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SITE
SUPERFUND INNOVATIVE
TECHNOLOGY EVALUATION

Technology Demonstration Summary

Magnum Water Technology CAV-OX® Cavitation Oxidation Process

As part of the Superfund Innovative Technology Evaluation (SITE) Program, the U.S. Environmental Protection Agency (EPA) demonstrated the Magnum Water Technology (Magnum) CAV-OX® cavitation oxidation process at Edwards Air Force Base (Edwards) Site 16 in California in March 1993. The CAV-OX® technology treated about 8,500 gal of groundwater contaminated primarily with trichloroethene (TCE) and benzene.

Demonstration results showed that the CAV-OX® process was capable of achieving average removal efficiencies from contaminated groundwater of over 99.9% for both TCE and benzene. Effluent from one process configuration met the 95% confidence level for State of California drinking water action levels and federal maximum contaminant levels (MCL) for TCE and benzene.

This technology may be applied at Superfund and other hazardous waste sites where groundwater or other aqueous wastes are contaminated with organic compounds. Economic data indicate that the costs of remediating groundwater using the CAV-OX® process range from $13 to $31 per 1,000 gal. These amounts include capital and operation and maintenance costs. Actual site remediation costs will, however, depend on the CAV-OX® process configuration and waste characteristics.

This Summary was developed by EPA's Risk Reduction Engineering Laboratory in Cincinnati, OH, to announce key findings of the SITE Program demonstration that is fully documented in separate reports (see ordering information at back).

Introduction

The SITE Program was established in 1986 to accelerate the development, demonstration, and use of new, innovative technologies that offer permanent cleanup solutions for hazardous wastes. One component of the SITE Program is the Demonstration Program, which develops reliable engineering, performance, and cost data for innovative treatment technologies. Data developed for the SITE Demonstration Program enables potential users to evaluate each technology's applicability to a specific waste site.

The SITE demonstration of the CAV-OX® technology was conducted at Edwards Site 16 over a 4-wk period. Edwards is a 310,000-acre U.S. Air Force

base about 75 mi northeast of Los Angeles. Edwards Site 16 occupies about 12 acres in an area that includes taxiways, hangars, office buildings, outside storage buildings, and open fields. The site contamination is attributed to a military-grade jet fuel (JP-4) release from a leaking fuel transfer line that runs along the western boundary of Site 16. The fuel leak, estimated to be between 250,000 and 300,000 gal, began about September 1983.

In November 1984, the Lahontan Region of the State of California Regional Water Quality Control Board issued Clean-Up and Abatement Order No. 84-10 for Site 16. This order was followed by remedial actions including pipeline replacement and monitoring well installation. Further investigation included a feasibility study, remedial action, and remedial design to clean up the fuel release. The resulting remedial action combined a recovery well system, a recovery fuel storage system, and a fuel-water separator system. This combined system collected fuel for later reuse. Potentially contaminated water was then routed to the base sanitary sewer system. Dissolved TCE was, however, later detected in the discharge water. Because water containing TCE could not be discharged to the sanitary sewer system, the recovery well system ceased operation in December 1987. A site assessment was completed in June 1989 under the Department of Defense Installation Restoration Program. A pilot plant study completed for the site proposed a treatment system that included an ultraviolet-oxidation unit and air stripping to treat contaminated groundwater from Site 16 recovery wells.

In February 1992, Magnum responded to EPA's annual solicitation for proposals to participate in the SITE Program. At that time, Magnum discussed the possibility of demonstrating the CAV-OX® technology to treat contaminated groundwater at Edwards. EPA subsequently accepted the CAV-OX® technology into the SITE Demonstration Program. The CAV-OX® technology demonstration had the following primary objectives:

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

Secondary objectives for the demonstration were:

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

Technology Description

Magnum developed the CAV-OX® technology to destroy organic contaminants dissolved in water. The technology uses hydrodynamic cavitation, ultraviolet (UV) radiation, and hydrogen peroxide to oxidize organic compounds present in water at parts per million (ppm) levels or less. The technology uses a cavitation chamber to generate hydrodynamic cavitation, which occurs when a liquid undergoes a dynamic pressure reduction while under constant temperature. The pressure reduction causes bubbles to explosively develop, grow, and then collapse. Acoustic cavitation decomposes water into extremely reactive hydrogen atoms and hydroxyl radicals. Based on the assumption that hydrodynamic cavitation produces similar effects to those of acoustic cavitation, Magnum combines hydrodynamic cavitation with UV radiation and hydrogen peroxide. This combination generates powerful oxidants that react with organic contaminants. End products of oxidation include water, carbon dioxide, halides (for example, chloride), and in some cases, organic acids.

Each portable, skid-mounted CAV-OX® technology configuration consists of the following main components: cavitation pump, cavitation chamber, UV reactor, and control panel unit. Contaminated water is pumped through the cavitation chamber, and then enters either the UV reactor or is recycled through the cavitation chamber. The selected hydraulic retention time (or flow rate) determines the recycle rate. In permanent applications of the technology, hydrogen peroxide is usually injected directly into the water downstream from the cavitation chamber.

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

Three configurations of the CAV-OX® technology were demonstrated. The CAV-OX® I low-energy process, operating at 360 watts, contained one UV reactor with six 60-watt UV lamps. The CAV-OX® II process consisted of two UV reactors with one UV lamp each, and operated at 5 or 10 kilowatts (kW). The low-energy and high-energy process configurations operated simultaneously. Figure 1 illustrates the main and ancillary components of the CAV-OX® process configurations.

Site Preparation

The demonstration required about 2,000 ft^2 of ground surface for the CAV-OX® technology and support equipment and facilities. Support equipment for the demonstration included a 7,500-gal bladder tank for untreated groundwater, a 21,000-gal storage tank for treated groundwater, a solid waste dumpster for disposal of nonhazardous wastes, 55-gal drums for storage of decontamination rinse water, a forklift for unloading and loading support equipment, three submersible positive displacement pumps with gasoline powered generators, sampling and analytical equipment, and health and safety equipment.

Utilities required for the demonstration included water, electricity, and telephone service. Water was required for equipment and personnel decontamination, field and mobile laboratory use, and drinking. Electricity was required to power the CAV-OX® process, a field trailer, and mobile laboratory equipment. Two cellular telephones located in the office and laboratory trailer were used to schedule deliveries and to order equipment, parts, reagents, and other chemical supplies.

Technology Demonstration

The technology was demonstrated at Edwards Site 16 over a 4-wk period in March 1993. During the demonstration, the CAV-OX® process treated about 8,500 gal of groundwater contaminated with volatile organic compounds (VOC). Groundwater was pumped from three wells into a 7,500-gal bladder tank to minimize variability in influent characteristics. Treated groundwater was stored in a 21,000-gal steel tank before discharge.

Principal groundwater contaminants included TCE and benzene, which were present at concentrations of up to 2,100 and 500 micrograms per liter (µg/L), re-

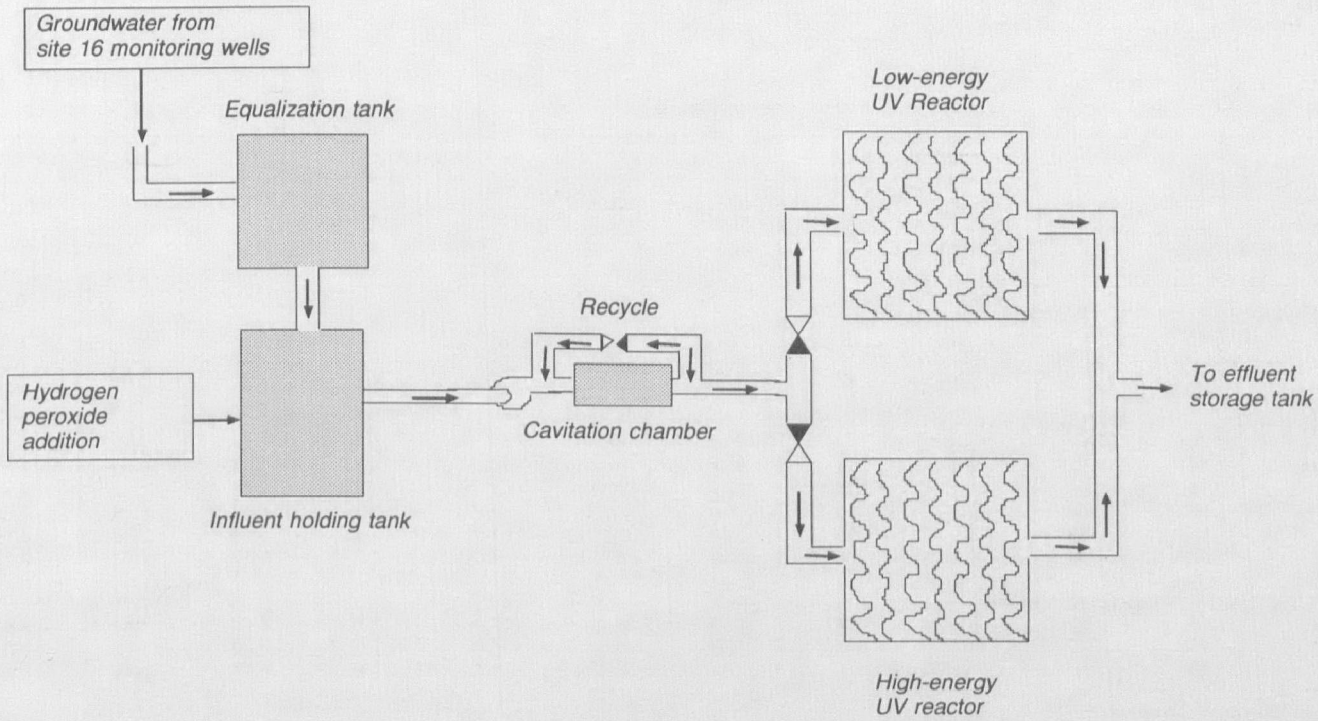


Figure 1. *The CAV-OX® technology as demonstrated.*

spectively. Other VOCs, such as carbon tetrachloride, chloroform, 1,1-dichloroethane, 1,2-dichloroethane, 1,1-dichloroethene, trans-1,2-dichloroethene, tetrachloroethene, 1,1,1-trichloroethane, and 1,1,2-trichloroethane, were present in groundwater at concentrations less than 300 µg/L.

During the demonstration, samples were collected at three locations. Samples of untreated groundwater were collected from the feed line exiting the influent holding tank. Samples of treated groundwater were collected from the effluent lines of both the CAV-OX® I and CAV-OX® II configurations. Influent and effluent samples were analyzed for the following parameters: TCE, BTEX, VOCs, hydrogen peroxide, total organic carbon (TOC), total carbon (TC), purgeable organic carbon (POC), metals, alkalinity, hardness, total recoverable petroleum hydrocarbons (TRPH), semivolatile organic compounds (SVOC), and turbidity. Measurements were made of pH, temperature, flow rate, and specific conductance. Bioassay tests were also conducted to determine the toxicity of influent and effluent to freshwater organisms. Samples were also analyzed to verify hydrogen peroxide concentrations in the influent holding tank.

The principal operating parameters for the Magnum CAV-OX® process include hydrogen peroxide concentration, UV lamp output, and flow rate. These parameters were varied to observe treatment process performance under different operating conditions. Initial operating conditions for the demonstration were based on the professional judgment and experience of Magnum personnel, and on groundwater characterizations performed by Edwards in 1990 and 1991. Preferred operating conditions were determined as conditions that 1) provided the greatest reduction of VOC concentrations, and 2) reduced VOC concentrations below target levels.

Operating information, such as power consumption rates, was recorded during the demonstration to estimate costs. Magnum provided operating and maintenance cost information for the technology.

Demonstration Results

Demonstration results were based on extensive laboratory analyses under rigorous quality control procedures, as well as observations made by SITE personnel during the CAV-OX® process demonstration. The following sections summarize the primary and secondary objective results of the CAV-OX® demonstration.

Summary of Primary Objective Results

Throughout the demonstration, only TCE and benzene were detected in the influent at concentrations well above target levels. Toluene, ethylbenzene, and xylenes were present in the influent at relatively low concentrations when compared with TCE and benzene. Therefore, this summary of the CAV-OX® technology's effectiveness pertains only to TCE and benzene.

Table 1 compares TCE and benzene removals among the three treatment process configurations. The major differences among the three configurations are UV lamp output and flow rate. As expected, contaminant removal efficiency increased with higher UV lamp output and with lower flow rates. The choice of a particular process configuration depends, however, on individual site-specific characteristics.

Under the preferred conditions — a flow rate of 0.6 gal per minute (gpm) and a hydrogen peroxide concentration of 23.4 milligrams per liter (mg/L) — effluent from the CAV-OX® I process configuration met State of California drinking water action levels and federal MCLs for benzene and TCE at the 95% confidence level. If a greater flow rate is required, the CAV-OX®

Table 1. *Contaminant Removal*

Run	Influent		Hydrogen Peroxide Concentration (mg/L)	CAV-OX® I			CAV-OX® II					
	TCE (µg/L)	Benzene (µg/L)		Flow (gpm)	Effluent		Flow (gpm)		Effluent			
					TCE (µg/L)	Benzene (µg/L)			TCE (µg/L)		Benzene (µg/L)	
							5-kW	10-kW	5-kW	10-kW	5-kW	10-kW
Low Hydrogen Peroxide Concentration												
1	1,980	263	0	0.6	1,570	315	2.0	2.0	275	31.0	189	99.1
2	2,000	265	0.4	1.5	1,500	300	1.6	1.6	169	17.3	150	86.0
3	1,780	243	0.4	1.5	1,790	301	3.9	4.0	632	270	234	174
Medium Hydrogen Peroxide Concentration												
4	1,930	285	4.9	1.5	657	36.9	4.0	3.9	278	41.5	35.6	4.44
5	1,580	333	4.9	1.5	617	65.9	3.9	3.4	287	96.3	44.1	18.0
6	1600	355	5.9	0.5	60.6	238	1.5	1.4	9.56	21.1	3.18	4.26
7	1,980	503	5.9	0.7	270	19.7	1.9	2.0	54.7	39.6	41.3	6.41
8	1,850	283	6.0	0.7	268	9.90	1.9	1.9	38.9	20.8	4.18	2.97
9	1,800	433	6.1	1.5	789	67.3	4.0	4.0	262	26.3	29.4	3.21
High Hydrogen Peroxide Concentration												
10	1,680	252	23.4	0.6	2.71	0.18	2.0	2.1	8.46	7.84	1.89	2.05
11	1,480	240	33.1	0.5	4.07	0.38	1.6	1.5	8.80	18.2	2.07	4.52
12	1,530	250	48.3	0.6	12.1	0.12	1.4	1.4	5.61	7.97	1.25	1.14
Vendor Selected Conditions												
13*	2,000	500	1.8	NA †	NA	NA	1.9	1.9	427	57.9	328	20
14 ‡,**	1,680	410	9.1	NA	NA	NA	NA	7.9	NA	257	NA	39.1
15‡,**,§	2,000	468	NA	NA	NA	NA	NA	0.8	NA	185 §§	NA	43.4 §§

Notes:
- * *CAV-OX® I not operated.*
- † *NA = not applicable.*
- ** *CAV-OX® I and 5-kW CAV-OX® II not operated.*
- ‡ *Influent pH adjusted.*
- § *CAV-OX® II high-energy process operated at 2.5 kW.*
- §§ *Sample collected after cavitation prior to the UV reactor.*

Values for TCE and benzene represent the 95% confidence limit.

II 5-kW or 10-kW process may be more suitable. Average effluent contaminant concentrations from the CAV-OX® II process configurations, operating under the preferred conditions, met State of California drinking water action levels and federal drinking water MCLs for TCE and benzene. However, because of data variability, many of these effluents did not achieve the 95% confidence level for TCE and benzene. Since the demonstration evaluated numerous operating conditions, not all of them produced effluent that met these discharge limits.

Figure 2 compares removal efficiencies of the three CAV-OX® process configurations for TCE. Figure 3 compares removal efficiencies of the three CAV-OX® process configurations for benzene.

Summary of Secondary Objective Results

The technology demonstration was also designed to evaluate analytical results of several other parameters and collect information to determine the costs of applying the technology. Results of demonstration procedures designed to satisfy secondary objectives are summarized below.

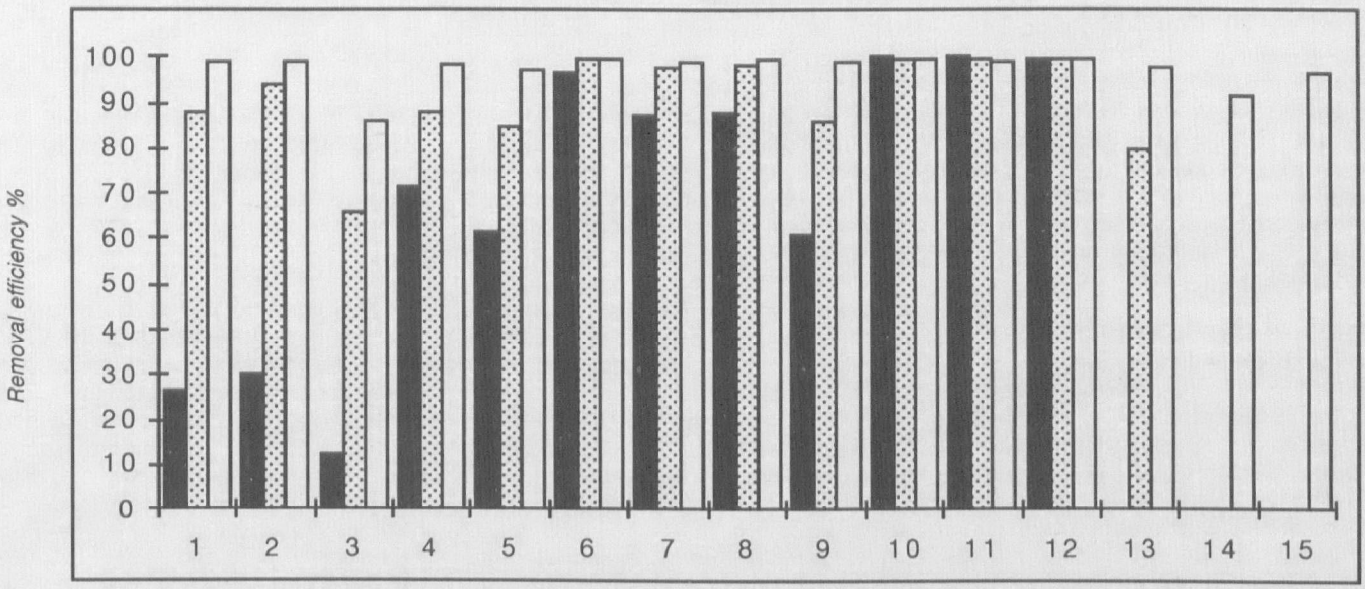
Process Chemical and Utility Requirements

A secondary objective of the demonstration was to estimate treatment costs by determining process chemical and utility requirements. Hydrogen peroxide is the only process chemical used in the CAV-OX® process. During the various demonstration runs, the process used between 0 and 48.3 mg of hydrogen peroxide per L of influent water. During the demonstration, hydrogen peroxide was added to the influent holding tank in an attempt to achieve optimal concentration of hydrogen peroxide.

The demonstration results show that removal efficiency increased with the addition of hydrogen peroxide. Magnum reports, however, that this increase in efficiency is limited, and that efficiency begins to decrease at some point specific to the influent water characteristics and operating parameters used. Table 1 shows the effects of varying hydrogen peroxide concentrations on contaminant removal efficiency.

Runs 13 and 14 were conducted under conditions chosen by Magnum. For these runs, Magnum chose not to operate the CAV-OX® I low-energy process. Run 13 repeated the conditions of Run 11 without hydrogen peroxide added. The results of these runs show that although some contaminant removal does occur without hydrogen peroxide, this additive is vital to achieving high removal efficiencies. Run 14 was conducted with a hydrogen peroxide concentration of 9.1 mg/L and a flow rate of 7.9 gpm. Results of this run showed that increased hydrogen peroxide concentrations did not compensate for the increased process flow rate (and consequent decreased retention time). However, because the influent's pH was lowered, it is difficult to draw definitive conclusions based on this run.

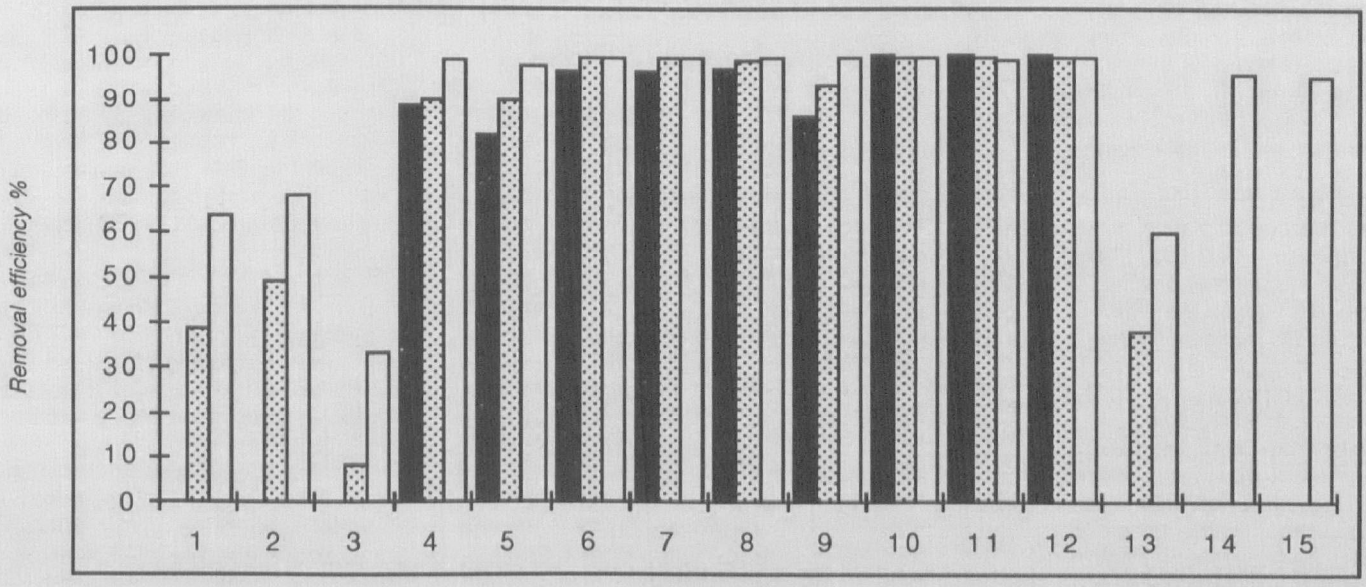
Electricity and water are required for the CAV-OX® process. Electricity demand



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CAV-OX® I	26.6	30.0	12.7	71.4	61.7	96.4	87.1	87.8	60.6	99.9	99.9	99.7	NA †	NA	NA
5-kW CAV-OX® II	88.1	94.1	65.8	87.8	85.1	99.6	97.8	98.4	86.2	99.7	99.6	99.8	80.1	NA	0 ‡
10-kW CAV-OX® II	98.6	99.2	86.1	98.1	97.1	99.4	99.2	99.3	98.9	99.7	99.2	99.7	97.6	91.6	96.3

Notes: * CAV-OX® II high-energy process operated at 2.5 kW.
† not applicable.
‡ Sample collected after cavitation chamber prior to UV reactor.

Figure 2. *Trichloroethene removal efficiency comparison for three operating conditions.*



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CAV-OX® I	NA †	NA	NA	88.6	81.6	96.4	96.5	96.9	86.1	99.9	99.9	99.9	NA	NA	NA
5-kW CAV-OX® II	39.0	49.1	8.2	89.7	89.5	99.5	99.4	98.8	93.5	99.5	99.4	99.8	38.5	NA	0 ‡
10-kW CAV-OX® II	63.7	68.1	33.0	98.7	97.8	99.4	99.5	99.3	99.5	99.5	98.8	99.8	60.5	95.8	95.4

Notes: * CAV-OX® II high-energy process operated at 2.5 kW.
† not applicable.
‡ Sample collected after cavitation chamber prior to UV reactor.

Figure 3. *Benzene removal efficiency comparison for three operating conditions.*

was 2.2 kW for the CAV-OX® I process, 6.4 kW for the 5-kW CAV-OX® II process, and 13.0 kW for the 10-kW CAV-OX® II process. During the demonstration, water was required in the following approximate amounts: 10 gallons per day (gpd) of potable water for equipment and personal decontamination; 5 gpd of distilled, deionized water for field laboratory use; and 5 to 10 gpd for drinking water.

Degradation By-Products

Gas chromatography/mass spectrometry (GC/MS) analysis of influent and effluent samples for VOCs and SVOCs indicated that no new target compounds or tentatively identified compounds (TIC) were formed during the treatment. TICs are compounds whose retention times on GC columns indicate, but do not confirm, the presence of a given compound. Several unknown TICs were identified in both the influent and effluent samples. Acetone and 2-butanone concentrations were generally higher in the effluent than in the influent.

Additional Groundwater Characterization

Groundwater characterization was also performed during the demonstration. This demonstration included bioassay testing to determine the toxicity of process influents and effluents.

Bioassay tests were performed to evaluate the acute toxicity of influent and effluent from Runs 13, 14, and 15. Two freshwater test organisms, the fathead minnow (*Pimephales promelas*) and the water flea (*Ceriodaphnia dubia*), were used in the bioassay tests. Toxicity was measured as the concentration at which 50% of the organisms died (LC_{50}) and was expressed as the percent of effluent or influent in the test water. One influent and one effluent sample were collected and analyzed in each run.

Bioassay analyses showed that (1) influent was generally toxic to both the fathead minnow and the water flea; (2) treated effluent from runs without hydrogen peroxide was nontoxic to the fathead minnow, but moderately toxic to the water flea; (3) treated effluent from runs with hydrogen peroxide added was toxic to both the fathead minnow and the water flea. Comparison of effluent toxicity with residual hydrogen peroxide concentration in the effluent indicates that effluent toxicity may be partially due to hydrogen peroxide residual rather than treatment by-products. These results represent conditions during the demonstration only and are site- and waste-specific. Additional studies are needed to draw definitive conclusions on the effluent toxicity.

No significant changes in pH, alkalinity, hardness, TOC, TC, POC, or specific conductance were observed during treatment. Also, the CAV-OX® process did not remove iron or manganese from the influent groundwater. Influent TRPH concentrations ranged from 0.64 to 1.15 mg/L. Effluent TRPH concentrations ranged from below detection limits to 0.78 mg/L.

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

Water temperature increased at an average rate of about 0.26°F/min of UV exposure in the CAV-OX® I process. In the 5-kW CAV-OX® II process, the water temperature increased at an average rate of about 2.36°F/min of UV exposure; and in the 10-kW CAV-OX® II process, the water temperature increased at an average rate of about 4.29°F/min of UV exposure. Because the treatment equipment is exposed to the surrounding environment, the temperature increase may vary with the ambient temperature or other atmospheric conditions.

Estimated Treatment Costs

Using information from the SITE demonstration, an economic analysis examined 12 separate cost categories for the CAV-OX® process applied to a hypothetical, 5-yr groundwater remediation project at a Superfund site. This analysis examined costs for the CAV-OX® I low-energy process and the CAV-OX® II high-energy process using flow rates of 10 and 25 gpm. Costs were determined in October 1993 dollars.

For the CAV-OX® I low-energy process, capital costs are estimated to be $314,500 for a 10-gpm process and $342,500 for the 25-gpm process. Annual operation and maintenance (O&M) costs are estimated to be $71,000 for the 10-gpm process and $78,000 for the 25-gpm process. Costs to treat 1,000 gal of contaminated groundwater are estimated to be $30 for the 10-gpm process and $13 for the 25-gpm process.

For the CAV-OX® II high-energy process, capital costs for both the 10- and 25-gpm processes are the same as those for the CAV-OX® I low-energy process. Annual O&M costs are estimated to be $75,000 for the 10-gpm process and $86,000 for the 25-gpm process. Costs to treat 1,000 gal of contaminated groundwater are estimated to be $31 for the 10-gpm process and $14 for the 25-gpm process.

Conclusions

The following preferred operating conditions were determined for the CAV-OX® I low-energy process: (1) an influent hydrogen peroxide concentration of 23.4 mg/L and (2) a flow rate of 0.6 gpm. Under these conditions, TCE and benzene concentrations in the effluent met State of California drinking water action levels and federal MCLs (target levels) for TCE and benzene (5 µg/L and 1 µg/L, respectively) at the 95% confidence level. The average removal efficiencies for TCE and benzene were both greater than 99.9%.

No preferred operating conditions were identified for the CAV-OX® II high-energy process. However, certain conditions did reduce the concentrations of either TCE or benzene, but not both, below target levels. Based on the results of the demonstration, the optimal conditions (as determined by percent reductions) appear to be: (1) an influent hydrogen peroxide level of 48.3 mg/L and (2) a flow rate of 1.4 gpm. Under these conditions, the average TCE and benzene concentrations in the effluent were reduced below target levels; however, due to data variability, these constituents were not reduced below target levels at the 95% confidence level. The average removal efficiencies for TCE and benzene were about 99.7% and 99.8%, respectively.

Bioassay tests were inconclusive as to whether the toxicity of effluent was caused by hydrogen peroxide or by CAV-OX® process treatment residuals. Because hydrogen peroxide appears to be toxic to certain aquatic organisms at levels greater than 10 mg/L, effluent hydrogen peroxide concentrations should be kept well below 10 mg/L. Also, additional bioassay tests should be performed on the process effluent to determine whether the effluent can be safely discharged to aquatic bodies.