-vapor UV lamps (LPUV-HP), irradiation with UV light emitted from a low-pressure mercury-vapor UV lamp with ozone sparging (LPUV-OZ), irradiation of hydrogen peroxide with photons emitted from a medium-pressure mercury-vapor UV lamp (MPUV-HP), and peroxone (ozone sparging with hydrogen peroxide dosing).

## Advanced Oxidation Processes

Advanced oxidation processes are oxidation processes that rely on the hydroxyl radical, OH<sup>•</sup>, as the primary mechanism for destruction of organic contaminants (American Water Works Association 1991). There are many different oxidation processes that may be considered an AOP. Examples include electron beam irradiation, supercritical oxidation, irradiation of oxidizers with UV light (all of the AOPs evaluated during this study except peroxone fall into this category), peroxone, sonozone, and irradiation of semiconductors. Technically all of these AOPs should provide sufficient treatment; however, when process economics and the potential for near-term field implementation are also considered, many of those processes become cost prohibitive for treating low levels of volatile organic contaminants (VOCs), such as those found in the Strasburg leachates.

To further understand some of the results presented in this report, brief descriptions of key hydroxyl radical reaction mechanisms are presented. Researchers at WES have recently published a numerical model for estimating the steady-state hydroxyl radical concentrations in various AOPs (Zappi 1995). The key mechanistic pathways for production and reaction with hydroxyl radicals are illustrated in Figure 1. From Figure 1, it can be seen that there are numerous chemical reactions that may occur that produce and subsequently remove radical species from an AOP reactor. Radical production mechanisms include photolytic, pH, and ozone-hydrogen peroxide reactions. Radical degradation or scavenging reactions (Si) include contaminant (Ai), inorganic constituent, and parent oxidizer-based reactions. Only those reactions that result in the destruction of the contaminant are considered beneficial. The other reactions usually have an adverse impact on reaction kinetics due to the scavenging of radicals that would have been available for contaminant destructive reactions. WES identified three predominant scavenging reactions that will likely occur within traditional AOP reactor systems. These are reactions with bicarbonate/carbonate ions, reduced cations (i.e., iron), and excessive amounts of primary oxidizers (i.e., ozone and hydrogen peroxide). Of key interest is that too much ozone or hydrogen peroxide may be added to an AOP system. Usually obtaining excessive amounts of ozone is difficult because ozonation is mass transfer limited (gas to water transfer). However,

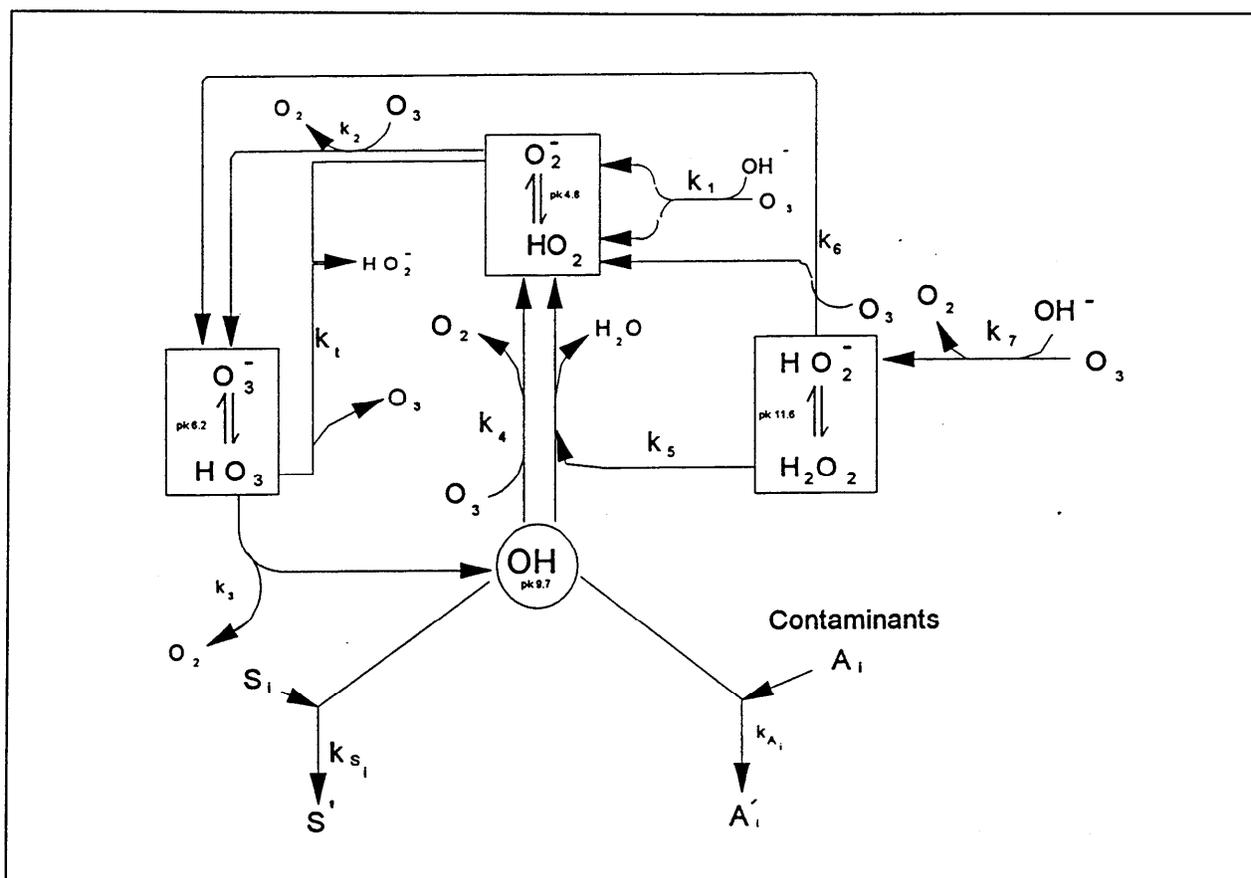


Figure 1. Free-radical reactions within ADP Systems

introduction of hydrogen peroxide (a liquid) is much easier and is likely a potential scavenging source in AOPs. There is an optimum dose for each oxidizer and optimum instantaneous stoichiometric mass-to-mass ratios for those AOPs utilizing both oxidizers, such as peroxone (Aieta et al. 1988). Some of the data presented in this report serve as excellent examples of these mechanisms. In other words, although ozone and/or hydrogen peroxide are required to form hydroxyl radicals, these same oxidizers can be added into ADPs using amounts in excess having adverse impact on the contaminant degradation. The parent oxidizers actually react with the hydroxyl radicals (see Figure 1), thereby eliminating the radicals that reacted with the parent oxidizers from reacting with the targeted contaminant(s).

This study focused on those candidate AOP systems that were considered both economically and technically attractive for treating the Strasburg groundwater. The following discussion is directed toward detailing the differences between the various AOPs studied in this effort. It is presented because it is essential that the reader fully understand the differences between each candidate AOP because these differences impact both treatment efficiency and process economics.

### **Medium-pressure mercury-vapor UV lamp with hydrogen peroxide dosing (MPUV-HP)**

The MPUV lamp produces a broad light spectra compared with the commonly used germicidal UV lamp (low-pressure mercury-vapor lamp). It has significant emittance within the 200-nm to 250-nm range, which is the primary adsorption band for hydrogen peroxide. Systems of this type are usually considered one of the most aggressive of all the UV-based AOPs currently commercially available for treating the VOCs present in the Strasburg leachate (Froelich 1992). Positive aspects of this AOP type include rapid contaminant removal kinetics, low capital costs, high potential for direct photolysis of photoreactive chemicals such as chloroform, and relative system simplicity. Negative aspects include high operation and maintenance (O&M) costs, high heat production from the lamps limiting the hydraulic residence time (HRT) within the reactor, and a greater tendency for fouling of the quartz sleeves that house the UV lamps.

### **Low-pressure mercury-vapor UV lamp with ozone sparging (LPUV-OZ)**

The LPUV lamp is commonly used for water and wastewater disinfection due to its germicidal properties. This lamp emits almost all of its light at the 254-nm wavelength. This wavelength is also the peak adsorption wavelength for ozone (actually 253.9 nm). Systems of this type represent the oldest commercialized AOP that has been used for wastewater and groundwater treatment (Barich and Zeff 1989). Positive aspects of this AOP type include low O&M costs, a low tendency for quartz sleeve fouling, and a high degree of system flexibility. Negative aspects are concerns about stripping of VOCs as ozone is sparged through the reactor, high capital costs, and longer HRTs due to reduced reaction kinetics.

### **Low-pressure mercury-vapor UV lamp with hydrogen peroxide dosing (LPUV-HP)**

This AOP has had very limited field application and is much less aggressive than the other AOPs (Sundstrom et al. 1986). Hydrogen peroxide has limited adsorption at the 254-nm wavelength, making the overall quantum yield relatively poor (quantum yield is the amount of UV energy utilized for beneficial reactions (i.e., radical formation) over the total amount of UV energy emitted). Positive aspects include low capital costs, simple system design, and low tendency for quartz sleeve fouling. Negative aspects include potentially high hydrogen peroxide bulk costs, high retention times due to relatively slower removal kinetics, and a high degree of sensitivity to varying influent UV transmissivity.

## Peroxone

This AOP is a dark reactor system in which no UV light is added to promote hydroxyl radical formation (Glaze and Kang 1988). The system relies primarily on radical formation due to the chemical reaction between ozone and hydrogen peroxide (high pH can also produce the hydroxyl radical from ozone; however, at a much lower reaction rate). This AOP has been successfully used for treatment of groundwaters containing similar VOCs to those detected within the Strasburg leachate. Peroxone has been used on a large scale (> 10 mgd) for municipal water treatment by many municipalities including the City of Los Angeles, CA, indicating a high potential for process field implementation for treating groundwaters (Metropolitan Water District of Southern California 1991). Advantages of this process include low overall design life costs, respectable reaction kinetics, no UV lamps to pose potential fouling problems or sensitivity to low influent UV transmissivity, and a high level of process flexibility. Disadvantages include limited field experience for groundwater treatment, little or no commercialization, and potential for VOC stripping due to ozone sparging.

## 2 Experimental Methods

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The groundwater sample used in this study was collected from the influent tank of the existing treatment system. It was collected by Baltimore District personnel during January 1994 and shipped to WES in 5-gal<sup>1</sup> containers using an overnight delivery shipper. Upon receipt at WES, the samples were stored in a walk-in cooler at 4 °C until needed for testing. Originally, the actual site leachate collected from surge tank of the existing treatment system without any form of pretreatment or VOC spiking was to serve as the test influents. Unfortunately, due to sponsor-imposed time limitations, WES proceeded with the AOP experiments without any verification of groundwater chemical quality using chemical analysis. Unfortunately, when the first set of chemical analytical data were received, it was observed that the groundwater samples shipped to WES did not contain detectable amounts of VOCs. Subsequent conversations with the Baltimore District indicated that at the time of sample collection, the melting of snow from a major winter storm was occurring at the site. It is speculated that this melt probably had diluted the groundwater influent, thereby resulting in a sample collected without detectable amounts of VOCs. Also, visual observations of the samples by WES personnel indicated that appreciable quantities of oxidized iron had precipitated within the 5-gal containers during shipment.

Based on discussions with the Baltimore District, WES was instructed to spike the groundwater samples with various VOCs that were considered commonly found in the Strasburg groundwater samples. These contaminants are listed in Table 1 along with the respective concentrations listed (note that these levels are those obtained after spiking). The table also lists the respective target treatment goals for each VOC. The groundwater samples were spiked with analytical grade VOCs by first transferring the samples from the shipping containers into clean 5-gal containers by pumping the groundwater from the shipping containers through a 1- $\mu$ m, fiber, in-line filter (to remove oxidized iron) using a peristaltic pump. The VOCs were dosed by adding each chemical to the 5-gal containers followed by slow agitation using a 1/15 hp laboratory mixer equipped with a stainless steel impeller. Upon observation of the filtered and spiked groundwater, samples indicated that more iron oxidation had occurred due to the mixing of the samples.

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<sup>1</sup> To convert gallons (U.S. liquid) to liters, multiply by 3.785412.

**Table 1**  
**Strasburg Groundwater Influent Attempted VOC Concentrations,**  
**Actual Spiked VOC Concentrations, and Target Treatment Goals**

VOC	Attempted Concentration, mg/L	Actual Concentration, mg/L	Target Goal, <sup>1</sup> mg/L	Required Percent Removal
Acetone	0.050	0.0259	4	AG
2-Butanone	0.050	0.0246	2	AG
Chlorobenzene	0.050	0.0474	0.202	AG
Chloroethane	0.050	0.0073	NG	---
Ethyl Benzene	0.100	0.0282	5.858	AG
Trichloroethene	0.100	0.1034	0.0065	94
Total Xylenes	0.200	0.1162	2.131	AG

<sup>1</sup> Effluent concentrations.

Note: AG = Above goal; VOC = Volatile organic compound; NG = Not given.

Therefore, the groundwater samples were filtered again using the in-line filters each time the samples were pumped into the AOP reactor for initiation of the experiments. The actual concentrations of VOCs listed in Table 1 represent an average of all of the initial (t = 0) samples collected throughout the course of this study. Although higher levels were added to the containers, significant VOC loss had occurred due to the agitation and filtering activities and from VOC volatilization into the headspace of the containers during storage in the walk-in cooler. Fortunately, the levels of VOCs detected in the samples used in the AOP experiments did contain appreciable levels of VOCs that were considered quite representative of the influent that the candidate AOPs likely have to treat at the site.

Figure 2 presents an illustration of the AOP reactor units used in this study. The outer shell of the reactors are constructed of borosilicate glass with the inner immersion well, which houses that UV lamps, being constructed of quartz glass. Quartz is required because most glass types or plastic materials cannot transmit UV photons. The immersion well is jacketed to control the temperature of the UV lamps, which can produce significant heat (especially the MPUV lamps). Cooling was accomplished by circulation of chilled water through the cooling jacket. The working (wetted) volume of the reactor is 1 L. Three UV light sources were used in this study: 450-W or 200-W medium-pressure mercury-vapor UV lamps and a 12-W low-pressure mercury-vapor UV lamp. Both lamps were manufactured by Hanovia, Inc., and marketed by Ace Glass, Inc., Vineland, NJ. The spectral characteristics of the 450-W and 200-W MPUV lamps used in this study in the far and middle UV band (220 nm to 320 nm) was 55.7 W and 30.2 W, respectively. The LPUV lamp 254-nm spectral output was 3.5 W.

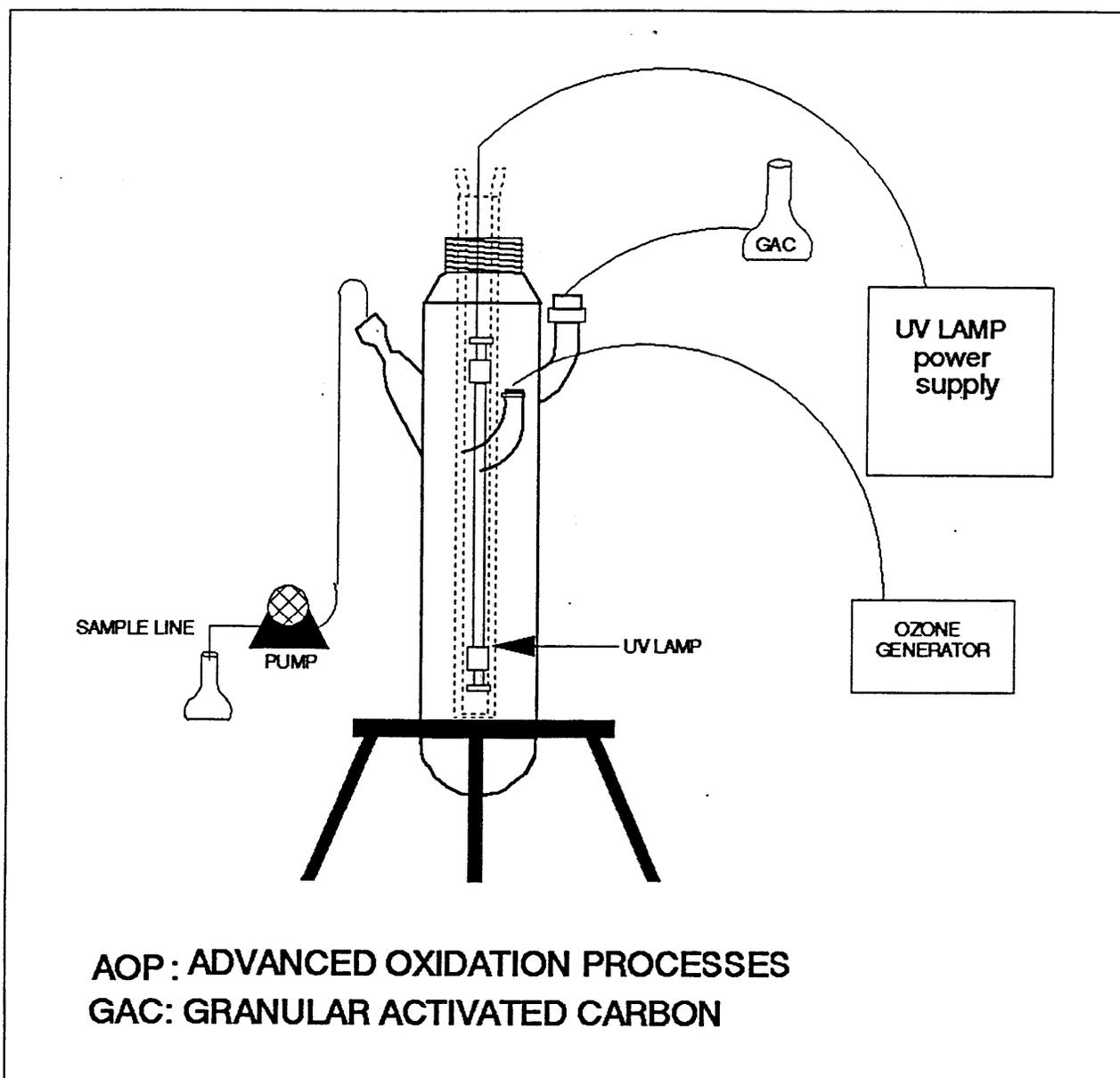


Figure 2. Bench-scale reactor—AOP experiments

Ozone was sparged into the reactor using an Ozoteq ozone generator with turn-down capability to control the percent ozone composition (w/w) of the sparged gas. A 50-percent (w/w) analytical grade hydrogen peroxide stock solution was used to dose the AOP reactor according to the target process formulation.

Table 2 lists the various process formulations evaluated during this study. Each of these experiments was performed in duplicate runs. During most of the experiments, samples were collected at test times of 3, 5, 10, 20, and 30 min of treatment. The samples were collected in precleaned, 40-ml

**Table 2**  
**Advanced Oxidation Processes (AOPs) Evaluated in Treating**  
**Strasburg Groundwater<sup>1</sup>**

Low-Pressure Mercury Lamp
1) 12 W / 1.5 percent ozone feed <sup>2</sup> 2) 12 W / 1.0 percent ozone feed 3) 12 W / 0.5 percent ozone feed 4) 12 W / 1.0 percent ozone feed / 50 mg/L hydrogen peroxide 5) 12 W / 1.5 percent ozone feed / 100 mg/L hydrogen peroxide <sup>3</sup> 6) 12 W / 100 mg/L hydrogen peroxide 7) 12 W / 500 mg/L hydrogen peroxide <sup>2</sup>
Medium-Pressure Mercury Lamp
1) 200 W / 100 mg/L hydrogen peroxide 2) 450 W / 50 mg/L hydrogen peroxide 3) 450 W / 250 mg/L hydrogen peroxide <sup>2</sup>
Hydrogen Peroxide and Ozone
1) 1.5 percent ozone feed / 0.1 mg/L hydrogen peroxide 2) 1.5 percent ozone feed / 1 mg/L hydrogen peroxide 3) 1.5 percent ozone feed / 10 mg/L hydrogen peroxide <sup>4</sup> 4) 1.5 percent ozone feed / 50 mg/L hydrogen peroxide 5) 1.5 percent ozone feed / 100 mg/L hydrogen peroxide <sup>2</sup>
<sup>1</sup> Samples were taken at test times of 0, 3, 5, 10, 20, and 30 min, unless otherwise noted. <sup>2</sup> Samples were also taken at test times of 60 and 90 min. <sup>3</sup> Samples were only taken at test times of 0, 60, and 90 min. <sup>4</sup> Chloride analysis was performed using Ion Chromatography Unit.

volatile organic aromatic (VOA) vials. Small quantities of bovine catalase were added to sample vials to remove residual oxidizer species from the sample vial to prevent further oxidation of the contaminants beyond the representative sampling times intended. Upon review of the results from the various experiments, it was observed that acetone and methylethylketone (2-butanone) levels were increasing throughout the test time spans evaluated (i.e.,  $t = 0$  to 30 min). Therefore, WES performed additional testing on selected AOP systems in which test times (HRTs) of 60 and 90 min were also investigated to determine the level of ketones removal (or possibly further production) obtained using longer HRTs than the 30 min originally investigated. Some additional systems, not originally investigated during the first series of experiments, were also investigated for their potential for removing ketones by tracking the progress of VOC removal through collection of samples at test times of 0, 60, and 90 min. Table 2 lists the samples collected during investigation of each listed AOP system investigated.

Reactor temperatures were maintained at operating temperature ranges of 25-30 °C. Table 3 lists the reactor temperatures and pH values for each experimental run. These temperatures were monitored using Fisher brand thermometers immersed into the reactors via a sampling port fitted with an O-ringed compression fitting. Reactor pH was periodically monitored by analysis of the

**Table 3**  
**Temperature and pH Values for Advanced Oxidation Processes Experiments in Strasburg Groundwater**

Low-Pressure Mercury Lamp							
12 W / 100 mg/L Hydrogen Peroxide				12 W / 100 mg/L Hydrogen Peroxide <sup>1</sup>			
Label	Time, min	pH	Temp, °C	Label	Time, min	pH	Temp, °C
STRASBURG-10-0	0	7.36	26.8	STRASBURG-24-0	0	7.83	26.2
STRASBURG-10-3	3	7.50	26.8	STRASBURG-24-3	3	7.91	26.1
STRASBURG-10-5	5	7.49	26.8	STRASBURG-24-5	5	7.91	26.1
STRASBURG-10-10	10	7.48	26.9	STRASBURG-24-10	10	7.83	26.1
STRASBURG-10-20	20	7.44	27.0	STRASBURG-24-20	20	7.78	26.0
STRASBURG-10-30	30	7.49	27.0	STRASBURG-24-30	30	7.74	26.0
12 W / 500 mg/L Hydrogen Peroxide				12 W / 500 mg/L Hydrogen Peroxide <sup>1</sup>			
Label	Time, min	pH	Temp, °C	Label	Time, min	pH	Temp, °C
STRASBURG-11-0	0	7.40	26.8	STRASBURG-25-0	0	7.87	25.8
STRASBURG-11-3	3	7.83	26.8	STRASBURG-25-3	3	7.94	25.8
STRASBURG-11-5	5	--	--	STRASBURG-25-5	5	7.90	25.8
STRASBURG-11-10	10	--	--	STRASBURG-25-10	10	7.82	25.8
STRASBURG-11-20	20	7.62	27.3	STRASBURG-25-20	20	7.68	25.8
STRASBURG-11-30	30	7.50	27.4	STRASBURG-25-30	30	7.61	25.7
12 W / 500 mg/L Hydrogen Peroxide							
Label	Time, min	pH	Temp, °C				
STRASBURG-30-0	0	6.98	26.7				
STRASBURG-30-60	60	6.90	26.7				
STRASBURG-30-90	90	6.82	26.8				
12 W / 0.5 % Ozone Feed				12 W / 0.5 % Ozone Feed <sup>1</sup>			
Label	Time, min	pH	Temp, °C	Label	Time, min	pH	Temp, °C
STRASBURG-8-0	0	7.34	25.7	STRASBURG-22-0	0	7.85	23.9
STRASBURG-8-3	3	8.12	25.8	STRASBURG-22-3	3	8.22	24.0
STRASBURG-8-5	5	8.19	25.8	STRASBURG-22-5	5	8.29	24.0
STRASBURG-8-10	10	8.38	25.8	STRASBURG-22-10	10	8.41	24.0
STRASBURG-8-20	20	8.50	25.0	STRASBURG-22-20	20	8.49	24.1
STRASBURG-8-30	30	8.55	26.1	STRASBURG-22-30	30	8.62	24.3
<i>(Sheet 1 of 5)</i>							
<sup>1</sup> Replicate.							

**Table 3 (Continued)**

Low-Pressure Mercury Lamp							
12 W / 1.0 % Ozone Feed				12 W / 1.0 % Ozone Feed <sup>1</sup>			
Label	Time, min	pH	Temp, °C	Label	Time, min	pH	Temp, °C
STRASBURG-7-0	0	7.45	28.6	STRASBURG-21-0	0	8.00	29.0
STRASBURG-7-3	3	8.3	28.3	STRASBURG-21-3	3	8.22	29.0
STRASBURG-7-5	5	8.32	28.3	STRASBURG-21-5	5	8.32	29.0
STRASBURG-7-10	10	8.43	28.3	STRASBURG-21-10	10	8.40	29.0
STRASBURG-7-20	20	8.51	28.4	STRASBURG-21-20	20	8.52	28.9
STRASBURG-7-30	30	8.55	28.4	STRASBURG-21-30	30	8.53	29.0
12 W / 1.5 % Ozone Feed				12 W / 1.5 % Ozone Feed <sup>1</sup>			
Label	Time, min	pH	Temp, °C	Label	Time, min	pH	Temp, °C
STRASBURG-6-0	0	7.32	27.8	STRASBURG-20-0	0	7.97	28.6
STRASBURG-6-3	3	7.96	27.8	STRASBURG-20-3	3	8.22	28.8
STRASBURG-6-5	5	8.11	27.8	STRASBURG-20-5	5	8.29	28.8
STRASBURG-6-10	10	8.26	27.8	STRASBURG-20-10	10	8.43	28.8
STRASBURG-6-20	20	8.39	27.8	STRASBURG-20-20	20	8.51	28.8
STRASBURG-6-30	30	8.46	27.9	STRASBURG-20-30	30	8.53	28.9
12 W / 1.5 % Ozone Feed							
Label	Time, min	pH	Temp, °C				
STRASBURG-31-0	0	6.96	26.1				
STRASBURG-31-60	60	8.16	26.1				
STRASBURG-31-90	90	8.18	26.3				
12 W / 1.0 % Ozone Feed / 50 mg/L Hydrogen Peroxide				12 W / 1.0 % Ozone Feed / 50 mg/L Hydrogen Peroxide <sup>1</sup>			
Label	Time, min	pH	Temp, °C	Label	Time, min	pH	Temp, °C
STRASBURG-9-0	0	7.44	26.3	STRASBURG-23-0	0	7.84	27.3
STRASBURG-9-3	3	8.06	26.3	STRASBURG-23-3	3	8.15	27.1
STRASBURG-9-5	5	8.18	26.3	STRASBURG-23-5	5	8.25	27.0
STRASBURG-9-10	10	8.32	26.3	STRASBURG-23-10	10	8.29	26.9
STRASBURG-9-20	20	8.43	26.4	STRASBURG-23-20	20	8.38	26.7
STRASBURG-9-30	30	8.51	26.4	STRASBURG-23-30	30	8.43	26.5

(Sheet 2 of 5)

**Table 3 (Continued)**

Low-Pressure Mercury Lamp							
12 W / 1.5 % Ozone Feed / 100 mg/L Hydrogen Peroxide							
Label	Time, min	pH	Temp, °C				
STRASBURG-32-0	0	6.93	26.3				
STRASBURG-32-60	60	8.14	26.9				
STRASBURG-32-90	90	8.17	26.9				
Medium-Pressure Mercury Lamp							
200 W / 100 mg/L Hydrogen Peroxide				200 W / 100 mg/L Hydrogen Peroxide <sup>1</sup>			
Label	Time, min	pH	Temp, °C	Label	Time, min	pH	Temp, °C
STRASBURG-14-0	0	7.72	25.9	STRASBURG-28-0	0	6.85	24.9
STRASBURG-14-3	3	7.73	25.8	STRASBURG-28-3	3	6.99	24.8
STRASBURG-14-5	5	7.73	25.7	STRASBURG-28-5	5	7.05	24.9
STRASBURG-14-10	10	7.58	25.7	STRASBURG-28-10	10	6.93	24.9
STRASBURG-14-20	20	7.51	25.6	STRASBURG-28-20	20	6.88	24.9
STRASBURG-14-30	30	7.47	25.5	STRASBURG-28-30	30	6.90	24.9
450 W / 50 mg/L Hydrogen Peroxide				450 W / 50 mg/L Hydrogen Peroxide <sup>1</sup>			
Label	Time, min	pH	Temp, °C	Label	Time, min	pH	Temp, °C
STRASBURG-12-0	0	7.72	24.3	STRASBURG-26-0	0	6.90	24.9
STRASBURG-12-3	3	7.52	24.3	STRASBURG-26-3	3	7.04	24.9
STRASBURG-12-5	5	7.50	24.3	STRASBURG-26-5	5	7.03	24.8
STRASBURG-12-10	10	7.49	24.3	STRASBURG-26-10	10	7.01	24.9
STRASBURG-12-20	20	7.42	24.3	STRASBURG-26-20	20	7.04	24.9
STRASBURG-12-30	30	7.43	24.5	STRASBURG-26-30	30	7.05	24.9
450 W / 250 mg/L Hydrogen Peroxide				450 W / 250 mg/L Hydrogen Peroxide <sup>1</sup>			
Label	Time, min	pH	Temp, °C	Label	Time, min	pH	Temp, °C
STRASBURG-13-0	0	7.66	24.8	STRASBURG-27-0	0	6.90	25.0
STRASBURG-13-3	3	7.72	24.9	STRASBURG-27-3	3	7.02	25.0
STRASBURG-13-5	5	7.60	24.9	STRASBURG-27-5	5	6.97	25.0
STRASBURG-13-10	10	7.42	24.9	STRASBURG-27-10	10	6.86	25.0
STRASBURG-13-20	20	7.25	25.1	STRASBURG-27-20	20	6.81	25.0
STRASBURG-13-30	30	7.29	25.2	STRASBURG-27-30	30	6.84	25.1

(Sheet 3 of 5)

**Table 3 (Continued)**

Medium-Pressure Mercury Lamp							
450 W / 250 mg/L Hydrogen Peroxide							
Label	Time, min	pH	Temp, °C				
STRASBURG-29-0	0	7.25	26.2				
STRASBURG-29-60	60	6.98	26.8				
STRASBURG-29-90	90	6.85	26.5				
Peroxone							
1.5 % Ozone Feed / 0.1 mg/L Hydrogen Peroxide				1.5 % Ozone Feed / 0.1 mg/L Hydrogen Peroxide <sup>1</sup>			
Label	Time, min	pH	Temp, °C	Label	Time, min	pH	Temp, °C
STRASBURG-4-0	0	7.42	28.2	STRASBURG-19-0	0	7.83	28.4
STRASBURG-4-3	3	8.09	28.1	STRASBURG-19-3	3	8.14	28.2
STRASBURG-4-5	5	8.18	28.1	STRASBURG-19-5	5	8.38	28.2
STRASBURG-4-10	10	8.32	28.1	STRASBURG-19-10	10	8.49	28.1
STRASBURG-4-20	20	8.48	28.1	STRASBURG-19-20	20	8.58	28.0
STRASBURG-4-30	30	8.52	28.3	STRASBURG-19-30	30	8.63	28.0
1.5 % Ozone Feed / 1 mg/L Hydrogen Peroxide				1.5 % Ozone Feed / 1 mg/L Hydrogen Peroxide <sup>1</sup>			
Label	Time, min	pH	Temp, °C	Label	Time, min	pH	Temp, °C
STRASBURG-1-0	0	7.16	27.2	STRASBURG-15-0	0	7.69	26.8
STRASBURG-1-3	3	7.91	27.2	STRASBURG-15-3	3	8.19	26.7
STRASBURG-1-5	5	7.98	27.2	STRASBURG-15-5	5	8.26	26.7
STRASBURG-1-10	10	8.09	27.3	STRASBURG-15-10	10	8.27	26.6
STRASBURG-1-20	20	8.28	27.3	STRASBURG-15-20	20	8.39	26.5
STRASBURG-1-30	30	8.34	27.4	STRASBURG-15-30	30	8.45	26.5
1.5 % Ozone Feed / 10 mg/L Hydrogen Peroxide				1.5 % Ozone Feed / 10 mg/L Hydrogen Peroxide <sup>1</sup>			
Label	Time, min	pH	Temp, °C	Label	Time, min	pH	Temp, °C
STRASBURG-2-0	0	7.16	27.4	STRASBURG-16-0	0	7.69	27.7
STRASBURG-2-3	3	7.92	27.4	STRASBURG-16-3	3	8.20	27.7
STRASBURG-2-5	5	7.96	27.4	STRASBURG-16-5	5	8.29	27.7
STRASBURG-2-10	10	8.14	27.4	STRASBURG-16-10	10	8.39	27.7
STRASBURG-2-20	20	8.27	27.4	STRASBURG-16-20	20	8.48	27.8
STRASBURG-2-30	30	8.33	27.4	STRASBURG-16-30	30	8.55	27.8

(Sheet 4 of 5)

**Table 3 (Concluded)**

Peroxone							
1.5 % Ozone Feed / 50 mg/L Hydrogen Peroxide				1.5 % Ozone Feed / 50 mg/L Hydrogen Peroxide <sup>1</sup>			
Label	Time, min	pH	Temp, °C	Label	Time, min	pH	Temp, °C
STRASBURG-3-0	0	7.80	27.5	STRASBURG-17-0	0	7.72	28.0
STRASBURG-3-3	3	7.85	27.5	STRASBURG-17-3	3	8.17	28.0
STRASBURG-3-5	5	8.01	27.4	STRASBURG-17-5	5	8.26	28.0
STRASBURG-3-10	10	8.14	27.5	STRASBURG-17-10	10	8.41	28.0
STRASBURG-3-20	20	8.32	27.5	STRASBURG-17-20	20	8.48	28.1
STRASBURG-3-30	30	8.32	27.5	STRASBURG-17-30	30	8.53	28.1
1.5 % Ozone Feed / 100 mg/L Hydrogen Peroxide				1.5 % Ozone Feed / 100 mg/L Hydrogen Peroxide <sup>1</sup>			
Label	Time, min	pH	Temp, °C	Label	Time, min	pH	Temp, °C
STRASBURG-5-0	0	7.35	25.9	STRASBURG-18-0	0	7.52	26.8
STRASBURG-5-3	3	8.05	26.0	STRASBURG-18-3	3	7.93	27.1
STRASBURG-5-5	5	8.12	26.1	STRASBURG-18-5	5	8.20	27.2
STRASBURG-5-10	10	8.23	26.1	STRASBURG-18-10	10	8.30	27.4
STRASBURG-5-20	20	8.38	26.3	STRASBURG-18-20	20	8.47	27.7
STRASBURG-5-30	30	8.48	26.3	STRASBURG-18-30	30	8.57	27.8
1.5 % Ozone Feed / 100 mg/L Hydrogen Peroxide							
Label	Time, min	pH	Temp, °C				
STRASBURG-33-0	0	7.02	27.0				
STRASBURG-33-60	60	8.30	27.1				
STRASBURG-33-90	90	8.23	27.0				
1.5 % Ozone Feed / 10 mg/L Hydrogen Peroxide							
Label	Time, min	pH	Temp, °C				
STRASBURG-34-0	0	6.84	25.8				
STRASBURG-34-5	5	7.84	26.1				
STRASBURG-34-10	10	8.05	26.2				
STRASBURG-34-20	20	8.18	26.3				
STRASBURG-34-60	60	8.25	26.4				
<i>(Sheet 5 of 5)</i>							

collected samples using a Beckman pH meter with a combination electrode that was calibrated using a standard two-point calibration (buffers of 4 and 10). The pH of test solutions within the reactor generally remained within the 7.0 to 8.5 range during the AOP experiments (Table 3).

The VOC analyses were run on a Hewlett-Packard MS/GC with an OI purge and trap using USEPA Method No. 8240. USEPA-required sample holding times were not exceeded during this study. The amount of free chloride liberated during a peroxone run was quantified using a Dionex 505 series ion chromatography unit by the Environmental Restoration Branch, WES.

An HNU brand photoionizer detector (PID), calibrated to benzene (i.e.,  $R = 1$  for  $C_6H_6$ ), was used to analyze the off-gases exiting a peroxone experiment to quantify the amount of VOCs stripped from the reactor during ozonation. This technique is capable of analyzing VOC levels as low as 1.0 ppm. Figure 3 illustrates the experimental setup used for off-gas analyses. The process off-gases were passed through two potassium iodide (KI) traps to remove excess ozone. After removal of the ozone, the gases were passed through the PID and the levels recorded. Ozone removal was required because the UV detector used in the PID is sensitive to ozone.

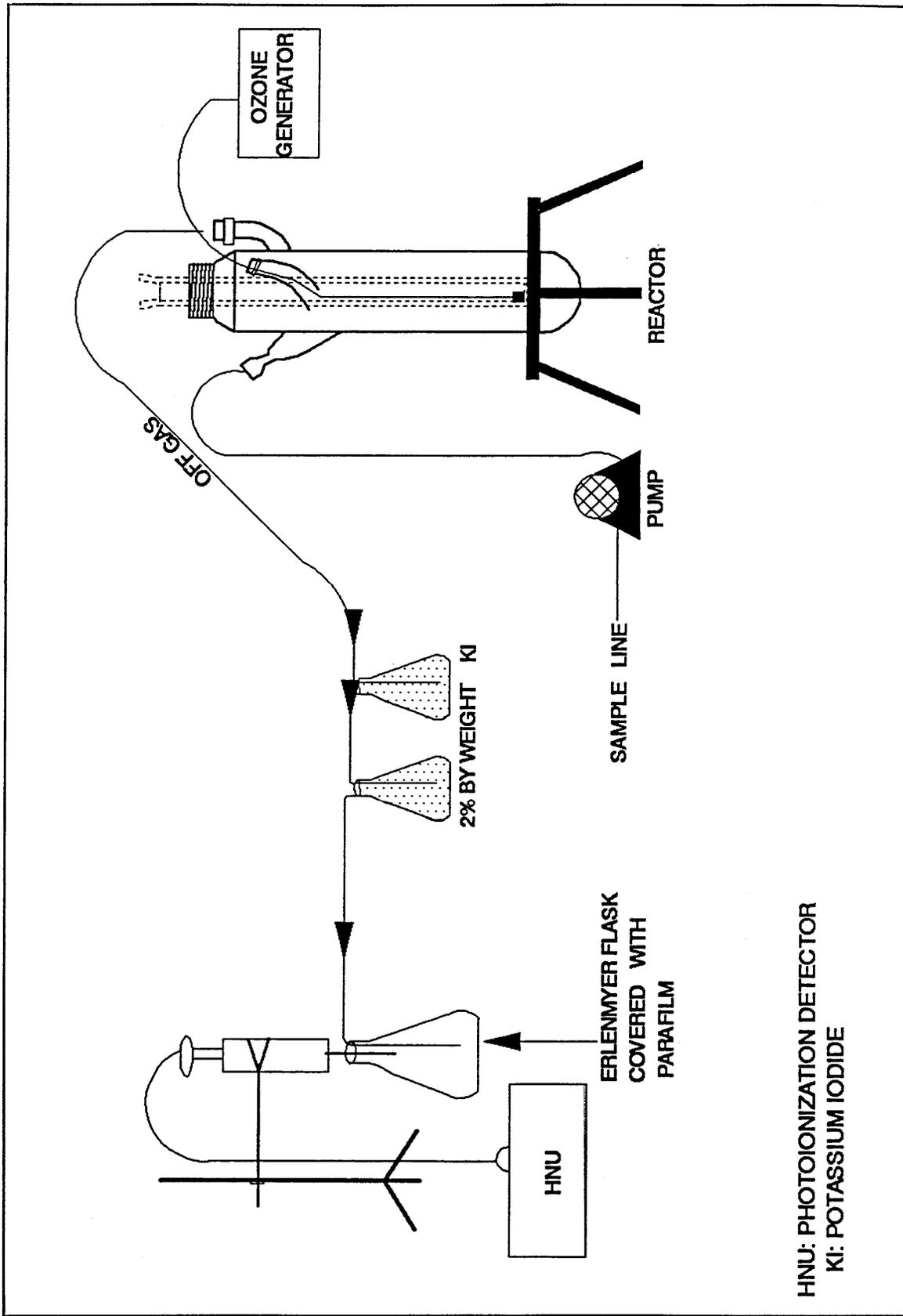


Figure 3. Strsburg groundwater off-gas testing

## 3 Results

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The results of this study are discussed on an individual VOC basis. Process effectiveness is evaluated based on the ability of the AOP to meet the target TCE treatment goals listed in Table 1 or a comparative evaluation on removal efficiency for those VOCs initially present at levels lower than the site treatment goal. Table 1 also presents the actual and targeted groundwater characteristics. The data discussed in the body of this report is presented using tables of test time (HRT) versus contaminant concentration. The results of each replicate run and the respective average of these runs are listed in the data tables. Figures plotting the numerical average values of the duplicate runs versus test time are presented in Appendix A. The averages shown in the tables for the experiment where one of the two replicates had detectable hits while the sister runs did not were calculated by assigning the less than detect data a numerical value of half of the detection limit shown. For example, a detection limit of 10 ppb was given a 5 ppb value for use in calculating the average. If neither of the two replicates had measurable amounts of VOCs, then the average was given a less than detect label. The raw data sheets for this study are included as Appendix B.

### Trichloroethylene

Trichloroethylene (TCE) was originally present in the groundwater influent at a concentration of approximately 0.1 mg/L, while the target treatment goal for TCE is 0.0065 mg/L (see Table 1). This requires an estimated percent removal of over 94 percent.

Table 4 presents the results for the experiments that evaluated MPUV/hydrogen peroxide- and LPUV/hydrogen peroxide-based AOPs for removal of TCE. With respect to the LPUV-HP systems evaluated, the 500-mg/L hydrogen peroxide-dosed system had a more rapid TCE removal rate than the 100-mg/L dose. Both systems did have measurable amounts of TCE after 30 min of treatment; however, the 100-mg/L hydrogen peroxide-dosed LPUV system did not meet the target treatment goal within the 30-min time frame evaluated. The 500-mg/L hydrogen peroxide-dosed system did meet target levels within 30 min of treatment. The higher removal rates observed in the 500-mg/L hydrogen peroxide-dosed experiments were likely obtained due to

**Table 4**  
**Trichloroethylene (mg/L) - MPUV and LPUV/Hydrogen Peroxide Oxidation Runs**

Run No.	STRASBURG-10	STRASBURG-24	AVG	STRASBURG-11	STRASBURG-25	STRASBURG-30	AVG	STRASBURG-12	STRASBURG-26	AVG
UV Source	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	450 W MPUV	450 W MPUV	450 W MPUV
H <sub>2</sub> O <sub>2</sub> Dose mg/L	100	100	100	500	500	500	500	50	50	50
Test Time min										
0	0.099	0.097	0.098	0.110	0.098	0.110	0.106	0.086	0.120	0.103
3	0.073	0.077	0.075	0.041	0.058	--	0.049	0.069	0.0097	0.039
5	0.065	0.068	0.066	0.035	0.049	--	0.042	0.042	0.0037J	0.023
10	0.051	0.058	0.054	0.017	0.024	--	0.020	0.013	<0.010	0.009
20	0.034	0.041	0.037	0.0039J	0.0083J	--	0.006	0.0035J	<0.025	0.008
30	0.022	0.030	0.026	0.0009J	<0.010	--	0.003	0.00088J	<0.025	0.006
60	--	--	--	--	--	<0.010	<0.010	--	--	--
90	--	--	--	--	--	<0.010	<0.010	--	--	--
% Removal			73.47				95.28			94.17
Run No.	STRASBURG-13	STRASBURG-27	AVG	STRASBURG-14	STRASBURG-28	STRASBURG-28	AVG			
UV Source	450 W MPUV	450 W MPUV	450 W MPUV	200 W MPUV	200 W MPUV	200 W MPUV	200 W MPUV			
H <sub>2</sub> O <sub>2</sub> Dose mg/L	250	250	250	100	100	100	100			
Test Time min										
0	0.082	0.140	0.085	0.102	0.087	0.100	0.093			
3	0.037	0.006	--	0.021	0.033	0.033	0.033			
5	0.014	0.0022J	--	0.008	0.015	0.013	0.014			
10	0.0025J	<0.010	--	0.006	0.0053J	0.0017J	0.004			
20	<0.010	<0.025	--	<0.010	0.0012J	<0.025	0.006			
30	<0.010	<0.025	--	<0.010	<0.010	<0.025	<0.010			
60	--	--	0.0023J	--	--	--	--			
90	--	--	<0.010	<0.010	--	--	--			
% Removal				95.10			94.62			

the increased amount of hydrogen peroxide available for conversion into the hydroxyl radical. The MPUV/hydrogen peroxide experiments indicated that TCE was easily oxidized using systems of this type. Target levels were reached within 10 min using hydrogen peroxide doses greater than 50 mg/L (100 and 250 mg/L) within the MPUV systems using the 200-W and 450-W UV lamps. The 450-W MPUV lamp system, which employed a 50-mg/L hydrogen peroxide dose, reached target levels within 20 min, indicating that it had a much slower TCE-removal rate than the MPUV systems using the higher doses. This observation indicates that TCE removal was not as dependent on UV power as it was on hydrogen peroxide dose. The 50-mg/L hydrogen peroxide dose was apparently did not provide enough hydrogen peroxide to maintain sufficient levels of hydroxyl radicals within the reactor.

Table 5 lists the TCE results for the ozonated LPUV systems. The experiments that used ozone compositions within the sparged gas of 1.5 and 1.0 percent (conversion to mass flow rate of ozone, Appendix C) resulted in similar removal rates, while the 0.5-percent ozone-sparged gas runs achieved a slightly slower TCE-removal rate. Within 10 min of treatment, no TCE was detected in the 0.5, 1.0, and 1.5-percent ozone-dosed experiments. Target treatment levels were reached within 5 min of treatment for both the 1.5 and 1.0-percent ozone experiments. The 0.5-percent ozone experiments had no detectable amounts of TCE after 10 min of treatment, indicating that at somewhere between 1.0- and 0.5-percent ozone content, the reactors may have been slightly ozone limited, thereby adversely impacting the steady-state soluble-phase ozone concentrations. The addition of 50-mg/L hydrogen peroxide to the LPUV-OZ system with 1.0-percent ozone sparging did not appear to improve the overall removal rate of TCE over the same ozone dose without hydrogen peroxide addition. Although not investigated, the addition of hydrogen peroxide to the 0.5 percent would have likely improved TCE-removal rate due to an increased hydroxyl radical production potential (i.e., both hydrogen peroxide and ozone photolysis).

Table 6 presents the results for the experiments that evaluated peroxone for removal of TCE. These data indicate that a hydrogen peroxide dose ranging from 1 to 10 mg/L produced slightly more rapid TCE-removal rates than the lower and higher hydrogen peroxide doses evaluated. The discussion of the radical scavenging mechanisms in the Introduction section of this report supports this observation in that an optimal hydrogen peroxide to ozone stoichiometric ratio does exist. If excessive amounts of hydrogen peroxide are dosed, then the residual hydrogen peroxide becomes a radical scavenger. If less than adequate amounts of hydrogen peroxide are dosed, then the radical production reactions become hydrogen peroxide starved and scavenged by excessive amounts of ozone. In any case, all of the peroxone systems evaluated removed TCE to target levels within 5 min of treatment.

**Table 5**  
**Trichloroethylene (mg/L) - LPUV/Ozone and LPUV/Peroxone Oxidation Runs**

Run No.	STRASBURG-6 12 W LPUV	STRASBURG-20 12 W LPUV	STRASBURG-31 12 W LPUV	AVG 12 W LPUV	STRASBURG-7 12 W LPUV	STRASBURG-21 12 W LPUV	AVG 12 W LPUV	STRASBURG-8 12 W LPUV	STRASBURG-22 12 W LPUV	AVG 12 W LPUV
UV Source	1.5	1.5	1.5	1.5	1.0	1.0	1.0	0.5	0.5	0.5
O <sub>3</sub> Feed, %	1.5	1.5	1.5	1.5	1.0	1.0	1.0	0.5	0.5	0.5
Test Time min										
0	0.110	0.100	0.140	0.117	0.130	0.088	0.109	0.110	0.090	0.100
3	0.013	0.012	--	0.012	0.0026J	0.013	0.008	0.016	0.021	0.018
5	0.0041J	0.0038J	--	0.004	0.0006J	0.0045J	0.003	0.0064	0.099	0.053
10	<0.010	<0.010	--	<0.010	<0.025	<0.010	<0.010	<0.005	0.0013J	0.002
20	<0.010	<0.010	--	<0.010	<0.025	<0.010	<0.010	<0.010	<0.010	<0.010
30	<0.025	<0.025	--	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025
60	--	--	<0.010	<0.010	--	--	--	--	--	--
90	--	--	<0.010	<0.010	--	--	--	--	--	--
% Removal				95.73			88.53			87.50
Run No.	STRASBURG-9	STRASBURG-23	AVG	STRASBURG-32						
UV Source	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV						
O <sub>3</sub> Feed, %	1.0	1.0	1.0	1.5						
H <sub>2</sub> O <sub>2</sub> Dose mg/L	50	50	50	100						
Test Time min										
0	0.093	0.091	0.092	0.130						
3	0.010	0.026	0.018	--						
5	0.0034J	0.0079	0.006	--						
10	<0.005	<0.010	<0.005	--						
20	<0.010	<0.010	<0.010	--						
30	<0.025	<0.025	<0.025	--						
60	--	--	--	<0.010						
90	--	--	--	<0.010						
% Removal			86.41							

**Table 6**  
**Trichloroethylene (mg/L) - Peroxone Oxidation Runs**

Run No.	STRASBURG-1	STRASBURG-15	STRASBURG-2	STRASBURG-16	STRASBURG-3	STRASBURG-17	AVG
O <sub>3</sub> Feed, %	1.5	1.5	1.5	1.5	1.5	1.5	1.5
H <sub>2</sub> O <sub>2</sub> Dose mg/L	1.0	1.0	10	10	50	50	50
Test Time, min							
0	0.130	0.083	0.120	0.086	0.130	0.082	0.106
3	0.011	0.0026J	0.010	0.0031J	0.015	0.007	0.011
5	0.0033J	0.00079J	0.0024J	0.0011J	0.0033J	0.0017J	0.003
10	<0.025	<0.010	<0.025	<0.010	<0.025	<0.010	<0.010
20	<0.025	<0.010	<0.025	<0.010	<0.025	<0.010	<0.010
30	<0.025	<0.010	<0.025	<0.025	<0.025	<0.025	<0.025
60	--	--	--	--	--	--	--
90	--	--	--	--	--	--	--
% Removal					87.86		88.21

Run No.	STRASBURG-4	STRASBURG-19	STRASBURG-5	STRASBURG-18	STRASBURG-33	STRASBURG-17	AVG
O <sub>3</sub> Feed, %	1.5	1.5	1.5	1.5	1.5	1.5	1.5
H <sub>2</sub> O <sub>2</sub> Dose mg/L	0.1	0.1	100	100	100	100	100
Test Time, min							
0	0.130	0.086	0.120	0.084	0.110	0.105	0.106
3	0.018	0.0063	0.016	0.0096	--	0.013	0.011
5	0.0048J	0.0011J	0.0076	0.0025J	--	0.005	0.003
10	<0.025	<0.010	<0.010	<0.010	--	<0.010	<0.010
20	<0.025	<0.010	<0.025	<0.010	--	<0.010	<0.010
30	<0.025	<0.025	<0.025	<0.025	--	<0.025	<0.025
60	--	--	--	--	<0.010	<0.010	<0.010
90	--	--	--	--	<0.010	<0.010	<0.010
% Removal						95.24	88.43

## Chlorobenzene

The initial chlorobenzene concentration detected in the groundwater influent was approximately 0.05 mg/L, while the target treatment level is 0.202 mg/L, indicating that this contaminant was already present at levels lower than the target treatment goals. Therefore, the comparative performance of the various candidate AOPs will be evaluated based on the amount of time required to achieve less than detection limit values.

Table 7 presents the results for the experiments that evaluated UV/hydrogen peroxide-based AOPs for removal of chlorobenzene. These results have similar trends to those observed with the TCE results. The 500-mg/L hydrogen peroxide-dosed LPUV system had a much more rapid chlorobenzene removal rate than the 100-mg/L dosed system. The 500-mg/L system removed chlorobenzene to the below-detection-limit value within 20 min of treatment, while the 100-mg/L system still had detectable levels of chlorobenzene (approximately 0.006 mg/L) at the 30-min mark. The results of the experiments that evaluated MPUV-based AOPs for removal of chlorobenzene indicated that the 200-W, 100-mg/L hydrogen peroxide-dosed system had a removal rate slightly slower than the 250-mg/L hydrogen peroxide-dosed and substantially greater than the 50-mg/L hydrogen peroxide-dosed systems, which used the 450-W MPUV lamp. This agrees with the TCE experiments in that the 450-W/250-mg/L hydrogen peroxide experiments had better TCE removals than the 100-mg/L dosed 200-W MPUV system. The 450-W/250-mg/L hydrogen peroxide and 200-W/100-mg/L hydrogen peroxide systems both removed the chlorobenzene within 20 min of treatment. The 450-W/50-mg/L hydrogen peroxide system still had detectable amounts of chlorobenzene (albeit very low) after 30 min of treatment.

Table 8 lists the results of the ozonated LPUV experiments. Much like the TCE results, the 1.5- and 1.0-percent ozonated air-sparged systems produced similar results. Within 10 min of treatment, both systems had no measurable amounts of chlorobenzene. The 0.5-percent ozonated air-sparged system had slightly slower removal kinetics by requiring 20 min to remove chlorobenzene to below detection limit values. The addition of 50-mg/L hydrogen peroxide did not improve chlorobenzene removal rate, but actually adversely impacted removal rate. The presence of the hydrogen peroxide likely served as a radical scavenger since ozone was probably outcompeting the hydrogen peroxide for the available UV photons.

Table 9 presents the results for the experiments that evaluated peroxone experiments for removal of chlorobenzene. The removal kinetics observed for chlorobenzene using peroxone were quite similar to those observed for TCE. The 0.1- to 50-mg/L doses seem to be superior doses compared with the 100-mg/L dose. The increased hydrogen peroxide dose likely had a scavenging effect that had a detrimental effect on the removal rate of chlorobenzene for this system.

**Table 7**

**Chlorobenzene (mg/L) - MPUV and LPUV/Hydrogen Peroxide Oxidation Runs**

Run No.	STRASBURG-10	STRASBURG-24	AVG	STRASBURG-11	STRASBURG-25	STRASBURG-30	AVG	STRASBURG-12	STRASBURG-26	AVG
UV Source	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	450 W MPUV	450 W MPUV	450 W MPUV
H <sub>2</sub> O <sub>2</sub> Dose mg/L	100	100	100	500	500	500	500	500	50	50
Test Time min										
0	0.043	0.017	0.030	0.052	0.018	0.072	0.047	0.029	0.120	0.074
3	0.033	0.041	0.037	0.013	0.019	--	0.016	0.035	0.0099	0.022
5	0.028	0.041	0.034	0.0086	0.014	--	0.011	0.021	0.0041J	0.012
10	0.019	0.027	0.023	0.0027J	0.0056J	--	0.004	0.007	<0.010	0.006
20	0.0089	0.015	0.011	<0.005	<0.010	--	<0.005	0.0022J	<0.025	0.007
30	0.0042J	0.0088J	0.006	<0.005	<0.010	--	<0.005	0.00072J	<0.025	0.007
60	--	--	--	--	--	<0.010	<0.010	--	--	--
90	--	--	--	--	--	<0.010	<0.010	--	--	--
% Removal			80.00				89.36			90.54
Run No.	STRASBURG-13	STRASBURG-27	AVG	STRASBURG-14	STRASBURG-28	AVG	STRASBURG-14	STRASBURG-28	AVG	STRASBURG-14
UV Source	450 W MPUV	450 W MPUV	450 W MPUV	200 W MPUV	200 W MPUV	200 W MPUV	200 W MPUV	200 W MPUV	200 W MPUV	200 W MPUV
H <sub>2</sub> O <sub>2</sub> Dose mg/L	250	250	250	250	100	100	100	100	100	100
Test Time min										
0	0.024	0.130	0.055	0.070	0.028	0.098	0.063			
3	0.011	0.0039J	--	0.007	0.0095	0.027	0.018			
5	0.0035J	0.0016J	--	0.002	0.0040J	0.0097J	0.006			
10	0.0012J	0.0013J	--	0.001	0.0013J	<0.010	0.003			
20	<0.010	<0.025	--	<0.010	<0.010	<0.025	<0.010			
30	<0.010	<0.025	--	<0.010	<0.010	<0.025	<0.010			
60	--	--	0.0011J	0.001	--	--	--			
90	--	--	<0.010	<0.010	--	--	--			
% Removal			92.86				92.06			

**Table 8**  
**Chlorobenzene (mg/L) - LPUV/Ozone and LPUV/Peroxone Oxidation Runs**

Run No.	STRASBURG-6	STRASBURG-20	STRASBURG-31	STRASBURG-7	STRASBURG-21	STRASBURG-8	STRASBURG-22	AVG
UV Source	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV
O <sub>3</sub> Feed, %	1.5	1.5	1.5	1.0	1.0	0.5	0.5	1.0
Test Time min								
0	0.058	0.017	0.076	0.062	0.016	0.052	0.018	0.039
3	0.015	0.0041J	--	0.0062	0.0046J	0.020	0.0077	0.005
5	0.006	0.013J	--	0.0025J	0.0024J	0.013	0.0053	0.002
10	<0.010	<0.010	--	<0.025	<0.010	0.0032J	0.0018J	<0.010
20	<0.010	<0.010	--	<0.025	<0.010	<0.010	<0.010	<0.010
30	<0.025	<0.025	--	<0.025	<0.025	<0.025	<0.010	<0.025
60	--	--	<0.010	--	--	--	--	--
90	--	--	<0.010	--	--	--	--	--
% Removal			90.00		67.95			85.71
Run No.	STRASBURG-9	STRASBURG-23	STRASBURG-32					
UV Source	12 W LPUV	12 W LPUV	12 W LPUV					
O <sub>3</sub> Feed, %	1.0	1.0	1.5					
H <sub>2</sub> O <sub>2</sub> Dose mg/L	50	50	100					
Test Time min								
0	0.041	0.018	0.029	0.078				
3	0.0096	0.014	0.011	--				
5	0.0041J	0.0054	0.004	--				
10	0.0005J	<0.010	0.002	--				
20	<0.010	<0.010	<0.010	--				
30	<0.025	<0.025	<0.025	--				
60	--	--	--	0.0010J				
90	--	--	--	<0.010				
% Removal			56.90					

**Table 9**  
**Chlorobenzene (mg/L) - Peroxone Oxidation Runs**

Run No.	STRASBURG-1	STRASBURG-15	AVG	STRASBURG-2	STRASBURG-16	AVG	STRASBURG-3	STRASBURG-17	AVG
O <sub>3</sub> Feed, %	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
H <sub>2</sub> O <sub>2</sub> Dose mg/L	1.0	1.0	1.0	10	10	10	50	50	50
Test Time, min									
0	0.061	0.029	0.045	0.060	0.029	0.044	0.062	0.023	0.042
3	0.013	0.0035J	0.008	0.011	0.0029	0.006	0.012	0.0047J	0.008
5	0.0051J	0.001J	0.003	0.0035J	0.0011J	0.002	0.0042J	0.00077J	0.002
10	<0.025	<0.010	<0.010	<0.025	<0.010	<0.010	<0.025	<0.010	<0.010
20	<0.025	<0.010	<0.010	<0.025	<0.010	<0.010	<0.025	<0.010	<0.010
30	<0.025	<0.010	<0.010	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025
60	--	--	--	--	--	--	--	--	--
90	--	--	--	--	--	--	--	--	--
% Removal			88.89			71.59			70.24
Run No.	STRASBURG-4	STRASBURG-19	AVG	STRASBURG-5	STRASBURG-18	STRASBURG-33	AVG	STRASBURG-33	AVG
O <sub>3</sub> Feed, %	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
H <sub>2</sub> O <sub>2</sub> Dose mg/L	0.1	0.1	0.1	100	100	100	100	100	100
Test Time, min									
0	0.060	0.026	0.043	0.062	0.026	0.071	0.053		
3	0.017	0.005	0.011	0.016	0.006	--	0.011		
5	0.0070J	0.0017J	0.004	0.0079	0.0012J	--	0.004		
10	<0.025	<0.010	<0.010	<0.009J	<0.010	--	0.002		
20	<0.025	<0.010	<0.010	<0.025	<0.010	--	<0.010		
30	<0.025	<0.025	<0.025	<0.025	<0.025	--	<0.025		
60	--	--	--	--	--	0.00077J	0.0007		
90	--	--	--	--	--	<0.010	<0.010		
% Removal			70.93			<0.010	<0.010		90.57

## Total Xylenes (T-Xylenes)

The initial T-xylenes concentration detected within the groundwater influent was approximately 0.12 mg/L. The target treatment level for T-xylene is 0.2 mg/L, indicating that this contaminant was already present at levels lower than the target treatment goals. Therefore, the extent of T-xylenes removal will be evaluated based on comparison of removal rate and amount of time required to remove T-xylene to below-detection-limit values for the various AOP systems tested.

Table 10 presents the results for the experiments that evaluated UV/hydrogen peroxide-based AOPs for removal of T-xylenes. As was observed with the other contaminants, the 500-mg/L hydrogen peroxide-dosed LPUV system had a more rapid removal rate than the 100-mg/L dose. Within 20 min of treatment, T-xylenes levels were reduced to below-detection-limit values using the 500-mg/L hydrogen peroxide system, while the 100-mg/L system still had detectable levels after 30 min of treatment. The 450-W/250-mg/L hydrogen peroxide system had a slightly more rapid removal rate than the 200-W/100-mg/L hydrogen peroxide dose, indicating a higher hydroxyl radical production rate than the lower UV energy/hydrogen peroxide-dosed system. The 50-mg/L dose exhibited a slower removal rate than either the 100-mg/L and 250-mg/L doses. This is probably due to lower steady-state radical concentrations maintained within the reactor. As is the case with the other contaminants, removal to less-than-detect levels did not occur for any of the MPUV/hydrogen peroxide systems until 20 min of treatment.

Table 11 presents the results of the ozonated LPUV systems. These data indicate that increasing ozone composition from 0.5 percent to levels of 1.0 percent or greater within the sparged gas resulted in increased the removal rates. Both the 1.0 and 1.5-percent ozone systems removed T-xylenes to below detection limit levels within 10 min of treatment. The 0.5-percent ozone system did not reach below detection levels until the 20 min of treatment. The addition of hydrogen peroxide to the ozone-sparged LPUV system had an adverse impact on removal rate by yielding a slightly slower removal rate than the same system without hydrogen peroxide dosing.

Table 12 presents the results of the experiments that evaluated peroxone for removal of T-xylenes. The 50-mg/L hydrogen peroxide-dosed peroxone run appears to have yielded a slightly more rapid removal rate than the other hydrogen peroxide doses evaluated. However, as was the case with the other VOCs, there was only a slight difference in performance between the various hydrogen peroxide doses within the peroxone systems evaluated during this study.

**Table 10  
T-Xylene (mg/L) - MPUV and LPUV/Hydrogen Peroxide Oxidation Runs**

Run No.	STRASBURG-10 12 W LPUV	STRASBURG-24 12 W LPUV	STRASBURG-11 12 W LPUV	STRASBURG-25 12 W LPUV	STRASBURG-30 12 W LPUV	STRASBURG-12 450 W MPUV	STRASBURG-26 450 W MPUV	AVG
UV Source	100	100	500	500	500	50	50	500
H <sub>2</sub> O <sub>2</sub> Dose mg/L	100	100	500	500	500	50	50	500
Test Time min								
0	0.140	0.0019J	0.170B	0.0018J	0.240	0.027	0.340	0.137
3	0.093	0.051	0.013B	0.016	--	0.090	0.015	0.014
5	0.074	0.045	0.0084B	0.0053	--	0.048	0.0045	0.007
10	0.042	0.027	0.0025BJ	0.0037J	--	0.013	<0.010	0.003
20	0.015	0.014	0.00064BJ	<0.010	--	0.0043J	<0.025	0.003
30	0.0051	0.0056J	<0.005	<0.010	--	0.0013J	<0.025	<0.005
60	--	--	--	--	0.0010J	--	--	0.001
90	--	--	--	--	<0.050	--	--	<0.050
% Removal								81.75
Run No.	STRASBURG-13 450 W MPUV	STRASBURG-27 450 W MPUV	STRASBURG-29 450 W MPUV	STRASBURG-14 200 W MPUV	STRASBURG-28 200 W MPUV	STRASBURG-12 450 W MPUV	STRASBURG-26 450 W MPUV	AVG
UV Source	250	250	250	100	100	50	50	200 W MPUV
H <sub>2</sub> O <sub>2</sub> Dose mg/L	250	250	250	100	100	50	50	100
Test Time min								
0	0.021	0.380	0.180	0.027	0.290	0.027	0.340	0.158
3	0.0081	0.0066	--	0.0061	0.053	0.090	0.015	0.030
5	0.0024J	0.0022J	--	0.0026J	0.013	0.048	0.0045	0.008
10	0.0017J	0.0017J	--	0.0017J	<0.010	0.013	0.0045	0.003
20	0.0014J	<0.025	--	0.0011J	<0.025	0.013	0.0045	0.007
30	<0.010	<0.025	--	<0.010	<0.025	0.013	0.0045	<0.010
60	--	--	0.0020J	--	<0.025	0.013	0.0045	--
90	--	--	<0.010	--	--	0.013	0.0045	--
% Removal								96.84

**Table 11**  
**T-Xylene (mg/L) - LPUV/Ozone and LPUV/Peroxone Oxidation Runs**

Run No.	STRASBURG-8 12 W LPUV	STRASBURG-20 12 W LPUV	STRASBURG-31 12 W LPUV	STRASBURG-7 12 W LPUV	STRASBURG-21 12 W LPUV	STRASBURG-8 12 W LPUV	STRASBURG-22 12 W LPUV	AVG
UV Source	1.5	1.5	1.5	1.0	1.0	0.5	0.5	1.0
O <sub>3</sub> Feed, %	1.5	1.5	1.5	1.0	1.0	0.5	0.5	1.0
Test Time min								
0	0.170	0.002J	0.230	0.190	0.0015J	0.150	0.0019J	0.096
3	0.019	<0.005	--	0.0034J	<0.005	0.035	<0.005	0.002
5	0.003J	<0.005	--	<0.010	<0.005	0.013	<0.005	<0.005
10	<0.010	<0.010	--	<0.025	<0.010	0.00071J	<0.005	<0.010
20	<0.010	<0.010	--	<0.025	<0.010	<0.010	<0.010	<0.010
30	<0.025	<0.025	--	<0.025	<0.025	<0.025	<0.025	<0.025
60	--	<0.010	<0.010	--	--	--	--	--
90	--	<0.010	<0.010	--	--	--	--	--
% Removal			96.27					89.78
Run No.	STRASBURG-9	STRASBURG-23	STRASBURG-32					
UV Source	12 W LPUV	12 W LPUV	12 W LPUV					
O <sub>3</sub> Feed, %	1.0	1.0	1.5					
H <sub>2</sub> O <sub>2</sub> Dose mg/L	50	50	100					
Test Time min								
0	0.130	0.002J	0.066					0.230
3	0.011	0.0076	0.009					--
5	0.0024J	0.0014J	0.002					--
10	<0.005	<0.010	<0.005					--
20	<0.010	<0.010	<0.010					--
30	<0.025	<0.025	<0.025					--
60	--	--	0.0018J					0.0018J
90	--	--	<0.010					<0.010
% Removal			81.06					
								83.55

**Table 12  
T-Xylene (mg/L) - Peroxone Oxidation Runs**

Run No.	STRASBURG-1	STRASBURG-15	AVG	STRASBURG-2	STRASBURG-3	STRASBURG-16	AVG	STRASBURG-17	AVG
O <sub>3</sub> Feed, %	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
H <sub>2</sub> O <sub>2</sub> Dose mg/L	1.0	1.0	1.0	10	10	10	10	50	50
Test Time, min									
0	0.190	0.025	0.107	0.170	0.026	0.026	0.098	0.021	0.101
3	0.016	0.00052J	0.008	0.013	0.00089J	0.00089J	0.007	0.0018J	0.010
5	0.0037J	<0.005	0.003	0.0017J	<0.005	<0.005	0.002	<0.005	<0.005
10	<0.025	<0.010	<0.010	<0.025	<0.010	<0.010	<0.010	<0.010	<0.010
20	<0.025	<0.010	<0.010	<0.025	<0.010	<0.010	<0.010	<0.010	<0.010
30	<0.025	<0.010	<0.010	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025
60	--	--	--	--	--	--	--	--	--
90	--	--	--	--	--	--	--	--	--
% Removal			95.33				87.24		87.62
Run No.	STRASBURG-4	STRASBURG-19	AVG	STRASBURG-5	STRASBURG-18	STRASBURG-33	AVG	STRASBURG-33	AVG
O <sub>3</sub> Feed, %	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
H <sub>2</sub> O <sub>2</sub> Dose mg/L	0.1	0.1	0.1	100	100	100	100	100	100
Test Time, min									
0	0.190	0.024	0.107	0.180	0.023	0.023	0.240	0.101	0.101
3	0.026	0.001J	0.013	0.028	0.0026J	0.0026J	--	0.015	0.015
5	0.006J	<0.005	0.004	0.010	<0.005	<0.005	--	0.006	0.006
10	<0.025	<0.010	<0.010	<0.010	<0.010	<0.010	--	<0.010	<0.010
20	<0.025	<0.010	<0.010	<0.025	<0.010	<0.010	--	<0.010	<0.010
30	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	--	<0.025	<0.025
60	--	--	--	--	--	--	0.0017J	0.002	0.002
90	--	--	--	--	--	--	<0.010	<0.010	<0.010
% Removal			88.32						95.05

## Ethyl Benzene

The initial ethyl benzene concentration detected within the groundwater influent was approximately 0.0282 mg/L (average); however, in many of the AOP experiments, ethyl benzene was not detected in the initial ( $t = 0$ ) samples. The target treatment level for ethyl benzene is 5.858 mg/L, indicating that this contaminant was already present at levels lower than the target treatment goals. Therefore, the extent of ethyl benzene removal will be evaluated based on the comparison of both removal rate and amount of time required to reach less-than-detection-limit value within the various candidate AOP systems.

Most of the AOP experiments were performed using groundwater samples that did not have detectable amounts of ethyl benzene. However, for those few runs that did have detectable amounts of ethyl benzene in the test influents, these data are presented in Tables 13 through 15. In all cases, ethyl benzene was removed to below-detection-limit values within 10 min of treatment, indicating that ethyl benzene at the concentrations tested is a relatively easy contaminant to remove using any of the AOPs evaluated during this study.

## Acetone

Most organic compounds generally undergo a similar oxidation pathway. This pathway usually involves oxidation through aldehydes and possibly ketones to simple organic acids followed by further (and kinetically slow) oxidation to inorganic constituents. WES researchers observed an increase in acetone concentrations during AOP treatment of a groundwater from a landfill in New Jersey contaminated with chlorinated solvents and simple aromatic hydrocarbons (Zappi, Fleming, and Cullinane 1992). This groundwater contained similar contaminants to those detected within the groundwater influent used in this study.

The results of the Strasburg AOP experiments indicated a buildup of acetone and 2-butanone over time. The formation of these ketone bodies within the AOP systems is attributed to the formation of ethyl and methyl radicals and acetaldehydes during oxidation of xylenes, chloroethylenes, and ethylbenzenes. The ethyl and methyl radicals likely combine with the acetyl radical to form 2-butanone and acetone, respectively.

Upon review of the results of the AOP experiments, an increase in acetone and 2-butanone was observed probably due to the proposed mechanistic scheme discussed above. However, the levels of ketone production was an order of magnitude less than target treatment levels listed in Table 1. Only the MPUV/hydrogen peroxide systems showed a peaking of acetone and 2-butanone concentrations at approximately 0.4 mg/L and 0.05 mg/L, respectively, with a definite downward trend noted at 30 min of treatment. Many of the other AOPs did show a leveling off of ketone formation, but not a

**Table 13**  
**Ethyl Benzene (mg/L) - MPUV and LPUV/Hydrogen Peroxide Oxidation Runs**

Run No.	STRASBURG-10	STRASBURG-24	AVG	STRASBURG-11	STRASBURG-25	STRASBURG-30	AVG	STRASBURG-12	STRASBURG-26	AVG	
UV Source	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	450 W MPUV	450 W MPUV	450 W MPUV	
H <sub>2</sub> O <sub>2</sub> Dose mg/L	100	100	100	500	500	500	500	50	50	50	
Test Time min											
0	<0.005	<0.005	<0.005	<0.005	<0.005	0.0075J	0.004	<0.005	0.270	0.136	
3	0.00078J	0.016	0.008	<0.005	0.0041J	--	0.003	0.0008J	0.210	0.105	
5	0.00074J	0.015	0.007	<0.005	0.0028J	--	0.002	0.0006J	0.007	0.004	
10	0.00060J	0.0094	0.005	<0.005	<0.010	--	<0.005	<0.005	<0.010	<0.005	
20	<0.005	0.0053J	0.004	<0.005	<0.010	--	<0.005	<0.005	<0.025	<0.005	
30	<0.005	0.0024J	0.002	<0.005	<0.010	--	<0.005	<0.005	<0.025	<0.005	
60	--	--	--	--	--	<0.010	<0.010	--	--	--	
90	--	--	--	--	--	<0.010	<0.010	--	--	--	
% Removal			20.00				-25.00			98.16	
Run No.	STRASBURG-13	STRASBURG-27	AVG	STRASBURG-14	STRASBURG-28	AVG	STRASBURG-14	STRASBURG-28	AVG	STRASBURG-14	STRASBURG-28
UV Source	450 W MPUV	450 W MPUV	450 W MPUV	200 W MPUV	200 W MPUV	200 W MPUV	200 W MPUV	200 W MPUV	200 W MPUV	200 W MPUV	200 W MPUV
H <sub>2</sub> O <sub>2</sub> Dose mg/L	250	250	250	250	100	100	100	100	100	100	100
Test Time min											
0	<0.005	0.260	0.0059J	0.089	<0.005	0.250	0.126				
3	<0.005	0.0029J	--	0.003	<0.005	0.063	0.033				
5	<0.005	0.0010J	--	0.002	<0.005	0.021	0.012				
10	<0.010	<0.010	--	<0.010	<0.010	<0.010	<0.010				
20	<0.010	<0.025	--	<0.010	<0.010	<0.025	<0.010				
30	<0.010	<0.025	--	<0.010	<0.010	<0.025	<0.010				
60	--	--	<0.005	<0.005	--	--	--				
90	--	--	<0.010	<0.010	--	--	--				
% Removal			94.38				96.03				

**Table 14**  
**Ethyl Benzene (mg/L) - LPUV/Ozone and LPUV/Peroxone Oxidation Runs**

Run No.	STRASBURG-6	STRASBURG-20	STRASBURG-31	STRASBURG-7	STRASBURG-21	STRASBURG-8	STRASBURG-22	AVG
UV Source	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV
O <sub>3</sub> Feed, %	1.5	1.5	1.5	1.0	1.0	0.5	0.5	0.5
Test Time min								
0	0.0082	<0.005	0.0075J	0.0062	<0.005	0.0012	<0.005	0.004
3	0.0007J	<0.005	--	<0.005	<0.005	0.00061J	<0.005	<0.005
5	<0.005	<0.005	--	<0.010	<0.005	<0.005	<0.005	<0.005
10	<0.010	<0.010	--	<0.025	<0.010	<0.005	<0.005	<0.010
20	<0.010	<0.010	--	<0.025	<0.010	<0.010	<0.010	<0.010
30	<0.025	<0.025	--	<0.025	<0.025	<0.025	<0.025	<0.025
60	--	--	<0.010	--	--	--	--	--
90	--	--	<0.010	--	--	--	--	--
% Removal			0.00					-212.50
Run No.	STRASBURG-9	STRASBURG-23	STRASBURG-32					
UV Source	12 W LPUV	12 W LPUV	12 W LPUV					
O <sub>3</sub> Feed, %	1.0	1.0	1.5					
H <sub>2</sub> O <sub>2</sub> Dose mg/L	50	50	100					
Test Time min								
0	<0.005	<0.005	0.0084J					
3	<0.005	0.0024J	0.002					
5	<0.005	<0.005	--					
10	<0.005	<0.010	--					
20	<0.010	<0.010	--					
30	<0.025	<0.025	--					
60	--	--	<0.010					
90	--	--	<0.010					
% Removal			-400.00					

**Table 15**  
**Ethyl Benzene (mg/L) - Peroxone Oxidation Runs**

Run No.	STRASBURG-1	STRASBURG-15	AVG	STRASBURG-2	STRASBURG-16	AVG	STRASBURG-3	STRASBURG-17	AVG
O <sub>3</sub> Feed, %	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
H <sub>2</sub> O <sub>2</sub> Dose mg/L	1.0	1.0	1.0	10	10	10	50	50	50
Test Time, min									
0	0.0071	<0.005	0.005	0.0055	<0.005	0.004	0.0075	<0.005	0.005
3	<0.025	<0.005	<0.005	0.0005J	<0.005	0.001	<0.005	<0.005	<0.005
5	<0.010	<0.005	<0.005	<0.010	<0.005	<0.005	<0.010	<0.005	<0.005
10	<0.025	<0.010	<0.010	<0.025	<0.010	<0.010	<0.025	<0.010	<0.010
20	<0.025	<0.010	<0.010	<0.025	<0.010	<0.010	<0.025	<0.010	<0.010
30	<0.025	<0.010	<0.010	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025
60	---	---	---	---	---	---	---	---	---
90	---	---	---	---	---	---	---	---	---
% Removal			0.00			-212.50			-150.00
Run No.	STRASBURG-4	STRASBURG-19	AVG	STRASBURG-5	STRASBURG-18	STRASBURG-33	AVG	STRASBURG-17	AVG
O <sub>3</sub> Feed, %	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
H <sub>2</sub> O <sub>2</sub> Dose mg/L	0.1	0.1	0.1	100	100	100	100	100	100
Test Time, min									
0	0.0056	<0.005	0.004	0.0075	<0.005	0.0065	0.006		
3	0.009J	<0.005	0.002	0.0011J	<0.005	---	0.002		
5	<0.010	<0.005	<0.005	<0.005	<0.005	---	<0.005		
10	<0.025	<0.010	<0.010	<0.005	<0.010	---	<0.005		
20	<0.025	<0.010	<0.010	<0.025	<0.010	---	<0.010		
30	<0.025	<0.025	<0.025	<0.025	<0.025	---	<0.025		
60	---	---	---	---	---	<0.010	<0.010		
90	---	---	---	---	---	<0.010	<0.010		
% Removal			-212.50				16.67		

downward trend. To ensure that ketone levels would not increase beyond the target levels with subsequent treatment, WES performed selected experiments of the most promising AOPs to include analysis of reactor effluents at test times of 60 and 90 min. The AOP systems selected were as follows:

- LPUV with 500-mg/L hydrogen peroxide.
- LPUV with 1.5-percent ozonated air sparging.
- 450 MPUV with 250-mg/L hydrogen peroxide.
- 1.5-percent ozonated sparging with 100-mg/L hydrogen peroxide.

Table 16 presents the results for the experiments that evaluated UV/hydrogen peroxide-based AOPs for removal of acetone. These data do show an overall increase in acetone during oxidation of the groundwater through 30 min of treatment for all of the system evaluated. The 100-mg/L hydrogen peroxide-dosed LPUV system indicated a much slower rate of acetone formation, indicating that this system was less aggressive in terms of organics destruction, which correlates nicely with the rates observed for the other contaminants. Extended treatment of the groundwater to 60 and 90 min using the 500-mg/L hydrogen peroxide-dosed system resulted in an apparently slower rate of acetone production; however, a downward trend was not observed. The data also does not appear to distinguish an optimal LPUV/hydrogen peroxide system for acetone removal nor do any of the AOPs appear to have a particularly higher acetone forming potential compared with the others. The two 450-W MPUV systems were the only systems evaluated in the first set of experiments that indicated a decreasing trend in acetone within 30 min of treatment. The extended oxidation experiment for the 450-W MPUV/250-mg/L hydrogen peroxide system indicated continued, but slow, reduction of acetone over the additional 60 min of treatment. The 200-W MPUV with 100-mg/L hydrogen peroxide did indicate signs of leveling off at 30 min of treatment. Several scenarios can be speculated regarding why the 450-W MPUV lamp performed better than the 200-W MPUV lamp in terms of acetone removal. It is possible that since the lamp does have almost twice the energy output of light than that of the 200 W, that the increased photon emissions provide more light energy for acetone photolysis. Another possibility is that the 450-W MPUV systems have increased hydroxyl radical formation rates (i.e., higher quantum yields for radical production) than the 200-W MPUV system; however, the data for the other organics do not support this. A final speculation could be made that the synergistic effect of increased photon emission stressing the chemical bonds due increased energy absorbance coupled with high radical production resulted in improved removal in the 450-W MPUV systems over the 200-W MPUV system.

Table 17 presents the acetone results for the ozonated LPUV systems. The 1.0- and 1.5-percent ozonated air sparged systems appeared to have a slightly higher rate of acetone formation than the 0.5-percent ozonated system. None of the experiments resulted in the formation of acetone to levels greater than

Table 16 Acetone (mg/L) - MPUV and LPUV/Peroxide Oxidation Runs												
Run No.	STRASBURG-10	STRASBURG-24	STRASBURG-11	STRASBURG-25	STRASBURG-30	STRASBURG-12	STRASBURG-26	AVG	STRASBURG-12	STRASBURG-26	AVG	AVG
UV Source	12 W LPUV	450 W MPUV	450 W MPUV	12 W LPUV	450 W MPUV	450 W MPUV	12 W LPUV	450 W MPUV				
H <sub>2</sub> O <sub>2</sub> Dose mg/L	100	100	500	500	500	500	500	500	500	500	500	50
Test Time min												
0	0.034B	0.015B	0.022BJ	0.015BJ	0.013BJ	0.040	0.0049BJ	0.017	0.040	0.0049BJ	0.022	0.022
3	0.037B	0.020B	0.047B	0.057B	---	0.025	0.130B	0.052	0.025	0.130B	0.078	0.078
5	0.055B	0.033B	0.056B	0.094B	---	0.045	0.210B	0.075	0.045	0.210B	0.128	0.128
10	0.076B	0.066B	0.096B	0.120B	---	0.074	0.290B	0.108	0.074	0.290B	0.182	0.182
20	0.040B	0.110B	0.170B	0.230B	---	0.170	0.370B	0.200	0.170	0.370B	0.270	0.270
30	0.110B	0.160B	0.200B	0.290B	---	0.130	0.380B	0.245	0.130	0.380B	0.255	0.255
60	--	--	--	--	0.27B	--	--	0.270	--	--	---	---
90	--	--	--	--	0.33B	--	--	0.330	--	--	---	---
% Increase			462.50					1,841.18				1,059.09
Run No.	STRASBURG-13	STRASBURG-27	STRASBURG-29	STRASBURG-14	STRASBURG-28	STRASBURG-14	STRASBURG-28	AVG	STRASBURG-14	STRASBURG-28	AVG	AVG
UV Source	450 W MPUV	450 W MPUV	450 W MPUV	200 W MPUV	200 W MPUV	200 W MPUV	200 W MPUV	450 W MPUV	200 W MPUV	200 W MPUV	200 W MPUV	200 W MPUV
H <sub>2</sub> O <sub>2</sub> Dose mg/L	250	250	250	100	100	100	100	250	100	100	100	100
Test Time min												
0	0.015BJ	0.043B	0.004BJ	0.110B	0.034B	0.072		0.021	0.034B	0.072		
3	0.058B	0.240B	---	0.067B	0.058B	0.063		0.149	0.058B	0.063		
5	0.150B	0.410B	---	0.110B	0.110B	0.110		0.280	0.110B	0.110		
10	0.300B	0.380B	---	0.200B	0.210B	0.205		0.340	0.210B	0.205		
20	0.350B	0.470B	---	0.300B	0.360B	0.330		0.410	0.360B	0.330		
30	0.240B	0.340B	---	0.280B	0.450B	0.365		0.290	0.450B	0.365		
60	--	--	0.230B	--	--	--		0.230	--	--		
90	--	--	0.200B	--	--	--		0.200	--	--		
% Increase			852.38			406.94						

**Table 17**  
**Acetone (mg/L) - LPUV/Ozone and LPUV/Peroxone Oxidation Runs**

Run No.	STRASBURG-6 12 W LPUV	STRASBURG-20 12 W LPUV	STRASBURG-31 12 W LPUV	AVG 12 W LPUV	STRASBURG-7 12 W LPUV	STRASBURG-21 12 W LPUV	AVG 12 W LPUV	STRASBURG-8 12 W LPUV	STRASBURG-22 12 W LPUV	AVG 12 W LPUV
UV Source	1.5	1.5	1.5	1.5	1.0	1.0	1.0	0.5	0.5	0.5
O <sub>3</sub> Feed, %	1.5	1.5	1.5	1.5	1.0	1.0	1.0	0.5	0.5	0.5
Test Time min										
0	0.017BJ	0.015BJ	0.0049BJ	0.012	0.017BJ	0.011BJ	0.014	0.041B	0.030B	0.036
3	0.078B	0.083B	--	0.080	0.120B	0.063B	0.092	0.019BJ	0.049B	0.034
5	0.120B	0.140B	--	0.130	0.160B	0.096B	0.128	0.050B	0.063B	0.057
10	0.260B	0.310B	--	0.285	0.270B	0.170B	0.220	0.100B	0.095B	0.098
20	0.390B	0.400B	--	0.395	0.360B	0.310B	0.335	0.210B	0.180B	0.195
30	0.570B	0.470B	--	0.520	0.470B	0.380B	0.425	0.340B	0.250B	0.295
60	--	--	0.400B	0.400	--	--	--	--	--	--
90	--	--	0.350BJ	0.350	--	--	--	--	--	--
% Increase				2,816.67			2,935.71			719.44
Run No.	STRASBURG-9	STRASBURG-23	AVG	STRASBURG-32						
UV Source	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV						
O <sub>3</sub> Feed, %	1.0	1.0	1.0	1.5						
H <sub>2</sub> O <sub>2</sub> Dose mg/L	50	50	50	100						
Test Time min										
0	0.023BJ	0.031B	0.027	0.0036J						
3	0.078B	0.082B	0.079	--						
5	0.099B	0.076B	0.088	--						
10	0.190B	0.220B	0.205	--						
20	0.340B	0.400B	0.370	--						
30	0.530B	0.460B	0.495	--						
60	--	--	0.380BJ	0.380BJ						
90	--	--	0.300BJ	0.300BJ						
% Increase			1,733.33							

0.5 mg/L, which is approximately 15 percent of the maximum allowable limit for the Strasburg site. Extended treatment using the 1.5-percent ozonated air sparged LPUV system showed a definite downward trend at the 60 min of treatment.

Table 18 presents the results for the experiments that evaluated peroxone-based AOPs for removal of acetone. The peroxone runs indicated only slight differences in performance in terms of acetone removal or formation within the first 30 min of treatment. In general, all of the hydrogen peroxide doses evaluated indicated a steady increase in acetone throughout the 30 min of oxidation. Extended evaluation of the 100-mg/L hydrogen peroxide-dosed peroxone system indicated a leveling off of acetone production at approximately 0.45 mg/L at 60 and 90 min, indicating that continued production of acetone within the peroxone system is not likely. This level is still an order of magnitude less than the target level of 4 mg/L.

## 2-Butanone

Table 19 presents the results for the experiments that evaluated UV/hydrogen peroxide-based AOPs for removal of 2-butanone. The LPUV/hydrogen peroxide systems appeared to maintain a constant 2-butanone concentration over the 30 min of treatment. The LPUV/500-mg/L hydrogen peroxide-dosed experiment indicated a gradual increase in 2-butanone throughout the 60 additional min of treatment (60 and 90 min of treatment). This system had a peak 2-butanone concentration of 0.045 mg/L at 90 min of treatment. Based on review of the 0- to 30-min experimental data for the MPUV systems, the 2-butanone levels initially increased then decreased at the 30-min increment. This is true for all the MPUV experiments except for the 450-W/250-mg/L hydrogen peroxide-dosed experiments, which had scattered data. However, the extended time experiment for the 450-W/250-mg/L hydrogen peroxide-dosed system did show a decrease in 2-butanone concentrations beyond 30 min of treatment. The 30-min 450-W/250-mg/L hydrogen peroxide 2-butanone concentration may likely be an anomaly. If the 30-min value is ignored, then the 2-butanone levels for this system appear to increase initially, then decrease with longer treatment.

Table 20 presents the 2-butanone results of the ozonated LPUV systems. All of the LPUV/ozone systems indicated that 2-butanone was formed during the early stages of oxidation with a decrease noted after approximately 20 min of further oxidation. The higher ozone content in the sparge gas, 1.5-percent ozone, indicated that 2-butanone removal rate appears dependent on the ozone input rate. As the mass rate of ozone into the LPUV systems was decreased, then the degradation rate also decreased.

Table 21 presents the results for the experiments that evaluated peroxone-based AOPs for removal of 2-butanone. The 100-mg/L hydrogen peroxide-dosed peroxone run did indicate better 2-butanone removal than the other peroxone systems evaluated through 30 min of treatment; however, the 60- and

**Table 18**  
**Acetone (mg/L) - Peroxone Oxidation Runs**

Run No.	STRASBURG-1	STRASBURG-15	AVG	STRASBURG-2	STRASBURG-16	AVG	STRASBURG-3	STRASBURG-17	AVG
O <sub>3</sub> Feed, %	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
H <sub>2</sub> O <sub>2</sub> Dose mg/L	1.0	1.0	1.0	10	10	10	50	50	50
Test Time, min									
0	0.0206J	0.016BJ	0.018	0.024BJ	0.013BJ	0.019	0.020BJ	0.017J	0.019
3	0.140B	0.092B	0.1167	0.100B	0.100B	0.100	0.091B	0.076J	0.084
5	0.240B	0.140B	0.190	0.230B	0.100B	0.165	0.140	0.130B	0.135
10	0.480B	0.210B	0.345	0.370B	0.220B	0.295	0.220	0.027B	0.124
20	0.580B	0.290B	0.435	0.490B	0.350B	0.420	0.630B	0.400B	0.515
30	0.690B	0.340B	0.515	0.500B	0.420B	0.460	0.710B	0.560B	0.635
60	--	--	--	--	--	--	--	--	--
90	--	--	--	--	--	--	--	--	--
% Increase			2,761.11			2,321.05			3,242.11
Run No.	STRASBURG-4	STRASBURG-19	AVG	STRASBURG-5	STRASBURG-18	STRASBURG-33	AVG		
O <sub>3</sub> Feed, %	1.5	1.5	1.5	1.5	1.5	1.5	1.5		
H <sub>2</sub> O <sub>2</sub> Dose mg/L	0.1	0.1	0.1	100	100	100	100		
Test Time, min									
0	0.043B	0.029B	0.036	0.016J	0.027B	0.033B	0.025		
3	0.110B	0.079B	0.095	0.064	0.079B	--	0.072		
5	0.230B	0.140B	0.185	0.050	0.140B	--	0.095		
10	0.410B	0.260B	0.335	0.160	0.270B	--	0.215		
20	0.520B	0.400B	0.460	0.310	0.350B	--	0.330		
30	0.610B	0.520B	0.565	0.360	0.540B	--	0.450		
60	--	--	--	--	--	0.400B	0.400		
90	--	--	--	--	--	0.450B	0.450		
% Increase			1,469.44				1,700.00		



Run No.	STRASBURG-6 12 W LPUV	STRASBURG-20 12 W LPUV	STRASBURG-31 12 W LPUV	STRASBURG-7 12 W LPUV	STRASBURG-21 12 W LPUV	STRASBURG-8 12 W LPUV	STRASBURG-22 12 W LPUV	AVG 12 W LPUV	AVG 12 W LPUV
UV Source	1.5	1.5	1.5	1.0	1.0	0.5	0.5	1.0	0.5
O <sub>3</sub> Feed, %	1.5	1.5	1.5	1.0	1.0	0.5	0.5	1.0	0.5
Test Time min									
0	0.042	0.0015J	<0.025	0.044	<0.025	0.025	0.0056BJ	0.028	0.015
3	0.048	0.0043J	--	0.056	0.0056BJ	0.0066J	0.0050BJ	0.030	0.005
5	0.051	0.011J	--	0.056	0.0083BJ	0.036	0.0081BJ	0.032	0.022
10	0.049J	0.025	--	0.054J	0.019BJ	0.043	0.0050BJ	0.036	0.024
20	0.044J	0.015	--	0.053J	0.016BJ	0.050	0.0050BJ	0.034	0.027
30	0.016BJ	0.015	--	0.037J	0.011BJ	0.046	0.015BJ	0.024	0.030
60	--	--	0.0079J	--	--	--	--	--	--
90	--	--	0.011J	--	--	--	--	--	--
% Removal			42.11					14.29	-100.00
Run No.	STRASBURG-9 12 W LPUV	STRASBURG-23 12 W LPUV	STRASBURG-32 12 W LPUV	STRASBURG-7 12 W LPUV	STRASBURG-21 12 W LPUV	STRASBURG-8 12 W LPUV	STRASBURG-22 12 W LPUV	AVG 12 W LPUV	AVG 12 W LPUV
UV Source	1.0	1.0	1.5	1.0	1.0	0.5	0.5	1.0	0.5
O <sub>3</sub> Feed, %	1.0	1.0	1.5	1.0	1.0	0.5	0.5	1.0	0.5
H <sub>2</sub> O <sub>2</sub> Dose mg/L	50	50	100						
Test Time min									
0	0.023BJ	0.0052BJ	0.0032J	0.044	<0.025	0.025	0.0056BJ	0.028	0.015
3	0.047B	0.0099BJ	--	0.056	0.0056BJ	0.0066J	0.0050BJ	0.030	0.005
5	0.036B	<0.025	--	0.056	0.0083BJ	0.036	0.0081BJ	0.032	0.022
10	0.050B	0.015BJ	--	0.054J	0.019BJ	0.043	0.0050BJ	0.036	0.024
20	0.058B	0.019BJ	--	0.053J	0.016BJ	0.050	0.0050BJ	0.034	0.027
30	0.0075BJ	0.031BJ	--	0.037J	0.011BJ	0.046	0.015BJ	0.024	0.030
60	--	--	<0.050	--	--	--	--	--	--
90	--	--	0.0084J	--	--	--	--	--	--
% Removal		-35.71						14.29	-100.00

**Table 21**  
**2-Butanone (mg/L) - Peroxone Oxidation Runs**

Run No.	STRASBURG-1	STRASBURG-15	AVG	STRASBURG-2	STRASBURG-16	AVG	STRASBURG-3	STRASBURG-17	AVG
O <sub>3</sub> Feed, %	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
H <sub>2</sub> O <sub>2</sub> Dose mg/L	1.0	1.0	1.0	10	10	10	50	50	50
Test Time, min									
0	0.050B	0.0079BJ	0.028	0.042	0.0061J	0.024	0.044	0.0032J	0.023
3	0.078B	0.0148J	0.046	0.049	0.014J	0.031	0.053	0.0034J	0.028
5	0.089B	0.0188J	0.053	0.063	0.014J	0.038	0.059	0.0046BJ	0.031
10	0.053BJ	0.0218J	0.037	0.061J	0.017J	0.039	0.053	0.017BJ	0.035
20	0.055BJ	0.021BJ	0.038	0.052J	0.026	0.039	0.022BJ	0.014BJ	0.018
30	0.037BJ	0.021BJ	0.029	0.044J	0.036	0.040	0.032BJ	0.023BJ	0.027
60	--	--	--	--	--	--	--	--	--
90	--	--	--	--	--	--	--	--	--
% Removal			-3.57			-66.32			-17.39
Run No.	STRASBURG-4	STRASBURG-19	AVG	STRASBURG-5	STRASBURG-18	STRASBURG-33	AVG		
O <sub>3</sub> Feed, %	1.5	1.5	1.5	1.5	1.5	1.5	1.5		
H <sub>2</sub> O <sub>2</sub> Dose mg/L	0.1	0.1	0.1	100	100	100	100		
Test Time, min									
0	0.052B	0.0035BJ	0.028	0.046B	0.0087BJ	0.017BJ	0.024		
3	0.073B	0.0087BJ	0.041	0.058B	0.0031BJ	--	0.030		
5	0.025BJ	0.0039BJ	0.014	0.023BJ	0.0041BJ	--	0.013		
10	0.058BJ	0.0063BJ	0.032	0.050B	0.013BJ	--	0.036		
20	0.043BJ	0.0059BJ	0.024	0.022BJ	0.0095BJ	--	0.015		
30	0.040BJ	0.013BJ	0.026	0.023BJ	0.0069BJ	--	0.014		
60	--	--	--	--	--	0.038BJ	0.038		
90	--	--	--	--	--	0.047BJ	0.047		
% Removal			7.14				-95.83		

90-min values for this system indicated an increase. These data did not show a downward turn even after 90 min of treatment. It is noteworthy to mention that the levels of 2-butanone measured in any of these experiments were approximately two orders of magnitude lower than the target treatment goal of 2.0 mg/L.

## Chloroethane

The initial concentration of chloroethane detected in the groundwater influent was approximately 0.007 mg/L. A target treatment goal was not identified for this VOC. Therefore, treatment efficiency with regard to removal to less than detection levels will be used to compare AOP performance.

Table 22 presents the results of the experiments that evaluated UV/hydrogen peroxide systems for removal of chloroethane from the groundwater influent. The results of these efforts generally followed the trends observed with the other VOCs. The 100-mg/L and 500-mg/L hydrogen peroxide-dosed LPUV systems performed similarly. The 500-mg/L hydrogen peroxide-dosed systems removed chloroethane down to less-than-detection-limit levels within 60 min of treatment, while the 100-mg/L dosed system still had detectable levels within 30 min of treatment (a 60-min analysis was not done for the 100-mg/L system). The MPUV systems in terms of chloroethane removal performed very similarly to the TCE data by indicating a dependence on hydrogen peroxide dose and not UV intensity. Both the 100-mg/L hydrogen peroxide-dosed, 200-W MPUV and the 250-mg/L hydrogen peroxide-dosed, 450-W MPUV systems removed chloroethane to below-detection-limit levels within 30 min of treatment.

Table 23 presents the results of the ozonated LPUV systems. All of the systems evaluated removed chloroethane to below detection limits within 5 min of treatment. Chloroethane is a saturated aliphatic that is not amenable to oxidation because of the lack of a double bond for formation of an ozonide or radical linkage. Therefore, based on the very uniform and rapid removal rates observed for chloroethane within the sparged LPUV systems, it is speculated that the primary mode of removal was likely to be stripping. The MPUV/hydrogen peroxide evaluated in these experiments is a relatively aggressive oxidation system compared with the various AOPs investigated during this study. LPUV/ozone is another very aggressive AOP. The dramatic difference in system performance between MPUV/hydrogen peroxide and LPUV/ozone for chloroethane removal indicates that volatilization (stripping) likely played a major role in chloroethane removal.

Table 24 presents the results of the chloroethane peroxone experiments. These experiments had very similar results to the ozonated LPUV systems (Table 23). Therefore, stripping is also speculated as the primary removal mechanism within the peroxone systems. In any case, chloroethane was

**Table 22**  
**Chloroethane (mg/L) - MPUV and LPUV/Hydrogen Peroxide Oxidation Runs**

Run No.	STRASBURG-10	STRASBURG-24	AVG	STRASBURG-11	STRASBURG-25	STRASBURG-30	AVG	STRASBURG-12	STRASBURG-26	AVG	
UV Source	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	12 W LPUV	450 W MPUV	450 W MPUV	450 W MPUV	
H <sub>2</sub> O <sub>2</sub> Dose mg/L	100	100	100	500	500	500	500	50	50	50	
Test Time min											
0	0.0078	0.010	0.008	0.0085	0.0079	0.0040J	0.007	0.0084	0.0034J	0.005	
3	0.0076	0.0093	0.008	0.004J	0.0065	--	0.005	0.0085	0.0012J	0.004	
5	0.0077	0.011	0.009	0.0036J	0.0062	--	0.004	0.0071	<0.010	0.006	
10	0.0069	0.0094	0.008	0.005	<0.010	--	0.005	0.0069	<0.010	0.005	
20	0.0069	0.0053	0.006	0.0027J	<0.010	--	0.003	0.0060	<0.025	0.009	
30	0.0060	0.0061	0.006	0.0014J	<0.010	--	0.003	0.0050	<0.025	0.008	
60	--	--	--	--	--	<0.010	<0.010	--	--	--	
90	--	--	--	--	--	<0.010	<0.010	--	--	--	
% Removal			25.00				28.57			-60.00	
Run No.	STRASBURG-13	STRASBURG-27	AVG	STRASBURG-14	STRASBURG-28	AVG	STRASBURG-14	STRASBURG-28	AVG	STRASBURG-14	STRASBURG-28
UV Source	450 W MPUV	450 W MPUV	450 W MPUV	200 W MPUV	200 W MPUV	200 W MPUV	200 W MPUV	200 W MPUV	200 W MPUV	200 W MPUV	200 W MPUV
H <sub>2</sub> O <sub>2</sub> Dose mg/L	250	250	250	250	100	100	100	100	100	100	100
Test Time min											
0	0.008	0.0052	0.0031J	0.005	0.0088	0.0028J	0.005	0.0088	0.0028J	0.005	
3	0.0047J	<0.010	--	0.004	0.0059	0.0024J	0.004	0.0059	0.0024J	0.004	
5	0.0036J	<0.010	--	0.004	0.0043	<0.010	0.004	0.0043	<0.010	0.004	
10	0.0043J	<0.010	--	0.004	0.0046	<0.010	0.004	0.0046	<0.010	0.004	
20	<0.010	<0.025	--	<0.010	<0.010	<0.025	<0.010	<0.010	<0.025	<0.010	
30	<0.010	<0.025	--	<0.010	<0.010	<0.025	<0.010	<0.010	<0.025	<0.010	
60	--	--	<0.005	<0.005	--	--	--	--	--	--	
90	--	--	<0.010	<0.010	--	--	--	--	--	--	
% Removal			0.00	0.00			0.00			0.00	

**Table 23**

**Chloroethane (mg/L) - LPUV/Ozone and LPUV/Peroxone Oxidation Runs**

Run No.	STRASBURG-6 12 W LPUV	STRASBURG-20 12 W LPUV	STRASBURG-31 12 W LPUV	AVG 12 W LPUV	STRASBURG-7 12 W LPUV	STRASBURG-21 12 W LPUV	AVG 12 W LPUV	STRASBURG-8 12 W LPUV	STRASBURG-22 12 W LPUV	AVG 12 W LPUV
0	0.011	0.0078	0.0037J	0.008	0.012	0.011	0.011	0.0088	0.008	0.008
3	<0.005	<0.005	--	<0.005	<0.005	0.00055J	0.001	<0.005	<0.005	<0.005
5	<0.005	<0.005	--	<0.005	<0.010	<0.005	<0.005	<0.005	<0.005	<0.005
10	<0.010	<0.010	--	<0.010	<0.025	<0.010	<0.010	<0.005	<0.005	<0.005
20	<0.010	<0.010	--	<0.010	<0.025	<0.010	<0.010	<0.010	<0.010	<0.010
30	<0.025	<0.025	--	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025
30	--	--	<0.010	<0.010	--	--	--	--	--	--
30	--	--	<0.010	<0.010	--	--	--	--	--	--
% Removal				37.50			-13.64			-56.25

**LPUV/Hydrogen Peroxide**

Run No.	STRASBURG-9 12 W LPUV	STRASBURG-23 12 W LPUV	AVG 12 W LPUV	STRASBURG-32 12 W LPUV
0	0.0075	0.0086	0.008	0.0012J
3	<0.005	0.0078	0.005	--
5	<0.005	<0.005	<0.005	--
10	<0.005	<0.010	<0.005	--
20	<0.010	<0.010	<0.010	--
30	<0.025	<0.025	<0.025	--
30	--	--	--	<0.010
30	--	--	--	<0.010
% Removal			-56.25	

**JRG-29**

AVG	STRASBURG-29 450 W MIPUV	200 W LPUV
0	250	

**Table 24  
Chloroethane (mg/L) - Peroxone Oxidation Runs**

Run No.	STRASBURG-1	STRASBURG-15	AVG	STRASBURG-2	STRASBURG-16	AVG	STRASBURG-3	STRASBURG-17	AVG
O <sub>3</sub> Feed, %	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
H <sub>2</sub> O <sub>2</sub> Dose mg/L	1.0	1.0	1.0	10	10	10	50	50	50
Test Time, min									
0	0.010	0.0066J	0.008	0.012	0.0075	0.009	0.011	0.0068	0.008
3	<0.005	<0.005	<0.005	0.0005J	<0.005	0.001	0.0007J	<0.005	0.001
5	<0.010	<0.005	<0.005	<0.010	<0.005	<0.005	<0.010	<0.005	<0.005
10	<0.025	<0.010	<0.010	<0.025	<0.010	<0.010	<0.025	<0.010	<0.010
20	<0.025	<0.010	<0.010	<0.025	<0.010	<0.010	<0.025	<0.010	<0.010
30	<0.025	<0.010	<0.010	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025
60	--	--	--	--	--	--	--	--	--
90	--	--	--	--	--	--	--	--	--
% Removal			37.50			-38.89			-56.25
Run No.	STRASBURG-4	STRASBURG-19	AVG	STRASBURG-5	STRASBURG-18	STRASBURG-33	AVG		
O <sub>3</sub> Feed, %	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
H <sub>2</sub> O <sub>2</sub> Dose mg/L	0.1	0.1	0.1	100	100	100	100	100	100
Test Time, min									
0	<0.005	0.007	0.004	0.011	0.0072	0.0045J	0.008		
3	<0.005	<0.005	<0.005	<0.005	<0.005	--	<0.005		
5	<0.010	<0.005	<0.005	<0.005	<0.005	--	<0.005		
10	<0.025	<0.010	<0.010	<0.010	<0.010	--	<0.010		
20	<0.025	<0.010	<0.010	<0.025	<0.010	--	<0.010		
30	<0.025	<0.025	<0.025	<0.025	<0.025	--	<0.025		
60	--	--	--	--	--	<0.010	<0.010		
90	--	--	--	--	--	<0.010	<0.010		
% Removal			-212.5				37.50		

removed to below-detection-limit levels within all of the peroxone systems evaluated within 5 min of treatment.

## Evaluation of VOC Off-Gassing

Volatilization of VOCs from any treatment process involving introduction of a gas phase into the aqueous medium undergoing treatment should be quantified to ensure that the primary mode of removal is not stripping (except in the case of air strippers). Quantifying volatilization or performing mass balance can be approached in ozonated systems using a variety of techniques that range from the simple to complex in terms of scope and costs. Due to time and cost limitations and realization of what probably constitutes improper VOC releases, the potential for excessive amounts of VOC releases was evaluated by analyzing the off-gases exiting the reactor using a photoionizing detector device (HNU, Inc.). Figure 3 illustrates the system employed in this study. These analyses did not indicate the presence of any detectable amounts of VOCs exiting the reactor at any point in time during ozonation. Therefore, based on these findings, a potential for significant off-gassing from an ozonated reactor is considered to be low.

## Chloride Production

As a further attempt to quantify the fate of the chlorinated compounds within an ozonated reactor, the extent of chloride production during peroxone treatment was measured using an ion-chromatography system. Chloride production is an indicator of the complete breakdown of chlorinated organics to their inorganic constituents (in this case, chloride, carbon dioxide, and water). Breakdown of organics to inorganic constituents is often referred to as mineralization. Figure 4 presents the buildup of chloride in a 10-mg/L hydrogen peroxide-dosed 1.5-percent ozonated peroxone reactor. These data clearly show a significant buildup of chloride in the reactor, supporting the conclusion that some degree of mineralization of the chlorinated VOCs was occurring.

## Summary of Results

Table 25 summarizes the results of the AOP experiments by listing the treatment times required to reach either the target treatment goal (if the VOC is present initially at greater amounts) or the time required to decrease the initial VOC levels to below-detection-limit levels (if the VOC is initially present at levels below the target treatment goal). Acetone and 2-butanone were not listed because their concentrations generally increased then decreased; however, their net decrease was rarely back to those levels initially present. The table also lists the initial concentrations, target treatment goals, and the

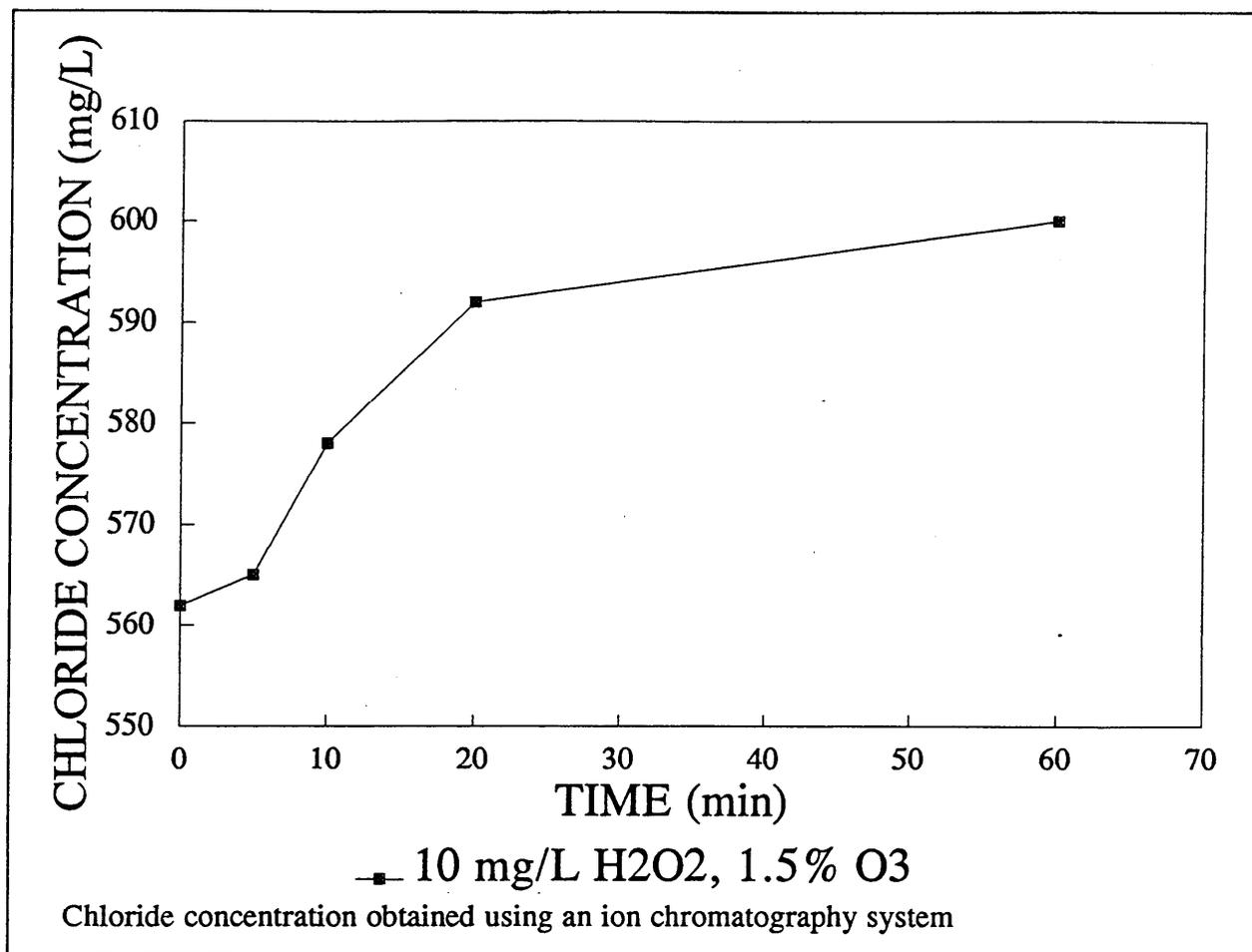


Figure 4. Chloride concentration obtained using an ion chromatography system

longest HRT required by each candidate AOP to meet the treatment goals for all of the VOCs (i.e., the rate-limiting VOC).

From Table 25, given the levels of chlorobenzene present, this VOC was the most difficult to remove to below detection limit of all the VOCs present within the Strasburg groundwater influent used in this study. The 1- to 1.5-percent ozone/LPUV and peroxone systems using hydrogen peroxide doses ranging from 0.1 to 50 mg/L required the shortest HRTs (10 min) to meet all of the treatment goals for this study. The 100-mg/L hydrogen peroxide-dosed LPUV system was the only AOP tested that did not indicate potential for treating the Strasburg groundwater influent.

The levels of ketones detected were far below the target goals established for this site and, in most cases, were declining with continual treatment beyond 30 min. In any case, the highest levels of ketones produced were still two orders of magnitude less than the target treatment goals.

**Table 25  
Summary of AOP Performance**

	TCE	EB	CA	CB	TX	Longest HRT, min
Initial Concentration, ppm	1.103	0.028	0.007	0.05	0.116	--
Target Treatment Goal ppm	0.0065	5.85	NG	0.202	2.131	--
<b>AOPs</b>						
100HP/LPUV	NR	NR	NR	NR	NR	NR
500HP/LPUV	30	10	60	20	30	60
50HP/450MPUV	30	10	NR	NR	NR	NR
100HP/200MPUV	10	10	20	20	NR	NR
250HP/450MPUV	10	10	20	20	20	20
0.5OZ/LPUV	10	5	3	20	20	20
1.0OZ/LPUV	5	3	5	10	5	10
1.5OZ/LPUV	5	5	3	10	10	10
0.1HP/1.5OZ	5	5	3	10	10	10
1HP/1.5OZ	5	3	3	10	10	10
10HP/1.5OZ	5	5	5	10	10	10
50HP/1.5OZ	5	3	5	10	10	10
100HP/1.5OZ	5	5	5	20	10	20
50HP/1.0OZ/LPUV	5	5	5	10	10	10
<p>Note: TCE = Trichloroethene; EB = Ethyl benzene; CA = Chloroethane; CB = Chlorobenzene; TX = T-Xylenes; HP = Hydrogen peroxide; OZ = Ozone; NR = Not reached; NG = Not given.</p>						

## 4 Conclusions

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All of the AOPs tested during this study except the 100-mg/L hydrogen peroxide-dosed LPUV system indicated potential for removing all of the contaminants from the spiked Strasburg Leachate. Acetone and 2-butanone were produced as the oxidation of the other organics present in the leachate occurred.

The AOP indicating the slowest contaminant removal rates was the LPUV with hydrogen peroxide dosing. This was not considered surprising based on the poor absorbance of UV photons by hydrogen peroxide at the 254-nm wavelength (the predominant spectral wavelength of LPUV lamps). The 500-mg/L hydrogen peroxide-dosed LPUV system had much higher removal rates than the 100-mg/L dose; however, with longer HRTs (> 30 min), the 100-mg/L hydrogen peroxide may provide sufficient treatment.

The ozonated air sparged LPUV systems provided excellent contaminant removal rates. The 1.0-percent ozone sparged air appeared to have slightly better contaminant removal rates than the 1.5-percent ozonated air. This is likely attributable to hydroxyl radical scavenging by the increased residual ozone levels within the test solutions. The addition of hydrogen peroxide generally hindered contaminant removal rate. The 0.5-percent ozonated air sparged experiments indicated that these systems were likely ozone limited. From strictly a contaminant-removal rate basis, the 1.0- and 1.5-percent ozonated air sparged LPUV system was one of the better AOPs evaluated during this study.

The MPUV-based systems tended to have slightly slower contaminant-removal rates than either the ozonated/LPUV or peroxone systems. This finding tends to indicate that stripping may be a factor in the increased removal rates observed in the ozonated systems; however, the PID and chloride analyses tended to support the concept that oxidation was a dominant VOC removal mechanism. This cannot be firmly proven unless a more elaborate mass balance study is initiated. The 450-W MPUV with 250-mg/L hydrogen peroxide dose provided improved conditions for overall VOC removals. The 200-W MPUV with 100 mg/L (a less costly configuration) provided removal rates competitive to the 450-W MPUV/250-mg/L hydrogen

peroxide system. The 50-mg/L hydrogen peroxide-dosed MPUV system appeared to be hydrogen peroxide limited.

The peroxone systems evaluated had similar VOC removal rates. The 1.0-mg/L hydrogen peroxide dose seemed to provide the most optimal conditions for VOC removal followed closely by the 10-mg/L dose. The 50-mg/L hydrogen peroxide dose was slightly superior to the 100-mg/L and 0.1-mg/L hydrogen peroxide doses. These conclusions support the work of WES and others in that a definite optimum concentration ratio of hydrogen peroxide to ozone does exist for peroxone systems. Based on the results generated from this study, the optimum hydrogen peroxide dose for a 1.5-percent ozonated air sparged system appears to be between 1.0 and 10 mg/L.

## 5 Recommendations

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Based on the results of this study and on the fact that the actual fielded treatment system will likely be operated in semibatch mode, then process selection should be based on the following factors:

- a.* Process economics using a design life basis for evaluation.
- b.* Relative ease of process operation.
- c.* Ability to meet flow rate objectives.
- d.* Ability to handle potentially high influent iron concentrations.
- e.* The ability of the process to easily meet these goals.

The following optimal process formulations for each candidate AOP are presented:

LPUV-HP - 500-mg/L hydrogen peroxide dose

LPUV-OZ - 1.0-percent ozonated air sparging

MPUV-HP - 100-mg/L hydrogen peroxide dose

Peroxone - 1-mg/L hydrogen peroxide dose with 1.5-percent ozone feed

The HRT is typically required for the design of any AOP. AOP vendors represent this parameter using a variety of units. The most common units are in minutes. Some vendors present HRT based on the total number of UV photons or watts dosed per gallon of water treated. Using a time-based HRT approach, the ozonated systems deemed optimal above appear to meet target levels within 10 min of treatment. The hydrogen peroxide system will require longer HRTs. Since the full-scale system may be operated in the batch or semibatch mode, then the knowledge that any of the candidate AOPs appear to have potential to successfully remove any of the contaminants evaluated during this study. Therefore, a firm HRT may not be required for system

design since recirculation of the groundwater undergoing treatment will add significantly long to an otherwise underdesigned system. The MPUV systems are the only systems where some caution must be exercised since the UV lamps typically used in systems of this type produce significant quantities of heat. Most applications of these units utilizing process water recirculation require some form of water cooling.

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# Appendix A

## Time Versus Concentration Plots for Oxidation Experiments

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NOTE: The averages plotted in the figures listed in this appendix were calculated using reported values that were less than the minimum allowable detection levels of the analytical method ("J" values). Analyses of samples where no contaminants could be detected and were reported as less than the instrument/procedural detection limit were given a value of zero for calculation of the averages used in the plots.

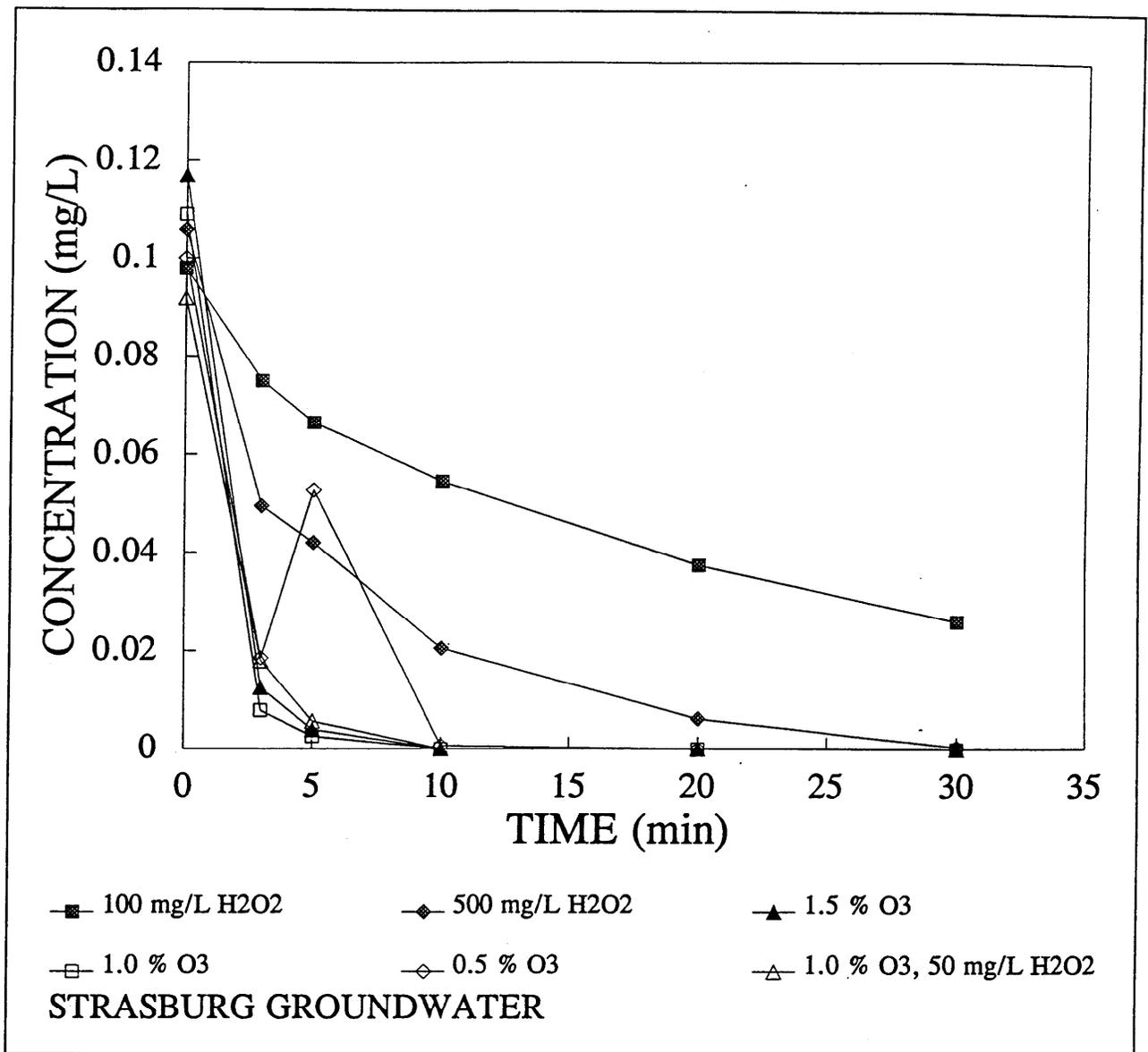


Figure A1. Low-pressure mercury lamp - trichloroethylene

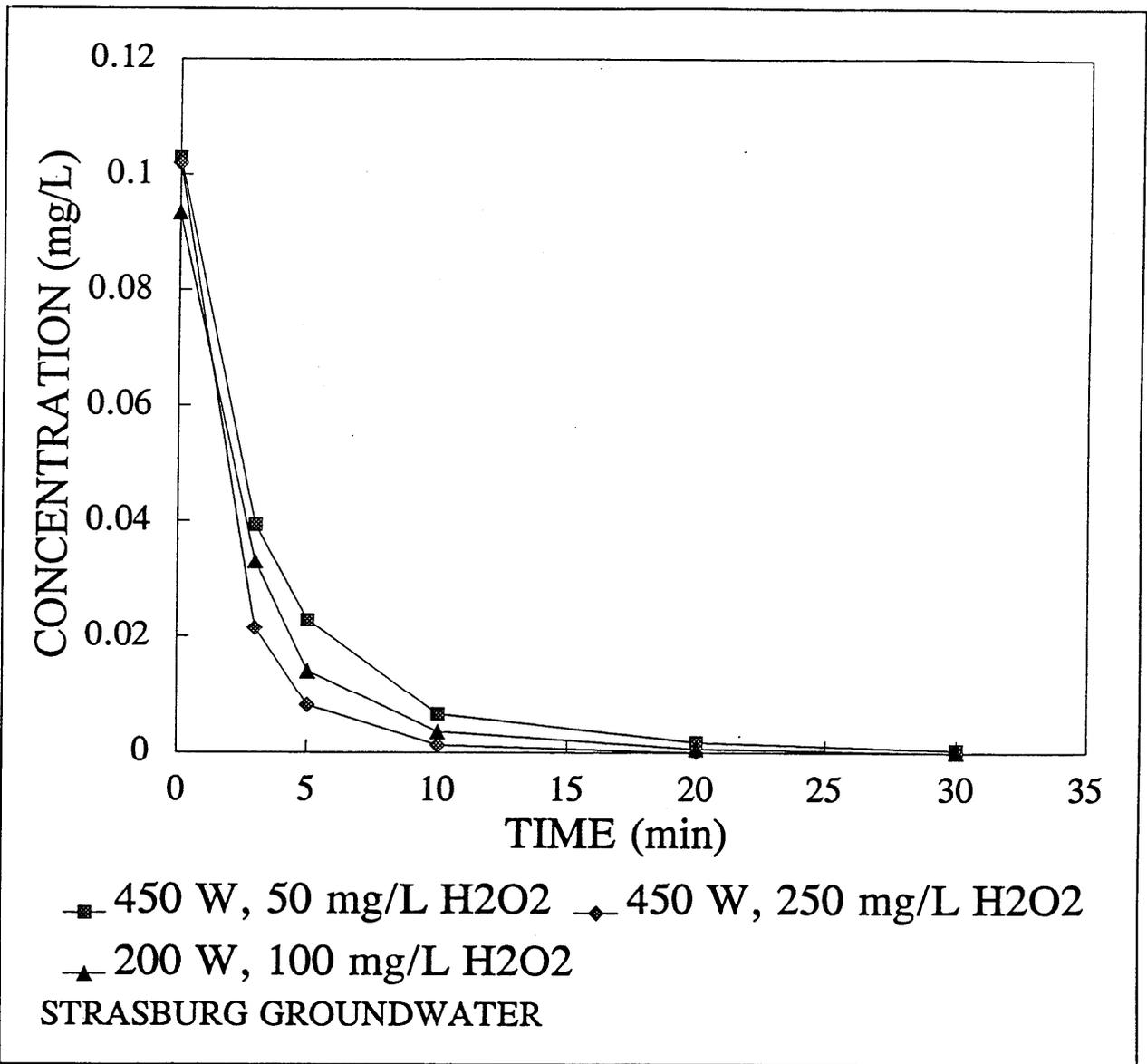


Figure A2. Medium-pressure mercury lamp - trichloroethylene

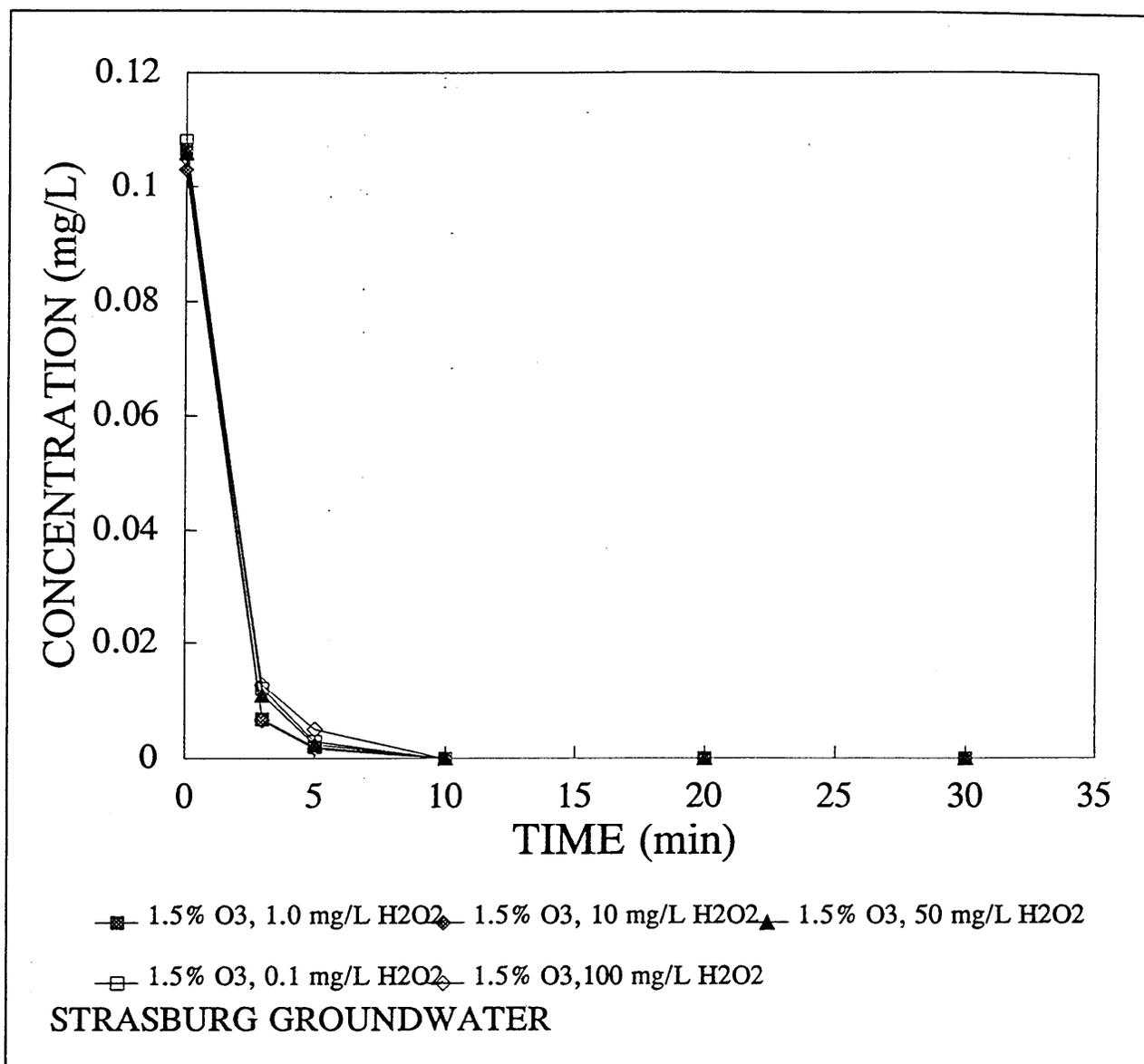


Figure A3. Peroxone - trichloroethylene

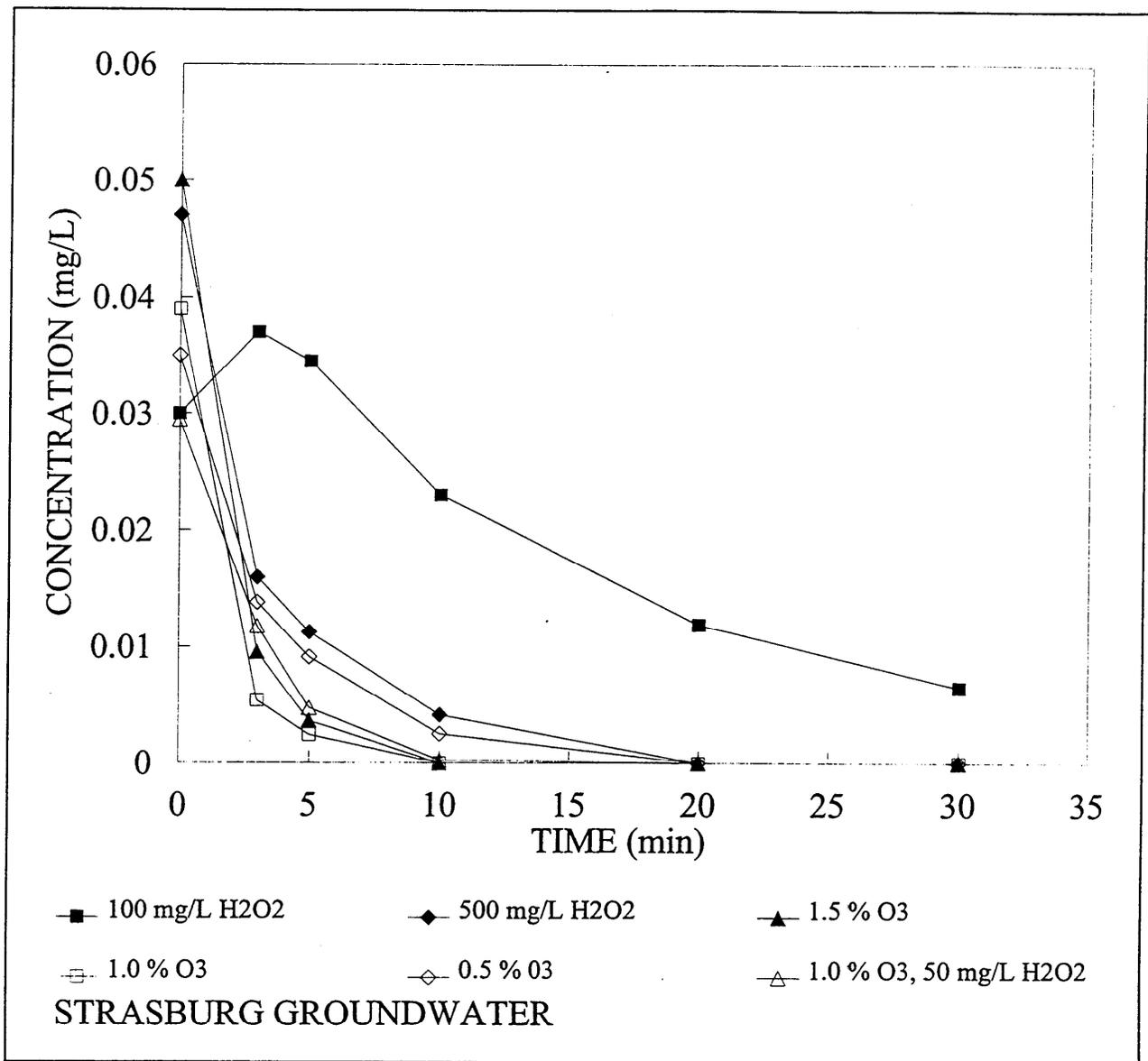


Figure A4. Low-pressure mercury lamp - chlorobenzene

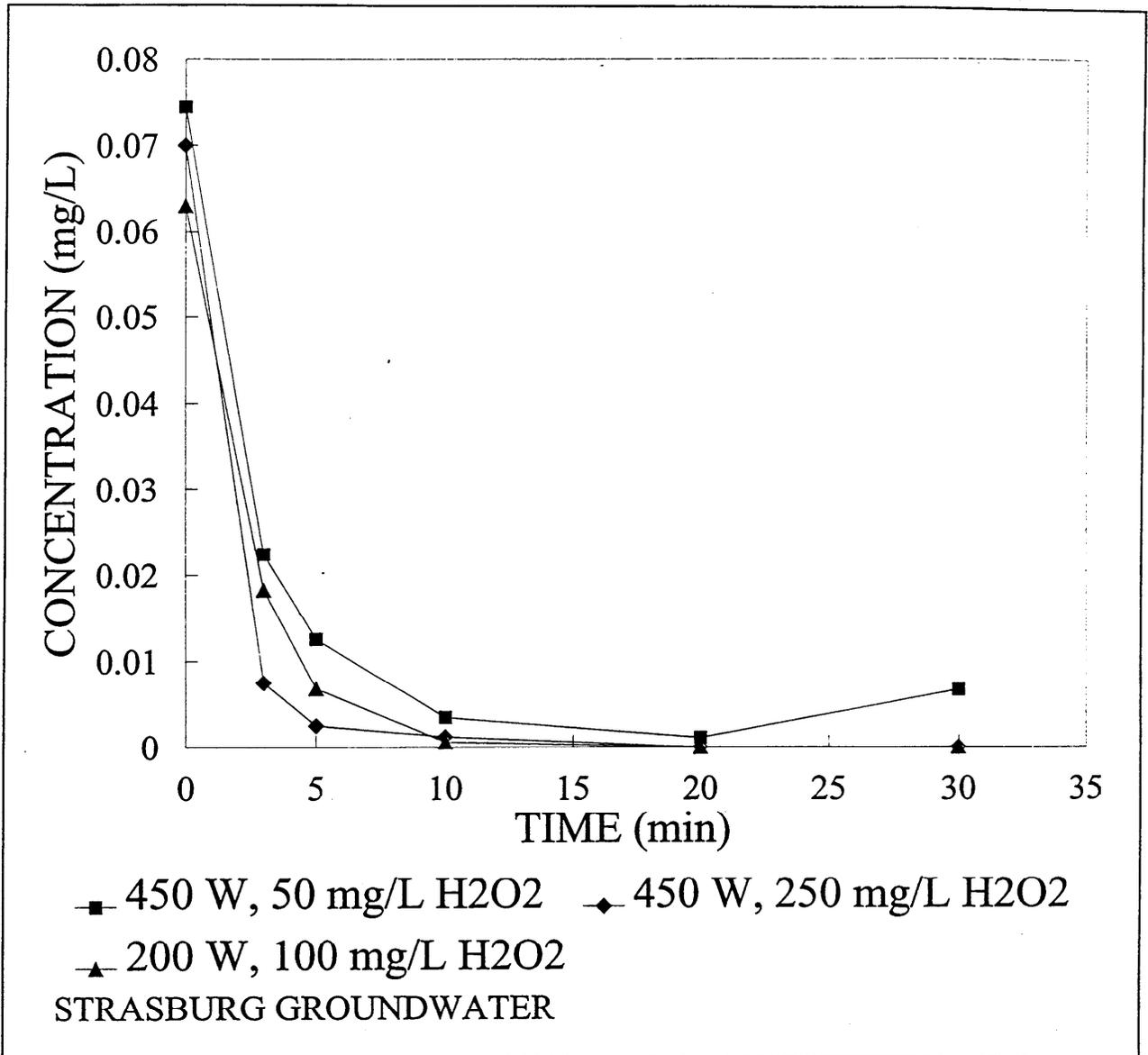


Figure A5. Medium-pressure mercury lamp - chlorobenzene

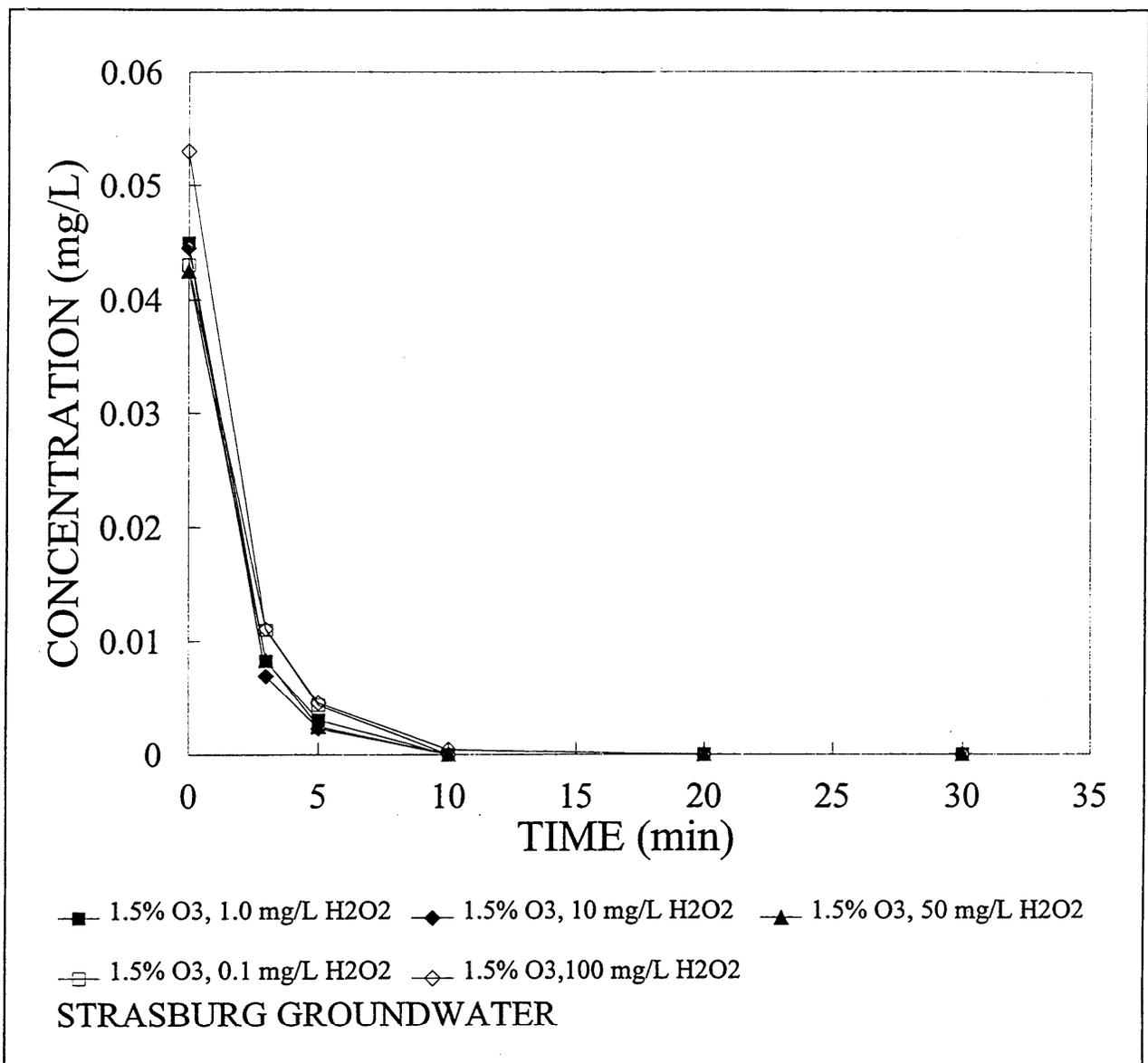


Figure A6. Peroxone - chlorobenzene

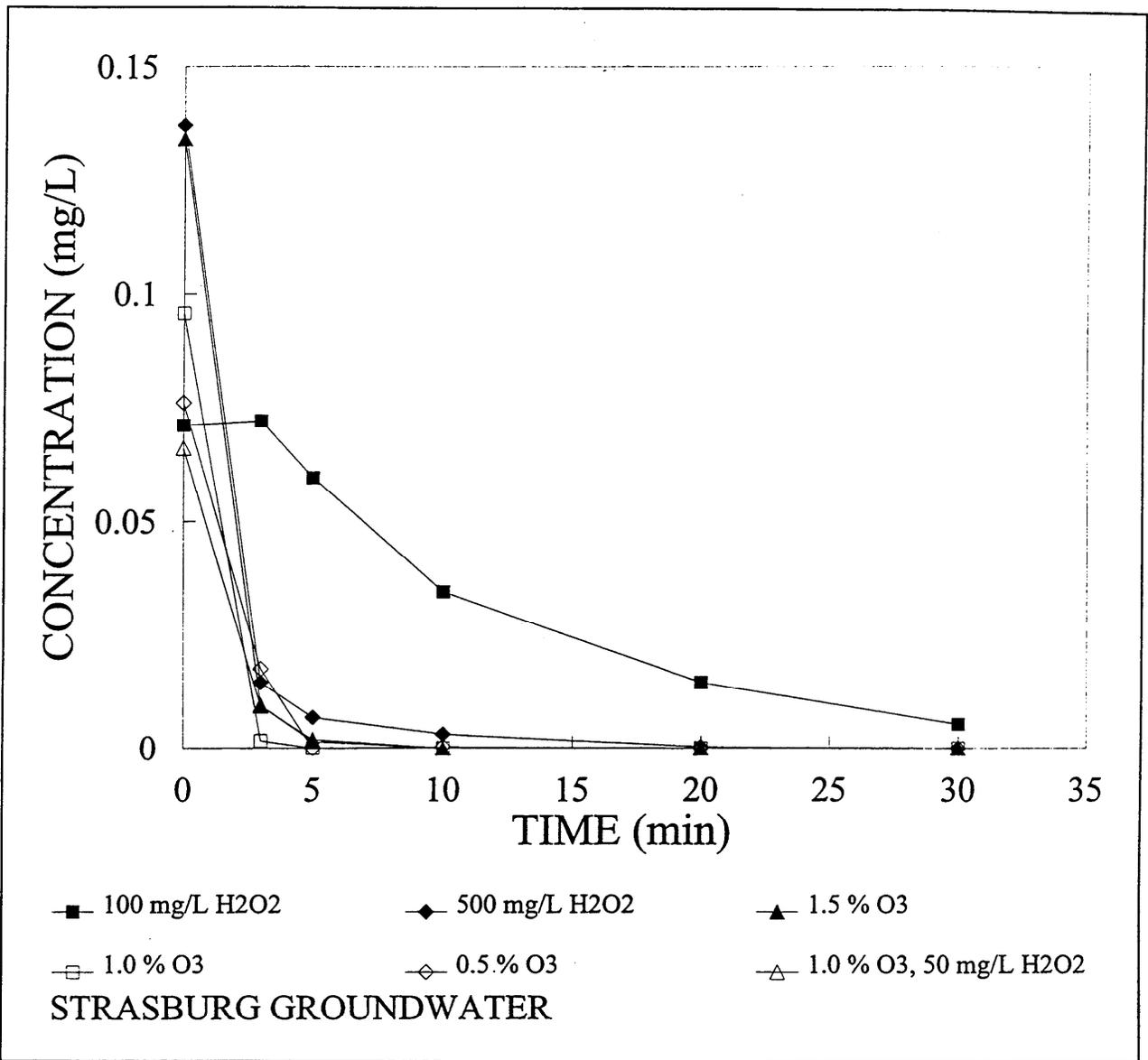


Figure A7. Low-pressure mercury lamp - T-xylene

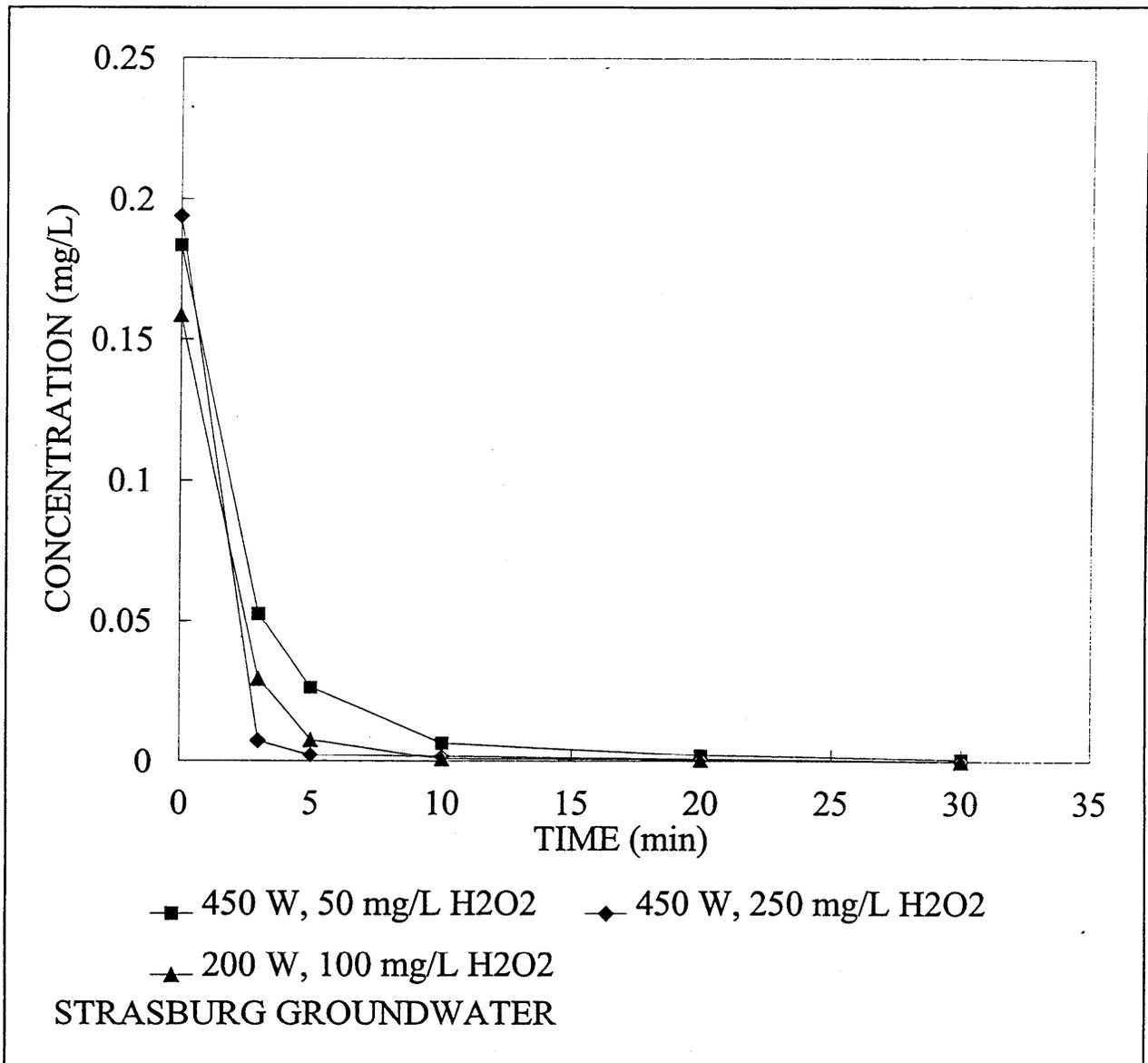


Figure A8. Medium-pressure mercury lamp - T-xylene

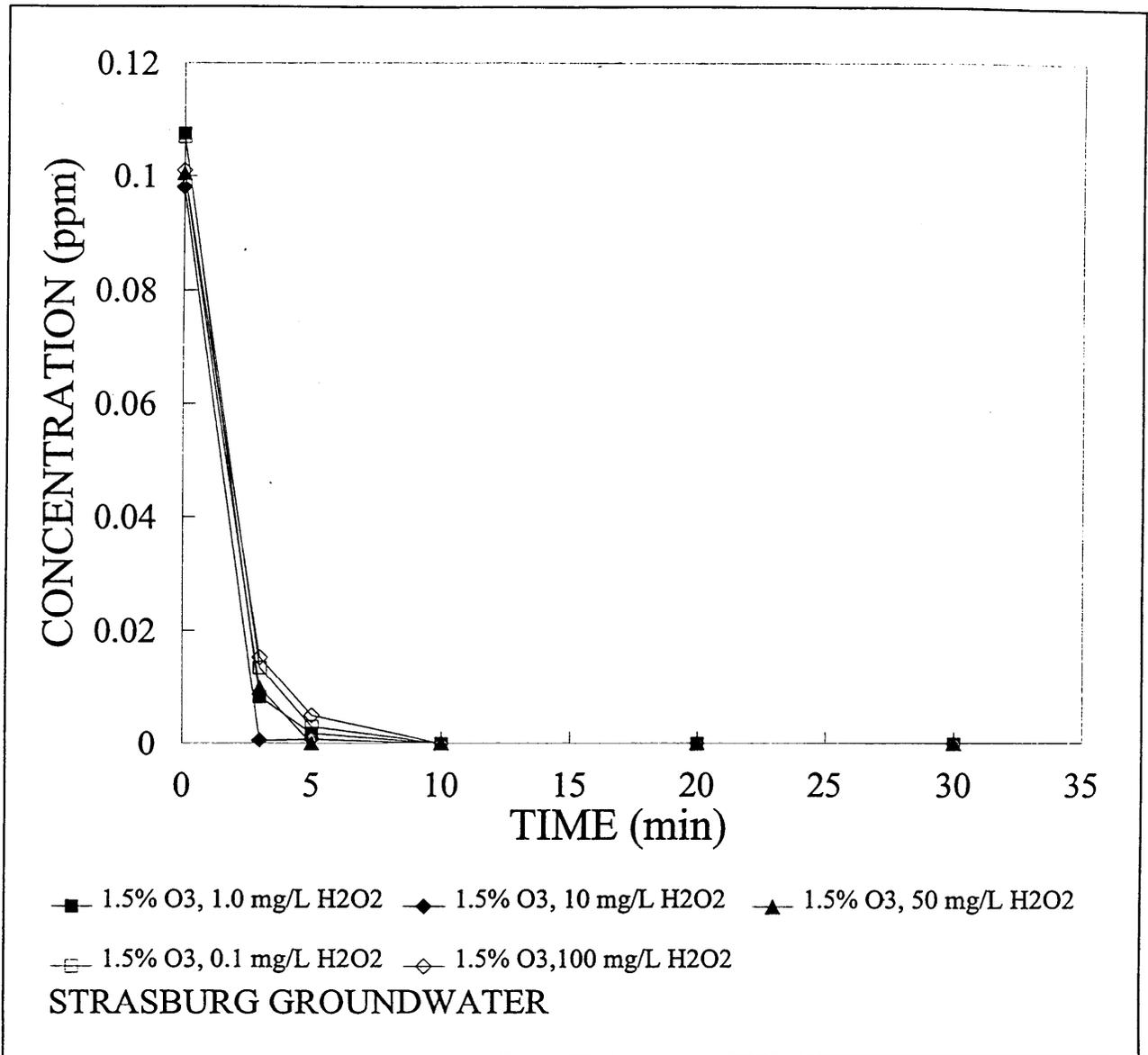


Figure A9. Peroxone - T-xylene

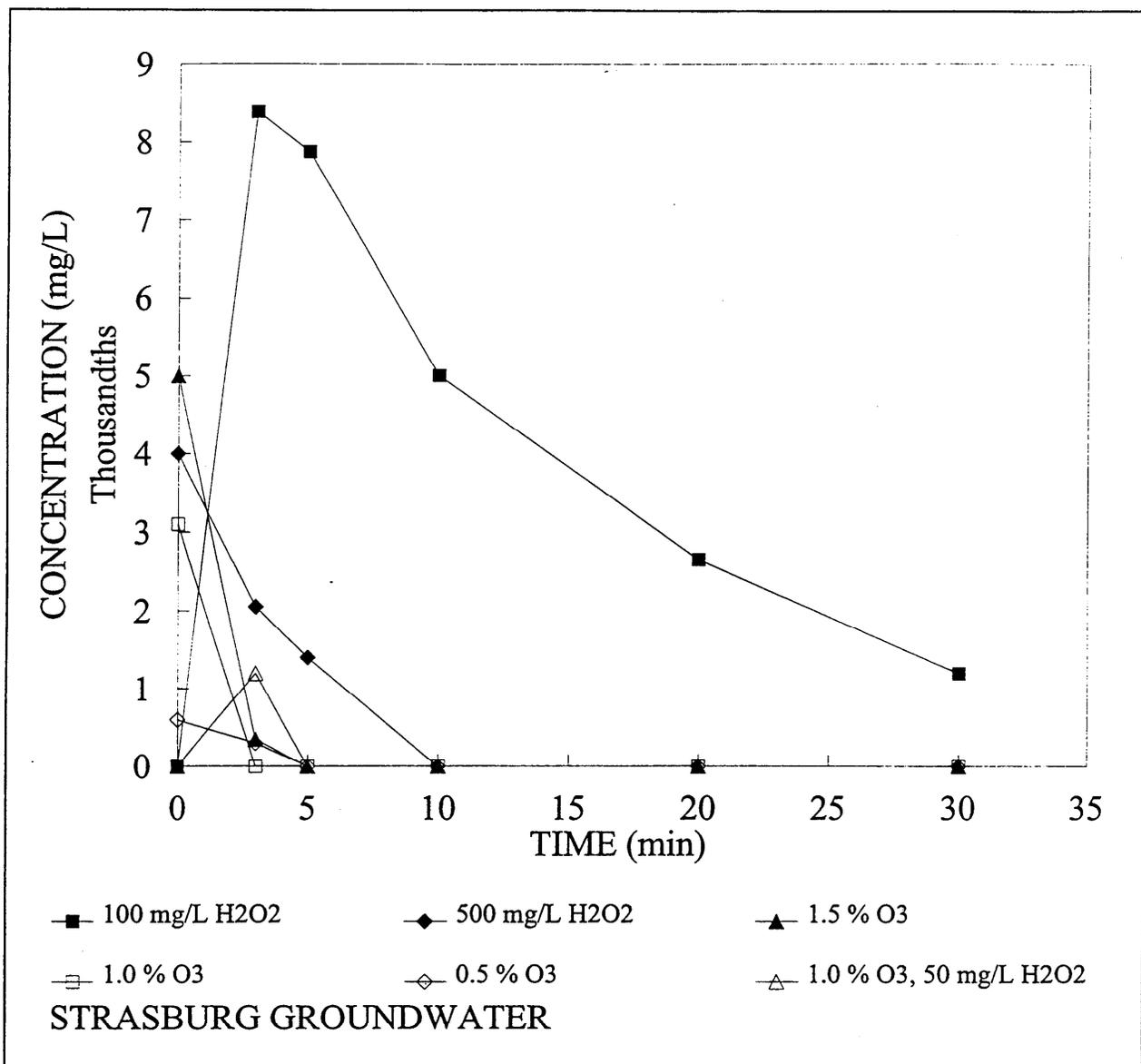


Figure A10. Low-pressure mercury lamp - ethyl benzene

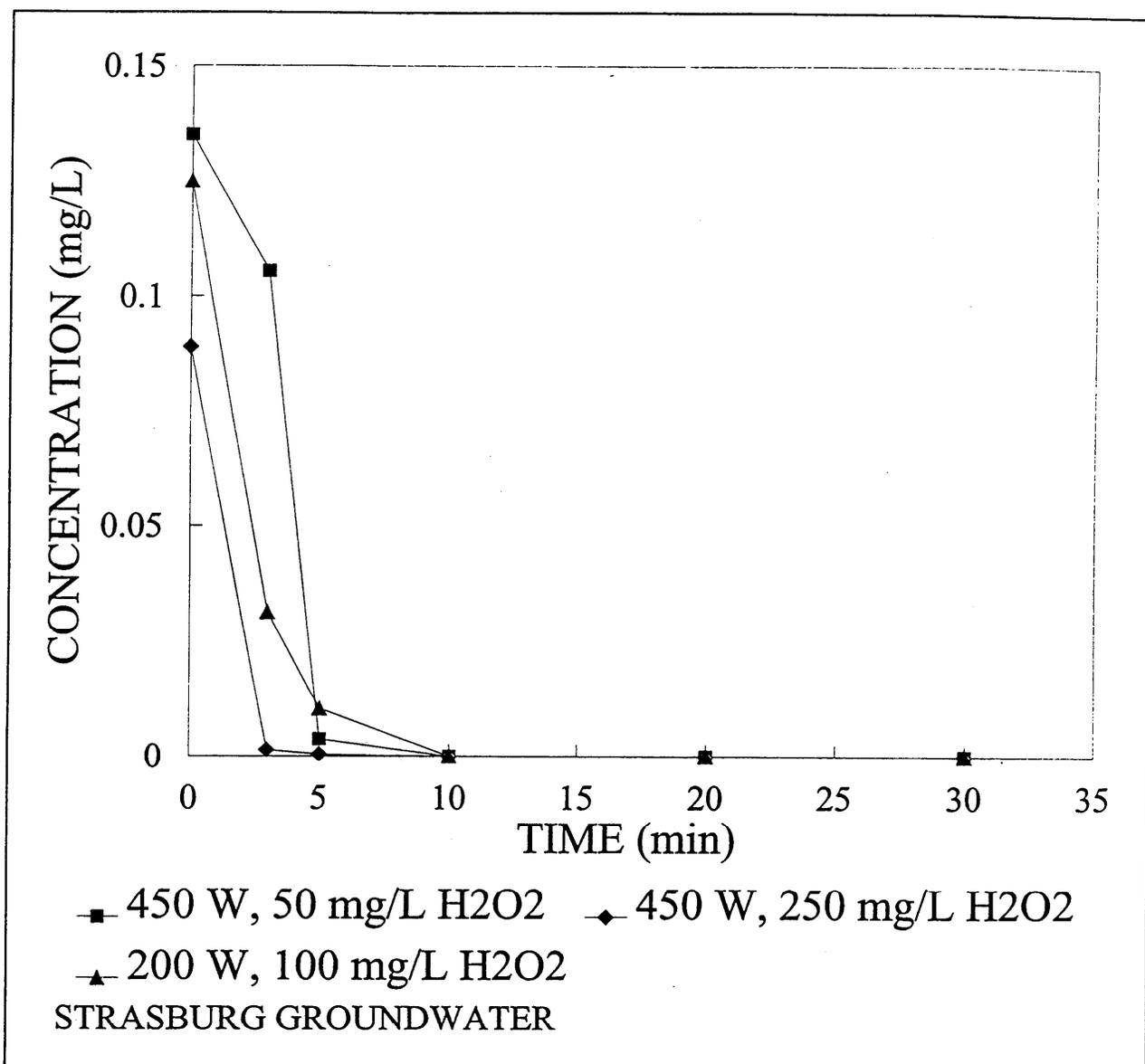


Figure A11. Medium-pressure mercury lamp - ethyl benzene

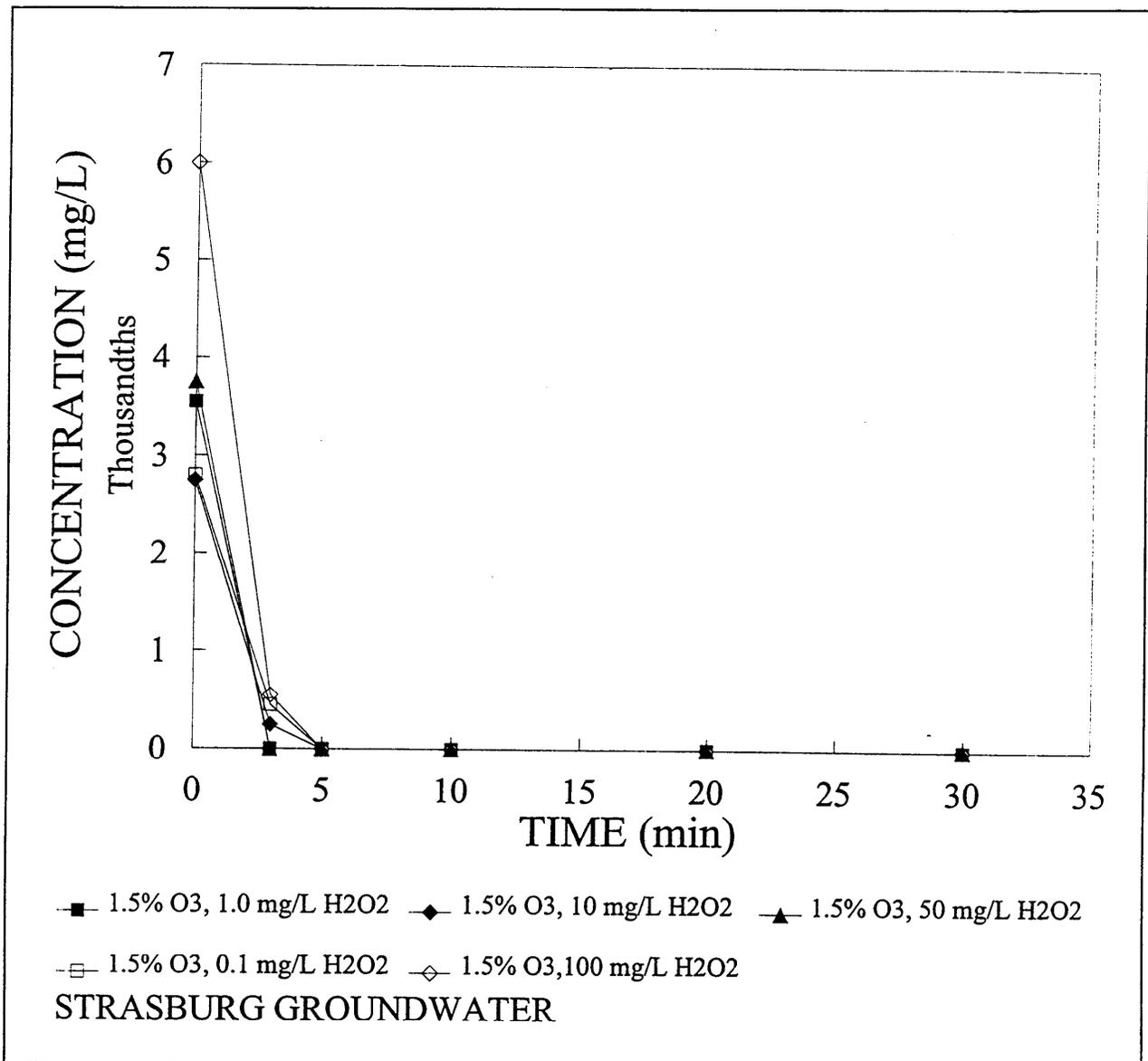


Figure A12. Peroxone - ethyl benzene

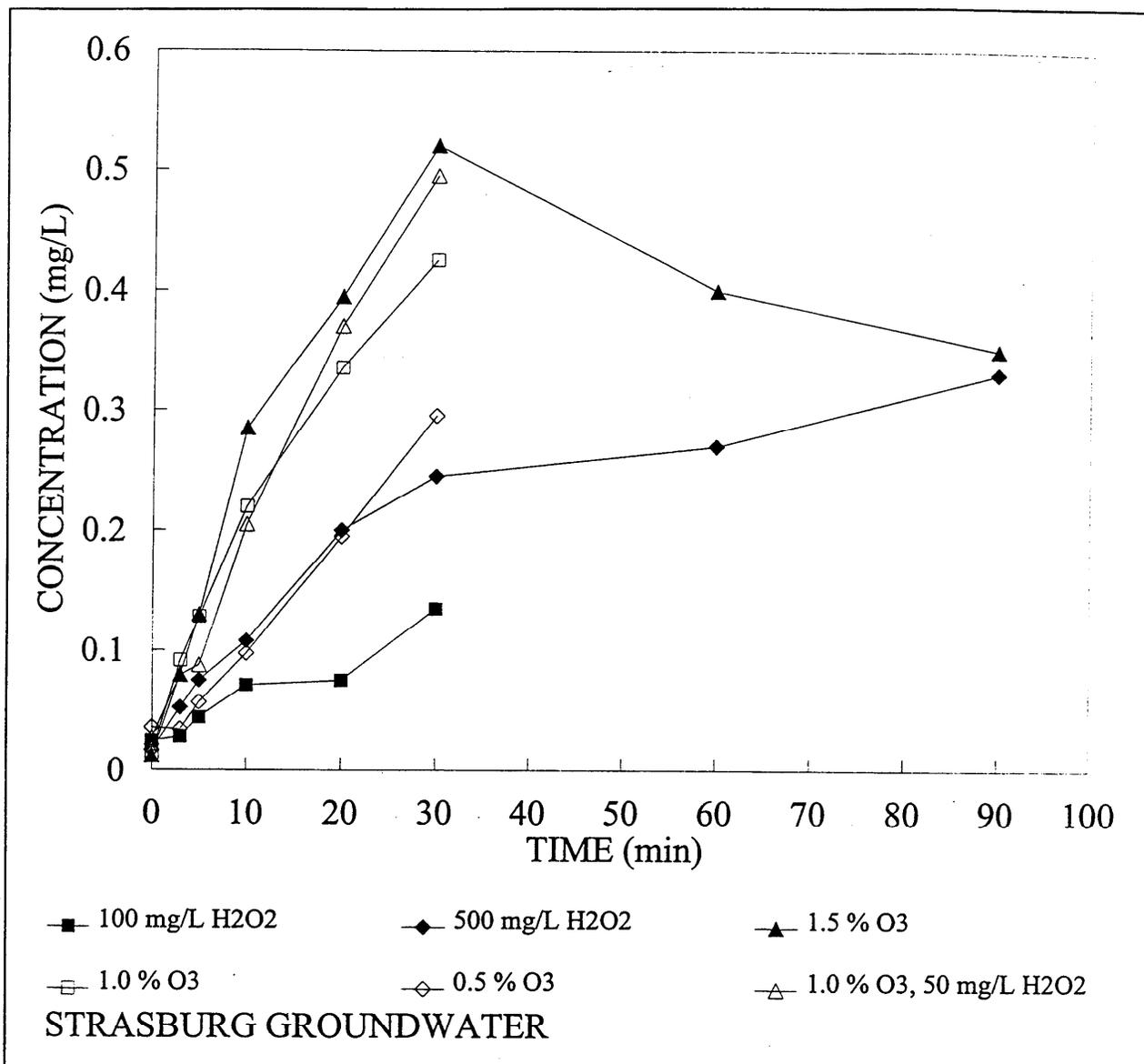


Figure A13. Low-pressure mercury lamp - acetone

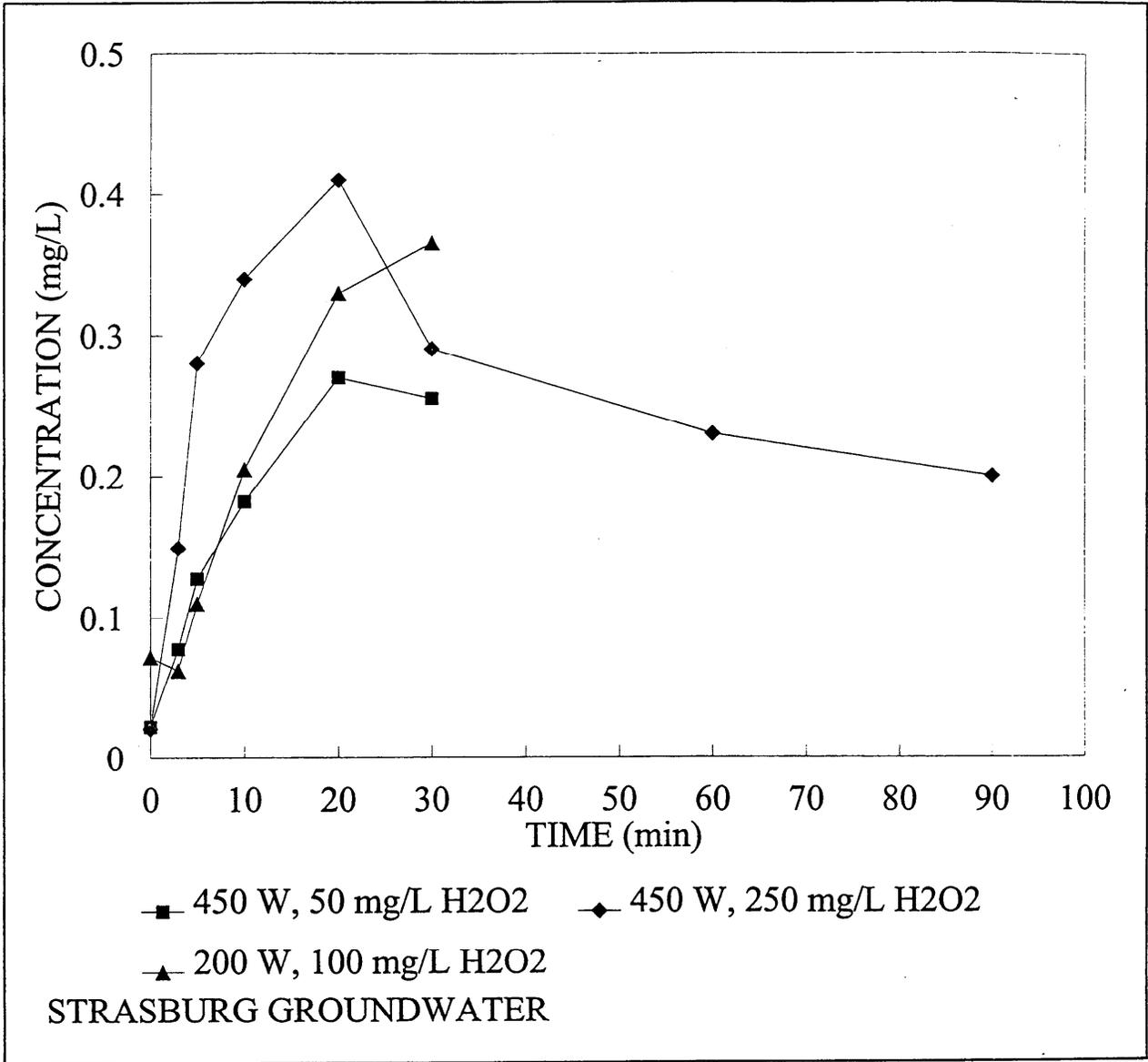


Figure A14. Medium-pressure mercury lamp - acetone

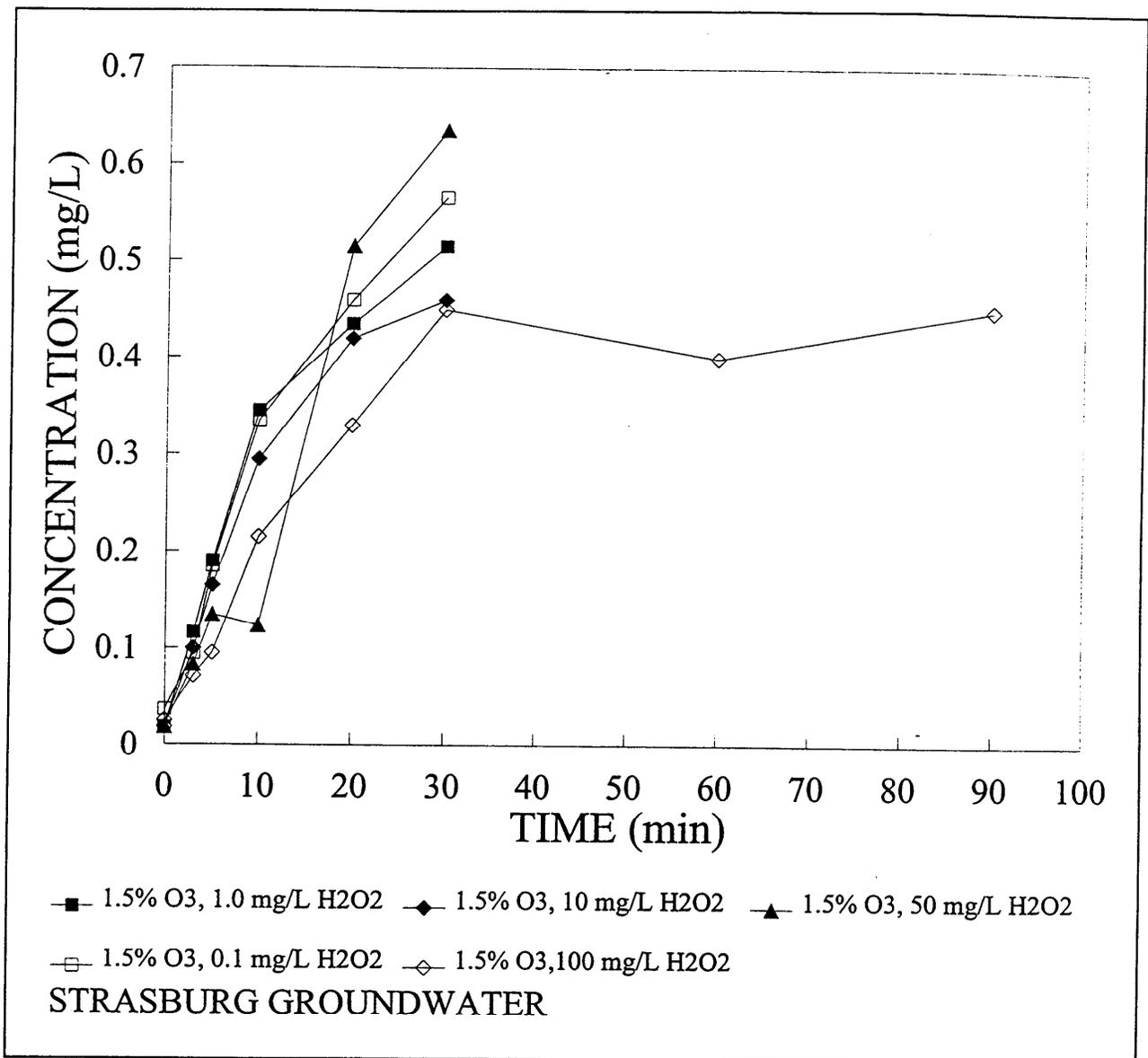


Figure A15. Peroxone - acetone

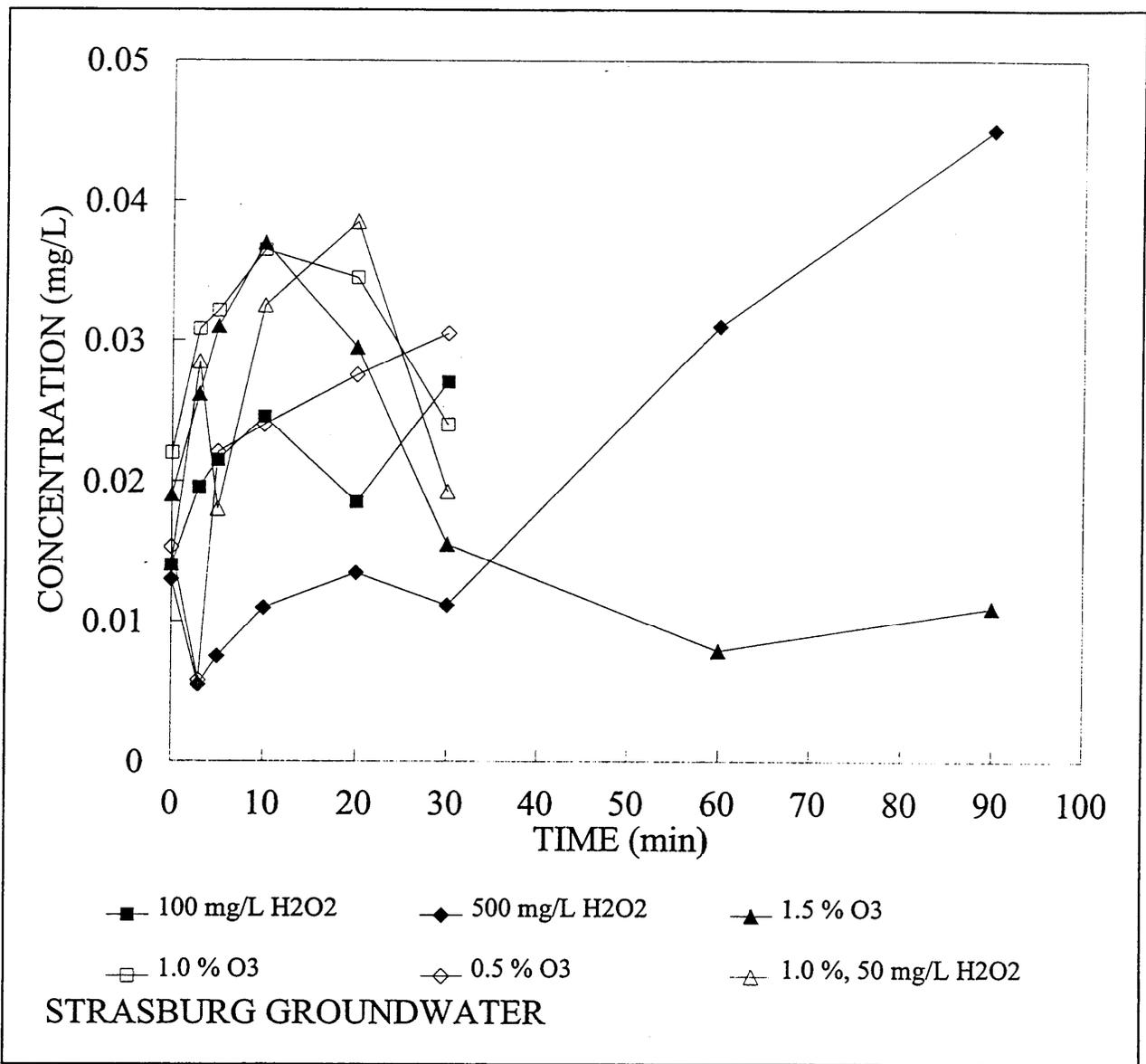


Figure A16. Low-pressure mercury lamp - 2-butanone

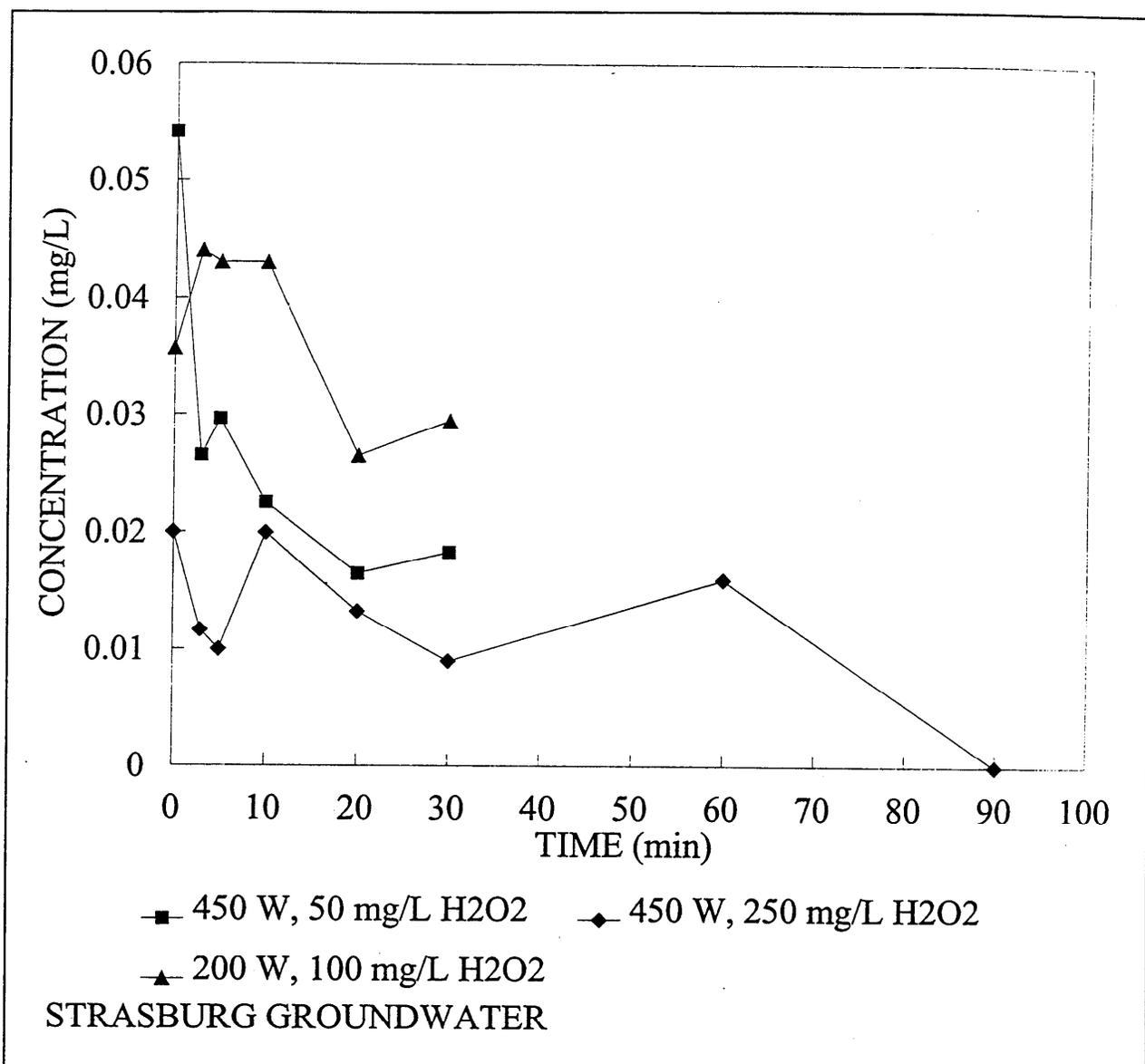


Figure A17. Medium-pressure mercury lamp - 2-butanone

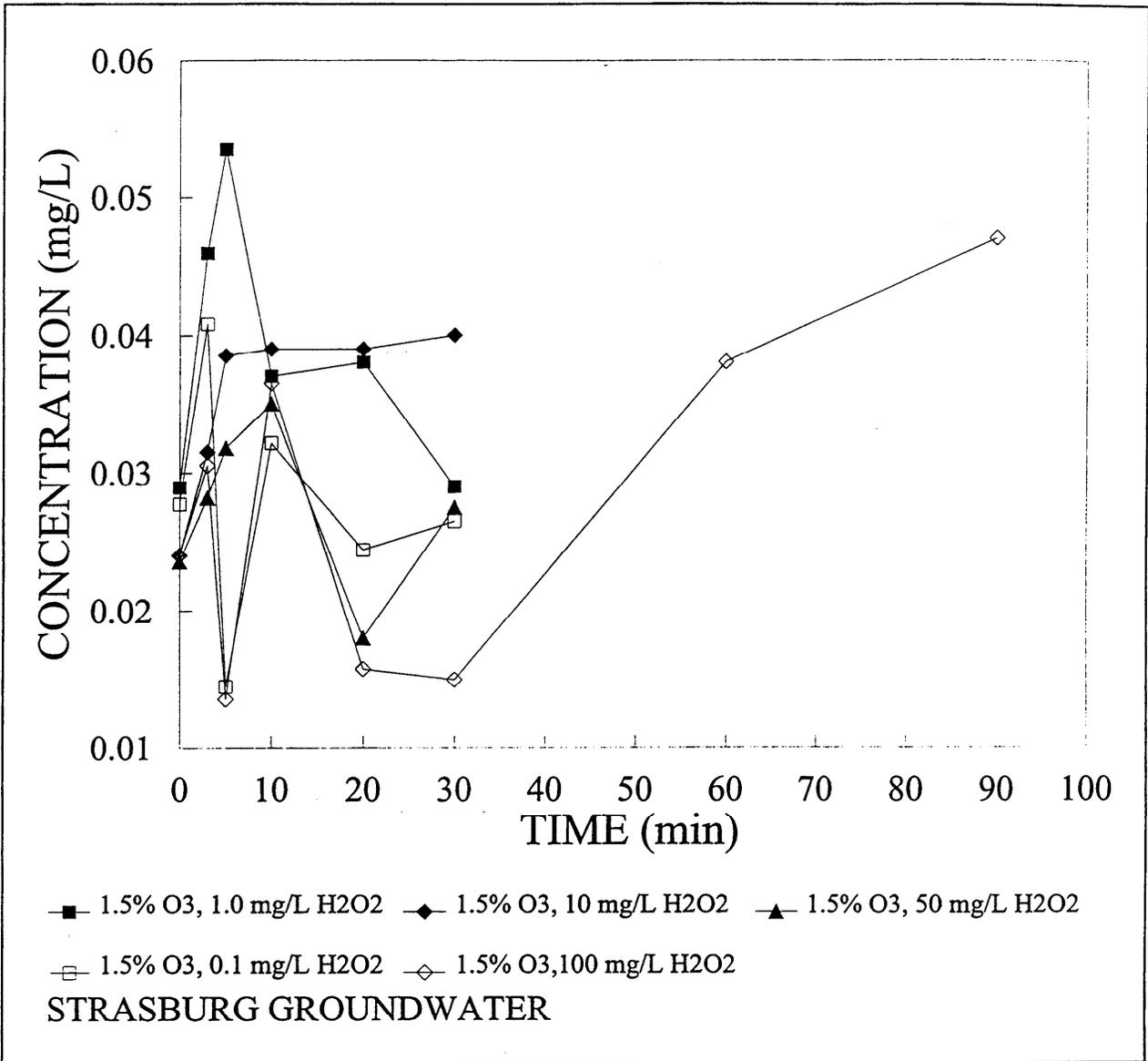


Figure A18. Peroxone - 2-butanone

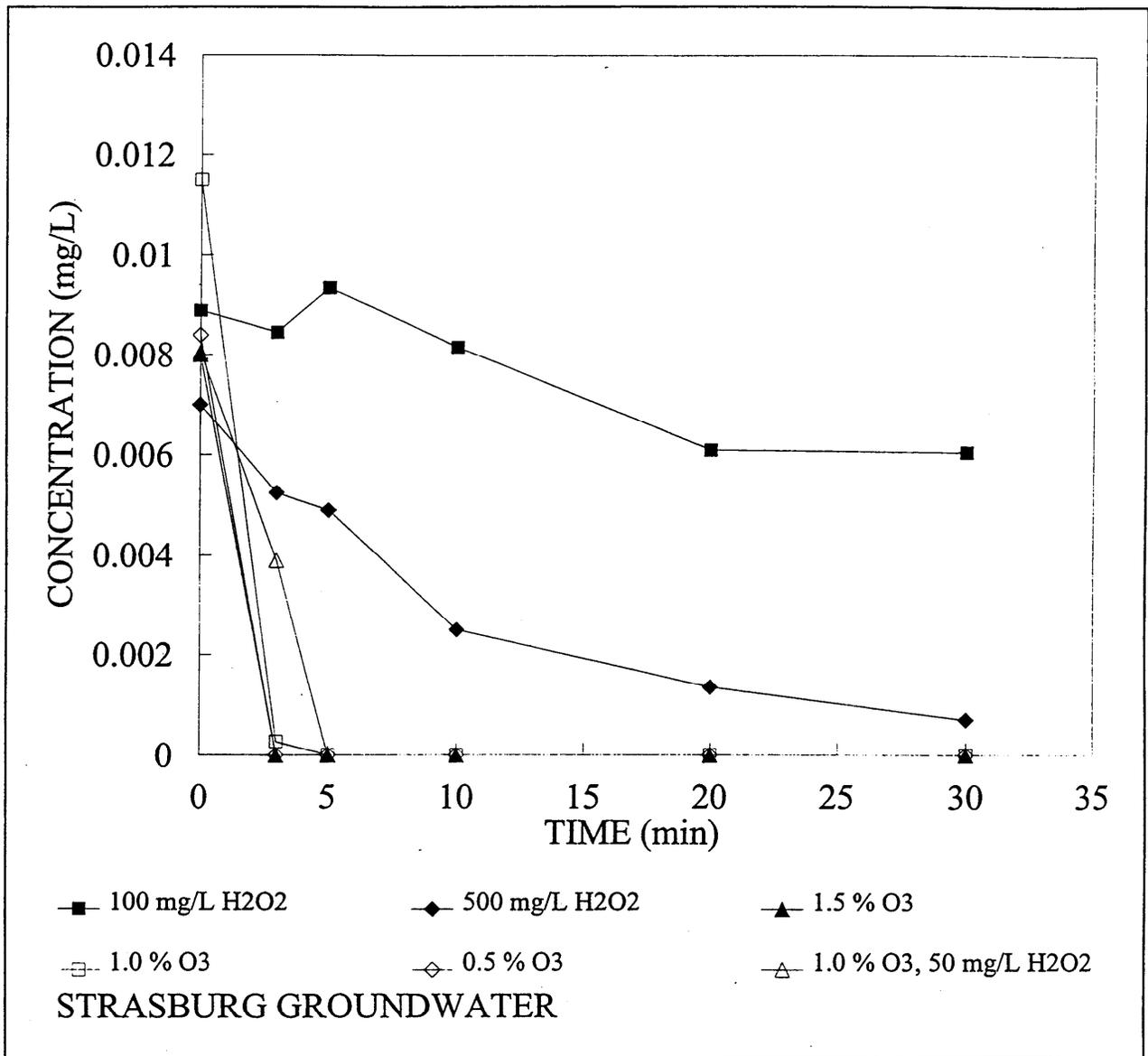


Figure A19. Low-pressure mercury lamp - chloroethane

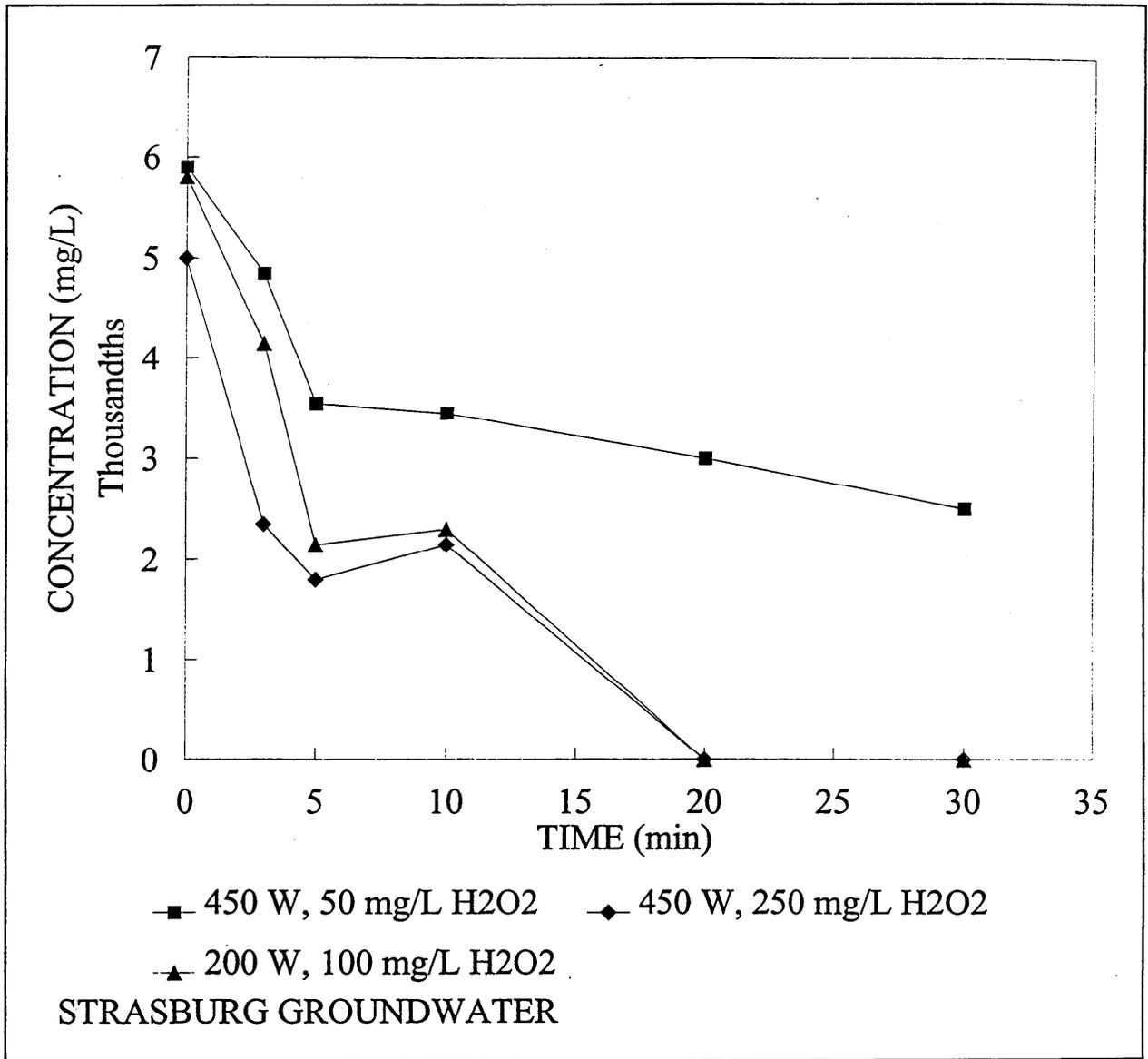


Figure A20. Medium-pressure mercury lamp - chloroethane

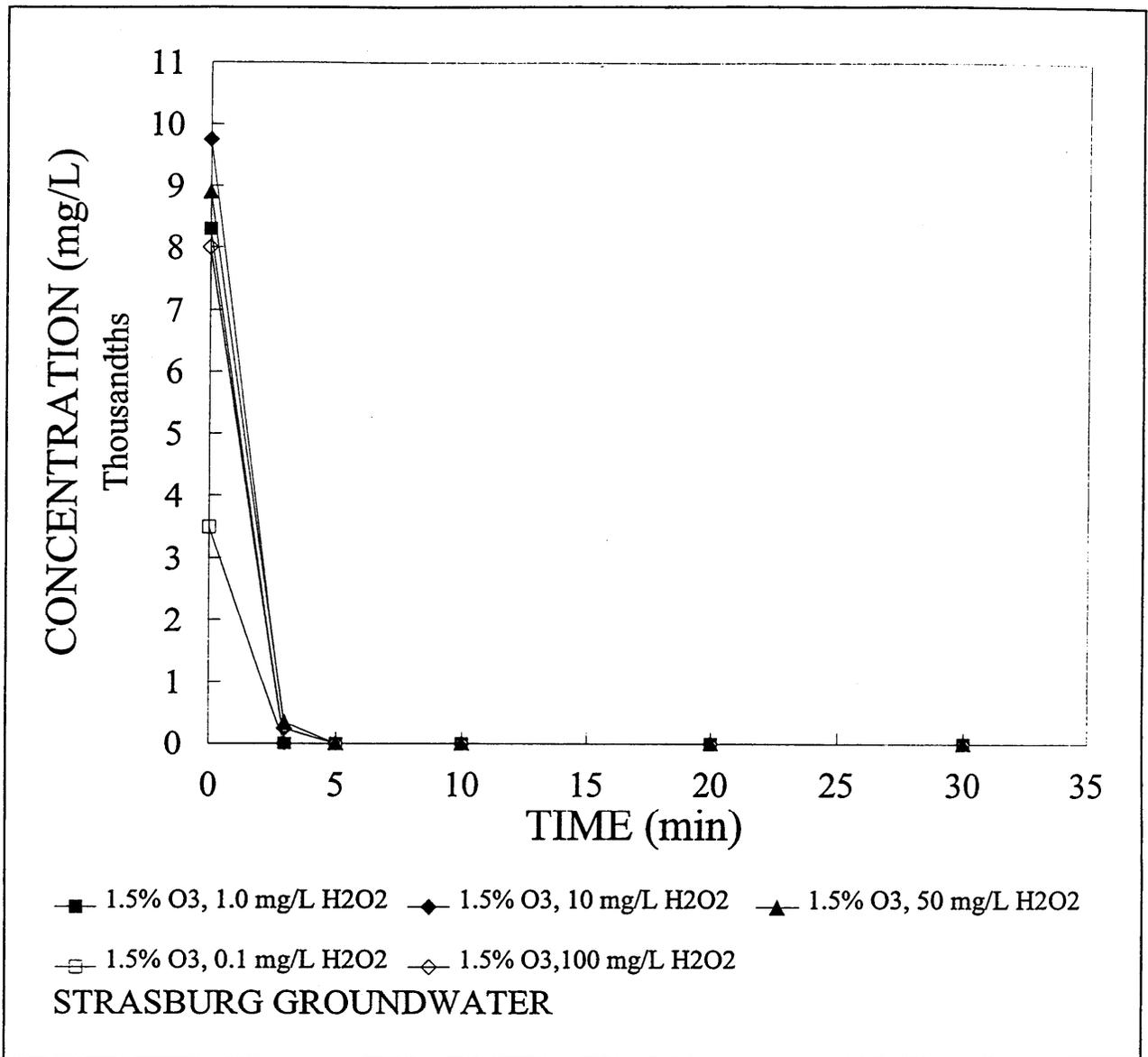


Figure A21. Peroxone - chloroethane

# Appendix B

## Percent of Ozone by Weight to Mass Flow Rate of Ozone (mg Ozone/minutes) Conversion Table

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<b>Table B1 Conversion From Ozone Percent by Weight to Ozone Mass Flow Rate</b>			
<b>Temperature, °C</b>	<b>25.35</b>	<b>26.65</b>	<b>27.95</b>
<b>Feed Gas</b>	<b>Air</b>	<b>Air</b>	<b>Air</b>
<b>Pressure, psi</b>	<b>15</b>	<b>15</b>	<b>15</b>
<b>Percent Ozone</b>	<b>mg/min Ozone</b>		
0.5	7.1154	7.0845	7.0539
1	14.2308	14.1691	14.1079
1.5	21.3462	21.2536	21.1618
2	28.4616	28.3381	28.2158
2.5	35.5769	35.4227	35.2697

Note: Average temperature - 26.65 °C; Standard Deviation = 1.30 °C.

# REPORT DOCUMENTATION PAGE

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<b>6. AUTHOR(S)</b> Mark E. Zappi, Evelyn Toro, Robert Jones, Mona Data, Jeff Talley	
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<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> U.S. Army Engineer Waterways Experiment Station 3909 Halls Ferry Road, Vicksburg, MS 39180-6199; U.S. Army Engineer District, Baltimore P.O. Box 1715, Baltimore, MD 21203-1715	<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>  Miscellaneous Paper IRRP-97-4
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<b>13. ABSTRACT (Maximum 200 words)</b>  <p>The Strasburg Landfill Superfund Site is located in Newlin and Bradford townships, Chester County, Pennsylvania. The site was closed in 1980. It was not until 1988 that the site was placed in the U.S. Environmental Protection Agency's National Priority List when leachate runoff into a nearby creek was discovered and contaminants were detected in groundwater and surface water. Chlorinated solvents and simple aromatics were commonly manifested. Treatment technologies for the prevention of further migration of contaminants into the environment are currently under evaluation by the U.S. Army Engineer District, Baltimore. Occasional failures of the current air stripper system to meet effluent concentrations have occurred, and in accordance with the Record of Decision, an advanced oxidation process (AOP) system should be evaluated as a potential replacement of the air stripping unit.</p> <p>Four bench-scale AOPs were evaluated by the U.S. Army Engineer Waterways Experiment Station as potential options to treat the contaminated Strasburg leachate. These AOPs were irradiation of hydrogen peroxide using a medium-pressure mercury lamp; irradiation of hydrogen peroxide using a low-pressure mercury lamp; irradiation with ozone sparging; and peroxone.</p> <p style="text-align: right;">(Continued)</p>
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<b>14. SUBJECT TERMS</b> AOPs Groundwater treatment Hydrogen peroxide (dose)	Ozone (%) Peroxone UV light	<b>15. NUMBER OF PAGES</b> 84	<b>16. PRICE CODE</b>
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13. (Concluded).

Successful treatment of the Strasburg leachate was achieved using the proposed AOPs, with the exception of the low-pressure ultraviolet light irradiation of the hydrogen peroxide system, which showed the slowest contaminant-removal rate. The best dosages of oxidizers for each of the AOPs were identified, as well as the required retention times. The ozonated systems exhibited the best contaminant-removal rates among all the AOPs studied, which may indicate that stripping may have been a factor in these removal increases.

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