



# High Voltage Environmental Applications, Inc. Electron Beam Technology

## Innovative Technology Evaluation Report

The SITE logo is centered at the bottom of the page. It consists of the letters "SITE" in a large, bold, stylized font. Below "SITE" are the words "SUPERFUND INNOVATIVE" and "TECHNOLOGY EVALUATION" in a smaller, sans-serif font. The entire logo is framed by a decorative border of wavy lines on the top and bottom, and solid horizontal lines on the left and right sides.

**SITE**  
SUPERFUND INNOVATIVE  
TECHNOLOGY EVALUATION

**High Voltage Environmental Applications, Inc.  
Electron Beam Technology**

Innovative Technology Evaluation Report

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

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## Foreword

The U.S. Environmental Protection Agency is charged by Congress with protecting the nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

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This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

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E. Timothy Oppelt, Director  
National Risk Management Research Laboratory

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## Abstract

This report evaluates a high-voltage electron beam (E-beam) technology's ability to destroy volatile organic compounds (VOC) and other contaminants present in liquid wastes. Specifically, this report discusses performance and economic data from a Superfund Innovative Technology Evaluation (SITE) demonstration of the technology and one case study.

The E-beam technology was developed by High Voltage Environmental Applications, Inc. (HVEA). The technology irradiates water with a beam of high-energy electrons, causing the formation of three primary transient reactive species: aqueous electrons, hydroxyl radicals, and hydrogen radicals. These reactive species undergo complex sequences of reactions with target organic compounds, which are either mineralized or broken down into low molecular weight compounds.

The E-beam technology was demonstrated under the SITE program at the U.S. Department of Energy's Savannah River Site in Aiken, SC, during three weeks in September and November 1994. A trailer-mounted E-beam system was used for the SITE demonstration. This system is housed in an 8- by 48-foot trailer and is rated for minimum and maximum flow rates of 15 and 50 gallons per minute, respectively. During the demonstration, the E-beam system treated about 70,000 gallons of groundwater contaminated with VOCs. The principal groundwater contaminants were trichloroethene (TCE) and tetrachloroethene (PCE), which were present at concentrations of about 27,000 and 11,000 micrograms per liter ( $\mu\text{g/L}$ ), respectively. The groundwater also contained low levels (40  $\mu\text{g/L}$ ) of cis-1,2-dichloroethene (1,2-DCE). During a portion of the demonstration, the influent was spiked with VOCs not present in the groundwater. The resultant influent concentrations were about 100 to 500  $\mu\text{g/L}$  for the following compounds: 1,1,1-trichloroethane (1,1,1-TCA); 1,2-dichloroethane (1,2-DCA); chloroform; carbon tetrachloride ( $\text{CCl}_4$ ); and aromatic VOCs, including benzene, toluene, ethylbenzene, and xylene (BTEX).

Thirteen test runs were performed to evaluate the E-beam system under different operating conditions. Four runs used unspiked groundwater, and nine runs used spiked groundwater. For the run with the best overall performance, the removal efficiencies (RE) observed for TCE and PCE were 98% and 99%, respectively. The REs for other chlorinated compounds ranged from 68% to >97%, and the REs for BTEX ranged from >96% to >98%. The HVEA system achieved the effluent target levels for 1,2-DCE,  $\text{CCl}_4$ , and BTEX. However, effluent target levels were not achieved for TCE, PCE, 1,1,1-TCA, 1,2-DCA, and chloroform. Influent and effluent samples were also collected for bioassay tests. The results from these tests indicate that treatment by the E-beam technology increased groundwater toxicity to fathead minnows but not to water fleas. Treatment system performance in terms of RE was found to be reproducible within 3% to 5%.

Potential sites for applying this technology include Superfund and other hazardous waste sites where groundwater or other liquid wastes are contaminated with organic compounds. Economic data indicate that groundwater remediation costs for the HVEA system used for the SITE demonstration could range from \$5 to \$8 per 1,000 gallons treated, depending on groundwater characteristics and operating conditions. Of these costs, HVEA system direct treatment costs could range from \$4 to \$6 per 1,000 gallons treated.

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## Acronyms, Abbreviations, and Symbols

<	Less than
>	Greater than
µg/L	Micrograms per liter
1,1,1-TCA	1,1,1-Trichloroethane
1,2-DCE	cis-1,2-Dichloroethene
1,2-DCA	1,2-Dichloroethane
ACL	Alternate concentration limit
AEA	Atomic Energy Act
APHA	American Public Health Association
ARAR	Applicable or relevant and appropriate requirement
BTEX	Benzene, toluene, ethylbenzene, and xylene
CAA	Clean Air Act
CaCO <sub>3</sub>	Calcium carbonate
CCl <sub>4</sub>	Carbon tetrachloride
CDEP	Connecticut Department of Environmental Protection
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
Cl <sup>-</sup>	Chloride ions
CO	Carbon monoxide
CO <sub>2</sub>	Carbon dioxide
CWA	Clean Water Act
DOE	U.S. Department of Energy
e <sup>-</sup> <sub>aq</sub>	Aqueous electrons
E-beam	Electron beam
EPA	U.S. Environmental Protection Agency
FTIR	Fourier transform infrared
gpm	Gallons per minute
H <sup>·</sup>	Hydrogen radicals
H <sub>2</sub>	Hydrogen
H <sub>2</sub> O	Water
H <sub>2</sub> O <sub>2</sub>	Hydrogen peroxide
H <sub>3</sub> O <sup>+</sup>	Hydronium ions
HCl	Hydrogen chloride
HVEA	High Voltage Environmental Applications, Inc.
ICT	Insulated core transformer
ITER	Innovative technology evaluation report
krad	Kilorad
kV	Kilovolts
kW	Kilowatts
kWh	Kilowatt hours
LC50	Concentration at which 50% of the organisms died
LDR	Land Disposal Restriction

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## Acronyms, Abbreviations, and Symbols (continued)

mA	Milliamperes
MCL	Maximum contaminant level
MCLG	Maximum contaminant level goal
mg/L	Milligrams per liter
mRem	MilliRems
M <sup>-1</sup> s <sup>-1</sup>	(Molar) <sup>-1</sup> (second) <sup>-1</sup>
N <sub>2</sub> O	Nitrous oxide
NA	Not applicable
NAAQS	National Ambient Air Quality Standards
NESHAP	National Emission Standards for Hazardous Air Pollutants
NOEL	No observable effect level
NPDES	National Pollutant Discharge Elimination System
NRC	Nuclear Regulatory Commission
NSPS	New Source Performance Standards
O&M	Operating and maintenance
O <sub>3</sub>	Ozone
OH <sup>-</sup>	Hydroxide ions
OH·	Hydroxyl radicals
ORD	Office of Research and Development
OSHA	Occupational Safety and Health Administration
OSWER	Office of Solid Waste and Emergency Response
PAH	Polynuclear aromatic hydrocarbon
PCB	Polychlorinated biphenyl
PCE	Tetrachloroethene
POC	Purgeable organic carbon
POTW	Publicly owned treatment works
PPE	Personal protective equipment
ppmv	Parts per million by volume
PRC	PRC Environmental Management, Inc.
QA/QC	Quality assurance and quality control
QAPP	Quality assurance project plan
RCRA	Resource Conservation and Recovery Act
RE	Removal efficiency
RTD	Resistance temperature device
SARA	Superfund Amendments and Reauthorization Act
SCDHEC	South Carolina Department of Health and Environmental Control
SDWA	Safe Drinking Water Act
SITE	Superfund Innovative Technology Evaluation
SRS	Savannah River Site
SVOC	Semivolatile organic compound
TCE	Trichloroethene
TER	Technology evaluation report
TIC	Total inorganic carbon
TOC	Total organic carbon
TOX	Total organic halides
TSCA	Toxic Substances Control Act
UCL	Upper confidence limit
VOC	Volatile organic compound
WQS	Water quality standards

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## Conversion Factors

	<i>To Convert From</i>	<i>To</i>	<i>Multiply By</i>
Length	inch	centimeter	2.54
foot	meter	0.305	
mile	kilometer	1.61	
Area	square foot	square meter	0.0929
acre	square meter	4,047	
Volume	gallon	liter	3.78
cubic foot	cubic meter	0.0283	
Mass	pound	kilogram	0.454
Energy	kilowatt-hour	megajoule	3.60
Power	kilowatt	horsepower	1.34
Temperature	(Fahrenheit - 32)	Celsius	0.556

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## Executive Summary

The high-voltage electron beam (E-beam) technology developed by High Voltage Environmental Applications, Inc. (HVEA), to destroy organic compounds in liquid wastes was demonstrated under the U.S. Environmental Protection Agency's (EPA) Superfund Innovative Technology Evaluation (SITE) program. The E-beam technology demonstration was conducted in September and November 1994 at the U.S. Department of Energy (DOE) Savannah River Site (SRS) in Aiken, SC.

The purpose of this innovative technology evaluation report is to present information that will assist Superfund decision-makers in evaluating the E-beam technology for application to a particular hazardous waste site cleanup. The report provides an introduction to the SITE program and HVEA's E-beam technology (Section 1), evaluates the technology's effectiveness and applications (Section 2), analyzes the economics of using the E-beam system to treat groundwater contaminated with volatile organic compounds (VOC) (Section 3), summarizes the technology's status (Section 4), and presents a list of references (Section 5). Vendor's claims for the technology and a case study of an E-beam technology application performed in Germany are included in Appendices A and B of the report, respectively.

This executive summary briefly describes the E-beam technology, provides an overview of the SITE demonstration of the technology, summarizes the SITE demonstration results, discusses the economics of using the E-beam system to treat groundwater contaminated with VOCs, and discusses the Superfund feasibility evaluation criteria for the E-beam technology.

### Technology Description

The E-beam technology was developed by HVEA to destroy organic compounds in liquid wastes. This technology irradiates water with a beam of high-energy electrons, causing the formation of three primary transient reactive species: aqueous electrons, hydroxyl radicals, and hydrogen radicals. Target organic compounds are either mineralized or broken down into low molecular weight compounds, primarily by these species.

The HVEA E-beam system (model M25W-48S) used for the SITE demonstration is housed in an 8- by 48-foot trailer and is rated for a minimum and maximum flow rate of 15 and 50 gallons per minute (gpm), respectively. The E-beam system includes the following components: a strainer basket, an influent pump, the E-beam unit, a cooling air processor, a blower, and a control console.

After particulates are removed from the influent by the strainer basket, the influent pump transfers contaminated water to the E-beam unit. This unit is made up of the following components: an electron accelerator, a scanner, a contact chamber, and lead shielding. The electron accelerator is capable of generating an accelerating voltage of 500 kilovolts and a maximum beam current of about 42 milliamps, which results in a maximum power rating of 21 kilowatts (kW). The scanner deflects the E-beam, causing the beam to scan the surface of the water as it flows through the contact chamber located beneath the scanner. Lead shielding surrounds the E-beam unit to prevent emission of x-rays. Also, a titanium window separates the scanner from the contact chamber to allow a vacuum to be maintained in the scanner. The E-beam significantly heats the titanium window, which is cooled by air recirculated through the contact chamber. The air is conditioned by a cooling air processor.

The E-beam technology is applicable for treatment of VOCs and semivolatile organic compounds (SVOC) in liquid wastes, including groundwater, wastewater, and landfill leachate.

### Overview of the E-Beam Technology SITE Demonstration

The E-beam technology was demonstrated at the SRS in Aiken, SC, during two different periods totaling 3 weeks in September and November 1994. During the demonstration, the E-beam system treated about 70,000 gallons of M-area groundwater contaminated with VOCs. The principal groundwater contaminants were trichloroethene (TCE) and tetrachloroethene (PCE), which were present at concentrations of about 27,000 and 11,000 micrograms per liter ( $\mu\text{g/L}$ ), respectively. The groundwater also contained low levels (40  $\mu\text{g/L}$ ) of cis-1,2-dichloroethene (1,2-DCE).

During a portion of the E-beam technology demonstration, the groundwater was spiked with 1,2-dichloroethane (1,2-DCA); 1,1,1-trichloroethane (1,1,1-TCA); chloroform; carbon tetrachloride ( $\text{CCl}_4$ ); and aromatic VOCs, including benzene, toluene, ethylbenzene, and xylene (BTEX). These compounds were chosen either because they are relatively difficult to remove using technologies such as the E-beam that employ free radical chemistry (1,2-DCA, 1,1,1-TCA, chloroform, and  $\text{CCl}_4$ ) or because they are common groundwater contaminants (BTEX). The influent concentrations of these spiking compounds ranged from 100 to 500  $\mu\text{g/L}$ . For the SITE demonstration, TCE, PCE, 1,2-DCE, and the VOCs used for spiking the groundwater were considered to be critical VOCs for evaluating the technology.

The primary objectives of the technology demonstration were as follows:

- Determine the removal efficiencies (RE) for critical VOCs in groundwater achieved by the HVEA treatment system at different doses
- Determine whether the treated water meets applicable target levels at a significance level of 0.05 (The effluent target levels were the most stringent limits of the Safe Drinking Water Act maximum contaminant levels [MCL], F039 multisource leachate guidelines, and National Pollutant Discharge Elimination System permit limits)
- Evaluate the change in groundwater acute toxicity after treatment at a significance level of 0.05
- Evaluate the reproducibility of treatment system performance in terms of RE and ability to meet applicable target effluent levels
- Estimate capital and operation and maintenance costs for treating groundwater contaminated with VOCs

The secondary objectives of the technology demonstration were as follows:

- Document the concentrations of potential E-beam treatment byproducts in groundwater
- Document the concentrations of VOCs, ozone (O<sub>3</sub>), and hydrogen chloride (HCl) in cooling air before and after the carbon adsorber in the cooling air processor
- Determine the REs for critical VOCs in groundwater and whether the effluent meets applicable target levels (at a significance level of 0.05) for the HVEA treatment system operated at the maximum or minimum limiting flow rate (50 or 15 gpm, respectively)
- Determine the REs for critical VOCs in groundwater and whether the effluent meets applicable target levels (at a significance level of 0.05) for the HVEA treatment system during treatment of groundwater with moderately high alkalinity (500 milligrams per liter [mg/L] as calcium carbonate [CaCO<sub>3</sub>])
- Document observed operating problems and their resolutions

Thirteen test runs were performed during the demonstration to evaluate the HVEA treatment system according to the project objectives. Of these, four runs used unspiked groundwater, and nine runs used spiked groundwater. Toward the end of the demonstration, HVEA adjusted the influent delivery system to enhance treatment system performance. One of the four unspiked groundwater runs and two of the nine spiked groundwater runs were performed using the improved delivery system.

During the demonstration, groundwater samples were collected at the E-beam system influent and effluent sampling locations,

and cooling air was sampled as it entered and left the cooling air processor. Groundwater samples collected during all runs were analyzed for VOCs and pH, and groundwater samples collected during selected runs were analyzed for SVOCs, haloacetic acids, aldehydes, hydrogen peroxide (effluent only), total inorganic carbon, total organic carbon, purgeable organic carbon (POC), total organic halides (TOX), chloride, alkalinity, and acute toxicity. Cooling air samples collected during nearly all runs were analyzed for VOCs, O<sub>3</sub>, and HCl.

## SITE Demonstration Results

During the SITE demonstration of the E-beam technology, the following key findings were made:

- In general, the highest VOC REs were observed in improved delivery system runs. The highest REs observed for TCE, PCE, and 1,2-DCE were greater than (>) 99%, 99%, and >91%, respectively. The highest REs for chlorinated spiking compounds ranged from 68% to >97%, and those for BTEX ranged from >96% to >98%.
- The effluent met the target levels for 1,2-DCE, CCl<sub>4</sub>, and BTEX at a significance level of 0.05. However, the effluent did not meet the target levels for TCE, PCE, 1,1,1-TCA, 1,2-DCA, and chloroform at a significance level of 0.05.
- In tests performed to evaluate the effluent's acute toxicity to water fleas and fathead minnows, more than 50% of the organisms died. The effluent LC50 values (the percentage effluent in the test water at which more than 50% of the organisms died) ranged from less than (<) 6.2% to 18% for the water fleas and from 8.6% to 54% for the fathead minnows. Treatment by the E-beam technology increased groundwater toxicity for the fathead minnows but not for the water fleas at a significance level of 0.05.
- In general, the VOC REs and effluent VOC concentrations were reproducible when the E-beam system was operated under identical conditions.
- POC, TOX, and chloride results showed significant mineralization of VOCs. However, formation of aldehydes (acetaldehyde, formaldehyde, glyoxal, and methylglyoxal) and haloacetic acids (mono, di, and trichloroacetic acid) indicated that not all VOCs were completely mineralized. The highest REs observed for POC and TOX were >91% and 93%, respectively. E-beam treatment increased chloride levels tenfold. The effluent contained dichloroacetic acid at levels >1,000 µg/L and contained mono and trichloroacetic acids and formaldehyde at levels >100 µg/L. The effluent also contained hydrogen peroxide at levels up to 9.5 mg/L.
- VOCs, O<sub>3</sub>, and HCl were detected in the air entering the cooling air processor and returning to the E-beam unit. For example, VOCs, O<sub>3</sub>, and HCl were present in

the air entering the cooling air processor at levels up to 5.7, 22.8, and 0.3 parts per million by volume (ppmv), respectively. Although initially unexpected, phosgene and carbon monoxide were formed in the cooling air at levels up to 4.9 and 37.6 ppmv, respectively. Minimal reduction of contaminants (<30%) was achieved by the cooling air processor.

- Decreasing the flow rate from 20 to 15 gpm (the minimum flow rate at which the trailer-mounted demonstration unit can be operated) and keeping the beam current the same increased the REs for 1,1,1-TCA, 1,2-DCA, and chloroform 8% to 10% but did not change the REs for other VOCs. During the minimum flow rate run, effluent target levels were met for 1,2-DCE, toluene, ethylbenzene, and xylenes, but were not met for other VOCs.
- Increasing influent alkalinity from 5 to 500 mg/L as CaCO<sub>3</sub> had different effects on VOC REs. The REs for 1,1,1-TCA and chloroform increased 8% and 12%, respectively; the RE for 1,2-DCA decreased 13%; and the REs for other VOCs remained practically the same. During the alkalinity-adjusted run, effluent target levels were met for 1,2-DCE, 1,1,1-TCA, CCl<sub>4</sub>, and BTEX but were not met for other VOCs.
- Several problems were experienced during the SITE demonstration. These problems involved the presence of bubbles in the influent as a result of dissolved gases in the groundwater, malfunctioning of temperature measurement devices in the E-beam system, elevated radiation levels outside the E-beam trailer, leaks in the cooling air processor lines, and loss of vacuum in the E-beam system. Although these problems resulted in significant downtime, they were resolved and the SITE demonstration was completed.

## Economics

Using information obtained from the SITE demonstration, HVEA, and other sources, an economic analysis was per-

formed to examine 12 separate cost categories for two cases in which HVEA E-beam systems were assumed to treat about 315 million gallons of contaminated groundwater at a Superfund site. The two cases were based on groundwater characteristics. In Case 1, the groundwater was assumed to contain unsaturated VOCs, primarily TCE and PCE. In Case 2, the groundwater was assumed to contain saturated VOCs (1,1,1-TCA, 1,2-DCA, chloroform, and CCl<sub>4</sub>) and aromatic VOCs (BTEX). For each case, the costs of using three different E-beam systems (21-kW, 45-kW, and 75-kW) were estimated. The estimated costs for the base-case scenarios (Case 1: 21-kW system operating at 40-gpm flow rate; Case 2: 21-kW system operating at 20-gpm flow rate) are summarized below.

For Case 1, the total costs directly related to the HVEA system are estimated to be \$4.07 per 1,000 gallons treated. Of these, the three largest cost categories are one-time, equipment maintenance, and utility costs, which represent 85.5% of the total. Specifically, one-time, equipment maintenance, and utility costs represent 39.3%, 22.9%, and 23.3% of the total direct costs, respectively.

For Case 2, the total costs directly related to the HVEA system are estimated to be \$5.99 per 1,000 gallons treated. Of these, the three largest cost categories are one-time, equipment maintenance, and utility costs, which represent 80.8% of the total. Specifically, one-time, equipment maintenance, and utility costs represent 19.3%, 30.5%, and 31.0% of the total direct costs, respectively.

In the case study provided in Appendix B, HVEA estimated the total direct costs for treating petroleum refinery wastewater to be \$4.77 per 1,000 gallons treated. HVEA's cost estimate is comparable to the cost estimates presented above.

## Superfund Feasibility Evaluation Criteria for the E-Beam Technology

Table ES-1 briefly discusses the Superfund feasibility evaluation criteria for HVEA's E-beam technology to assist Superfund decision-makers considering the technology for remediation of contaminated groundwater at hazardous waste sites.

**Table ES-1.** Superfund Feasibility Evaluation Criteria for the HVEA E-Beam Technology

Criterion	Discussion
Overall Protection of Human Health and the Environment	<ul style="list-style-type: none"> <li>• The E-beam technology is expected to protect human health by providing treated water that has significantly lower concentrations of organic contaminants.</li> <li>• Overall reduction of human health risk should be evaluated on a site-specific basis because of the potential for formation of harmful treatment byproducts (for example, aldehydes, haloacetic acids, and hydrogen peroxide).</li> <li>• The technology protects the environment by curtailing migration of contaminated groundwater.</li> <li>• Protection of the environment at and beyond the point of treated water discharge should be evaluated based on uses of the receiving water body, concentrations of residual contaminants and treatment byproducts, and the dilution factor.</li> </ul>
Compliance with Applicable or Relevant and Appropriate Requirements (ARAR)	<ul style="list-style-type: none"> <li>• The technology's ability to comply with existing federal, state, or local ARARs (for example, MCLs and F039 multisource leachate guidelines) should be determined on a site-specific basis.</li> <li>• The technology's ability to meet any future chemical-specific ARARs for byproducts should be considered because of the potential for formation of aldehydes and haloacetic acids during treatment.</li> <li>• The technology's ability to meet any state or local requirement such as passing bioassay tests should be considered because of the potential for treatment byproduct formation.</li> <li>• Status may require notification and registration for system operation, depending on the radiation level at the equipment surface.</li> <li>• Design, construction, operation, and maintenance of the system must comply with general radiation exposure regulations; as this and similar technologies become more common, additional and more specific regulations may be enacted.</li> </ul>
Long-Term Effectiveness and Permanence	<ul style="list-style-type: none"> <li>• Human health risk can be reduced to acceptable levels by treating groundwater to 10<sup>-6</sup> cancer risk level; the time needed to achieve cleanup goals depends primarily on contaminated aquifer characteristics.</li> <li>• The technology can effectively control groundwater contaminant migration because it is operated in pump-and-treat mode.</li> <li>• The treatment achieved is permanent because the E-beam is a destruction technology.</li> <li>• Periodic review of treatment system performance is needed because application of the technology to contaminated groundwater at hazardous waste sites is fairly new.</li> </ul>
Reduction of Toxicity, Mobility, or Volume Through Treatment	<ul style="list-style-type: none"> <li>• Although contaminants are destroyed by the technology, the reduction in overall toxicity should be determined on a site-specific basis because of the potential for formation of byproducts (for example, aldehydes, haloacetic acids, and hydrogen peroxide).</li> <li>• The technology reduces the volume and mobility of contaminated groundwater because it is operated in pump-and-treat mode.</li> </ul>
Short-Term Effectiveness	<ul style="list-style-type: none"> <li>• Worker monitoring is required because of the potential for radiation and fugitive emissions exposure; however, no impact on nearby communities is anticipated.</li> <li>• During the pump-and-treat operation, aquifer drawdown may impact vegetation in the treatment zone.</li> </ul>

(Continued)

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**Table ES-1.** (Continued)

Criterion	Discussion
Implementability	<ul style="list-style-type: none"><li>• The technology can be implemented using a mobile, transportable, or permanent E-beam system.</li><li>• State and local permits must be obtained to operate radiation-generating equipment; a National Pollutant Discharge Elimination System permit is routinely needed to implement the technology.</li></ul>
Cost	<ul style="list-style-type: none"><li>• Treatment costs vary significantly depending on contaminant characteristics and levels, cleanup goals, the volume of contaminated water to be treated, and the length of treatment; for a typical groundwater cleanup operation, the treatment cost is expected to be \$4 to \$6 per 1,000 gallons of contaminated water treated.</li></ul>
State Acceptance	<ul style="list-style-type: none"><li>• This criterion is generally addressed in the record of decision; state acceptance of the technology will likely depend on (1) the concentrations of residual organic contaminants and treatment byproducts in treated water and the toxicity of treated water and (2) permitting requirements for operating radiation-generating equipment.</li></ul>
Community Acceptance	<ul style="list-style-type: none"><li>• This criterion is generally addressed in the record of decision after community responses are received during the public comment period; because communities are not expected to be exposed to harmful levels of radiation, noise, or fugitive emissions, the level of community acceptance of the technology is expected to be high.</li></ul>

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## Section 1

### Introduction

This section briefly describes the Superfund Innovative Technology Evaluation (SITE) program and SITE reports; states the purpose of the innovative technology evaluation report (ITER); provides background information on the development of the High Voltage Environmental Applications, Inc. (HVEA), electron beam (E-beam) technology under the SITE program; describes the E-beam technology; identifies wastes to which this technology may be applied; and provides a list of key contacts.

#### 1.1 Brief Description of SITE Program and Reports

This section provides information about the purpose, history, and goals of the SITE program and about the reports used to document SITE demonstration results.

##### 1.1.1 Purpose, History, and Goals of the SITE Program

The primary purpose of the SITE program is to advance the development and demonstration, and thereby establish the commercial availability, of innovative treatment technologies applicable to Superfund and other hazardous waste sites. The SITE program was established by the U.S. Environmental Protection Agency (EPA) Office of Solid Waste and Emergency Response (OSWER) and Office of Research and Development (ORD) in response to the Superfund Amendments and Reauthorization Act of 1986 (SARA), which recognized the need for an alternative or innovative treatment technology research and demonstration program. The SITE program is administered by ORD's National Risk Management Research Laboratory. The overall goal of the SITE program is to carry out a program of research, evaluation, testing, development, and demonstration of alternative or innovative treatment technologies that may be used in response actions to achieve more permanent protection of human health and welfare and the environment.

The SITE program consists of four component programs: (1) the Demonstration program, (2) the Emerging Technology program, (3) the Monitoring and Measurement Technologies program, and (4) the Technology Transfer program. This ITER was prepared under the SITE Demonstration program. The objective of the demonstration program is to provide reliable performance and cost data on innovative technologies so that potential users can assess a given technology's suitability for specific site cleanups. To produce useful and reliable data,

demonstrations are conducted at hazardous waste sites or under conditions that closely simulate actual waste site conditions.

Data collected during a demonstration are used to assess the performance of the technology, the potential need for pretreatment and post-treatment processing of the waste, the types of wastes and media that may be treated by the technology, potential operating problems, and approximate capital and operating costs. Demonstration data can also provide insight into a technology's long-term operating and maintenance (O&M) costs and long-term application risks.

Each SITE demonstration evaluates a technology's performance in treating an individual waste at a particular site. Successful demonstration of a technology at one site does not ensure its success at other sites. Data obtained from the demonstration may require extrapolation to estimate a range of operating conditions over which the technology performs satisfactorily. Also, any extrapolation of demonstration data should be based on other information about the technology, such as information available from case studies.

Implementation of the SITE program is a significant, ongoing effort involving ORD, OSWER, various EPA regions, and private business concerns, including technology developers and parties responsible for site remediation. The technology selection process and the demonstration program together provide objective and carefully controlled testing of field-ready technologies. Innovative technologies chosen for a SITE demonstration must be pilot- or full-scale applications and must offer some advantage over existing technologies; mobile technologies are of particular interest. Each year the SITE program sponsors demonstrations of about 10 technologies.

##### 1.1.2 Documentation of SITE Demonstration Results

The results of each SITE demonstration are reported in four documents: the demonstration bulletin, technology capsule, technology evaluation report (TER), and ITER.

The demonstration bulletin provides a two-page description of the technology and project history, notification that the demonstration was completed, and highlights of demonstration results. The technology capsule provides a brief description of the project and an overview of the demonstration results and con-

clusions. The purpose of the TER is to consolidate all information and records acquired during the demonstration. It contains both a narrative portion and tables and graphs summarizing data. The narrative portion includes discussions of predemonstration, demonstration, and postdemonstration activities as well as any deviations from the demonstration quality assurance project plan (QAPP) during these activities and their impact. The data tables and graphs summarize test results in terms of whether project objectives and applicable or relevant and appropriate requirements (ARAR) were met. The tables also summarize quality assurance and quality control (QA/QC) data and data quality objectives. The TER is not formally published by EPA. Instead, a copy is retained as a reference by the EPA project manager for responding to public inquiries and for recordkeeping purposes. The purpose of the ITER is discussed in Section 1.2.

In addition to the four documents, a videotape is also prepared that displays and discusses the technology, demonstration site, equipment used, tests conducted, results obtained, and key contacts. The videotape is typically about 15 minutes long.

## 1.2 Purpose of the ITER

Information presented in the ITER is intended to assist Superfund decision makers evaluating specific technologies for a particular cleanup situation. Such evaluations typically involve the nine remedial technology feasibility evaluation criteria, which are listed in Table 1-1 along with the sections of the ITER where information related to each criterion is discussed. The ITER represents a critical step in the development and commercialization of a treatment technology. The report discusses the effectiveness and applicability of the technology and analyzes costs associated with its application. The technology's effectiveness is evaluated based on data collected during the SITE demonstration and from other case studies. The applicability of the technology is discussed in terms of waste and site characteristics that could affect technology performance, mate-

**Table 1-1.** Correlation Between Superfund Feasibility Evaluation Criteria and ITER Sections

Evaluation Criterion <sup>a</sup>	ITER Section
Overall protection of human health and the environment	2.2.1 through 2.2.8
Compliance with ARARs	2.2.2 through 2.2.4, 2.2.7, and 2.2.8
Long-term effectiveness and permanence	1.4 and 2.2.5 through 2.2.8
Reduction of toxicity, mobility, or volume through treatment	2.2.1 and 2.2.3 through 2.2.5
Short-term effectiveness	2.2.1 through 2.2.4, 2.2.7, and 2.2.8
Implementability	1.4, 2.2.9, and 2.4
Cost	3.0
State acceptance	1.4, 2.2.2 through 2.2.6, and 2.9
Community acceptance	2.2.1 through 2.2.6 and 2.9

<sup>a</sup>Source: EPA 1988b

rial handling requirements, technology limitations, and other factors.

## 1.3 Background of E-Beam Technology in the SITE Program

The HVEA E-beam technology was accepted into the SITE Emerging Technology program in 1990. The Emerging Technology program promotes technology development by providing funds to developers with bench- or pilot-scale systems in order to support continuing research. In March 1993, the HVEA E-beam system was accepted into the SITE Demonstration program. The system was demonstrated at the Department of Energy (DOE) Savannah River Site (SRS) in Aiken, SC. The demonstration took place during two different periods totaling three weeks in September and November 1994.

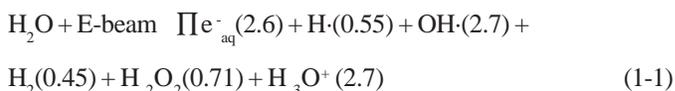
## 1.4 Technology Description

This section includes descriptions of the E-beam technology process chemistry, the HVEA treatment system, and innovative features of the technology.

### 1.4.1 Process Chemistry

HVEA developed the E-beam technology to destroy organic compounds in liquid wastes. This technology irradiates water (H<sub>2</sub>O) with a beam of high-energy electrons, causing the formation of three primary transient reactive species: aqueous electrons (e<sup>-</sup><sub>aq</sub>), hydrogen radicals (H·), and hydroxyl radicals (OH·). Because both strong reducing species (e<sup>-</sup><sub>aq</sub> and H·) and strong oxidizing species (OH·) are formed in approximately equal concentrations, multiple mechanisms or chemical pathways for organic compound destruction are provided by the technology.

As high-energy electrons impact flowing water, the electrons slow down, lose energy, and react with the water to produce the three reactive species responsible for organic compound destruction as well as hydrogen (H<sub>2</sub>), hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>), and hydronium ions (H<sub>3</sub>O<sup>+</sup>). This reaction is described by Equation 1-1 (Cooper and others 1993a, 1993b):



Equation 1-1 indicates the estimated relative concentrations of the reaction products 10<sup>-7</sup> seconds after the E-beam impacts the water. The actual concentrations of reactive species produced depend on the E-beam dose. Dose is the amount of energy from the E-beam that is absorbed by the irradiated water per unit mass. Dose is expressed in kilorads (krad); a krad is defined as 10<sup>5</sup> ergs of absorbed energy per gram of material.

Equation 1-1 indicates that OH· and e<sup>-</sup><sub>aq</sub> account for about 90% of the three primary reactive species formed by the E-beam; therefore, the chemistry of these two species is of primary interest for the E-beam technology. According to published experimental results and computer models that simulate radiation chemistry in water, some compounds are preferentially destroyed by either OH· or e<sup>-</sup><sub>aq</sub>. For example, chlorinated hydrocarbons such as chloroform are dechlorinated by a reaction with e<sup>-</sup><sub>aq</sub>, which initiates a series of subsequent reduction and oxida-

tion reactions that lead to hydrocarbon mineralization (Cooper and others 1993a, 1993b). Other organic compounds undergo a variety of reactions with  $\text{OH}\cdot$ , including addition, hydrogen abstraction, electron transfer, and radical-radical combination. In most cases,  $\text{OH}\cdot$  and  $\text{e}^-_{\text{aq}}$  are initiators of complex reaction sequences that ultimately result in the destruction of organic contaminants. However, in some cases  $\text{OH}\cdot$  and  $\text{e}^-_{\text{aq}}$  can combine to form the hydroxide ion ( $\text{OH}^-$ ).

HVEA has studied byproduct formation during E-beam treatment of water containing trichloroethene (TCE), tetrachloroethene (PCE), toluene, and benzene. One investigation showed that TCE and PCE treatment byproducts include formaldehyde, acetaldehyde, glyoxal, and formic acid. Aldehydes were formed at concentrations that accounted for less than 1% of the total organic carbon (TOC). At low E-beam doses (50 krad), formic acid accounted for up to 10% of the TOC; however, this percentage decreased at higher doses (greater than 200 krad). Chloride ion ( $\text{Cl}^-$ ) mass balances indicated that complete conversion of organic chlorine to  $\text{Cl}^-$  occurred during treatment (Cooper and others 1993b). Other research indicates that haloacetic acids, such as chloroacetic acids, may be formed (Gehring and others 1988).

In another study, HVEA investigated benzene and toluene treatment byproducts. Byproducts identified for benzene include phenol; 1,2-, 1,3-, and 1,4-dihydroxybenzene; formaldehyde; acetaldehyde; and glyoxal. Byproducts identified for toluene include o-cresol, formaldehyde, acetaldehyde, glyoxal, and methylglyoxal. These treatment byproducts accounted for less than 9% of the TOC for benzene and less than 2% of the TOC for toluene at a dose of 200 krad (EPA 1993; Nickelsen and others 1992).

Some compounds commonly present in water may interact with the reactive species formed by the E-beam, thereby exerting an additional demand for reactive species on the system. These compounds are called scavengers, and they can potentially impact system performance. A scavenger is defined as any compound in the water other than the target contaminants that consumes reactive species ( $\text{OH}\cdot$ ,  $\text{e}^-_{\text{aq}}$ , and  $\text{H}\cdot$ ). Carbonate and bicarbonate ions are examples of  $\text{OH}\cdot$  scavengers found in most natural waters and wastewaters. Therefore, alkalinity is an important operating parameter. If the alkalinity is high, influent alkalinity adjustment may be required to shift the carbonate-bicarbonate equilibrium from carbonate (a scavenger) to carbonic acid (not a scavenger). Other scavengers (and the reactive species they consume) include oxygen ( $\text{e}^-_{\text{aq}}$  and  $\text{H}\cdot$ ), nitrate ions ( $\text{e}^-_{\text{aq}}$ ), and methanol ( $\text{OH}\cdot$ ) (Nickelsen and others 1992).

### 1.4.2 HVEA Treatment System

Figure 1-1 shows a schematic of the HVEA E-beam treatment system (model M25W-48S). The E-beam system is housed in an 8- by 48-foot trailer and is rated for a maximum flow rate of 50 gallons per minute (gpm). The E-beam system includes the following components: a strainer basket, an influent pump, the E-beam unit, a cooling air processor, a blower, and a control console (not shown in Figure 1-1). These components are situated in three separate rooms: the pump room, process room, and control room. The pump room contains all ancillary equip-

ment for the E-beam unit for both water and air handling; the process room contains the radiation-shielded E-beam unit itself; and the control room contains the control console where system operating conditions are monitored and adjusted.

During the SITE demonstration, the influent pump transferred contaminated groundwater from an equalization tank to the E-beam unit. A strainer basket located upstream of the influent pump removed particulates larger than 0.045 inch from the influent to prevent them from interfering with operation of the influent pump and other components of the treatment system.

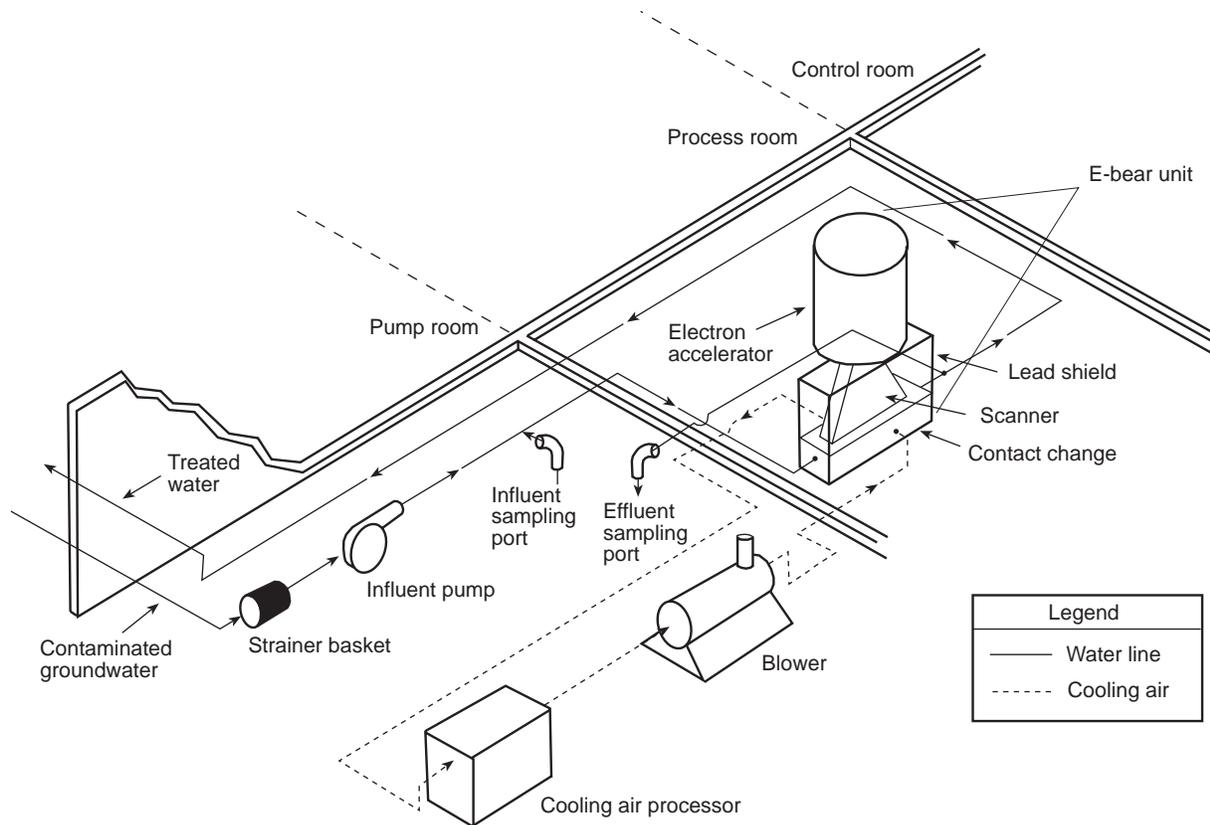
The E-beam unit is made up of the following components: an electron accelerator, a scanner, a contact chamber, and lead shielding. The electron accelerator produces the E-beam. Within the electron accelerator, a stream of electrons is emitted when an electric current (beam current) is passed through a tungsten wire filament. The number of electrons emitted per unit time is proportional to the beam current. The electron stream is accelerated by applying an electric field at a specified voltage and is focused into a beam by collimating devices. The electron accelerator used for the demonstration is capable of generating an accelerating voltage of 500 kilovolts (kV) and a beam current of between 0 and 42 milliamperes (mA). The accelerating voltage determines the energy (speed) of the accelerated electrons, which affects the depth to which the E-beam penetrates the water being treated.

A pyramid-shaped scanner located beneath the electron accelerator deflects the E-beam, causing it to scan the flowing water (the E-beam scanner operation is similar to the scanner operation in a television set). Contaminated groundwater is pumped through the contact chamber, which is located beneath the scanner.

The extent to which VOCs are destroyed depends primarily on the E-beam dose. E-beam dose is a function of several parameters including the density and thickness of the water stream; E-beam power, which is a function of beam current and accelerating voltage; and the time the water is exposed to the E-beam, which depends on the flow rate. Of these parameters, HVEA typically adjusts beam current and flow rate to change the dose. In some cases, the thickness of the water stream may also be modified in order to achieve site-specific performance requirements.

A titanium window separates the scanner from the contact chamber. This window is necessary to maintain a vacuum in the scanner; the vacuum is required to minimize E-beam energy losses. As the E-beam passes through the titanium window, some of the E-beam's energy is absorbed by the window. This energy absorption is manifested in the form of heat. The titanium window is cooled by chilled air. Cooling air exiting the contact chamber flows through a cooling air processor and is returned to the contact chamber by a blower.

During the SITE demonstration, the cooling air processor included an air filter, a carbon adsorber, and an air chiller. The air filter is normally used to remove particulates from the cooling air. However, during the demonstration the air filter was not operated because, according to HVEA, no particulates were



**Figure 1-1.** HVEA E-Beam treatment system schematic.

expected to be present in the cooling air. The carbon adsorber was used to destroy the ozone ( $O_3$ ) that is formed in the cooling air when it is exposed to the E-beam <sup>3</sup>.  $O_3$  must be removed from the cooling air to prevent corrosion in the air lines and the blower. According to HVEA, any volatile organic compounds (VOC) present in the cooling air as a result of incidental VOC volatilization in the contact chamber are destroyed by the E-beam. Vapor phase VOCs that are not destroyed by the E-beam may be removed by the carbon adsorber. Since the completion of the demonstration, HVEA has replaced the carbon adsorber with an  $O_3$  destruction unit. The air chiller was used to cool the air. According to HVEA, under normal operating conditions, cooling air is recirculated in a closed loop through the contact chamber and cooling air processor. When the E-beam system is operated, both the influent pump and the blower run continuously. If either water or cooling air flow stops, the system automatically shuts down.

Lead shielding surrounds the E-beam unit to prevent x-ray emissions. X-rays are formed when the E-beam contacts various internal stainless steel surfaces. As an added safety measure, the process room is inaccessible during system operation.

Resistance temperature devices (RTD) are used to measure the temperature of groundwater before and after treatment. HVEA

uses the change in water temperature to estimate the E-beam dose according to established equations defining the relationship between dose and temperature change (Nickelsen and others 1992). The HVEA E-beam system is configured with two RTDs immediately upstream and two RTDs immediately downstream from the contact chamber. Output from the RTDs is fed into a computer in the control room for processing and recordkeeping.

Contaminated water flow rate is monitored at a point upstream from the contact chamber. Flow rate is manually adjusted in the pump room and is measured by a flow meter.

### 1.4.3 Innovative Features of the Technology

Common methods for treating groundwater contaminated with solvents and other organic compounds include air stripping, steam stripping, carbon adsorption, biological treatment, and chemical oxidation. As regulatory requirements for secondary wastes and treatment byproducts become more stringent and more expensive to comply with, technologies involving free radical chemistry offer a major advantage over other treatment techniques: these technologies destroy contaminants rather than transfer them to another medium, such as activated carbon

or the ambient air. Also, technologies involving free radical chemistry offer faster reaction rates than other technologies, such as some biological treatment processes. According to HVEA, in its system the entire sequence of reactions between organic compounds and reactive species occurs in the area where the E-beam impacts the water and is completed in milliseconds.

The E-beam technology generates strong reducing species (e and H<sup>-</sup>) and strong oxidizing species (OH<sup>·</sup>) simultaneously and in approximately equal concentrations. Because three reactive species are formed, multiple mechanisms or chemical pathways for organic compound destruction are provided. In this way, the E-beam technology differs from other technologies that involve free radical chemistry. Such technologies typically rely on a single organic compound destruction mechanism, usually one involving OH.

The E-beam system does not generate residue, sludge, or spent media that require further processing, handling, or disposal. Target organic compounds are either mineralized or broken down into low molecular weight compounds. When complete destruction occurs at high E-beam doses, reactive species react with contaminants to produce intermediate species that are ultimately oxidized to carbon dioxide (CO<sub>2</sub>), water, and salts. However, at low to intermediate doses, incomplete oxidation results in formation of low molecular weight aldehydes, organic acids, and semivolatile organic compounds (SVOC). Table 1-2 compares several treatment options for water contaminated with VOCs.

## 1.5 Applicable Wastes

Based on SITE demonstration results and results from other case studies, the E-beam technology may be used to treat VOCs and SVOCs in liquids, including groundwater, wastewater, drinking water, and landfill leachate.

## 1.6 Key Contacts

Additional information on the HVEA E-beam system, the SITE program, and the SRS can be obtained from the following sources:

### 1. The HVEA E-Beam System

William Cooper  
High Voltage Environmental Applications, Inc.  
9562 Doral Boulevard  
Miami, FL 33178  
(305) 593-5330

### 2. The SITE Program

Franklin Alvarez  
U.S. Environmental Protection Agency  
National Risk Management Research Laboratory  
Office of Research and Development  
26 W. Martin Luther King Drive  
Cincinnati, OH 45268  
(513) 569-7631

### 3. The SRS

Gene Turner  
U.S. Department of Energy  
Savannah River Field Office  
Aiken, SC 29802  
(803) 725-3648

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

Technology	Advantages	Disadvantages
Air stripping	Effective for high concentrations; mechanically simple; relatively inexpensive	Inefficient for low concentrations; VOCs discharged to air
Steam stripping	Effective for all concentrations	VOCs discharged to air; high energy consumption
Air stripping with carbon adsorption of vapors	Effective for high concentrations	Inefficient for low concentrations; requires disposal or regeneration of spent carbon; relatively expensive
Air stripping with carbon adsorption of vapors and spent carbon regeneration	Effective for high concentration; no carbon disposal costs; product can be reclaimed	Inefficient for low concentrations; high energy consumption
Carbon adsorption	Low air emissions; effective for high concentrations	Inefficient for low concentrations; requires disposal or regeneration of spent carbon; relatively expensive
Biological treatment	Low air emissions; relatively inexpensive disposal required	Inefficient for high concentrations; slow rates of removal; sludge treatment and
Chemical oxidation	No air emissions; no secondary waste; VOCs destroyed such as O <sub>3</sub> and H <sub>2</sub> O <sub>2</sub>	Not cost-effective for high contaminant concentrations; may require chemicals
E-beam system	No secondary waste; multiple mechanisms for VOC destruction; no chemicals (such as O <sub>3</sub> or H <sub>2</sub> O <sub>2</sub> ) required	High electrical energy consumption; not cost-effective for high contaminant concentrations; relatively expensive

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## Section 2

### Technology Effectiveness and Applications Analysis

This section addresses the effectiveness and applicability of the E-beam technology for treating water contaminated with organic compounds. Vendor claims regarding the effectiveness and applicability of the E-beam technology are included in Appendix A. Because the SITE demonstration provided extensive data on the HVEA E-beam system, this evaluation of the technology's effectiveness and potential applicability to contaminated sites is based mainly on the demonstration results, which are presented in this section. However, the demonstration results are supplemented by data from other applications of the E-beam technology, including a study conducted in Germany with the HVEA system used for the SITE demonstration and other studies conducted by HVEA under the SITE Emerging Technology program using synthetic wastes. This section summarizes the additional performance data. More details on the German study are presented in Appendix B.

This section also provides an overview of the SITE demonstration and discusses the following topics regarding the applicability of the E-beam technology: factors affecting technology performance, site characteristics and support requirements, material handling requirements, technology limitations, potential regulatory requirements, and state and community acceptance.

#### 2.1 Overview of E-Beam Technology SITE Demonstration

The E-beam technology demonstration was conducted at the DOE SRS in Aiken, SC, during two different periods totaling three weeks in September and November 1994. During the demonstration, about 70,000 gallons of M-area groundwater contaminated with VOCs was treated. The principal groundwater contaminants were TCE and PCE, which were present at concentrations of about 27,000 and 11,000 micrograms per liter ( $\mu\text{g/L}$ ), respectively. The groundwater also contained low levels (40  $\mu\text{g/L}$ ) of cis-1,2-dichloroethene (1,2-DCE). Before treatment, groundwater was pumped from a recovery well into a 7,500-gallon equalization tank to minimize any variability in influent characteristics. Treated groundwater was stored in a 10,000-gallon tank before being pumped to an on-site air stripper, which was treating contaminated groundwater from the demonstration area.

During a portion of the E-beam technology demonstration, the groundwater was spiked with VOCs not present in the M-area groundwater. The resultant influent concentrations ranged from about 100 to 500  $\mu\text{g/L}$  for the following spiking compounds: 1,1,1-trichloroethane (1,1,1-TCA); 1,2-dichloroethane (1,2-

DCA); chloroform; carbon tetrachloride ( $\text{CCl}_4$ ); and benzene, toluene, ethylbenzene, and p-xylene (BTEX). Saturated VOCs (1,1,1-TCA, 1,2-DCA, chloroform, and  $\text{CCl}_4$ ) were chosen as spiking compounds because they are relatively difficult to destroy using technologies such as the E-beam technology that involve free radical chemistry. BTEX were chosen because they are common groundwater contaminants at Superfund and other contaminated sites.

For the SITE technology demonstration, TCE, PCE, 1,2-DCE, and the spiking compounds were considered to be critical VOCs.

The following sections describe the project objectives for the E-beam technology demonstration, the demonstration approach that was followed to meet the project objectives, and the sampling and analytical procedures that were used.

#### 2.1.1 Project Objectives

Project objectives were developed based on EPA's understanding of the E-beam technology and the HVEA system, SITE Demonstration program goals, and input from the technology developer. The E-beam technology demonstration had both primary and secondary objectives. Primary objectives were considered to be critical for the technology evaluation. Secondary objectives involved collection of additional data that were useful, but not critical, to the technology evaluation. The technology demonstration objectives listed below are numbered and are designated by the letters "P" for primary and "S" for secondary.

The primary objectives of the technology demonstration were as follows:

- P1 Determine the removal efficiencies (RE) for critical VOCs in groundwater achieved by the HVEA treatment system at different doses
- P2 Determine whether the treated water meets the applicable target levels listed in Table 2-1 at a significance level of 0.05
- P3 Evaluate the change in groundwater acute toxicity after treatment at a significance level of 0.05
- P4 Evaluate the reproducibility of treatment system performance in terms of RE and ability to meet applicable target effluent levels

**Table 2-1. System Effluent Target Levels<sup>a</sup>**

VOC	SDWA Levels <sup>b</sup> (µg/L)	F039 Levels <sup>c</sup> (µg/L)	NPDES Discharge Limits <sup>d</sup> (µg/L)
TCE	[5]	54	5
PCE	[5]	56	5
1,2-DCE	70	[54]	NA <sup>e</sup>
1,1,1-TCA	200	[54]	NA
1,2-DCA	[5]	59	NA
Chloroform	100	[46]	NA
CCl <sub>4</sub>	[5]	57	NA
Benzene	[5]	140	NA
Toluene	1,000	[80]	NA
Ethylbenzene	700	[57]	NA
Xylenes <sup>f</sup>	10,000	[320]	NA

<sup>a</sup> The most stringent level for each VOC was considered to be the target level for the SITE technology demonstration. The most stringent levels are identified in brackets.

<sup>b</sup> Concentration levels established by the 1986 Safe Drinking Water Act (SDWA)

<sup>c</sup> Concentration levels established by guidelines for multisource leachate (liquids that have percolated through land-disposed wastes: hazardous waste code F039) (Code of Federal Regulations Title 40 [40 CFR] Part 268 1992)

<sup>d</sup> National Pollutant Discharge Elimination System (NPDES) permitted daily average concentrations in discharges from the SRS M-area

<sup>e</sup> NA = Not available; no discharge limits for these VOCs are included in the M-area NPDES permit

<sup>f</sup> Although p-xylene was used to spike the groundwater during the technology demonstration, the effluent target level is for total xylenes (o, m, and p isomers). Therefore, total xylene results are presented in this report.

P5 Estimate capital and O&M costs for treating groundwater contaminated with VOCs

S5 Document observed operating problems and their resolutions

The secondary objectives of the technology demonstration were as follows:

- S1 Document the concentrations of potential E-beam treatment byproducts in groundwater
- S2 Document the concentrations of VOCs, O<sub>3</sub>, and hydrogen chloride (HCl) in cooling air before and after the carbon adsorber
- S3 Determine the REs for critical VOCs in groundwater and whether the effluent meets applicable target levels (at a significance level of 0.05) for the HVEA treatment system operated at the maximum or minimum limiting flow rate (50 or 15 gpm, respectively)
- S4 Determine the REs for critical VOCs in groundwater and whether the effluent meets applicable target levels (at a significance level of 0.05) for the HVEA treatment system during treatment of groundwater with moderately high alkalinity (500 milligrams per liter [mg/L] as calcium carbonate [CaCO<sub>3</sub>])

### 2.1.2 Demonstration Approach

The technology demonstration was conducted in five phases. Thirteen test runs were performed during these five phases to evaluate the performance of the HVEA treatment system. During each run, influent characteristics or operating parameters were changed to collect information to meet project objectives. The demonstration approach is summarized in Table 2-2 and described below.

During Phase 1, beam current, one of the principal operating parameters, was varied to observe how E-beam dose affects treatment system performance at a constant flow rate of 40 gpm. Three runs were conducted during Phase 1 using unspiked groundwater.

During Phase 2, spiked groundwater was used to collect information on treatment system performance in destroying VOCs other than those present in the M-area groundwater. Two runs were performed using different beam currents and a constant flow rate of 40 gpm. Phase 2 also included a zero dose run to identify reductions in VOC concentrations resulting from mecha-

**Table 2-2.** Demonstration Approach for the HVEA E-Beam Technology

Run No.	Groundwater	Beam Current (mA)	Alkalinity (as CaCO <sub>3</sub> )	Flow Rate (gpm)	Project Objectives
<i>Phase 1: Unspiked Groundwater Tests</i>					
1	Unspiked	7	U <sup>a</sup>	40	P1, P2, S2, and S5
2	Unspiked	14	U	40	P1, P2, S2, and S5
3	Unspiked	42	U	40	P1, P2, P5, S2, and S5
<i>Phase 2: Spiked Groundwater Tests</i>					
4	Spiked	17	U	40	P1, P2, P3, S2, and S5
5	Spiked	21	U	40	P1, P2, P3, S2, and S5
6	Spiked	0.5	U	40	P1, P2, S2, and S5
<i>Phase 3: Reproducibility Tests</i>					
7	Spiked	42	U	20	P1, P2, P3, P4, S2, and S5
8	Spiked	42	U	20	P1, P2, P3, P4, S4, S2, and S5
9	Spiked	42	U	20	P1, P2, P3, P4, S1, S2, and S5
<i>Phase 4: Flow Rate Test</i>					
10	Spiked	42	U	15	P1, P2, S2, S3, and S5
<i>Phase 5: Improved Delivery System Tests</i>					
11	Unspiked	42	U	20	P1, P2, P3, S1, and S5
12	Spiked	42	U	20	P1, P2, P3, S1, and S5
13	Spiked	42	500 mg/L	20	P1, P2, P3, P5, S4, and S5

<sup>a</sup>U = unadjusted (about 5 mg/L)

nisms other than VOC destruction by the E-beam (for example, volatilization).

Phase 3 tested the reproducibility of HVEA system performance for treating spiked groundwater. Three runs were performed under identical operating conditions, which were determined based on preliminary treatment results from Phases 1 and 2.

Phase 4 consisted of one run whose purpose was to evaluate HVEA system performance at the minimum limiting flow rate (15 gpm) of the system used for the demonstration. The minimum flow rate was chosen because preliminary results from Phases 1, 2, and 3 indicated that the HVEA system did not meet effluent target levels at higher flow rates and using maximum beam current.

Phase 5 began four weeks after Phase 4 was completed. The interval between Phases 4 and 5 gave HVEA time to evaluate preliminary results from Phases 1 through 4 and conduct additional studies on spiked and unspiked groundwater from M-area recovery well RWM-1 to determine Phase 5 operating conditions. Based on information from the test runs and additional studies, HVEA adjusted the influent delivery system to improve overall treatment system performance. This was accomplished by increasing the dose without increasing the beam current or lowering the flow rate.

To evaluate the effect of the improved delivery system in Phase 5, HVEA selected the same flow rate (20 gpm) and beam current (42 mA) as were used in the reproducibility runs. Of the

three Phase 5 runs, one used unspiked groundwater; one used spiked groundwater; and one used alkalinity-adjusted, spiked groundwater. Alkalinity was adjusted in one run because carbonate and bicarbonate ions scavenge OH<sup>-</sup>, potentially affecting VOC RE. During this run, a sodium bicarbonate solution was added to the influent to adjust alkalinity from less than (<) 5 mg/L to about 500 mg/L as CaCO<sub>3</sub>, which is within the typical range of groundwater alkalinity levels in the U.S.

### 2.1.3 Sampling and Analytical Procedures

During the demonstration, groundwater samples were collected at E-beam influent and effluent sampling locations, and cooling air samples were collected before and after the carbon adsorber.

Each test run lasted about three hours, and four groundwater sampling events were conducted at 45-minute intervals during each test run. Groundwater samples for VOC analysis were collected during each sampling event so that average influent and effluent concentrations could be calculated based on four replicate data points. Groundwater samples for other analyses were typically collected during two of the sampling events.

Groundwater samples were collected during all runs for VOC and pH analyses. Groundwater samples were collected during selected runs for analysis for SVOCs, haloacetic acids, aldehydes, H<sub>2</sub>O<sub>2</sub> (effluent only), TOC, purgeable organic carbon (POC), total inorganic carbon (TIC), total organic halides (TOX), chloride, alkalinity, and acute toxicity. Influent and effluent samples were analyzed using EPA-approved methods such as those found in Test Methods for Evaluating Solid Waste and Methods for Chemical Analysis of Water and Wastes (EPA

1990 and EPA 1983, respectively) or other standard or published methods (APHA 1992; Boltz and Howell 1979).

During Runs 1 through 10, cooling air samples were collected and analyzed for VOCs, O<sub>3</sub>, and HCl using an on-site Fourier transform infrared (FTIR) interferometer. Cooling air samples were not collected during Runs 11, 12, and 13 (Phase 5) because of high costs associated with maintaining the FTIR interferometer in the field during the 4-week interval between Phases 4 and 5. This approach did not affect project objectives because cooling air was analyzed only for noncritical parameters to meet a secondary objective. On-site measurements of flow rate, beam current, and power consumption were recorded during all runs.

In all cases, EPA-approved sampling, analytical, and QA/QC procedures were followed to obtain reliable data. These procedures are described in the QAPP written specifically for the E-beam technology demonstration (PRC 1994) and are summarized in the TER, which is available from the EPA project manager (see Section 1.6).

## 2.2 SITE Demonstration Results

This section summarizes the results from the E-beam technology SITE demonstration for both critical and noncritical parameters and discusses the effectiveness of the E-beam technology in treating groundwater contaminated with VOCs. Table 2-3 presents the range of critical VOC concentrations in the influent to the E-beam unit for unspiked and spiked test runs.

Performance data collected during the demonstration are presented in this section in tabular and graphic form. In most cases, the reported data are based on average values from replicate sampling events. In some cases, samples were analyzed at two dilutions; when this occurred, the results for the lower dilution were used to calculate the average value. For influent samples with analyte concentrations at nondetectable levels, the detection limit was used as the estimated concentration when the average value was calculated. For effluent samples with analyte

concentrations at nondetectable levels, one-half the detection limit was used as the estimated concentration when the average value was calculated. If all replicate effluent samples had nondetectable concentrations of any analyte, the detection limit was used as the average value, the RE was reported as a greater-than (>) value, and the 95% upper confidence limit (UCL) was not calculated.

After the demonstration data were reviewed, it was determined that more than one approach should be used to handle nondetectable influent and effluent values to calculate averages. For influent nondetectable values, the detection limit was used in place of the nondetectable value. Although this approach deviates from typical environmental engineering practice, which is to use one-half the detection limit for nondetectable values, using the full detection limit is more appropriate in this case because (1) there is less variability in influent concentrations than in effluent concentrations and (2) 50% or more of the influent samples had VOC concentrations above the detection limit. For example, in about 50% of the influent samples (28 out of 52 samples collected in 13 runs), the concentration of 1,2-DCE was reported as nondetectable (the detection limit is 40 µg/L); in the remaining samples, this compound was present at concentrations of up to 50 µg/L. For effluent nondetectable values, however, using the typical practice for handling nondetectable values is more appropriate. This is the case because the effluent data have greater variability as a result of E-beam treatment and because the data are more limited (the effluent data from all the runs cannot be pooled together because the operating conditions generally varied from run to run).

Analytical results presented for cooling air samples are average concentrations measured before the carbon adsorber and after the carbon adsorber. The average values were calculated based on two sampling events about 45 minutes apart. Each sampling event included two scans, and each scan consisted of about 200 signals representative of analyte concentrations.

The remainder of this section is organized according to the project objectives stated in Section 2.1.1. Specifically, Sections 2.2.1 through 2.2.4 address the primary objectives except for objective P5 (estimation of costs), which is discussed in Section 3. Sections 2.2.5 through 2.2.9 address secondary objectives.

### 2.2.1 VOC REs at Different Doses

Table 2-4 summarizes the VOC REs for unspiked and spiked groundwater runs conducted at different E-beam doses. As discussed in Section 2.4.2, HVEA controls dose by adjusting the beam current, the flow rate, and the thickness of the water stream impacted by the E-beam. In HVEA's system, the beam current is controlled directly from the control panel, the flow rate is controlled by manually adjusting the influent pump, and the thickness of the water stream is controlled by the influent delivery system.

During Phase 1, unspiked groundwater was treated at three different doses. For these runs, the dose was varied by changing the beam current, while the flow rate remained constant. As shown in Table 2-4, REs for TCE, PCE, and 1,2-DCE increased

**Table 2-3.** VOC Concentrations in Unspiked and Spiked Groundwater Influent

VOC	Unspiked Groundwater (µg/L)	Spiked Groundwater (µg/L)
TCE	25,000 to 30,000	25,000 to 37,000
PCE	9,200 to 12,250	9,200 to 14,000
1,2-DCE	40 to 43	<40 to 45
1,1,1-TCA	ND <sup>a</sup>	200 to 500
1,2-DCA	ND	210 to 840
Chloroform	ND	240 to 650
CCl <sub>4</sub>	ND	150 to 400
Benzene	ND	220 to 550
Toluene	ND	170 to 360
Ethylbenzene	ND	95 to 250
Xylenes	ND	85 to 200

<sup>a</sup> ND = Not detected

**Table 2-4.** VOC REs

VOC	VOC RE (%) <sup>a</sup>							
	Phase 1			Phase 2		Phase 3	Phase 5	
	Run 1 BC <sup>b</sup> = 7 FR <sup>c</sup> = 40	Run 2 BC = 14 FR = 40	Run 3 BC = 42 FR = 40	Run 4 BC = 17 FR = 40	Run 5 BC = 21 FR = 40	Runs 7, 8, and 9 BC = 42 FR = 20	Run 11 BC = 42 FR = 20	Run 12 BC = 42 FR = 20
TCE	73	92	97	91	93	94 to 96	>99	98
PCE	50	83	96	76	87	95	99	99
1,2-DCE	>53	>83	>90	NA <sup>d</sup>	>85	85 to >91	>91	>88
1,1,1-TCA				17	33	61 to 62		73
1,2-DCA				25	30	60 to 65		70
Chloroform				24	28	56 to 57		68
CCl <sub>4</sub>				46	73	89 to 91		>97
Benzene				96	98	93 to 97		>98
Toluene				>97	>96	95 to 96		>98
Ethylbenzene				>93	>94	95 to 97		>97
Xylenes				>91	>93	>93 to 95		>96

<sup>a</sup> REs for the zero dose run (Run 6), the flow rate run (Run 10) and alkalinity-adjusted run (Run 13) are discussed in Sections 2.2.6, 2.2.7, and 2.2.8, respectively.

<sup>b</sup> BC = beam current (mA)

<sup>c</sup> FR = flow rate (gpm)

<sup>d</sup> NA = not applicable (because 1,2-DCE was not detected in any sample collected during Run 4)

when the beam current was increased. A similar effect was observed during Phase 2, which involved spiked groundwater. The dose was increased further during Phase 3 by lowering the flow rate from 40 to 20 gpm and increasing the beam current to the maximum level (42 mA); corresponding increases in REs were observed, particularly for spiked compounds. Finally, for Phase 5, HVEA adjusted the delivery system, and these adjustments increased the dose although the beam current and flow rate were set at the same levels as were used for Phase 3. HVEA considers information regarding the delivery system to be proprietary. Phase 5 results indicate that the delivery system adjustments increased REs for most VOCs. In fact, the operating conditions during Phase 5 generally yielded the highest REs observed during the demonstration.

Table 2-4 also shows that in all spiked groundwater runs, REs for TCE, PCE, 1,2-DCE, and BTEX were much higher than REs for 1,1,1-TCA, 1,2-DCA, chloroform, and CCl<sub>4</sub>. The difference in system performance for these two groups of VOCs is due to the presence of double bonds between carbon atoms in TCE, PCE, and 1,2-DCE and aromatic bonds between carbon atoms in BTEX, which makes these compounds more amenable to oxidation by free radicals generated by the E-beam. Furthermore, regarding the saturated chlorinated compounds, REs for CCl<sub>4</sub> were consistently higher than REs for 1,1,1-TCA, 1,2-DCA, and chloroform. This effect may be a consequence of the relatively large number of chlorine atoms in CCl<sub>4</sub>. The four chlorine atoms facilitate CCl<sub>4</sub> destabilization and are good “leaving groups” in the presence of free radicals; therefore,

CCl<sub>4</sub> may be easier to oxidize than similar compounds with fewer chlorine atoms.

## 2.2.2 Compliance with Applicable Effluent Target Levels

Applicable effluent target levels are summarized in Table 2-1. Compliance with these target levels was evaluated by comparing the 95% UCL of the effluent VOC concentrations during Runs 11 and 12 with the most stringent effluent target levels (see Table 2-5). A 95% UCL could not be calculated for some VOCs because the effluent concentration was below the detection limit. However, in all such cases, the detection limit was below the effluent target level.

Table 2-5 shows that the HVEA treatment system achieved the effluent target levels for 1,2-DCE, CCl<sub>4</sub>, and BTEX. Effluent target levels were not achieved for 1,1,1-TCA, 1,2-DCA, and chloroform when these compounds were present at spiked levels (230, 440, and 316 µg/L for 1,1,1-TCA, 1,2-DCA, and chloroform, respectively). Effluent target levels were also not achieved for TCE and PCE when they were present at existing levels in M-area groundwater (27,000 and 11,000 µg/L for TCE and PCE, respectively).

Only effluent concentrations for Runs 11 and 12 are shown in Table 2-5 because the HVEA treatment system displayed the best overall performance in terms of REs during these runs. However, effluent target levels were met for toluene, ethylbenzene, and xylenes during the reproducibility runs (see Figure 2-4 in Section 2.2.4).

**Table 2-5.** Compliance with Applicable Effluent Target Levels

VOC	Effluent Target Level (µg/L)	95% UCL for Effluent Concentration (µg/L)	
		Run 11	Run 12
TCE	5	190	1,100
PCE	5	100	250
1,2-DCE <sup>a</sup>	54	4U <sup>b</sup>	4U
1,1,1-TCA	54	NA <sup>c</sup>	83
1,2-DCA	5	NA	180
Chloroform	46	NA	130
CCl <sub>4</sub>	5	NA	4U
Benzene	5	NA	4U
Toluene	80	NA	4U
Ethylbenzene	57	NA	4U
Xylenes <sup>a</sup>	320	NA	4U

<sup>a</sup> Influent concentrations for 1,2-DCE and xylenes were below the effluent target levels (see Table 2-3)

<sup>b</sup> U = analyte not detected in the treatment system effluent at or above the value shown

<sup>c</sup> NA = not applicable (because the analyte was not detected in the treatment system influent)

### 2.2.3 Effect of Treatment on Groundwater Toxicity

During Phases 2, 3, and 5, bioassay tests were performed to evaluate the change in acute toxicity of the groundwater after treatment by the HVEA system. Two common freshwater test organisms, a water flea (*Ceriodaphnia dubia*) and a fathead minnow (*Pimephales promelas*), were used in the bioassay tests. Toxicity was measured as the concentration at which 50% of the organisms died (LC50) and was expressed as the percentage of influent or effluent in the test water. One influent sample and one effluent sample from each run were tested.

Table 2-6 presents the bioassay test results for influent and effluent samples from Runs 4 and 5; the reproducibility runs; and Runs 11, 12, and 13 (Phase 5). These results show that some influent samples and all effluent samples were acutely toxic to both test organisms. The change in groundwater toxicity resulting from treatment by the HVEA system was evaluated statistically using data from the reproducibility runs. Specifically, the mean difference between the influent and effluent LC50 values was compared to zero using a two-tailed paired Student's t-test. The null hypothesis was that the mean difference between influent and effluent LC50 values equaled zero at a 0.05 significance level. The critical t value at this significance level with two degrees of freedom is 4.303. The calculated t values for the water flea and fathead minnow were 1.47 and 31.6, respectively. These results indicate that treatment by the E-beam technology statistically increased groundwater toxicity for the fathead minnow but not for the water flea.

As noted above, influent and effluent samples for bioassay testing were collected during Runs 11, 12, and 13, which were conducted after HVEA adjusted the influent delivery system to increase the dose. Although toxicity data for these runs cannot be statistically evaluated because the influent characteristics

**Table 2-6.** Acute Toxicity Data

Run <sup>a</sup>	LC50 (%)			
	<i>Ceriodaphnia dubia</i>		<i>Pimephales promelas</i>	
	Influent	Effluent	Influent	Effluent
4	35	8.8	72	8.6
5	68	18	100	15
7 <sup>b</sup>	>100	17	>100	8.8
8 <sup>b</sup>	17	<6.2	>100	16
9 <sup>b</sup>	16	<6.2	>100	18
11	37	<6.2	89	8.8
12	37	<6.2	83	9.8
13	>100	12	>100	54

<sup>a</sup> Runs 7, 8, and 9 were the reproducibility runs (Phase 3). Runs 11, 12, and 13 were conducted after HVEA adjusted the influent delivery system (Phase 5). Run 11 was conducted with unspiked groundwater, Run 12 was conducted with spiked groundwater, and Run 13 was conducted with alkalinity-adjusted, spiked groundwater.

<sup>b</sup> Using data from the three reproducibility runs, a two-tailed paired Student's t-test with a 0.05 significance level was performed for each organism. The null hypothesis was that the mean difference between the influent and effluent LC50 values equaled zero. For LC50 values shown as >100 and <6.2, 100 and 6.2 were used to calculate the mean difference. The calculated t values were 1.47 and 31.6 for *Ceriodaphnia dubia* and *Pimephales promelas*, respectively.

were different, the data suggest that the difference between the influent and effluent LC50 values decreased for fathead minnows. For fathead minnows, the increase in toxicity resulting from E-beam treatment (the difference between influent and effluent LC50 values) in Run 12 was less than the average increase in toxicity in Runs 8 and 9. This fact may be related to the higher VOC REs and reduced byproduct formation achieved when the dose was increased by adjusting the influent delivery system for Run 12. However, for water fleas, the LC50 data could not be compared because the increases in LC50 values resulting from E-beam treatment were not observed to be absolute values (that is, all observations were > values).

Published reports indicate that H<sub>2</sub>O<sub>2</sub> generated by technologies involving free radicals may contribute to effluent toxicity (EPA 1993). The average effluent H<sub>2</sub>O<sub>2</sub> concentration was 8.0 mg/L during the reproducibility runs and 8.9 mg/L during Phase 5 runs (see Section 2.2.5 for detailed H<sub>2</sub>O<sub>2</sub> data). Literature data indicate that the LC50 for H<sub>2</sub>O<sub>2</sub> for the water flea is about 2 mg/L. Because no statistically significant increase in acute toxicity for the water flea was observed during E-beam treatment despite high levels of H<sub>2</sub>O<sub>2</sub> in the effluent, it is likely that any increase in toxicity associated with H<sub>2</sub>O<sub>2</sub> was counteracted by a decrease in toxicity resulting from VOC removal. The fathead minnow is less sensitive to H<sub>2</sub>O<sub>2</sub> than the water flea. The Connecticut Department of Environmental Protection (CDEP) reported an LC50 value of 18.2 mg/L of H<sub>2</sub>O<sub>2</sub> with 95% confidence limits of 10 and 25 mg/L for the fathead minnow (CDEP 1993). Therefore, the statistically significant increase in acute toxicity for the fathead minnow during E-beam treatment is more likely to have been caused by residual VOCs or treatment byproducts than by H<sub>2</sub>O<sub>2</sub>.

## 2.2.4 Reproducibility of Treatment System Performance

VOC REs in the Phase 3 reproducibility runs (Runs 7, 8, and 9) are shown in Figure 2-1. This figure shows that the REs for all VOCs were reproducible. The maximum difference among REs for the three runs occurred for 1,2-DCA, for which REs ranged from 60% to 65%, and 1,2-DCE, for which REs ranged from 85% to >91%. However, for other VOCs, the REs differed by only 2% to 3% for the three runs. The ranges of VOC REs during the Phase 3 reproducibility runs are shown in Table 2-4.

Figures 2-2, 2-3, and 2-4 show the average Phase 3 influent and effluent concentrations for unsaturated VOCs (TCE, PCE, and 1,2-DCE), saturated VOCs (1,1,1-TCA, 1,2-DCA, chloroform, and CCl<sub>4</sub>), and BTEX, respectively. During the reproducibility runs, target effluent levels were met for toluene, ethylbenzene, and xylenes at a 0.05 significance level; target effluent levels for other critical VOCs were not met.

## 2.2.5 Treatment Byproducts and Additional Parameters

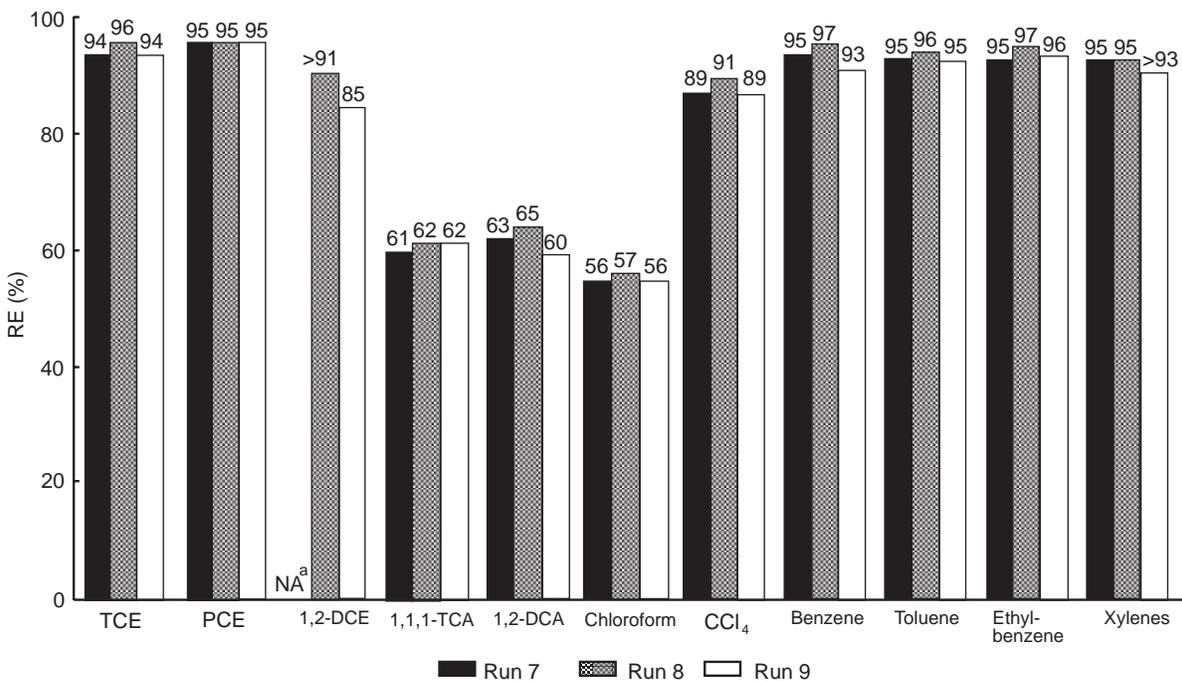
During Runs 8, 9, 11, and 12, samples were collected for analysis for VOCs and several additional parameters selected to evaluate formation of treatment byproducts. These additional parameters included SVOCs, haloacetic acids, aldehydes, TOC, POC, TIC, TOX, and chloride. The analytical results for the additional parameters are presented and discussed below.

Samples collected during Runs 8 and 9 were analyzed for SVOCs. Except for butyl benzyl phthalate, no SVOCs were

detected in the influent or effluent samples. The average butyl benzyl phthalate concentrations in the influent and effluent were 21 and 5 µg/L, respectively. These results showed that no SVOCs were created during treatment; therefore, samples collected during subsequent runs, which were conducted at equal or greater doses, were not analyzed for SVOCs.

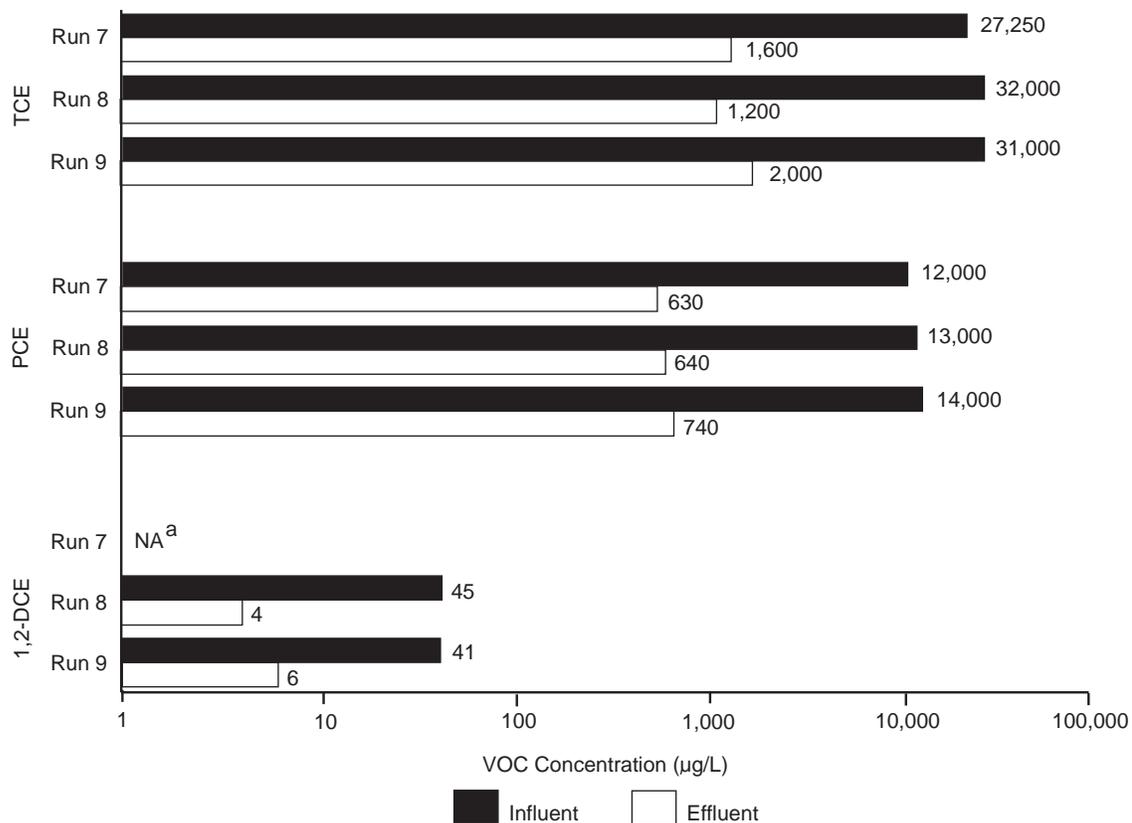
Several research studies have indicated that haloacetic acids and aldehydes may be formed during E-beam treatment of water containing chlorinated and aromatic VOCs (see Section 1.4.1). The sample analytical results for haloacetic acids and aldehydes are provided in Table 2-7. Three chloroacetic acids (mono-, di-, and tri-chloroacetic acids) and four aldehydes (acetaldehyde, formaldehyde, glyoxal, and m-glyoxal) were formed during treatment. Of these compounds, the mono- and tri-chloroacetic acids and formaldehyde were detected in the effluent at levels between 80 and 400 µg/L, and dichloroacetic acid was present at concentrations between 1,250 and 2,000 µg/L.

The effluent concentrations of all chloroacetic acids and aldehydes were lower during Runs 11 and 12 than during Runs 8 and 9. Research evidence indicates that byproducts such as chloroacetic acids and aldehydes are results of incomplete VOC oxidation; therefore, these compounds are more likely to be present at low to intermediate doses. Thus, the lower byproduct concentrations measured during Runs 11 and 12 can be attributed to the greater dose delivered during these runs as a result of the improved delivery system.



Note: NA<sup>a</sup> 1,2-DCE was not detected in Run 7

Figure 2-1. VOC REs in reproducibility runs.



Note: NA<sup>a</sup> 1,2-DCE was not detected in Run 7

**Figure 2-2.** Average influent and effluent levels for TCE, PCE, and 1,2-DCE during the reproducibility runs.

The other byproduct formed during treatment was H<sub>2</sub>O<sub>2</sub>. Effluent samples collected during Runs 4, 5, 7, 8, 9, 11, 12, and 13 were analyzed for H<sub>2</sub>O<sub>2</sub>. The results from these analyses are summarized in Table 2-8. The formation of H<sub>2</sub>O<sub>2</sub> was consistent with Equation 1-1, which shows that H<sub>2</sub>O<sub>2</sub> is formed when the E-beam reacts with water. As with the reactive species, the concentration of H<sub>2</sub>O<sub>2</sub> formed depends on the dose. The direct relationship between dose and H<sub>2</sub>O<sub>2</sub> formation can be seen in Table 2-8. During the technology demonstration, the dose was gradually increased during each successive phase by changing various operating parameters. The effluent H<sub>2</sub>O<sub>2</sub> concentrations generally paralleled the increasing dose, rising from 2.3 mg/L during Run 5 to 9.5 mg/L during Runs 11 and 12. Although the operating conditions during Runs 11, 12, and 13 were identical, the effluent H<sub>2</sub>O<sub>2</sub> concentration during Run 13 (the alkalinity-adjusted run) was lower because of OH<sup>-</sup> scavenging by bicarbonate ions, which may have resulted in decreased formation of H<sub>2</sub>O<sub>2</sub> from OH<sup>-</sup> combination. Another possibility is that enhanced decomposition of H<sub>2</sub>O<sub>2</sub> occurred at the higher pH associated with high alkalinity.

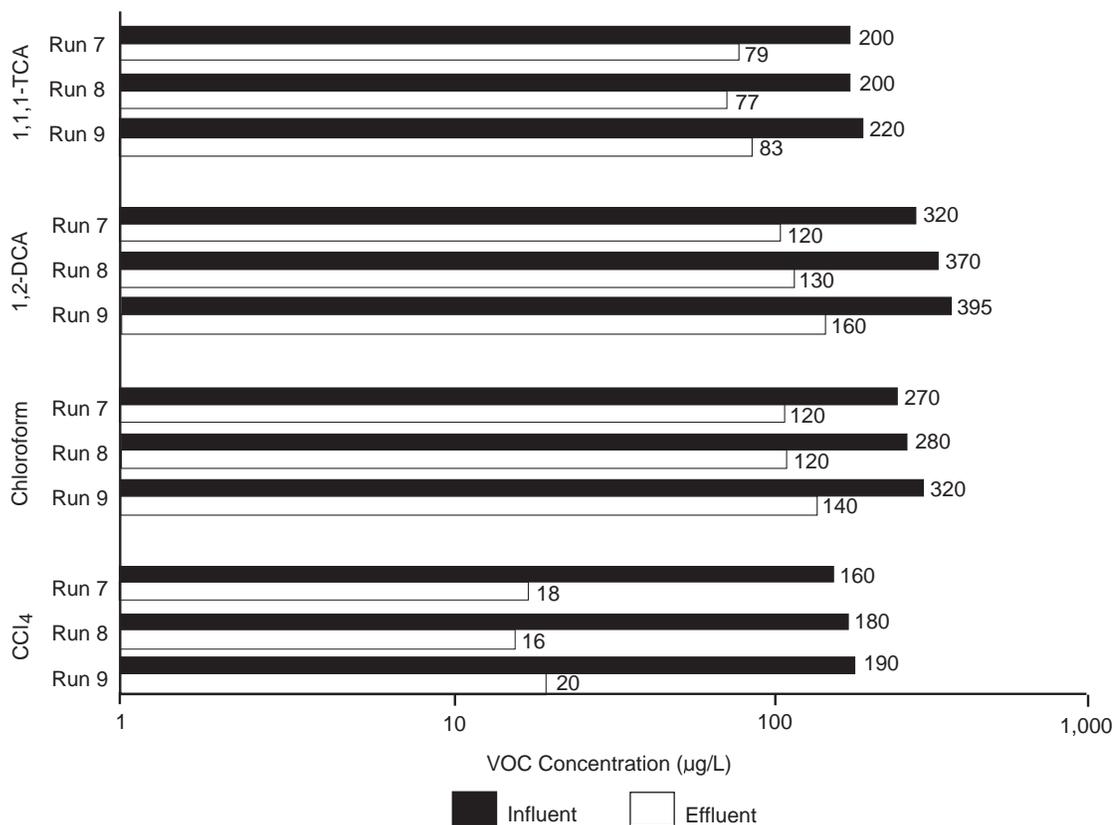
The TOC, POC, and TIC concentrations in influent and effluent samples collected during Runs 8 and 9 are presented in Table 2-9. The TOC concentration decreased about 68% during treatment; that is, about 68% of the organic carbon was completely oxidized to CO<sub>2</sub>. However, the TOC data do not indicate

whether the organic carbon originated from the VOCs or some other compounds present in the groundwater.

As shown in Table 2-9, more than 91% of the POC was removed during treatment. Assuming that most of the organic carbon associated with VOCs could be measured as POC, the data show that more than 91% of the volatile organic carbon was converted to either nonpurgeable organic carbon or CO<sub>2</sub>.

TIC increased 140% and 65% during Runs 8 and 9, respectively. The increase in TIC does not correspond to the decrease in TOC because some inorganic carbon was lost during treatment in the form of CO<sub>2</sub>. The formation of CO<sub>2</sub> during treatment was indicated by an increase in TIC (which is equivalent to CO<sub>2</sub> at low pH). CO<sub>2</sub> formation was enhanced by reductions in pH during treatment. During Runs 8 and 9, the average influent pH values were 4.8 and 4.4, respectively, and the average effluent pH values were 3.0 and 2.8, respectively.

Table 2-9 also shows data for TOX and chloride. The HVEA system achieved TOX reductions of 76%, 92%, and 93% for Runs 8, 9, and 12, respectively. The TOX reductions were generally accompanied by corresponding increases in chloride concentrations. However, the magnitudes of the TOX and chloride changes were not equal during all runs, which cannot be explained at this time.



**Figure 2-3.** Average influent and effluent levels for 111-TCA, 1,2-DCA, chloroform, and CCl<sub>4</sub> during the reproducibility runs.

## 2.2.6 VOC Volatilization and Air Phase Byproduct Formation

VOC volatilization and air phase byproduct formation during treatment were investigated by measuring the influent and effluent VOC concentrations under zero dose conditions and measuring the concentrations of VOCs, O<sub>3</sub>, and HCl in cooling air before and after the carbon adsorber. The results of these investigations are discussed below.

### VOC Volatilization Under Zero Dose Conditions

During Run 6, spiked groundwater was pumped at 40 gpm through the E-beam unit when the beam current was off; the resting beam current is about 0.5 mA, which produces a negligible dose. Table 2-10 shows the REs for critical VOCs during Run 6. The REs for TCE, PCE, and ethylbenzene were about 50%; the REs for other critical VOCs, except 1,2-DCA and chloroform, ranged between 4% and 25%. These data indicate that some VOCs were volatilized as contaminated groundwater flowed through the E-beam unit.

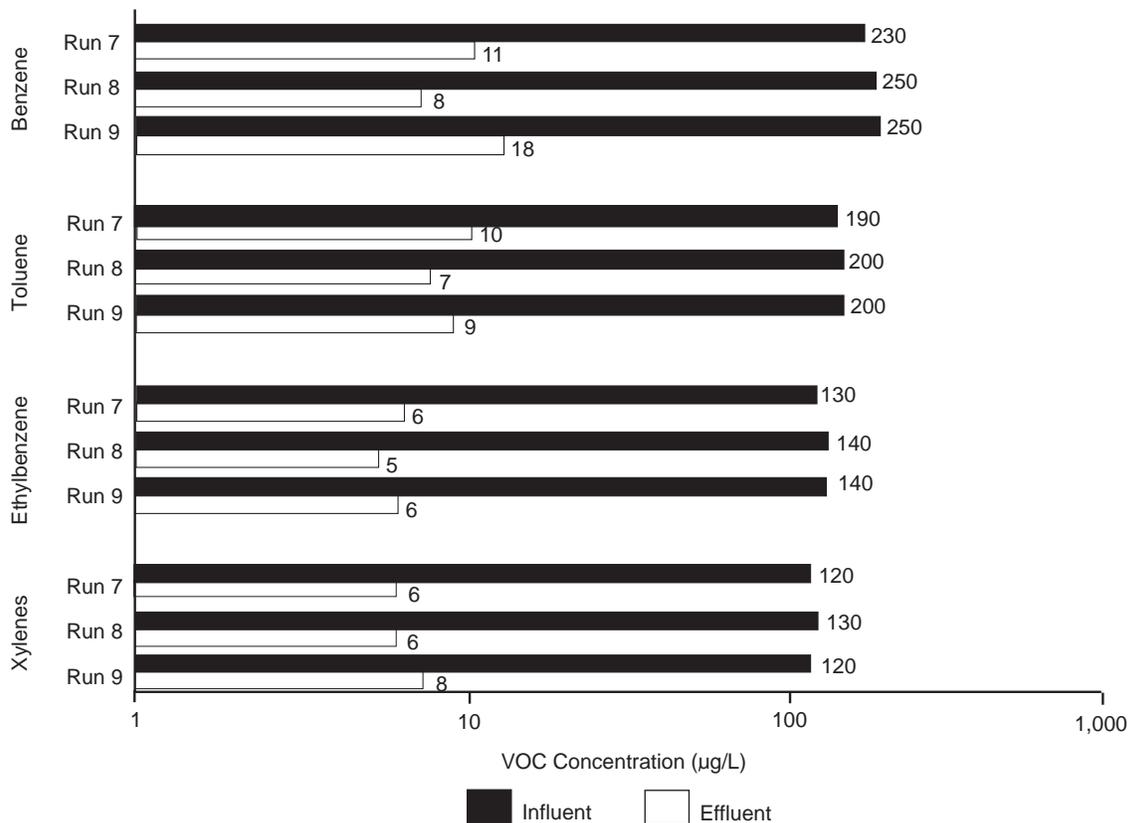
The effluent concentrations of 1,2-DCA and chloroform were 14% and 8% higher, respectively, than the influent concentrations, suggesting that these compounds were formed during the run. The apparent increase in concentrations is probably associated with sampling and analytical precision for these VOCs.

### Air Phase Byproduct Formation

Table 2-11 summarizes the average concentrations of VOCs and several inorganic compounds in cooling air before and after the carbon adsorber during Runs 1 through 10. The VOCs include all critical VOCs and phosgene; the inorganic compounds include O<sub>3</sub>, HCl, carbon monoxide (CO), CO<sub>2</sub>, nitrous oxide (N<sub>2</sub>O), and H<sub>2</sub>O. The analytical data for these compounds are discussed below.

### VOCs in Cooling Air Before and After the Carbon Adsorber

Table 2-11 shows that all critical VOCs except xylene were detected in the cooling air both before and after the carbon adsorber. In general, during Run 6 the critical VOC concentrations in the cooling air were much higher than during other runs. Because Run 6 was performed at negligible beam current (0.5 mA) and at the highest flow rate (40 gpm), water phase VOC concentrations in the E-beam unit were much higher than those in any other run and therefore provided a greater driving force for volatilization. The VOC concentration data for other runs show that 1,2-DCA was present at the highest level in Run 10 before the carbon adsorber (5.72 parts per million by volume [ppmv]) and that TCE was present at the highest level in Run 7 after the carbon adsorber (4.27 ppmv).



**Figure 2-4.** Average influent and effluent levels for BTEX during the reproducibility runs.

**Table 2-7.** E-Beam Treatment Byproduct Data

Parameter	Influent Concentration <sup>a</sup> (µg/L)	Effluent Concentration (µg/L)			
		Run 8	Run 9	Run 11	Run 12
Monochloroacetic acid	2	360	380	290	325
Dichloroacetic acid	1.2	1,800	2,000	1,300	1,250
Trichloroacetic acid	1	340	390	295	265
Acetaldehyde	1.7	5.0	6.5	1.0	4.5
Formaldehyde	5	100	100	82.5	81
Glyoxal	1	19	23	8.5	10
m-Glyoxal	1	4.0	4.5	1.0	5.5

<sup>a</sup> Influent concentrations were measured only during Runs 8 and 9, and the average values are reported in this table.

The concentrations of critical VOCs that were present in the cooling air at levels greater than 2 ppmv during at least one run are plotted in Figures 2-5 through 2-8. The concentration profiles for TCE, PCE, 1,2-DCA, and toluene are dissimilar. In addition, in several cases the VOC concentrations after the carbon adsorber were higher than those before the carbon adsorber. For example, the 95% confidence intervals for TCE shown in Figure 2-5 indicate that in 7 out of 10 runs, TCE concentrations after the carbon adsorber were significantly higher than those before the carbon adsorber. A similar obser-

vation was made, though less frequently, for PCE. However, the concentrations of 1,2-DCA and toluene were not significantly different before and after the carbon adsorber.

Table 2-11 shows that phosgene was also consistently detected during all runs except Run 6. The highest concentrations of phosgene detected were 4.93 and 3.86 ppmv in the cooling air before and after the carbon adsorber, respectively. Figure 2-9 shows that phosgene was present whenever CO was present in the cooling air, although the correlation is not proportional in

**Table 2-8.** Effluent H<sub>2</sub>O<sub>2</sub> Concentrations

Run No.	Operating Parameters		Effluent H <sub>2</sub> O <sub>2</sub> (mg/L)
	Flow Rate (gpm)	Beam Current (mA)	
4	40	17	2.3
5	40	21	3.8
7	20	42	8.2
8	20	42	7.9
9	20	42	7.9
11 <sup>a</sup>	20	42	9.5
12 <sup>a</sup>	20	42	9.5
13 <sup>a</sup>	20	42	7.8

<sup>a</sup> Runs 11, 12, and 13 were conducted after HVEA adjusted the influent delivery system to increase the dose from that used during the reproducibility runs (Runs 7, 8, and 9).

**Table 2-9.** Carbon, TOX, and Chloride Concentrations

Parameter	Carbon, TOX, and Chloride Concentrations (mg/L)					
	Run 8		Run 9		Run 12	
	Influent	Effluent	Influent	Effluent	Influent	Effluent
TOC	12	3.8	14	4.5	Not measured during Run 12	
POC	11	<1.0	12	<1.0	Not measured during Run 12	
TIC	2.0	4.8	3.5	5.8	Not measured during Run 12	
TOX	8.0	1.9	28	2.1	33	2.4
Chloride	4.0	44	3.0	41	Not measured during Run 12	

**Table 2-10.** VOC REs Under Zero Dose Conditions

VOC <sup>a</sup>	RE (%)
TCE	46
PCE	61
1,1,1-TCA	3.7
1,2-DCA	(14) <sup>b</sup>
Chloroform	(8.3)
CCl <sub>4</sub>	9.1
Benzene	11
Toluene	25
Ethylbenzene	50
Xylenes	5.6

<sup>a</sup>1,2-DCE was not detected in the influent during the zero-dose run.

<sup>b</sup>Values in parentheses represent negative REs.

all cases. In industrial practice, phosgene is typically formed by passing a mixture of CO and chlorine over activated carbon. During the demonstration, CO was present in the cooling air during all runs at concentrations up to 37.6 ppmv. The lowest concentration of CO was 0.22 ppmv during Run 6, when no phosgene was detected. Because the concentrations of chlorine in the cooling air were not measured, the data are not adequate to verify how the phosgene was formed. However, Holden and others (1993) report chlorine, CO, and phosgene as some of the byproducts of TCE oxidation in the vapor phase. This indicates that during the demonstration, phosgene could have formed as a result of E-beam air phase reactions in the cooling air or as a result of a reaction between CO and chlorine on the activated carbon surface in the cooling air processor.

The lack of consistent trends in VOC data could be the result of a combination of several factors, including the following: (1) cooling air is recirculated, possibly resulting in a buildup of compounds during a run and over several runs; (2) several chemical reactions could have occurred in the air phase within the E-beam unit and on the activated carbon surface; and (3) the cooling air processor and lines were not airtight, as was evidenced by a smell of O<sub>3</sub> in the pump room throughout the demonstration (see Section 2.2.9).

### O<sub>3</sub> in Cooling Air Before and After the Carbon Adsorber

O<sub>3</sub> was consistently detected in the cooling air during all runs. Figure 2-10 shows the O<sub>3</sub> concentrations before and after the carbon adsorber. The concentrations of O<sub>3</sub> before the carbon adsorber were relatively high compared to the concentrations after the carbon adsorber; however, the carbon adsorber did not eliminate O<sub>3</sub> in the cooling air stream. The concentrations of O<sub>3</sub> were observed to be highest during Run 10 (22.81 ppmv before the carbon adsorber and 16.21 ppmv after the carbon adsorber). During Run 6, when the E-beam dose was negligible, the O<sub>3</sub> concentrations were lowest (less than 0.02 ppmv both before and after the carbon adsorber).

### HCl in Cooling Air Before and After the Carbon Adsorber

HCl was detected in relatively small concentrations before and after the carbon adsorber. The HCl probably resulted from mineralization of chlorinated organics in the vapor phase during treatment by the E-beam system.

**Table 2-11. Cooling Air Characteristics**

**Before the Carbon Adsorber (ppmv)<sup>a</sup>**

Run No.	VOCs										Inorganics						
	TCE	PCE	1,1,1-TCA	1,2-DCA	Chloroform	CCl <sub>4</sub>	Benzene	Toluene	Ethylbenzene	p-Xylene	Phosgene	O <sub>3</sub>	HCl	CO	CO <sub>2</sub>	N <sub>2</sub> O	H <sub>2</sub> O
1	3.86 <sup>b</sup>	4.16 <sup>b</sup>	<0.05 <sup>b</sup>	<0.23 <sup>b</sup>	0.46 <sup>b</sup>	0.22	<0.35 <sup>b</sup>	0.46	0.72 <sup>b</sup>	<0.73 <sup>b</sup>	4.93	4.05	0.05	28.7 <sup>b</sup>	1,210	4.49 <sup>b</sup>	23,700
2	1.40	2.28	0.11	<0.08	0.68	0.50	<0.11	<0.25	0.28	<0.13	3.53	15.7	<0.04	37.6	1,550	6.35	27,600
3	3.60	1.75	0.10	<0.08	0.25	0.80	<0.16	<0.54	0.30	<0.10	0.74	13.4	0.31	26.5	1,540	8.86	24,500
4	1.22	1.65	0.52	0.35	1.17	0.45	<0.07	0.63	0.24	<0.11	2.36	12.3	<0.09	29.9	1,240	5.58	20,700
5	1.06	1.03	0.36	0.26	0.85	0.49	<0.04	<0.38	0.28	<0.06	1.08	19.3	<0.18	26.5	1,350	8.06	25,800
6	84.4	32.3	1.05	0.20	1.21	1.05	1.09	0.95	0.51	<1.30	<0.29	<0.02	<0.07	0.22	1,290	3.40	20,700
7	1.75	0.73	<0.04	<0.13	0.32	0.80	<0.03	1.27	0.32	<0.22	0.49	13.2	<0.14	14.3	1,200	8.09	22,300
8	1.08	0.60	<0.05	<0.21	0.21	0.83	0.12	<0.50	0.37	<0.21	0.43	17.0	<0.14	23.7	1,290	13.5	27,200
9	1.26	0.76	<0.14	3.69	0.17	0.87	<0.10	4.17	0.57	<0.44	0.50	11.8	<0.18	24.8	1,410	12.3	30,400
10	0.96	0.55	<0.15	5.72	0.26	0.91	<0.10	3.33	0.44	<0.33	0.21	22.8	<0.27	21.4	1,210	17.1	24,600

**After the Carbon Adsorber (ppmv)<sup>a</sup>**

Run No.	VOCs										Inorganics						
	TCE	PCE	1,1,1-TCA	1,2-DCA	Chloroform	CCl <sub>4</sub>	Benzene	Toluene	Ethylbenzene	p-Xylene	Phosgene	O <sub>3</sub>	HCl	CO	CO <sub>2</sub>	N <sub>2</sub> O	H <sub>2</sub> O
1	3.39 <sup>b</sup>	3.26 <sup>b</sup>	<0.05 <sup>b</sup>	<0.23 <sup>b</sup>	0.41 <sup>b</sup>	0.18	<0.38 <sup>b</sup>	0.42	0.68 <sup>b</sup>	<0.64 <sup>b</sup>	3.86	1.90	0.05	25.7 <sup>b</sup>	1,120	3.97 <sup>b</sup>	23,000
2	1.63	1.83	0.10	<0.05	0.60	0.33	<0.02	0.45	0.27	<0.10	2.25	10.2	<0.03	33.6	1,250	5.47	22,700
3	2.00	0.83	0.10	<0.09	0.24	0.62	<0.16	<0.37	0.30	<0.10	0.51	7.71	0.15	23.5	1,230	7.86	19,900
4	1.63	1.51	0.44	0.34	0.96	0.31	0.07	0.53	0.23	<0.10	1.58	8.45	<0.03	28.4	1,010	5.10	18,100
5	1.44	0.87	0.27	0.21	0.67	0.30	<0.02	0.58	0.27	<0.05	0.74	11.8	<0.08	23.4	1,060	7.10	22,100
6	68.6	26.2	0.82	0.15	0.85	0.79	0.89	0.73	0.43	<0.98	<0.11	<0.02	<0.06	0.27	1,080	3.02	17,800
7	4.27	1.14	<0.05	<0.14	0.27	0.61	0.10	0.88	<0.12	<0.21	0.31	7.16	<0.10	12.9	997	7.11	19,300
8	2.47	0.83	<0.05	<0.22	0.18	0.80	0.13	<0.38	0.41	<0.18	0.34	12.3	<0.05	21.6	1,130	12.1	24,000
9	3.22	1.16	<0.14	3.71	0.17	0.78	<0.07	3.39	0.53	<0.30	0.38	6.16	0.24	23.3	1,220	11.4	29,300
10	1.83	0.73	<0.05	<0.23	0.26	0.91	<0.11	2.62	0.34	<0.17	0.22	16.2	0.10	19.7	1,080	14.7	22,000

<sup>a</sup> 1,2-DCE could not be quantified because of the lack of an appropriate reference standard; however, the FTIR data indicate that it was not present at levels >0.5 ppmv.

<sup>b</sup> The result may be biased high or low because it was measured without the scrubber operating. (The data quality impact cannot be quantified.)

**Other Compounds in Cooling Air Before and After the Carbon Adsorber**

The cooling air also contained CO, CO<sub>2</sub>, H<sub>2</sub>O, and N<sub>2</sub>O (see Table 2-11 and Figure 2-9). The concentrations of CO remained at similar levels during all runs except Run 6. The concentrations of CO<sub>2</sub> and H<sub>2</sub>O did not vary significantly between runs. The concentrations of N<sub>2</sub>O generally increased as dose increased during Runs 1 through 5 and 7 through 10; the lowest N<sub>2</sub>O concentrations were observed during Run 6 (the zero dose run).

**2.2.7 Flow Rate Test**

During Run 10, the flow rate was reduced from 20 to 15 gpm, which is the minimum limiting flow rate for the HVEA system used in the SITE demonstration. As discussed in Section 1.4.2, flow rate and E-beam dose are inversely related; that is, the dose increases when the flow rate is reduced. Therefore, any change in system performance that occurred when the flow rate was reduced cannot be attributed to hydraulic effects only.

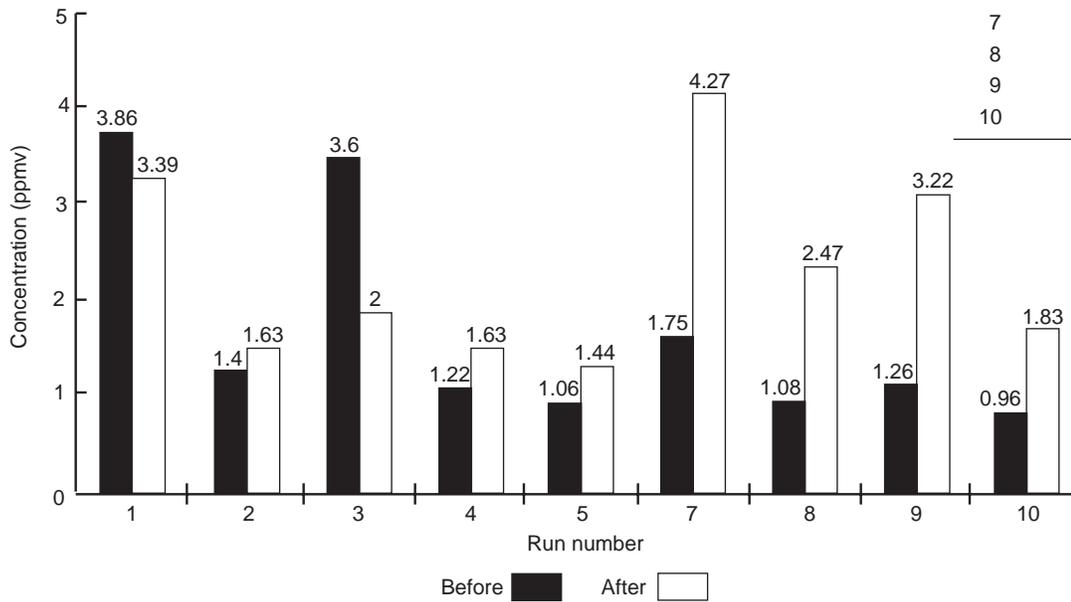
Except for flow rate, the influent characteristics and operating conditions for Run 10 and for the reproducibility runs were the

same. Therefore, the effect of operating the system at the lowest possible flow rate can be evaluated by comparing the VOC RE results from Run 10 to the average VOC REs during the reproducibility runs (see Figure 2-11). Lowering the flow rate by 5 gpm increased the REs for 1,1,1-TCA, 1,2-DCA, and chloroform 8% to 10%. The impact on the REs for other critical VOCs was not significant (less than 2%). Consequently, HVEA returned the flow rate to 20 gpm for Phase 5 so that the results for Runs 11, 12, and 13 could be compared to those for the reproducibility runs.

**2.2.8 Alkalinity-Adjusted Spiked Groundwater Test**

The effect of alkalinity on VOC REs was tested during Run 13, which was identical to Run 12 except that the alkalinity was increased from 5 to 500 mg/L as CaCO<sub>3</sub> by adding sodium bicarbonate to the influent. The runs were conducted under identical operating conditions using spiked groundwater, although the concentrations of some spiked VOCs were about 80% higher during Run 13 than during Run 12. The VOC REs for Runs 12 and 13 are shown in Figure 2-12. REs changed less than 2% for TCE, PCE, CCl<sub>4</sub>, and BTEX after alkalinity

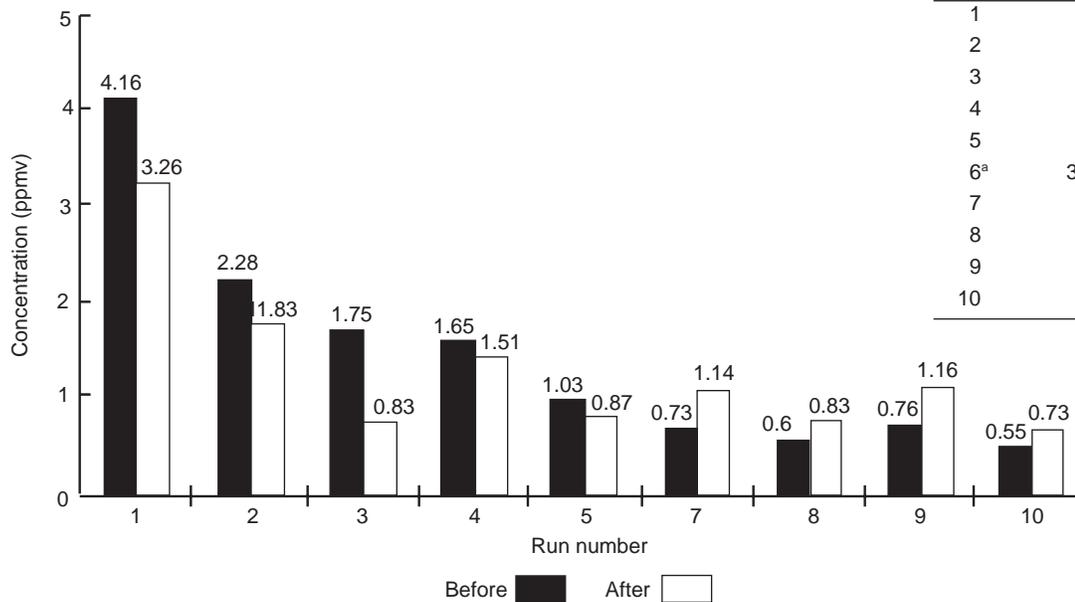
Run No.	95% Confidence Interval (ppmv)	
	Before	After
1	3.59-4.12	3.19-3.59
2	1.38-1.41	1.62-1.65
3	3.59-3.62	1.99-2.02
4	1.22-1.23	1.63-1.64
5	1.05-1.06	1.43-1.44
6 <sup>a</sup>	83.77-85.01	68.38-68.91
7	1.73-1.77	4.24-4.29
8	1.07-1.10	2.45-2.48
9	1.21-1.32	3.17-3.28
10	0.87-1.05	1.80-1.85



Note: <sup>a</sup> Run 6 data are not plotted on the graph

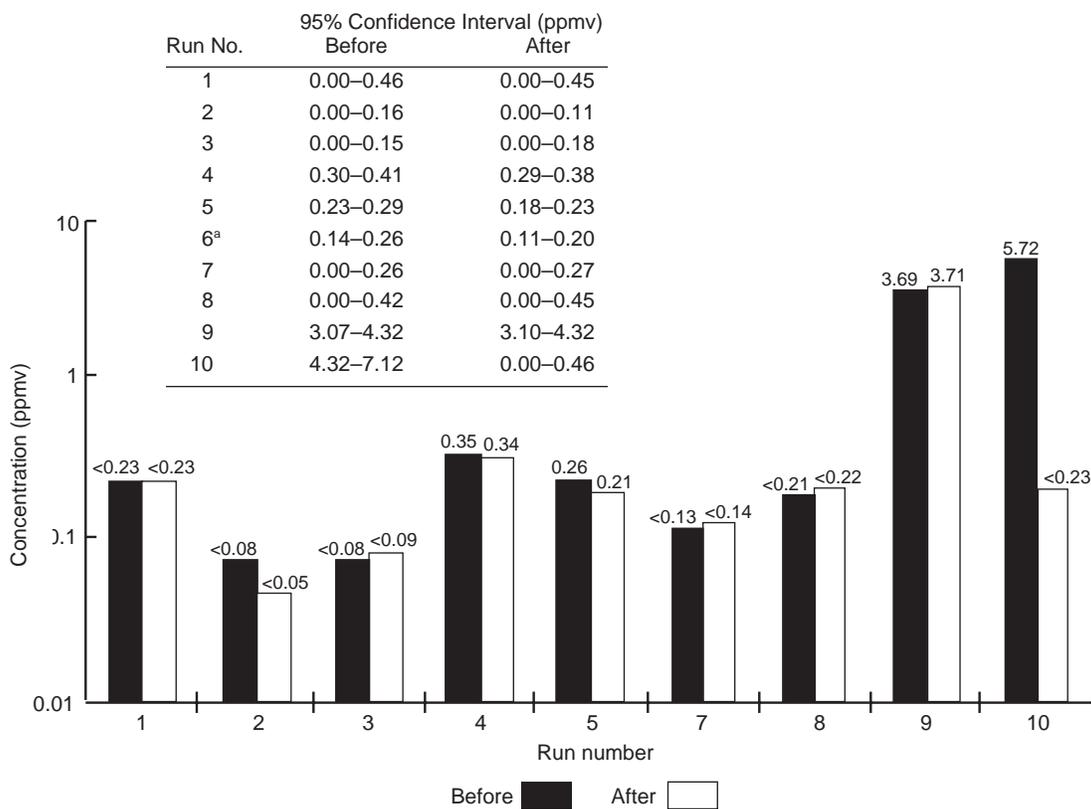
**Figure 2-5.** TCE levels before and after the carbon adsorber.

Run No.	95% Confidence Interval (ppmv)	
	Before	After
1	4.13-4.18	3.24-3.28
2	2.27-2.30	1.82-1.85
3	1.74-1.76	0.82-0.84
4	1.64-1.66	1.51-1.52
5	1.02-1.03	0.87-0.88
6 <sup>a</sup>	32.09-32.54	26.11-26.37
7	0.72-0.74	1.13-1.15
8	0.59-0.61	0.82-0.84
9	0.74-0.78	1.14-1.18
10	0.54-0.57	0.71-0.74



Note: <sup>a</sup> Run 6 data are not plotted on the graph

**Figure 2-6.** PCE levels before and after the carbon adsorber.



Note: <sup>a</sup> For values preceded by a “<”, a nondetect was recorded and the graph shows the detection limit. Run 6 data are not plotted on the graph.

**Figure 2-7.** 1,2-DCA levels before and after the carbon adsorber.

adjustment. However, REs for other critical VOCs appear to have been impacted by the higher alkalinity. Specifically, REs for 1,1,1-TCA and chloroform increased 8% and 12%, respectively, while the RE for 1,2-DCA decreased 13%.

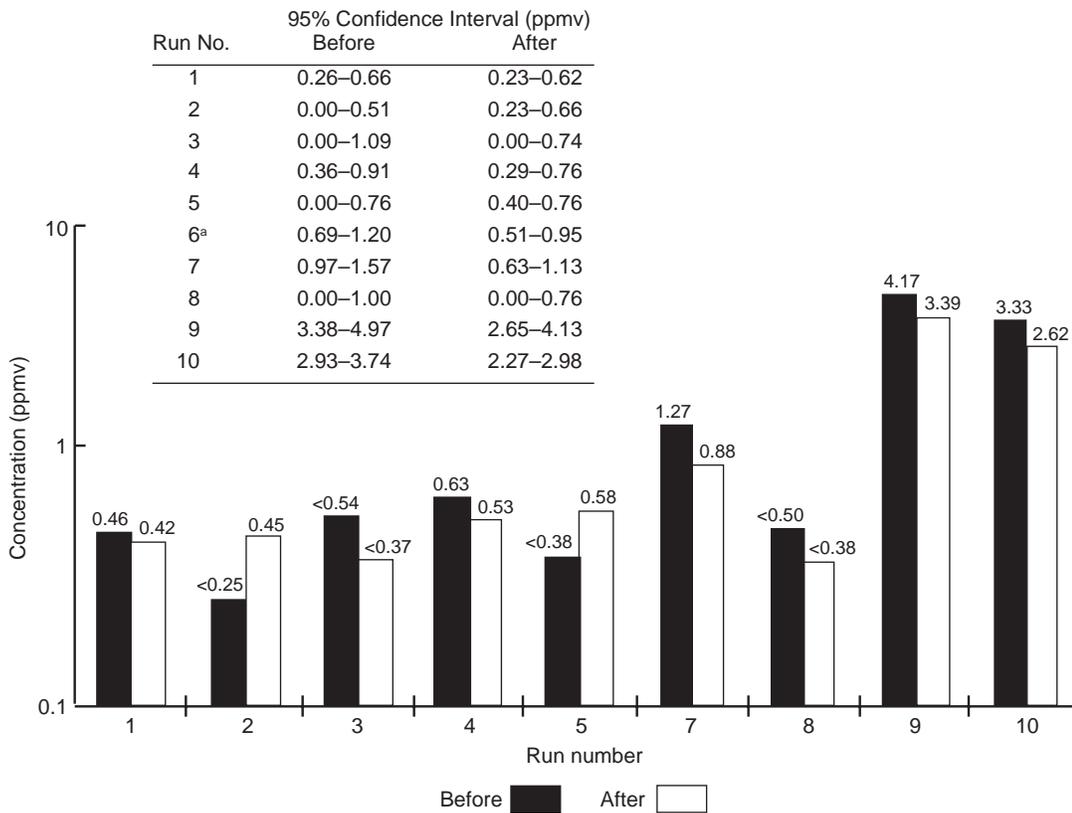
The changes in RE for different VOCs may be attributed to different destruction mechanisms. If the alkalinity is high, carbonate and bicarbonate ions scavenge  $\text{OH}\cdot$ . During Run 13, the influent and effluent pH was 7.6 and 7.1, respectively. At this pH, bicarbonate is the predominant form of inorganic carbon. The loss of  $\text{OH}\cdot$  to scavengers effectively results in higher REs for VOCs destroyed by chemical pathways involving  $\text{H}\cdot$  or  $\text{e}_{\text{aq}}^-$  as opposed to VOCs destroyed by chemical pathways involving  $\text{OH}\cdot$ . The rate constant for the reaction between a VOC and a reactive species can be used as a relative indicator of the preferred destruction pathway. During Run 13, the REs for three VOCs were significantly affected by the increased alkalinity: 1,1,1-TCA, chloroform, and 1,2-DCA. Of these three VOCs, rate constants for reactions with  $\text{OH}\cdot$ ,  $\text{H}\cdot$ , and  $\text{e}_{\text{aq}}^-$  are known only for chloroform ( $5.0 \times 10^{-6}$ ,  $1.1 \times 10^{-7}$ , and  $3.0 \times 10^{10} \text{ M}^{-1}\text{s}^{-1}$ , respectively) (Buxton and others 1988). The relative orders of magnitude between these rate constants indicate that chloroform is primarily destroyed by  $\text{e}_{\text{aq}}^-$  as opposed to  $\text{OH}\cdot$ . This explains why the RE for chloroform increased when

the alkalinity (in other words, the bicarbonate concentration) was increased.

### 2.2.9 Operating Problems

HVEA system’s operation was observed throughout the technology demonstration to record problems and their resolutions. Some of the problems were directly related to the system’s operation, while others were specific to the demonstration activities. The problems and their resolutions are described below.

Run 1 was preceded by a startup run that was performed under conditions identical to those for Run 1, including the use of unspiked groundwater. During the startup run, a significant number of bubbles were observed in the influent to the HVEA system. These bubbles were caused by evolution of dissolved gases in the groundwater as it was pumped to the surface. At the request of HVEA, the bubbles were dissipated upstream of the E-beam unit by pumping the groundwater through a 500-gallon, covered tank with a 3-foot freeboard. According to HVEA, the E-beam system has not been tested using water containing bubbles; therefore, the effect of bubbles on system performance is unknown. This approach did not significantly affect influent VOC concentrations, and all influent VOC samples were collected beyond the covered tank.



Note: <sup>a</sup> For each value preceded by a “<”, a nondetect was recorded and the graph shows the detection limit. Run 6 data are not plotted on the graph.

**Figure 2-8.** Toluene levels before and after the carbon adsorber.

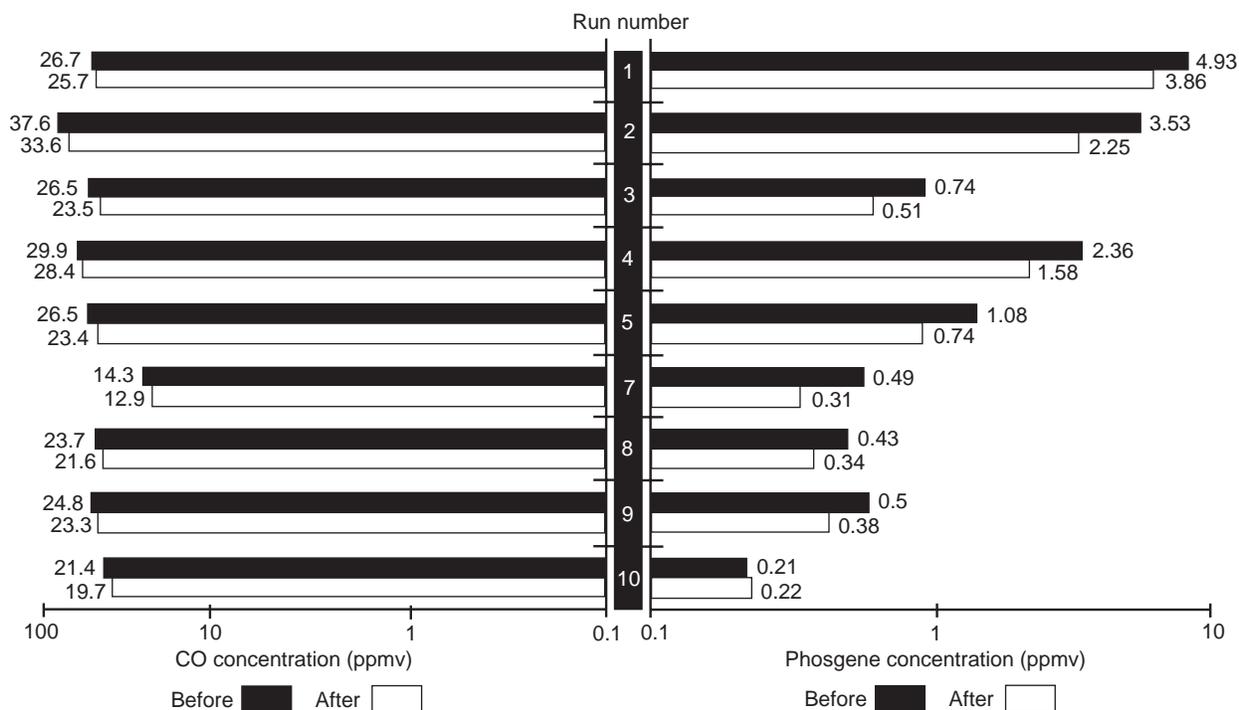
The HVEA system was configured with a pair of RTDs immediately before and after the E-beam contact chamber to measure the temperature of the groundwater before and after treatment. HVEA measures the change in water temperature to estimate the E-beam dose according to established equations (Nickelsen and others 1992). During the technology demonstration, the output from the RTDs, which was recorded by a computer in the control room, showed significant drift or displayed values that correlated to unreasonable doses given the established beam current and flow rate. Consequently, the RTD data were considered unreliable and were not used. This did not impact HVEA system operation because, from a practical standpoint, beam current and flow rate are the main parameters used to set the E-beam dose.

During the startup and Phase 1 runs, radiation was detected along the outside wall of the E-beam trailer near the E-beam process room. Radiation levels between 4 and 9 milliRems (mRem) per hour were recorded during the startup run and Run 3. Radiation in the form of x-rays is generated when the E-beam contacts various internal stainless steel surfaces. The E-beam unit was initially surrounded with lead shielding; however, the thickness and placement of the shielding did not completely prevent radiation from escaping the trailer. HVEA resolved this

problem by placing additional lead shielding around the E-beam unit, after which no radiation was detected outside the E-beam process room.

During Phase 1, a joint in the cooling air ductwork developed a leak that released cooling air to the atmosphere. Although the exact cause of the leak is unknown, O<sub>3</sub> formed in the cooling air during treatment may have reacted with the rubber joint and compromised its integrity. The field sampling team smelled O<sub>3</sub> in the area around the leak. HVEA personnel immediately repaired the leak using duct tape. HVEA’s troubleshooting significantly reduced the leak, although it did not completely prevent small leaks. The field team smelled traces of O<sub>3</sub> throughout the demonstration.

Phase 5 was conducted in November 1994. During the night before Run 13 was conducted, the ambient air temperature fell to about 32 °F after a warm, sunny day of about 75 °F. Run 13 was scheduled for 8:00 a.m., but during system startup, HVEA reported difficulty maintaining an acceptable vacuum in the E-beam unit. However, by noon the vacuum was regained, and the run was conducted without incident. The cause of the vacuum loss is unknown; however, one explanation involves the unusually cold night before the incident. The vacuum may have been lost through small leaks created when gaskets on the



Note: <sup>a</sup> Run 6 data are not plotted on the graph.

Run No.	CO 95% Confidence Interval (ppmv)		Run No.	Phosgene 95% Confidence Interval (ppmv)	
	Before	After		Before	After
1	26.66–30.73	23.84–27.59	1	4.85–5.02	3.80–3.93
2	33.80–41.37	30.24–37.01	2	3.47–3.60	2.21–2.29
3	25.63–27.27	22.76–24.15	3	0.73–0.76	0.50–0.52
4	28.35–31.40	27.07–29.78	4	2.32–2.40	1.55–1.61
5	24.17–28.81	21.33–25.44	5	1.06–1.11	0.72–0.75
6 <sup>a</sup>	0.17–0.27	0.21–0.33	6 <sup>a</sup>	0.00–0.57	0.00–0.22
7	13.12–15.51	11.83–13.93	7	0.48–0.51	0.30–0.33
8	22.96–24.49	20.91–22.23	8	0.42–0.44	0.33–0.34
9	24.04–25.56	22.59–23.96	9	0.49–0.52	0.36–0.40
10	20.12–22.62	18.52–20.87	10	0.18–0.23	0.20–0.23

Figure 2-9. CO and phosgene levels before and after the carbon adsorber.

E-beam unit contracted during the cold night. As the ambient air temperature rose on the following day, the gaskets expanded and the vacuum was restored.

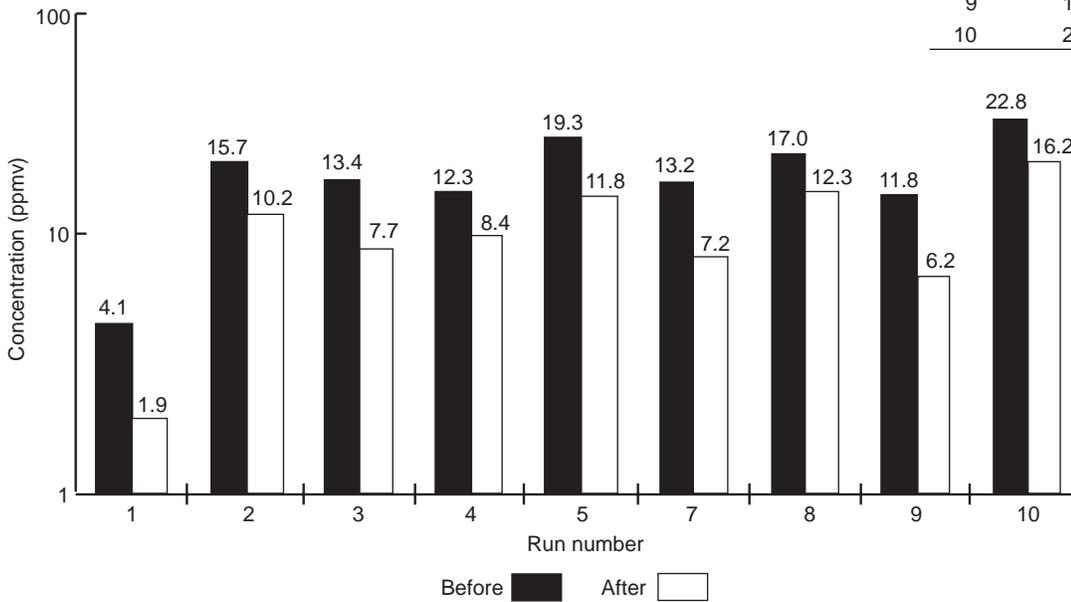
### 2.3 Additional Performance Data

This section summarizes performance data for the E-beam technology in addition to the data collected during the SITE demonstration. Provided below are the significant results from one study conducted in Germany using the HVEA trailer-mounted system and from two other studies conducted using an E-beam system permanently installed at the Virginia Key (Central District) Wastewater Treatment Plant in Miami, FL.

Additional details on the study performed in Germany using the HVEA system are presented in Appendix B.

In December 1994, several treatability studies were conducted in Halle-Dieskau, Germany, using the HVEA trailer-mounted E-beam treatment system. In one of the studies, 270 gallons of petroleum refinery process wastewater containing phenol, BTEX, and polynuclear aromatic hydrocarbons (PAH) was treated to evaluate the effectiveness of the E-beam system. The wastewater was treated in recirculation mode at a flow rate of 25 gpm and a beam current of 40 mA for about 45 minutes. The highest REs for phenol, total BTEX, and total PAHs were observed to be 99.1%, >99.2%, and >99.5%, respectively. The treated

Run No.	95% Confidence Interval (ppmv)	
	Before	After
1	4.02–4.07	1.88–1.92
2	15.48–15.82	10.09–10.32
3	13.25–13.55	7.63–7.79
4	12.20–12.37	8.39–8.50
5	19.08–19.61	11.69–11.84
6 <sup>a</sup>	0.00–0.04	0.00–0.03
7	13.03–13.37	7.03–7.28
8	16.79–17.16	12.20–12.44
9	11.51–12.12	5.85–6.47
10	22.38–23.24	15.91–16.50



Note: <sup>a</sup> Run 6 data are not plotted on the graph.

**Figure 2-10.** O<sub>3</sub> levels before and after the carbon adsorber.

wastewater met German wastewater regulatory limits for phenol, BTEX, and PAHs.

Under the SITE Emerging Technology program, HVEA performed several experiments at the Virginia Key Plant using an electron accelerator operated at 1.5 million volts and a maximum beam current of 50 mA. The experiments were conducted using potable water and wastewater spiked with TCE and PCE. The objectives of these experiments were to test the effects of water quality, solute concentration, and E-beam dose on REs for TCE and PCE and on formation of reaction byproducts. The results showed that the E-beam dose required to remove 99% of the TCE and PCE was less for potable water than for wastewater. PCE removal required a higher dose than TCE removal under equivalent conditions. The results also showed that the presence of up to 3% suspended solids in the form of clay had no significant effect on the removal of TCE or PCE compared to solutions that had no clay. Aldehydes and formic acid were identified as reaction byproducts (EPA 1992).

In another study conducted under the Emerging Technology program, HVEA performed several experiments to evaluate the removal of benzene and toluene from aqueous solutions as a

function of solute concentration, E-beam dose, pH, total solids content, and byproduct formation. These experiments were also conducted at the Virginia Key Plant. The results showed that the REs for benzene and toluene were not affected by solution pH. Also, the presence of 3% kaolin clay did not appear to significantly affect the RE for either benzene or toluene. The reaction byproducts identified for benzene removal included phenol; 1,2-, 1,3-, and 1,4-dihydroxybenzene; formaldehyde; acetaldehyde; and glyoxal. The reaction byproducts identified for toluene removal included o-cresol, formaldehyde, acetaldehyde, glyoxal, and methylglyoxal (EPA 1993).

## 2.4 Factors Affecting Performance

Several factors influence the effectiveness of the E-beam technology. These factors can be grouped into three categories: (1) feed waste characteristics, (2) operating parameters, and (3) maintenance requirements. These categories are discussed in the following sections.

### 2.4.1 Feed Waste Characteristics

The E-beam technology is applicable for treatment of VOCs and SVOCs in groundwater, wastewater, drinking water, and

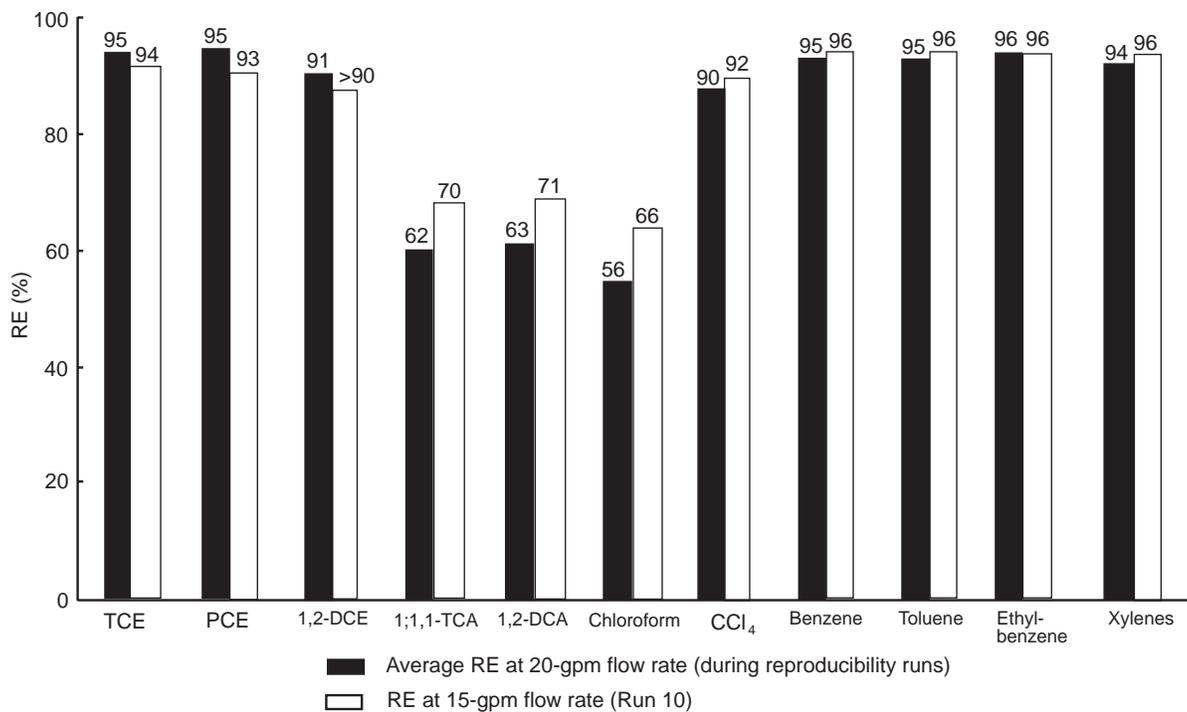


Figure 2-11. Flow rate test results for VOC REs.

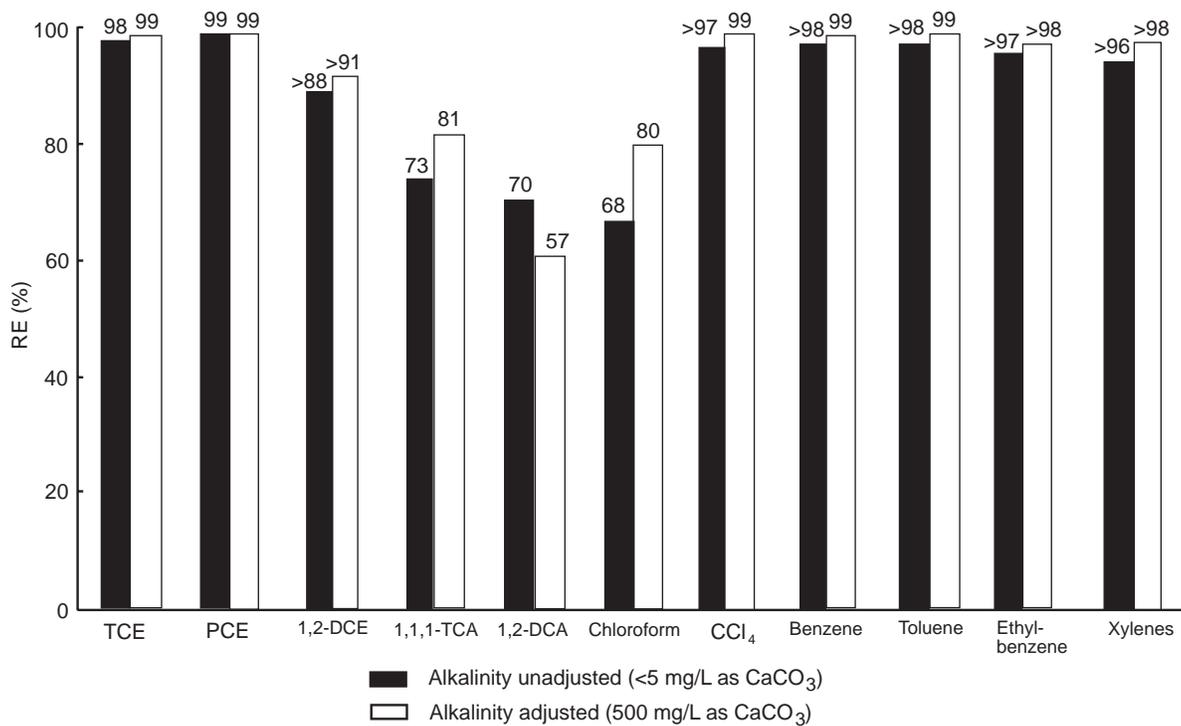


Figure 2-12. Effect of alkalinity on VOC REs.

landfill leachate. Under a given set of operating conditions, contaminant REs depend on the chemical structure of the contaminants. REs are high for organic contaminants with double bonds (such as TCE, PCE, and 1,2-DCE) and aromatic compounds (such as BTEX), because these compounds are easy to oxidize. Organic contaminants without double bonds (such as 1,1,1-TCA, chloroform, and 1,2-DCA) are not easily oxidized and are thus more difficult to remove.

If the feed waste cannot be treated to meet treatment goals in one pass and if the waste is provided by a source that allows for controlled, intermittent feeding to the E-beam system, the system can operate in a batch recycle mode. Operation in this mode allows multiple exposures of highly contaminated wastes to the E-beam, thereby improving overall system performance. However, if the feed waste is provided by a continuous source, such as a groundwater extraction system, operating in the batch recycle mode may not be feasible at high influent flow rates.

Some compounds commonly present in water may interact with the reactive species formed by the E-beam, thereby exerting an additional demand for reactive species on the system. These compounds are called scavengers, and they may impact system performance. A scavenger is defined as any compound in the water other than the target contaminants that consumes reactive species ( $\text{OH}\cdot$ ,  $\text{e}^{-\text{aq}}$ , and  $\text{H}\cdot$ ). Carbonate and bicarbonate ions are examples of  $\text{OH}\cdot$  scavengers found in most natural waters. Therefore, alkalinity is an important operating parameter. If the alkalinity is high, influent alkalinity adjustment may be required to shift the carbonate-bicarbonate equilibrium from carbonate (a scavenger) to carbonic acid (not a scavenger). Other scavengers (and the reactive species they consume) include oxygen ( $\text{e}^{-\text{aq}}$  and  $\text{H}\cdot$ ), nitrate ions ( $\text{e}^{-\text{aq}}$ ), and methanol ( $\text{OH}\cdot$ ) (Nickelsen and others 1992).

Other influent characteristics of concern include the presence of suspended solids and air bubbles. Fine suspended solids not captured by the strainer basket may clog the influent delivery system for the E-beam unit. According to HVEA, the E-beam system has not been tested using water containing bubbles and the effect of bubbles on system performance is unknown. However, during the technology demonstration HVEA requested that the bubbles be removed from the influent.

## 2.4.2 Operating Parameters

Operating parameters are those parameters that can be varied during the treatment process to achieve desired REs and treatment goals. The principal factor affecting E-beam system performance is the E-beam dose. Although dose cannot be directly varied or measured, it is a function of several other parameters that can be directly adjusted and measured. Dose depends on E-beam power, which is a function of beam current and accelerating voltage; how long the water is exposed to the E-beam, which depends on the flow rate; and the thickness of the water stream exposed to the E-beam. Of these parameters, HVEA typically adjusts beam current and flow rate to change the dose. In some cases, the thickness of the water stream may also be adjusted to achieve site-specific performance requirements.

As the beam current passes through a tungsten wire filament within the electron accelerator, a stream of electrons is emitted that comprises the E-beam. The number of electrons emitted

per unit time is proportional to the beam current. Therefore, for a given flow rate, dose is increased by increasing the beam current, which increases the number of electrons impacting the liquid and, consequently, the number of reactive species formed. The electron accelerator in the HVEA system used for the SITE demonstration is capable of generating a maximum beam current of about 42 mA. The beam current is adjusted and monitored at the control panel in the E-beam trailer control room.

Flow rate through the treatment system determines how long the water is exposed to the E-beam. In general, increasing the exposure time (decreasing the flow rate) improves treatment efficiency by increasing the number of reactive species formed as more high-speed electrons impact a discrete volume of water. According to HVEA, the E-beam system used during the demonstration cannot be operated below a minimum flow rate of 15 gpm. If treatment goals are not met at this flow rate, treatment efficiency can be improved by increasing the beam current or adjusting the influent delivery system. The flow rate provided by the influent pump is monitored and adjusted in the E-beam trailer pump room.

The voltage applied to the E-beam affects the depth to which the E-beam penetrates the water being treated. At a given E-beam penetration depth, the portion of flowing water directly irradiated by the beam depends on the thickness of the flowing water. The thickness of the flowing water can be controlled by adjusting the influent delivery system for the E-beam unit. The internal components of the delivery system and its dimensions are proprietary information.

## 2.4.3 Maintenance Requirements

The maintenance requirements for the E-beam system summarized in this section are based on direct observations and discussions with HVEA during and after the SITE demonstration. This section addresses only maintenance requirements for components specific to the E-beam technology and not general maintenance requirements for support components. Regular maintenance by trained personnel is essential for successful operation of the E-beam system. A summary of the maintenance requirements for the titanium window gasket, electrostatic filter, air chiller, and influent delivery system is provided below.

The gasket that seals the titanium window may need to be replaced periodically, particularly if the E-beam system is not operated continuously during cold weather. The gasket is necessary to maintain the vacuum in the scanner. The gasket is heated considerably by the E-beam during operation of the system and then cools when the system is shut down. As the gasket expands and contracts with these temperature changes, the airtight seal can be broken and the vacuum lost. When this occurs, the gasket and titanium window may need to be replaced.

The electrostatic filter in the cooling air processor was not operated during the demonstration. However, when it is operated, the filter requires periodic maintenance to remove and dispose of the particulates removed from the cooling air and collected on the filter. Similarly, the air chiller in the cooling air

processor collects condensate from the cooling air that requires periodic removal. Although not observed during the demonstration, the condensate may be treated by the E-beam unit.

The influent delivery system may require periodic maintenance if suspended solids in the influent are small enough to pass through the strainer basket. If these solids are deposited in the delivery system, the system becomes clogged and requires cleaning to remove the solids.

## **2.5 Site Characteristics and Support Requirements**

In addition to feed waste characteristics and effluent discharge requirements, site characteristics and support requirements are important when considering the E-beam technology. Site-specific factors can impact the application of the E-beam technology, and these factors should be considered before selecting the technology for remediation of a specific site. Site-specific factors addressed in this section include site access, area, and preparation requirements; climate; utility and supply requirements; required support systems; and personnel requirements. According to HVEA, both transportable and permanently installed E-beam systems are available (see Section 4, Technology Status, and Appendix A, Vendor's Claims for the Technology). The support requirements for these systems are likely to vary. This section presents support requirements based on the information collected for the trailer-mounted system used during the SITE demonstration.

### **2.5.1 Site Access, Area, and Preparation Requirements**

The site must be accessible for a tractor-trailer truck with an 8-by-48-foot trailer weighing about 35 tons. An area of 8 by 48 feet must be available for the trailer that houses the E-beam system, and additional space must be available to allow personnel to move freely around the outside of the trailer. The area containing the E-beam trailer should be paved or covered with compacted soil or gravel to prevent the trailer from sinking into soft ground. The trailer is equipped with a 500-gallon influent holding tank and three effluent holding tanks with a total capacity of 200 gallons, but space outside the trailer may be required for additional influent and effluent holding tanks if more holding capacity is needed. Also, an additional area may be required for an office or laboratory building or trailer. During the demonstration, an area of about 100 by 70 feet was used for the E-beam trailer, a 7,500-gallon equalization tank, a mobile laboratory trailer, an office trailer, an outdoor staging area, and miscellaneous equipment.

The E-beam trailer is equipped with influent and effluent ports on the exterior trailer wall. The influent port is plumbed to an influent pump in the pump room that is rated for a maximum flow rate of 50 gpm, and the effluent port is plumbed from the effluent holding tanks. Plumbing must be provided to the influent port from the groundwater well or other feed waste source and from the effluent port to the discharge point.

### **2.5.2 Climate**

All components of the E-beam system used for the demonstration are housed inside the trailer, which provides protection from rain and snow. The trailer is equipped with air conditioning and heating to protect personnel and equipment from extreme temperatures. If the E-beam system is operated intermittently during cold weather, heating is necessary to prevent interior pipes from freezing and to prevent components of the system from contracting and causing air leaks, which can result in loss of the vacuum in the E-beam unit. If below-freezing temperatures are expected for a long period, influent storage tanks and associated plumbing outside the trailer should be insulated or kept in a heated shelter. The E-beam system components should also be protected from heavy precipitation.

### **2.5.3 Utility and Supply Requirements**

The E-beam system may be operated using 480-volt, 3-phase electrical service. The E-beam trailer is also equipped with a diesel-powered generator that allows the system to be operated without an external electrical source. Additional electrical service may be needed to operate groundwater extraction well pumps, light office and laboratory buildings, and on-site office and laboratory equipment, as applicable.

HVEA maintains and services its E-beam systems; therefore, no inventory of spare parts is required.

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

### **2.5.4 Required Support Systems**

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

To prevent problems with solids accumulation, particularly in the influent delivery system of the E-beam unit, particulates should be removed from the influent. Depending on particulate size and concentration, cartridge filters, sand filters, or settling tanks may be used to remove suspended solids. Solids removed from the influent should be dewatered, containerized, and analyzed to determine whether they should be disposed of as hazardous or nonhazardous waste.

If the contaminated water contains carbonate and bicarbonate ions at high levels, pH adjustments may be required. Carbonate and bicarbonate ions act as oxidant scavengers and present an additional load to the treatment system. The only material handling associated with pH adjustment involves handling chemicals such as acids (for pretreatment) and bases (for post-treatment, if required for meeting discharge limits). Adjustment of pH should not create any additional waste streams requiring disposal.

Influent groundwater may contain CO<sub>2</sub> or other gases that are released from solution as bubbles when the groundwater is depressurized as it is brought to the ground surface. A nonpressurized influent holding tank must be provided to allow the bubbles to escape before the influent is pumped under pressure into the E-beam unit.

Treated water can be disposed of either on or off site. Examples of on-site disposal options for treated water include groundwater recharge or temporary on-site storage for sanitary use. Examples of off-site disposal options include discharge into surface water bodies, storm sewers, and sanitary sewers. Bioassay tests may be required in addition to routine chemical and physical analyses before treated water is disposed of.

### **2.5.5 Personnel Requirements**

Personnel requirements for the E-beam system are minimal. Generally, one trained operator is required to conduct a daily system check. The operator should be capable of performing the following: (1) starting-up the system, including beam conditioning (a process involving slowly increasing the accelerating voltage); (2) operating the controls in the control room and the influent pump in the pump room; (3) operating the diesel-powered generator if no external electrical source is available; (4) taking measurements of operational parameters, including flow rate and parameters displayed on the control panel; and (5) collecting samples for off-site analyses.

Before operating the E-beam system at a hazardous waste site, the operator should have completed the training requirements under the Occupational Safety and Health Act (OSHA) outlined in 29 CFR §1910.20, which covers hazardous waste operations and emergency response. The operator should also have completed radiation worker training in accordance with 10 CFR Part 20, which covers standards for protection against radiation. Finally, the operator should participate in a medical monitoring program as specified under OSHA and the Nuclear Regulatory Commission (NRC).

### **2.6 Material Handling Requirements**

Other than the air chiller condensate mentioned in Section 2.4.3, the E-beam system does not generate treatment residuals, such as sludge or spent filter media, that require further processing, handling, or disposal. The E-beam unit and the other components of the system produce no air emissions that require special controls. Pretreatment requirements for contaminated water and post-treatment considerations for treated water are discussed in Section 2.5.4.

### **2.7 Technology Limitations**

Three limiting factors were identified based on the operation of the HVEA demonstration unit (Model M25W-48S): limited operation flow rates, byproduct formation, and operational problems associated with suspended solids in the influent. System operation is limited by the minimum and maximum flow rates at which a single unit can be operated. For example, during the SITE demonstration, system hydraulics required that a minimum flow rate of 15 gpm be maintained for the demonstration unit. If treatment goals are not met while the system operates at the minimum flow rate and at maximum beam

current, the dose cannot be further increased to improve system performance. Such a case would require operating additional E-beam units in series, obtaining a larger E-beam unit, or adding pretreatment or post-treatment, any of which would increase space requirements and costs. According to HVEA, the demonstration unit was configured for a maximum flow rate of 50 gpm. Treatment at a higher flow rate would require modifying the influent delivery system for the unit, operating additional units in parallel, or obtaining a larger unit rated for a greater maximum flow rate; the latter two options would increase space requirements and costs.

Based on research studies performed by HVEA and SITE demonstration results, toxic byproducts are formed when water containing chlorinated and aromatic VOCs is treated by the E-beam system. If byproducts are a concern at a particular site, the E-beam system would need to be operated in such a way that byproduct formation would be reduced to acceptable levels.

A third limiting factor involves the presence of suspended solids in the influent. Fine suspended solids not captured by the strainer basket might clog the influent delivery system for the E-beam unit.

## **2.8 Potential Regulatory Requirements**

This section discusses regulatory requirements pertinent to use of the HVEA technology at Superfund and Resource Conservation and Recovery Act (RCRA) corrective action sites. The regulations applicable to implementation of this technology depend on site-specific remediation logistics and the type of contaminated liquid being treated; therefore, this section presents a general overview of the types of federal regulations that may apply under various conditions. State requirements should also be considered; because these requirements vary from state to state, they are not presented in detail in this section. Table 2-12 summarizes the environmental laws discussed below.

Depending on the characteristics of the liquid to be treated, pretreatment or post-treatment may be required for successful operation of the HVEA system. For example, solids may need to be filtered before treatment; a strainer basket was used to remove particulates larger than 0.045 inch during the SITE demonstration. As another example, if the contaminated liquid exhibits high alkalinity, alkalinity adjustment may be required so that the VOC RE is not impaired (see Section 1.4). Each pretreatment or post-treatment process might involve additional regulatory requirements that would need to be determined in advance. This section focuses on regulations applicable to the HVEA system only.

### **2.8.1 Comprehensive Environmental Response, Compensation, and Liability Act**

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended by SARA, authorizes the federal government to respond to releases of hazardous substances, pollutants, or contaminants that may present an imminent and substantial danger to public health or welfare. Remedial alternatives that significantly reduce the volume,

**Table 2-12. Summary of Regulations**

Act/Authority	Applicability	Application to HVEA Treatment System	Citation
CERCLA	Superfund sites	This program authorizes and regulates the cleanup of environmental contamination. It applies to all CERCLA site cleanups and requires that other environmental laws be considered as appropriate to protect human health and the environment.	40 CFR Part 300
RCRA	Superfund and RCRA sites	RCRA defines and regulates the treatment, storage, and disposal of hazardous wastes. RCRA also regulates corrective action at generator, treatment, storage, and disposal facilities.	40 CFR Parts 260 to 270
CWA	Discharges to surface water bodies	NPDES requirements of CWA apply to both Superfund and RCRA sites where treated water is discharged to surface water bodies. Pretreatment standards apply to discharges to POTWs.	40 CFR Parts 122 to 125, Part 403
SDWA	Water discharges, water reinjection, and sole-source aquifer and wellhead protection	Maximum contaminant levels and contaminant level goals should be considered when setting water cleanup levels at RCRA corrective action and Superfund sites. (Water cleanup levels are also discussed under RCRA and CERCLA.) Reinjection of treated water would be subject to underground injection control program requirements, and sole sources and protected wellhead water sources would be subject to their respective control programs.	40 CFR Parts 141 to 149
CAA	Air emissions from stationary and mobile sources	If O <sub>3</sub> emissions occur or hazardous air pollutants are of concern, these standards may be applicable to ensure that air pollution is not associated with use of this technology. State air program requirements will be important to consider.	40 CFR Parts 50, 60, 61, and 70
TSCA	PCB contamination	If PCB-contaminated wastes are treated, TSCA requirements should be considered when determining cleanup standards and disposal requirements. RCRA also regulates solid waste containing PCBs.	40 CFR Part 761
AEA and RCRA	Mixed wastes	AEA and RCRA requirements apply to the treatment, storage, and disposal of mixed waste containing both hazardous and radioactive components. OSWER and DOE directives provide guidance for addressing mixed waste.	AEA (10 CFR) and RCRA (see above)
OSHA	All remedial actions	OSHA regulates on-site construction activities and the health and safety of workers at hazardous waste sites. Installation and operation of the system at Superfund or RCRA sites must meet OSHA requirements.	29 CFR Parts 1900 to 1926
NRC	All remedial actions	These regulations include radiation protection standards for NRC-licensed activities.	10 CFR Part 20

Acronyms used in this table are defined in text.

toxicity, or mobility of hazardous materials and provide long-term protection are preferred. Selected remedies must also be cost-effective and protective of human health and the environment. Therefore, Superfund site remediation activities must comply with environmental regulations to protect human health and the environment during and after remediation.

Treatment of contaminated liquid using the HVEA system will generally take place on site, while effluent discharge may take place either on or off site. CERCLA requires that on-site actions meet all substantive state and federal ARARs. Substantive requirements (for example, effluent standards) pertain directly to actions or conditions in the environment. Off-site actions must comply with both substantive and administrative ARARs. Administrative requirements (such as permitting) facilitate implementation of substantive requirements. Subject to specific conditions, EPA allows ARARs to be waived for on-site actions. Six ARAR waivers are provided for by CERCLA: (1) interim measures waiver, (2) equivalent standard of performance waiver, (3) greater risk to health and the environment waiver, (4) technical impracticability waiver, (5) inconsistent application of state standard waiver, and (6) fund-balancing waiver. The justification for a waiver must be clearly demonstrated (EPA 1988a). Off-site remediations are not eligible for ARAR waivers, and all applicable substantive and administrative requirements must be met.

CERCLA requires identification and consideration of environmental laws that are ARARs for site remediation before implementation of a remedial technology at a Superfund site. Additional regulations pertinent to use of the HVEA system are discussed in the following sections. No direct air emissions or residuals (such as sludge) are generated by the HVEA treatment process. Condensate is generated from the cooling air when it enters the air chiller, but HVEA states that this liquid can be recirculated through the system. Therefore, only regulations addressing contaminated liquid storage, treatment, and discharge; potential fugitive air emissions; and additional considerations are discussed below.

## **2.8.2 Resource Conservation and Recovery Act**

RCRA, as amended by the Hazardous and Solid Waste Amendments of 1984, regulates management and disposal of municipal and industrial solid wastes. EPA and RCRA-authorized states (listed in 40 CFR Part 272) implement and enforce RCRA and state regulations. Some of the RCRA requirements under 40 CFR Part 264 generally apply at CERCLA sites that contain RCRA hazardous waste because remedial actions generally involve treatment, storage, or disposal of hazardous waste.

According to HVEA, the E-beam system can treat liquid contaminated with most organic compounds, including solvents, pesticides, PAHs, and petroleum hydrocarbons. Contaminated liquid treated by the system may be classified as a RCRA hazardous waste or may be sufficiently similar to a RCRA hazardous waste that RCRA regulations will be applicable requirements. For example, HVEA claims that its technology can treat landfill leachate that meets the hazardous waste char-

acteristics for EPA hazardous waste number F039 (multisource leachate). The F039 number applies to liquid that has percolated through one or more land-disposed RCRA hazardous wastes (40 CFR Parts 260 to 299). Criteria for identifying hazardous wastes are provided in 40 CFR Part 261. Pertinent RCRA requirements are discussed below.

If the contaminated liquid to be treated is determined to be a hazardous waste or is sufficiently similar to a hazardous waste, RCRA requirements for hazardous waste storage and treatment must be met. The HVEA system may require tank storage of hazardous waste liquid before treatment. Tank storage of hazardous waste liquid must meet the requirements of 40 CFR Part 264 or 265, Subpart J.

RCRA Parts 264 and 265, Subparts AA, BB, and CC, address air emissions from hazardous waste treatment, storage, and disposal facilities. Subpart AA regulations apply to process vents associated with specific treatment operations for wastes contaminated with organic constituents. Because the HVEA system has no process vents, these regulations would not be ARARs. Subpart BB regulations apply to fugitive emissions (equipment leaks) from hazardous waste treatment, storage, and disposal facilities that treat waste containing organic concentrations of at least 10% by weight. These regulations address pumps, compressors, open-ended valves or lines, and flanges. Subpart BB regulations could be ARARs if fugitive emissions were found to be associated with the HVEA system. Although no direct air emissions are associated with the HVEA treatment process, any organic air emissions from storage tanks would be subject to the RCRA organic air emission regulations in 40 CFR Parts 264 and 265, Subpart CC. These regulations address air emissions from hazardous waste treatment, storage, and disposal facility tanks, surface impoundments, and containers. The Subpart CC regulations were issued in December 1994 and became effective in July 1995 for facilities regulated under RCRA. Presently, EPA is deferring application of the Subpart CC standards to waste management units used solely to treat or store hazardous waste generated on site from remedial activities required under RCRA corrective action or CERCLA response authorities (or similar state remediation authorities). Therefore, Subpart CC regulations would not immediately impact implementation of the HVEA system. The most important air requirements are probably associated with the Clean Air Act (CAA) and state air toxics programs (see Section 2.8.5).

Use of the HVEA system would constitute treatment as defined by RCRA (40 CFR §260.10). Therefore, treatment requirements may apply if the HVEA system is found to belong to a treatment category classification regulated under RCRA and if it is used to treat a RCRA listed or characteristic waste. Treatment requirements under in 40 CFR Part 264, Subpart X, which regulate hazardous waste storage, treatment, and disposal in miscellaneous units, may be relevant to the HVEA system. Subpart X requires that treatment in miscellaneous units be protective of human health and the environment. Treatment requirements in 40 CFR Part 265, Subpart Q (Chemical, Physical, and Biological Treatment), could also apply. Subpart Q includes requirements for automatic influent shutoff, waste analysis, and trial tests. RCRA also contains special standards

for ignitable or reactive wastes, incompatible wastes, and special categories of waste (40 CFR Parts 264 and 265, Subpart B). These standards may apply to the HVEA system, depending on the waste material to be treated.

The HVEA system may also be used to treat contaminated liquids at RCRA-regulated facilities as part of RCRA corrective actions. Requirements for corrective actions at RCRA-regulated facilities are included in the regulations of 40 CFR Part 264, Subparts F and S; these subparts generally apply to remediation at Superfund sites. The regulations include requirements for initiating and conducting RCRA corrective actions, remediating groundwater, and operating temporary units associated with remediation operations (40 CFR Parts 260 to 299). In states authorized to implement RCRA, any more stringent state RCRA standards must also be addressed.

### **2.8.3 Clean Water Act**

The Clean Water Act (CWA) is designed to restore and maintain the chemical, physical, and biological quality of navigable surface waters by establishing federal, state, and local discharge standards. If treated liquid is discharged to surface water bodies or publicly owned treatment works (POTW), CWA regulations apply. On-site discharges to surface water bodies must meet substantive NPDES requirements but do not require an NPDES permit. A direct discharge of CERCLA wastewater would qualify as “on-site” if the receiving water body is in the area of contamination or in very close proximity to the site and if the discharge is necessary to implement the response action. Off-site discharges to a surface water body require an NPDES permit and must meet NPDES permit discharge limits. Discharge to a POTW is considered to be an off-site activity, even if an on-site sewer is used. Therefore, compliance with substantive and administrative requirements of the National Pretreatment Program is required in such a case. General pretreatment regulations are included in 40 CFR Part 403.

Any applicable local or state requirements, such as local or state pretreatment requirements or water quality standards (WQS), must also be identified and satisfied. State WQSs are designed to protect existing and attainable surface water uses (for example, recreation and public water supply). WQSs include surface water use classifications and numerical or narrative standards (including effluent toxicity standards, chemical-specific requirements, and bioassay requirements to demonstrate no observable effect level [NOEL] from a discharge) (EPA 1988a). These standards should be reviewed on a state- and location-specific basis before discharges are made to surface water bodies. During the SITE demonstration, bioassay tests were conducted to determine whether the treated liquid was toxic to particular aquatic species. Similar bioassay tests might be required if the HVEA system is implemented in particular states and if it discharges treated liquids to surface water bodies.

### **2.8.4 Safe Drinking Water Act**

The SDWA, as amended in 1986, required EPA to establish regulations to protect human health from contaminants in drinking water. EPA has developed the following programs to achieve this objective: (1) a drinking water standards program, (2) an

underground injection control program, and (3) sole-source aquifer and wellhead protection programs.

SDWA primary (or health-based) and secondary (or aesthetic) maximum contaminant levels (MCL) generally apply as cleanup standards for water that is, or may be, used as drinking water. In some cases, such as when multiple contaminants are present, more stringent maximum contaminant level goals (MCLG) may be appropriate. In other cases, alternate concentration limits (ACL) based on site-specific conditions may be applied. CERCLA and RCRA standards and guidance should be used in establishing ACLs (EPA 1987a). During the SITE demonstration, HVEA treatment system performance was tested for compliance with SDWA MCLs for several critical VOCs.

Water discharge through injection wells is regulated by the underground injection control program. Injection wells are categorized as Classes I through V, depending on their construction and use. Reinjection of treated water involves Class IV (reinjection) or Class V (recharge) wells and should meet SDWA requirements for well construction, operation, and closure. If the groundwater treated is a RCRA hazardous waste, the treated groundwater must meet RCRA Land Disposal Restriction (LDR) treatment standards (40 CFR Part 268) before reinjection.

The sole-source aquifer and wellhead protection programs are designed to protect specific drinking water supply sources. If such a source is to be remediated using the HVEA system, appropriate program officials should be notified, and any potential regulatory requirements should be identified. State groundwater antidegradation requirements and WQSs may also apply.

### **2.8.5 Clean Air Act**

The CAA, as amended in 1990, regulates stationary and mobile sources of air emissions. CAA regulations are generally implemented through combined federal, state, and local programs. The CAA includes chemical-specific standards for major stationary sources that would not be applicable but could be relevant and appropriate for HVEA system use. For example, the HVEA system would usually not be a major source as defined by the CAA, but it could emit  $O_3$ , which is a criteria pollutant under the CAA’s National Ambient Air Quality Standards (NAAQS). Therefore, the HVEA system may need to be controlled to ensure that air quality is not impacted. This would be particularly pertinent in localities that are “non-attainment” areas for  $O_3$ . The National Emission Standards for Hazardous Air Pollutants (NESHAP) could also be relevant and appropriate if regulated hazardous air pollutants are emitted and if the treatment process is considered sufficiently similar to one regulated under these standards. In addition, New Source Performance Standards (NSPS) could be relevant and appropriate if the pollutant emitted and the HVEA system are sufficiently similar to a pollutant and source category regulated by an NSPS. Finally, state and local air programs have been delegated significant air quality regulatory responsibilities, and some have developed programs to regulate toxic air pollutants (EPA 1989). Therefore, state air programs should be consulted regarding HVEA treatment technology installation and use.

## 2.8.6 Toxic Substances Control Act

Testing, premanufacture notification, and record-keeping requirements for toxic substances are regulated under the Toxic Substances Control Act (TSCA). TSCA also includes storage requirements for polychlorinated biphenyls (PCB) (see 40 CFR §761.65). The HVEA system may be used to treat liquid contaminated with PCBs, and TSCA requirements would apply to pretreatment storage of PCB-contaminated liquid. The SDWA MCL for PCBs is 0.05 µg/L; this MCL is generally the treatment standard for groundwater remediation at Superfund and RCRA corrective action sites. RCRA LDRs for PCBs may also apply, depending on PCB concentrations (see 40 CFR Part 268). For example, treatment of liquid hazardous waste containing PCB concentrations equal to or greater than 50 ppm must meet the treatment requirements of 40 CFR §761.70.

## 2.8.7 Mixed Waste Regulations

As defined by the Atomic Energy Act (AEA) and RCRA, mixed waste contains both radioactive and hazardous components. Such waste is subject to the requirements of both acts. However, when application of both AEA and RCRA regulations results in a situation that is inconsistent with the AEA (for example, an increased likelihood of radioactive exposure), AEA requirements supersede RCRA requirements (EPA 1988a). Use of the HVEA system at sites with radioactive contamination might involve treatment or generation of mixed waste.

OSWER, in conjunction with the NRC, has issued several directives to assist in identification, treatment, and disposal of low-level radioactive, mixed waste. Various OSWER directives include guidance on defining, identifying, and disposing of commercial, mixed, low-level radioactive and hazardous waste (EPA 1987b). If the HVEA system is used to treat low-level mixed waste, these directives should be considered. If high-level mixed waste or transuranic mixed waste is treated, internal DOE orders should be considered when developing a protective remedy (DOE 1988). The SDWA and CWA also contain standards for maximum allowable radioactivity levels in water supplies.

## 2.8.8 Occupational Safety and Health Act

OSHA regulations in 29 CFR Parts 1900 through 1926 are designed to protect worker health and safety. Both Superfund and RCRA corrective actions must meet OSHA requirements, particularly §1910.120, Hazardous Waste Operations and Emergency Response. Part 1926, Safety and Health Regulations for Construction, applies to any on-site construction activities. For example, electric utility hookups for the HVEA system must comply with Part 1926, Subpart K, Electrical. Product chemicals such as H<sub>2</sub>O<sub>2</sub>, sulfuric acid, and sodium hydroxide, if used with the HVEA system, must be managed in accordance with OSHA requirements (for example, Part 1926, Subpart D, Occupational Health and Environmental Controls, and Subpart H, Materials Handling, Storage, and Disposal). Any more stringent state or local requirements must also be met. In addition, health and safety plans for site remediations should address chemicals of concern and include monitoring practices to ensure that worker health and safety are maintained.

## 2.8.9 Additional Considerations

The HVEA system generates a high-energy stream of electrons (ionizing radiation). These electrons are primarily directed to a contaminated liquid stream. However, some other radiation (x-ray) is generated when stray electrons hit metal components of the system. Therefore, regulations covering radiation-generating equipment could be considered ARARs. At the SRS, DOE regulations for radiation-generating equipment were applied. However, the HVEA system is totally enclosed, and with adequate lead shielding of the E-beam trailer, radiation monitoring did not reveal any OSHA compliance problems. Most equipment of this nature is regulated at a state level (for example, x-ray and other medical and laboratory equipment).

Relevant standards for protection against radiation are included in the NRC regulations of 10 CFR Part 20. These standards are designed to limit radiation hazards caused by NRC-licensed activities. The regulations apply to all NRC licensees regardless of the type or quantity of radioactive material possessed or the type of operations conducted. These regulations require that (1) levels of radiation and dose be “as low as is reasonably achievable” and (2) radiation exposure limits for worker and public protection in 10 CFR Part 20 be met. The HVEA system had a health and rehabilitative services (HRS) license issued by the State of Florida at the time of the SITE demonstration. Additional state-specific requirements should also be considered.

## 2.9 State and Community Acceptance

Because few applications of the E-beam technology have been attempted beyond the bench or pilot scale, limited information is available to assess state and community acceptance of the technology. Therefore, this section discusses state and community acceptance of the E-beam technology with regard to the SITE demonstration.

Before the demonstration, the primary concerns of the South Carolina Department of Health and Environmental Control (SCDHEC) involved the ability of the E-beam system to meet effluent target levels and the formation of treatment byproducts. These concerns were addressed by performing calculations to show that no environmental impact was anticipated because any treatment residuals in the E-beam system effluent would be removed by a permitted air stripper. At other sites, state acceptance of the technology may involve consideration of performance data from applications such as the SITE demonstration and results from on-site, pilot-scale studies using the actual waste to be treated during later, full-scale remediation.

During the SITE demonstration, about 100 people from SCDHEC, EPA Region 4, nearby universities, and the local community attended Visitors’ Day to observe demonstration activities and ask questions pertaining to the technology. The visitors expressed no concerns regarding operation of the E-beam system.

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## Section 3

### Economic Analysis

This economic analysis presents cost estimates for using the HVEA E-beam technology to treat groundwater contaminated with VOCs. Cost data were compiled during the SITE demonstration at the SRS and from information obtained from independent vendors and HVEA. Costs have been placed in 12 categories applicable to typical cleanup activities at Superfund and RCRA sites (Evans 1990). Costs are presented in February 1995 dollars and are considered to be order-of-magnitude estimates with an expected accuracy within 50% above and 30% below the actual costs.

This section describes two cases selected for economic analysis (Section 3.1), summarizes the major issues involved and assumptions made in performing the analysis (Section 3.2), discusses costs associated with using the HVEA E-beam technology to treat groundwater contaminated with VOCs (Section 3.3), and presents conclusions of the economic analysis (Section 3.4).

#### 3.1 Introduction

The economic analysis presents and compares the two cases based on groundwater characteristics. In Case 1, the groundwater has an insignificant level of alkalinity ( $<5$  mg/L as  $\text{CaCO}_3$ ) and contains VOCs that are easy to destroy using free radical chemistry. In Case 2, the groundwater has moderate to high alkalinity (500 mg/L as  $\text{CaCO}_3$ ) and contains additional VOCs, a few of which are more difficult to destroy. In Case 1, a 21-kilowatt (kW) system is used to treat groundwater at 40 gpm; in Case 2, the same system is used to treat the groundwater at 20 gpm.

Tables 3-1 and 3-2 present the costs evaluated in this analysis for Case 1 and Case 2, respectively. Additional analysis is provided in these tables that compares the costs of addressing both cases with a 45-kW system and a 75-kW system. In Case 1, the 45-kW system treats groundwater at 80 gpm, and the 75-kW unit treats it at 130 gpm. In Case 2, the 45-kW system treats groundwater at 40 gpm, and the 75-kW unit treats it at 65 gpm.

#### 3.2 Issues and Assumptions

This section summarizes major issues and assumptions regarding site-specific factors, equipment and operating parameters, and financial calculations used in this economic analysis of the E-beam technology. Issues and assumptions are presented in Sections 3.2.1 through 3.2.3. Assumptions are summarized in bullets following each section. Certain assumptions were made

to account for variable site and waste parameters. Other assumptions were made to simplify cost estimating for situations that actually would require complex engineering or financial functions. Section 3.2.4 provides a hypothetical base-case scenario developed from the assumptions.

In general, E-beam system operating issues and assumptions are based on information provided by HVEA and observations made during the SITE demonstration. Other issues and assumptions are based primarily on the operating parameters and results observed during Runs 3 and 13 of the demonstration.

##### 3.2.1 Site-Specific Factors

Site-specific factors can affect the costs of using the E-beam treatment system. These factors can be divided into the following two categories: waste-related factors and site features.

Waste-related factors affecting costs include waste volume, contaminant types and levels, treatment goals, and regulatory requirements. Waste volume affects total project costs because a larger volume takes longer to remediate. However, economies of scale are realized with a larger-volume project when the fixed costs, such as equipment costs, are distributed over the larger volume. The contaminant types and levels in the groundwater and the treatment goals for the site determine (1) the appropriate E-beam treatment system size, which affects capital equipment costs; (2) the flow rate at which treatment goals can be met; and (3) periodic sampling requirements, which affect analytical costs. Regulatory requirements affect permitting costs and effluent monitoring costs.

Site features affecting costs include groundwater recharge rates, groundwater chemistry, site accessibility, availability of utilities, and geographic location. Groundwater recharge rates affect the time required for cleanup. Groundwater alkalinity may increase or decrease E-beam technology REs depending on the contaminant involved (see Section 2.2.8 for a discussion of alkalinity). Site accessibility, availability of utilities, and site location and size all affect site preparation costs.

Site-specific assumptions include the following:

- For Case 1, the contaminants and their average concentrations are TCE at 28,000  $\mu\text{g/L}$  and PCE at 11,000  $\mu\text{g/L}$ .

**Table 3-1.** Costs Associated with the E-Beam Technology—Case 1<sup>a</sup>

Cost Categories	Treatment System Configurations in Kilowatts (kW)					
	21-kW (40 gpm)		45-kW (80 gpm)		75-kW (130 gpm)	
	Itemized	Total	Itemized	Total	Itemized	Total
Site Preparation <sup>b</sup>		\$175,600		\$219,600		\$241,600
Administrative	\$35,000		\$35,000		\$35,000	
Treatment area preparation	117,600		161,600		183,600	
Treatability study and system design	23,000		23,000		23,000	
Permitting and Regulatory <sup>b</sup>		5,000		5,000		5,000
Mobilization and Startup <sup>b</sup>		20,000		25,000		25,000
Transportation	10,000		10,000		10,000	
Assembly and shakedown	10,000		15,000		15,000	
Equipment <sup>b</sup>		842,000		1,208,000		1,432,000
Labor <sup>c</sup>		10,000		10,000		10,000
Supplies <sup>c</sup>		1,700		1,700		1,700
Disposable personal protective equipment	600		600		600	
Fiber drums	100		100		100	
Sampling supplies	1,000		1,000		1,000	
Utilities <sup>c</sup>		25,700		52,600		87,500
Effluent Treatment and Disposal <sup>c</sup>		0		0		0
Residual Waste Shipping and Handling <sup>c</sup>		6,000		6,000		6,000
Analytical Services <sup>c</sup>		24,000		24,000		24,000
Equipment Maintenance <sup>c</sup>		25,300		36,200		43,000
Site Demobilization <sup>b</sup>		15,000		15,000		15,000
Total One-Time Costs <sup>b</sup>		\$1,057,600		\$1,472,600		\$1,718,600
Total Annual O&M Costs <sup>c</sup>		92,700		130,500		172,200
Groundwater Remediation:						
Total costs <sup>d,e,f</sup>		\$2,764,000		\$2,514,400		\$2,527,900
Net present value <sup>g</sup>		1,626,600		1,963,700		2,223,400
Costs per 1,000 Gallons <sup>h</sup>		\$5.16		\$6.23		\$7.06

<sup>a</sup> Costs are in February 1995 dollars.

<sup>b</sup> Fixed costs.

<sup>c</sup> Annual variable costs.

<sup>d</sup> Fixed and variable costs combined.

<sup>e</sup> Future value using annual inflation rate of 5%.

<sup>f</sup> To complete groundwater remediation, it is assumed that the 21-kW unit will take 15 years, the 45-kW unit will take 7.5 years, and the 75-kW unit will take 4.6 years to treat 315 million gallons of water.

<sup>g</sup> Annual discount rate of 7.5%.

<sup>h</sup> Net present value.

- For Case 1, the groundwater has an insignificant alkalinity of <5 mg/L as CaCO<sub>3</sub>.
- For Case 2, some of the additional contaminants are saturated VOCs that are relatively difficult to treat. These VOCs are 1,1,1-TCA, 1,2-DCA, chloroform, and CCl<sub>4</sub>; their concentrations range from 370 to 840 µg/L. The other additional contaminants are BTEX compounds present at concentrations ranging from 200 to 550 µg/L.
- For Case 2, the groundwater has a moderate alkalinity of 500 mg/L as CaCO<sub>3</sub>.
- The site is a Superfund site located near an urban area. As a result, utilities and other infrastructure features (for example, access roads to the site) are readily available.
- The site is located in the southeastern United States. This region has relatively mild temperatures during the winter months.
- Contaminated water is located in an aquifer no more than 100 feet below ground surface.
- The groundwater remediation project involves a total of 315 million gallons of water that needs to be

**Table 3-2** Costs Associated with the E-Beam Technology—Case 2<sup>a</sup>

Cost Categories	Treatment System Configurations in Kilowatts (kW)					
	21-kW (20 gpm)		45-kW (40 gpm)		75-kW (65 gpm)	
	Itemized	Total	Itemized	Total	Itemized	Total
Site Preparation <sup>b</sup>		\$175,600		\$219,600		\$241,600
Administrative	\$35,000		\$35,000		\$35,000	
Treatment area preparation	117,600		161,600		183,600	
Treatability study and system design	23,000		23,000		23,000	
Permitting and Regulatory <sup>b</sup>		5,000		5,000		5,000
Mobilization and Startup <sup>b</sup>		20,000		25,000		25,000
Transportation	10,000		10,000		10,000	
Assembly and shakedown	10,000		15,000		15,000	
Equipment <sup>b</sup>		842,000		1,208,000		1,432,000
Labor <sup>c</sup>		10,000		10,000		10,000
Supplies <sup>c</sup>		1,700		1,700		1,700
Disposable personal protective equipment	600		600		600	
Fiber drums	100		100		100	
Sampling supplies	1,000		1,000		1,000	
Utilities <sup>c</sup>		25,700		52,600		87,500
Effluent Treatment and Disposal <sup>c</sup>		0		0		0
Residual Waste Shipping and Handling <sup>c</sup>		6,000		6,000		6,000
Analytical Services <sup>c</sup>		24,000		24,000		24,000
Equipment Maintenance <sup>c</sup>		25,300		36,200		43,000
Site Demobilization <sup>b</sup>		15,000		15,000		15,000
Total One-Time Costs <sup>b</sup>		\$1,057,600		\$1,472,600		\$1,718,600
Total Annual O&M Costs <sup>c</sup>		92,700		130,500		172,200
Groundwater Remediation:						
Total costs <sup>d,e,f</sup>		\$6,281,600		\$3,994,600		\$3,547,200
Net present value <sup>g</sup>		2,472,900		2,350,700		2,618,100
Costs per 1,000 Gallons <sup>h</sup>		\$7.85		\$7.46		\$8.31

<sup>a</sup> Costs are in February 1995 dollars.

<sup>b</sup> Fixed costs.

<sup>c</sup> Annual variable costs.

<sup>d</sup> Fixed and variable costs combined.

<sup>e</sup> Future value using annual inflation rate of 5%.

<sup>f</sup> To complete groundwater remediation, it is assumed that the 21-kW unit will take 30 years, the 45-kW unit will take 15 years, and the 75-kW unit will take 9.3 years to treat 315 million gallons of water.

<sup>g</sup> Annual discount rate of 7.5%.

<sup>h</sup> Net present value.

treated. This groundwater volume corresponds to the volume treated by a 21-kW unit operating continuously for 15 years at a flow rate of 40 gpm.

### 3.2.2 Equipment and Operating Parameters

The E-beam treatment system can be used to treat aqueous waste streams such as groundwater and wastewater contaminated with VOCs and SVOCs. This analysis provides costs for treating groundwater contaminated with VOCs only.

HVEA will provide the appropriate E-beam system configuration based on site-specific conditions, of which groundwater recharge rates and contaminant types are the primary consider-

ations. The E-beam system can be configured to meet certain power requirements by varying the accelerating voltage and beam current, which are also derived from site conditions. The E-beam system is modular in design, which allows for setting up modules either in series or in parallel to treat groundwater.

This analysis focuses on the costs associated with the 21-kW unit demonstrated at SRS. This E-beam system can treat contaminated groundwater at a rate of 40 gpm in Case 1 and 20 gpm in Case 2. The system can operate on a continuous flow cycle, 24 hours per day, 7 days per week. Based on these assumptions, the system can treat nearly 21 million gallons per year in Case 1, and the system can treat about 10.5 million gallons per year in Case 2. Because most groundwater remedia-

tion projects are long-term projects, this analysis assumes that about 315 million gallons of water needs to be treated in both cases to complete the groundwater remediation project. Based on this assumption, Case 1 remediation will take about 15 years to complete, and Case 2 remediation will take about 30 years to complete. It is difficult in practice to determine both the volume of groundwater to treat and the actual duration of a project, but these figures have been assumed to perform this economic analysis.

Neither depreciation nor salvage value is applied to the costs presented in this analysis because the equipment is not purchased by a customer. All depreciation and salvage value is assumed to be incurred by HVEA and is reflected in the ultimate cost of leasing the E-beam treatment equipment.

Equipment and operating parameter assumptions are listed below.

- A 21-kW system is used as the basis of the economic analysis discussion, and costs for 45-kW and 75-kW systems are presented in Tables 3-1 and 3-2 for comparison.
- The treatment system is operated 24 hours per day, 7 days per week, 52 weeks per year.
- The treatment system operating at full power has a maximum voltage of 500 kV and a maximum beam current of 42 mA.
- The treatment system operates automatically without the constant attention of an operator and will shut down in the event of system malfunction.
- Modular components consisting of the equipment needed to meet treatment goals are mobilized to the site and assembled by HVEA.
- Air emissions monitoring is not necessary.
- E-beam equipment will be maintained by HVEA and will last for the duration of the groundwater remediation project with proper maintenance.

### 3.2.3 Financial Calculations

Most groundwater remediation projects are long-term in nature. For this reason, the total costs for completing the groundwater remediation projects presented in this analysis are calculated using the time periods stated for each case. In the tables included in this section, total costs for each case are presented in future values, and the costs per 1,000 gallons treated are presented as net present values. This analysis assumes a 5% annual inflation rate to estimate the future values. The future values are then presented as net present values using a discount rate of 7.5%, which is the current yield on a 30-year Treasury bond. Using a higher discount rate makes the initial costs weigh more heavily in the calculation, while using a lower discount rate makes the future operating costs weigh more heavily. Because the costs of demobilization will occur at the end of the project, the appropriate future values of these costs were used to

calculate the totals presented at the bottom of Tables 3-1 and 3-2.

### 3.2.4 Base-Case Scenario

A hypothetical base-case scenario has been developed using the issues and assumptions described above for the purposes of formulating this economic analysis. The costs presented in the text are for the 21-kW system. As stated earlier, Case 1 involves treatment of contaminated groundwater by the 21-kW system at a flow rate of 40 gpm, and Case 2 involves treatment of contaminated groundwater by the 21-kW system at a flow rate of 20 gpm. Tables 3-1 and 3-2 provide the costs for the 21-kW system as well as for a 45-kW system and a 75-kW system. Certain costs are higher for these scenarios; where this is the case, an explanation is provided in the text.

Additional premises used for this base-case scenario are listed below.

- Costs are rounded to the nearest \$100.
- Contaminated groundwater is treated to achieve the REs observed in SITE demonstration Runs 3 and 13 for Cases 1 and 2, respectively. During the demonstration, the effluent did not meet all MCLs or other applicable target cleanup levels that are usually required to be met at Superfund sites. For this reason, the costs presented in this analysis may need to be adjusted based on site-specific goals.
- The E-beam system is mobilized to the remediation site from within 500 miles of the site.
- Operating and sampling labor costs are incurred by the client. HVEA performs maintenance and modification activities that are paid for by the client.
- Initial operator training is provided by HVEA.
- Four groundwater extraction wells already exist on site. They are assumed to be capable of providing the flow rates discussed in this economic analysis.

### 3.3 Cost Categories

Tables 3-1 and 3-2 present cost breakdowns addressing the 12 cost categories applied to Cases 1 and 2, respectively. The tables present cost breakdowns for the base-case scenario using the 21-kW treatment system; costs for the 45-kW and 75-kW treatment systems are also provided for comparison.

Cost data associated with the E-beam technology have been presented for the following categories: (1) site preparation, (2) permitting and regulatory, (3) mobilization and startup, (4) equipment, (5) labor, (6) supplies, (7) utilities, (8) effluent treatment and disposal, (9) residual waste shipping and handling, (10) analytical services, (11) equipment maintenance, and (12) site demobilization. Each of these cost categories is discussed below.

### 3.3.1 Site Preparation Costs

Site preparation costs include administrative, treatment area preparation, treatability study, and system design costs. For this analysis, site preparation administrative costs, such as costs for legal searches, access rights, and site planning activities, are estimated to be \$35,000.

Treatment area preparation includes constructing a shelter building and installing pumps, valves, and piping from the extraction wells to the shelter building. The shelter building needs to be constructed before mobilization of the E-beam system. A 400-square-foot building is required for the 21-kW system. The 45-kW system requires 800 square feet of building space, and the 75-kW system requires 1,000 square feet of building space. HVEA will provide the shelter building design specifications. Construction costs are estimated to be about \$110 per square foot, which covers installation of radiation shielding materials. A natural gas heating and cooling unit and ductwork cost about \$20,000 installed. The total shelter building construction costs for the 21-kW system are estimated to be \$64,000.

This analysis assumes that four extraction wells exist on site and that they are located 200 feet from the shelter building. Four 35-gpm, 1.5-horsepower, variable-speed Teflon<sup>®</sup> pumps are required to maintain the flow rates necessary for each case. The total pump costs, including all electrical equipment and installation, are \$5,600. Piping and valve connection costs are about \$60 per foot, which covers underground installation. Therefore, the total piping costs are \$48,000. The total treatment area preparation costs are estimated to be \$117,600.

A treatability study and system design will be conducted by HVEA before it determines the appropriate E-beam treatment system. HVEA will transport its mobile system to the site to test the equipment under site conditions. Six to eight samples will be collected from the influent and effluent and will be analyzed off site for VOCs. HVEA estimates the treatability study cost to be \$18,000, including labor and equipment costs. System design includes determining which E-beam system will achieve treatment goals and designing the configuration. The system design is estimated to cost \$5,000.

Total site preparation costs for each case are estimated to be \$175,600.

### 3.3.2 Permitting and Regulatory Costs

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

Permitting and regulatory costs in this analysis include permit fees for discharging treated water to a surface water body. The cost of this permit would be based on regulatory agency re-

quirements and treatment goals for a particular site. In general, for this analysis, discharge levels must remain within SDWA limits. The discharge permit for each case is estimated to cost \$5,000. Costs of highway permits for overweight vehicles are included in the costs of mobilization because HVEA retains the services of a cartage company to mobilize the E-beam equipment (see Section 3.3.3).

### 3.3.3 Mobilization and Startup Costs

Mobilization and startup costs include the costs of transporting the E-beam system to the site, assembling the E-beam system, and performing the initial shakedown of the treatment system. HVEA provides trained personnel to assemble and conduct preliminary tests on the E-beam system. HVEA personnel are assumed to be trained in hazardous waste site health and safety procedures, so health and safety training costs are not included as a direct startup cost. Initial operator training is needed to ensure safe, economical, and efficient operation of the system. HVEA provides initial operator training to its clients as part of providing the E-beam equipment.

Transportation costs are site-specific and vary depending on the location of the site in relation to the equipment. For this analysis, the E-beam equipment is assumed to be transported 1,000 miles. HVEA retains the services of a cartage company to transport all E-beam treatment system equipment. Mobilization costs are about \$10 per mile, for a total cost of \$10,000. The costs of highway permits for overweight vehicles are included in this total cost.

Assembly costs include the costs of unloading equipment from the trailers, assembling the E-beam system, hooking up extraction well piping, and hooking up electrical lines. A two-person crew will work three 8-hour days to unload and assemble the system and perform the initial shakedown. The total startup costs are about \$10,000, including labor and hookup costs.

For the 45-kW and 75-kW scenarios, completion of initial assembly and shakedown activities is expected to require the two-person crew to work about five 8-hour days. More time is needed because the E-beam systems are larger in these scenarios. As a result, the startup costs for these scenarios are about \$15,000, including labor and electrical hookup costs.

Total mobilization and startup costs for each case are estimated to be \$20,000.

### 3.3.4 Equipment Costs

Equipment costs include the costs of leasing the E-beam treatment system. HVEA provides the complete E-beam treatment system configured for site-specific conditions. All E-beam treatment equipment is leased to the client. As a result, all depreciation and salvage value is incurred by HVEA, which is reflected in the price for leasing the equipment. At the end of a treatment project, HVEA decontaminates and demobilizes its treatment equipment (see Section 3.3.12, Site Demobilization Costs). HVEA assumes that this equipment will operate for the duration of the groundwater remediation project and will still function after the remediation is complete as a result of routine maintenance and modifications.

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Equipment costs are determined by the size of the E-beam system needed to complete the remediation project and are incurred as a lump sum; as a result, even though the equipment is leased to the client, it is not priced out at a monthly rate. For this analysis, HVEA estimates that the capital equipment for both cases costs \$842,000 for a 21-kW system; \$1,208,000 for a 45-kW system; and \$1,432,000 for a 75-kW system.

### **3.3.5 Labor Costs**

Once the system is functioning, it is assumed to operate continuously at the designed flow rate except during routine maintenance, which HVEA conducts (see Section 3.3.11, Equipment Maintenance Costs). One operator trained by HVEA performs routine equipment monitoring and sampling activities. Under normal operating conditions, an operator is required to monitor the system about once each week.

This analysis assumes that the work is conducted by a full-time employee of the site owner and is assigned to be the primary operator to perform system monitoring and sampling duties. Further, it is assumed that a second person, also employed by the site owner, will be trained to act as a backup to the primary operator. Based on observations made at the SITE demonstration, it is estimated that operation of the system requires about one-quarter of the primary operator's time. Assuming that the primary operator earns \$40,000 per year, the total direct annual labor costs for each case are estimated to be \$10,000.

### **3.3.6 Supply Costs**

No chemicals or treatment additives are expected to be needed to treat the groundwater using the E-beam technology. Therefore, no direct supply costs are expected to be incurred. Supplies that will be needed as part of the overall groundwater remediation project include Level D, disposable personal protective equipment (PPE), PPE disposal drums, and sampling and field analytical supplies.

Disposable PPE typically consists of latex inner gloves, nitrile outer gloves, radiation badges, and safety glasses. This PPE is needed during periodic sampling activities. Disposable PPE for each case is assumed to cost about \$600 per year for the primary operator. Used PPE is assumed to be hazardous and needs to be disposed of in 24-gallon, fiber drums. One drum is assumed to be filled every two months, and each drum costs about \$12. For each case, the total annual drum costs are about \$100.

Sampling supplies consist of sample bottles and containers, ice, labels, shipping containers, and laboratory forms for off-site analyses. For routine monitoring, laboratory glassware is also needed. The numbers and types of sampling supplies needed are based on the analyses to be performed. Costs for laboratory analyses are presented in Section 3.3.10. For each case, sampling supply costs are assumed to be \$1,000 per year.

During the demonstration at SRS, the average pH level of the influent was about 4.7; the average pH level of the effluent ranged between 3.0 and 3.5. Depending on discharge permit levels and influent and effluent pH levels, the pH may require

adjustment. In this event, additional supplies will be necessary. The quantity of supplies needed is highly site-specific and difficult to determine; therefore, this analysis does not present post-treatment pH adjustment costs.

Total annual supply costs for each case are estimated to be \$1,700.

### **3.3.7 Utility Costs**

Electricity is the only utility used by the E-beam system. Electricity is used to run the E-beam treatment system, pumps, blower, and air chiller. This analysis assumes that electrical power lines are available at the site. Electricity costs can vary considerably depending on the geographical location of the site and local utility rates. Also, the consumption of electricity varies depending on the E-beam system used, the total number of pumps and other electrical equipment operating, and the use of the air chiller.

This analysis assumes a constant rate of electricity consumption based on the electrical requirements of the E-beam treatment system (21-kW). The pumps, blower, and air chiller are assumed to draw an additional 20 kW, which is based on observations made during the SITE demonstration at SRS. Therefore, the 21-kW unit operating for one hour draws about 42 kW hours (kWh) of electricity. The total annual electrical energy consumption is estimated to be about 366,910 kWh. Electricity is assumed to cost \$0.07 per kWh, including demand and usage charges. The total annual electricity costs for each case are estimated to be about \$25,700. The total annual electricity costs are estimated to be \$52,600 for the 45-kW system and \$87,500 for the 75-kW system.

Water and natural gas usage are highly site specific but assumed to be minimal for each case in this analysis. As a result, no costs for these utilities are presented.

### **3.3.8 Effluent Treatment and Disposal Costs**

At the SRS demonstration, the E-beam system did not meet target treatment levels for about half of the VOCs. Depending on the treatment goals for a site, additional effluent treatment may be required, and thus additional treatment or disposal costs may be incurred. Because of the uncertainty associated with additional treatment or disposal costs, this analysis does not include effluent treatment or disposal costs.

The E-beam system does not produce air emissions because the water delivery and cooling air systems are enclosed. As a result, no cost for air emissions treatment is incurred.

Effluent monitoring is routinely conducted by the primary operator (see Section 3.3.5). The effluent can be discharged directly to a nearby surface water body, provided that appropriate permits have been obtained (see Section 3.3.2).

### **3.3.9 Residual Waste Shipping and Handling Costs**

The only residuals produced during E-beam system operation are fiber drums containing used PPE and waste sampling and

field analytical supplies, all of which are typically associated with a groundwater remediation project. This waste is considered hazardous and requires disposal at a permitted facility. For each case, this analysis assumes that about six drums of waste are disposed of annually. The cost of handling and transporting the drums and disposing of them at a hazardous waste disposal facility is about \$1,000 per drum. The total drum disposal costs for each case are about \$6,000 per year.

Condensate is generated from the air chiller. This condensate can be treated by the E-beam system, but such treatment may require additional permits from regulatory authorities. Because of the uncertainty associated with the need for additional permits, the costs for such additional permits were not included in this analysis.

### **3.3.10 Analytical Services Costs**

Required sampling frequencies and number of samples are highly site specific and are based on treatment goals and contaminant concentrations. Analytical costs associated with a groundwater remediation project include the costs of laboratory analyses, data reduction, and QA/QC. This analysis assumes that one sample of untreated water, one sample of treated water, and associated QC samples (trip blanks, field duplicates, and matrix spike/matrix spike duplicates) will be analyzed for VOCs every month. Therefore, monthly analytical costs are about \$2,000.

The total annual analytical costs for each case are estimated to be \$24,000.

### **3.3.11 Equipment Maintenance Costs**

HVEA estimates that annual equipment maintenance costs are about 3% of the capital equipment costs. Therefore, the total annual equipment maintenance costs for each case are about \$25,300 for the 21-kW system, \$36,200 for the 45-kW system, and \$43,000 for the 75-kW system.

### **3.3.12 Site Demobilization Costs**

Site demobilization includes treatment system shutdown, disassembly, and decontamination; site cleanup and restoration; utility disconnection; and transportation of the E-beam equipment off site. A two-person crew will work about five 8-hour days to disassemble and load the system. This analysis assumes that the equipment will be transported 1,000 miles either for storage or to the next job site. HVEA estimates that the total cost of demobilization is about \$15,000 for each case. This total includes all labor, material, and transportation costs.

## **3.4 Conclusions of Economic Analysis**

This analysis presents cost estimates for treating contaminated groundwater with the E-beam treatment system. Two cases based on groundwater characteristics are presented and compared. In Case 1, the groundwater contains contaminants that are easy to destroy using free radical chemistry. In Case 2, the groundwater contains additional contaminants, some of which are more difficult to destroy. In both cases, a 21-kW treatment system is used; however, in Case 1 groundwater is treated at a rate of 40 gpm, while in Case 2 it is treated at a rate of 20 gpm.

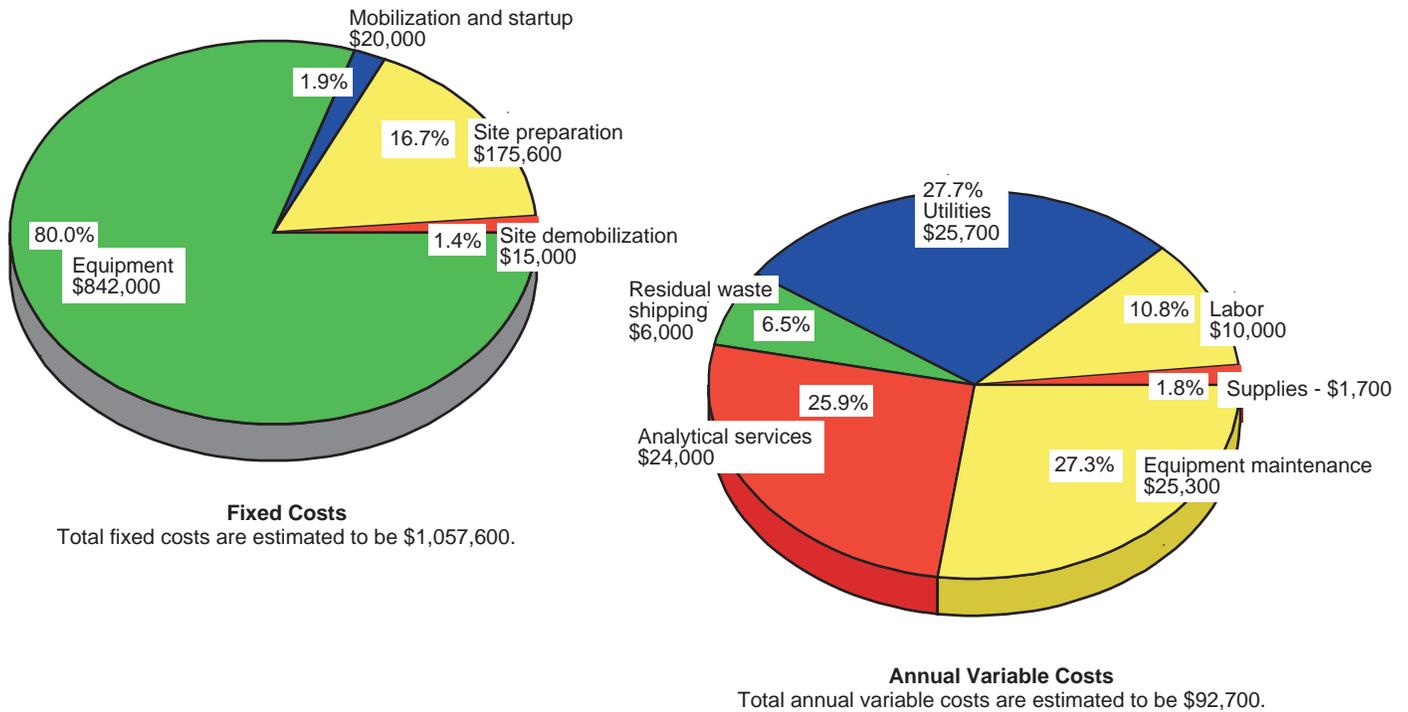
Additional analyses are provided in Tables 3-1 and 3-2 that compare the costs of treatment using a 45-kW system and a 75-kW system for both cases.

Figure 3-1 shows the fixed and annual variable costs for both cases. Total costs and percentages of the totals are presented. Permitting and regulatory costs are not included in Figure 3-1 because they represent less than 0.5% of the total fixed costs. Total estimated fixed costs are about \$1,057,600 for each case. Of this total, \$842,000 or about 80% is for E-beam equipment costs. Over 16% of the total fixed cost is for site preparation; this cost is not entirely attributable to operating the treatment system but rather is necessary for setting up the system. Total estimated annual variable costs are about \$92,700 for each case. Of the total annual variable costs, analytical service costs make up about 26%, equipment maintenance costs make up about 27%, and utility costs make up nearly 28%.

This analysis of a base-case scenario involving the E-beam technology shows that operating costs are strongly affected by the E-beam system and flow rate used. The larger systems take less time to complete a groundwater remediation project, but the higher equipment and utility costs result in a higher cost per 1,000 gallons of groundwater treated. The base-case scenario assumes that the total amount of groundwater to be treated is 315 million gallons. In Case 1, 15 years would be needed to complete the remediation project; in Case 2, 30 years would be needed. The total estimated cost of the project is \$2,764,000 for Case 1 and \$6,281,000 for Case 2. The estimated cost per 1,000 gallons of groundwater treated in net present value is \$5.16 for Case 1 and \$7.85 for Case 2.

Table 3-3 presents only the direct costs associated with the E-beam treatment system. This analysis is provided to segregate the direct costs of procuring and operating the E-beam system from the total costs of a groundwater remediation project. The direct costs are the same for both cases. Total fixed costs are estimated to be \$900,000, and total annual variable costs are estimated to be \$67,000. The analytical supplies cost has been excluded because at \$1,000 per year, it represents about 1% of the total annual variable costs. The direct cost per 1,000 gallons of groundwater treated is estimated to be \$4.07 for Case 1 and \$5.99 for Case 2.

Figure 3 -2 shows the distribution of direct treatment costs for the duration of the groundwater remediation project. This figure shows that one-time costs, which consist of site preparation, mobilization and startup, equipment, and site demobilization costs, constitute a major cost variance between the cases. Although the direct costs are the same for both cases, this variance occurs because the one-time costs are distributed over a longer period in Case 2. While the same HVEA system is used to treat the same volume of groundwater in both cases, Case 2 involves treatment of contaminants that are more difficult to destroy. Figure 3-2 also shows that utility and equipment maintenance costs are the major cost contributors in Case 2. The combined utility and equipment maintenance costs make up 46% of the total direct treatment costs for Case 1 and 61% of the total direct treatment costs for Case 2.



**Figure 3-1.** Distribution of fixed and annual variable costs for groundwater remediation project.

**Table 3-3.** E-Beam Treatment System Direct Costs<sup>a</sup>

Cost Categories	Treatment System Configurations in Kilowatts (kW)					
	21-kW		45-kW		75-kW	
	Itemized	Total	Itemized	Total	Itemized	Total
Site Preparation <sup>b</sup>		\$23,000		\$23,000		\$23,000
Treatability study and system design	\$23,000		\$23,000		\$23,000	
Mobilization and Startup <sup>b</sup>		20,000		25,000		25,000
Transportation	10,000		10,000		10,000	
Assemble and shakedown	10,000		10,000		10,000	
Equipment <sup>b</sup>		842,000		1,208,000		1,432,000
Labor <sup>c</sup>		10,000		10,000		10,000
Utilities <sup>c</sup>		25,700		52,600		87,500
Residual Waste Shipping and Handling <sup>c</sup>		6,000		6,000		6,000
Equipment Maintenance <sup>c</sup>		25,300		36,200		43,000
Site Demobilization <sup>b</sup>		15,000		15,000		15,000
<b>Total One-Time Costs<sup>b</sup></b>		<b>\$900,000</b>		<b>\$1,271,000</b>		<b>\$1,495,000</b>
<b>Total Annual O&amp;M Costs<sup>c</sup></b>		<b>67,000</b>		<b>104,800</b>		<b>146,500</b>
Costs per 1,000 gallons treated—Case 1 <sup>d</sup>		\$4.07		\$5.17		\$6.07
Costs per 1,000 gallons treated—Case 2 <sup>e</sup>		\$5.99		\$6.05		\$7.10

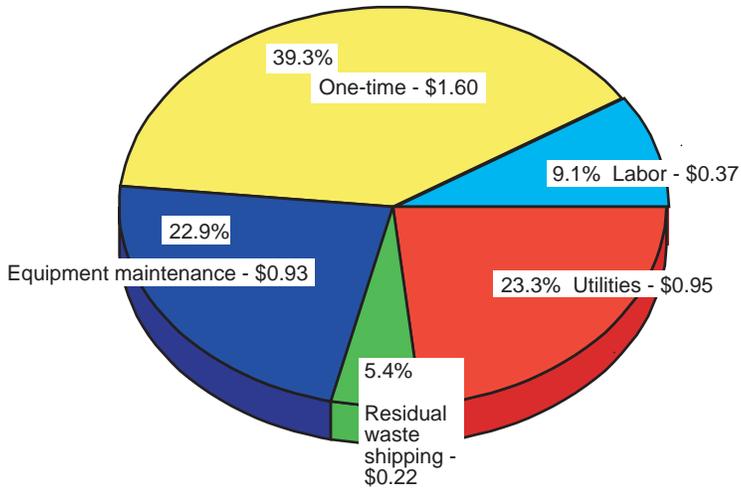
<sup>a</sup> This table presents direct costs associated with the E-beam treatment system segregated from the costs incurred as a result of conducting a groundwater remediation project. All assumptions used in this analysis apply.

<sup>b</sup> Fixed costs.

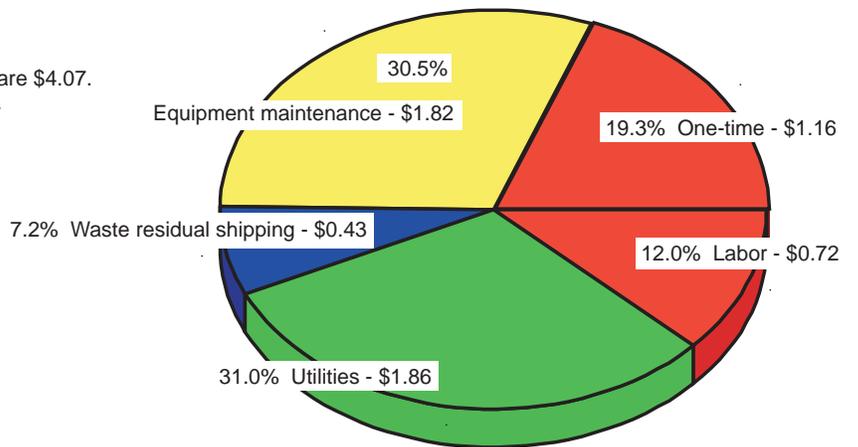
<sup>c</sup> Variable costs.

<sup>d</sup> Net present value using the same assumptions used in Table 3-1.

<sup>e</sup> Net present value using the same assumptions used in Table 3-2.



**Case 1—Direct Costs**  
 Total direct costs per 1,000 gallons treated are \$4.07.  
 The Case 1 project lasts 15 years.



**Case 2—Direct Costs**  
 Total direct costs per 1,000 gallons treated are \$5.99.  
 The Case 2 project lasts 30 years.

**Figure 3-2.** Distribution of HVEA System treatment costs.

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## Section 4

### Technology Status

According to HVEA, E-beam treatment systems are available as trailer-mounted systems, transportable systems, and permanent facilities. Trailer-mounted systems are finished semi-trailers with permanently mounted treatment system components. These systems are 48 feet long and 8 feet wide and include E-beam units with a power rating (accelerating voltage multiplied by beam current) up to 25 kW. Trailer-mounted systems are best suited for small-scale site cleanups and can be used for performing pilot-scale treatability studies.

Skid-mounted, transportable systems are transported to sites on flatbed trucks and off-loaded on temporary facilities. These systems can be mobilized and demobilized within a few days. The power rating of the transportable systems ranges from 50 to 75 kW. These systems are best suited for medium-scale site cleanups that may last for a few years. Once remediation of a particular site is completed, the transportable system can be moved to another site requiring remediation.

Permanent facilities generally involve high-powered E-beam systems requiring heavy radiation shielding. These systems are best suited for large-scale remediation projects that require many years of cleanup. They are also applicable for treatment of industrial or municipal waste streams produced on a continuous basis.

All HVEA E-beam treatment systems are modular in design. Each system includes an electron source, a reaction chamber, water handling equipment, and control components. If a par-

ticular waste stream does not meet treatment objectives after being treated once in the E-beam system, the waste stream can be recycled as many times as required until the treatment objectives are met. HVEA can also provide treatment trains with multiple modules for treatment of highly contaminated waste streams or large volumes of wastewater.

HVEA E-beam treatment systems can be fully automated. This allows remote operation of a system via a computer and telephone line. All parameters can be continuously monitored by the control console computer to ensure that all system components are operating within acceptable limits.

HVEA employs the following three-phase approach in implementing its E-beam technology for a particular treatment application. During Phase 1, a bench-scale treatability study is performed using a small quantity (two gallons) of wastewater. During bench-scale testing, a <sup>60</sup>Co cobalt source is used to generate an E-beam. The purpose of this phase is to determine the effectiveness of the E-beam process in removing the contaminants of interest and to develop a preliminary cost estimate for full-scale application of the HVEA system. During Phase 2, a pilot-scale treatability study is conducted on site using HVEA's trailer-mounted system. The results of this study will be used to (1) size a full-scale system that can meet treatment goals and (2) estimate the capital and O&M costs for full-scale system operation. During Phase 3, HVEA designs and configures the full-scale system.

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## Appendix A

### Vendor's Claims for the Technology

Hazardous waste treatment and disposal options have traditionally been influenced by regulatory, economic, technical, and public opinion factors. Regulatory mandates and public “outcry” have resulted in EPA’s establishing an 18-month (from May 1994) capacity freeze on hazardous waste incineration while it reviews and improves federal rules governing hazardous waste incineration. This decision will make it more difficult for new and expanded incineration facilities to obtain permits, which could increase incineration costs and divert wastes to other treatment alternatives. Thus, innovative technologies for remediation of contaminated sites are continually being considered as treatment options. Additionally, from an economic standpoint, the treatment costs of conventional technologies continue to increase, and from an environmental impact standpoint, treatment technologies are being sought that destroy contaminants without creating additional disposal problems.

#### A.1 Introduction

HVEA’s E-beam technology has the capability of treating complex mixtures of hazardous waste. The technology draws on the expertise developed from seven years and over \$3 million worth of research. The result has been the development of a line of hazardous waste treatment systems based on the innovative E-beam technology, which can treat any water, wastewater, or sediment matrix containing toxic organic chemicals.

#### A.2 Technology Description

HVEA’s E-beam treatment systems use insulated core transformer (ICT) electron accelerators developed by High Voltage Engineering, Inc. In this type of accelerator, the high voltage is produced by a three-phase transformer with multiple secondary windings that are energized by insulated core segments in an iron core. The resulting voltage and current are transferred to an accelerator tube and tungsten wire filament, respectively. The electrons emitted by the tungsten filament are then accelerated by means of voltage differential. Once the accelerated electrons pass through the accelerator tube, they are deflected magnetically (scanned) so as to sweep a larger irradiation field. The scanned E-beam then impacts a flowing stream or slurry, producing highly reactive species capable of destroying all toxic organic compounds in aqueous solution. The reactive species formed are  $\text{OH}\cdot$ ,  $\text{e}_{\text{aq}}^-$ , and  $\text{H}\cdot$ . The reactions occur at diffusion-limited rates, and the treatment is complete in less than one second. When the organic compounds are completely destroyed,  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ , and salt are formed as a result.

#### A.3 Advantages of the E-Beam Process

The HVEA E-beam process has a number of advantages that make it uniquely suitable for use as a treatment process for hazardous organic chemicals. These advantages are described below.

- The process is broadly applicable for the destruction of organic chemicals because strongly reducing reactive species ( $\text{e}_{\text{aq}}^-$  and  $\text{H}\cdot$ ) and strongly oxidizing reactive species ( $\text{OH}\cdot$ ) are formed at the same time and in approximately the same concentrations in solution. Furthermore, the E-beam system is the only treatment technology in which  $\text{H}\cdot$  is produced.
- Reactions of organics with the E-beam-induced reactive species are very rapid, occurring in less than one second. This has allowed HVEA to design a flow-through system with good process flexibility at full scale; this system can accommodate flow rates that vary over time. The full-scale system is modular in design, thereby allowing for decreased operational cost if the quality of the waste improves over time (that is, if the concentrations of organic compounds decrease).
- The process can completely mineralize organic contaminants.
- Formation of the reactive species is pH-independent in the range 3 to 11. Therefore, any differences in pH that exist over time do not adversely affect treatment efficiency.
- The process can effectively treat aqueous streams and slurried soils, sediments, and sludges.
- The process is temperature-independent within normal water temperature ranges. The E-beam system is usually housed in a building, and except for the control room, no temperature conditioning is required. Also, variations in water temperature have no practical effect on the treatment efficiency of the process.
- The process produces no organic sludge. The target organic chemicals are either mineralized or broken down into low molecular weight organic compounds. The process has not been thought to result in removal

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of heavy metals, but in recent studies involving E-beam treatment of hazardous waste leachate containing metals, an inorganic precipitate was formed in the treated samples.

- The process produces no air emissions. Because this is a water-based technology, no oxides of nitrogen or sulfur are produced. The influent delivery system is closed, and therefore there is no external release of toxic organic compounds.
- For all these reasons, the E-beam process can be used efficiently and effectively as a pretreatment process for biological remediation. The E-beam process can “break apart” complex organic compounds, making them amenable for microbiological degradation.

#### **A.4 HVEA Treatment Systems**

HVEA E-beam treatment systems are modular in design. Each system includes an electron source, a reaction chamber, water handling equipment, and control components. This allows for great flexibility in handling contaminated waste streams of differing composition. For example, if a particular waste stream will not meet waste treatment objectives in a single pass using one module, a system can be built to recycle the waste stream as many times as required for complete remediation. Also, single-pass treatment trains with multiple modules can be built to remediate highly contaminated waste streams (ppm to 1% solutions) and to accommodate high flow rates (over 250 gpm). Table A-1 summarizes some of the capabilities of HVEA’s treatment systems.

#### **A.5 System Applications**

HVEA’s E-beam systems are ideally suited for treatment of complex mixtures of industrial and hazardous wastes dissolved or suspended in aqueous media. A partial list of contaminants and pollutants that can be treated using HVEA systems is presented in Table A-2. The general ranges of contaminants in aqueous matrices that can be successfully treated by HVEA’s systems are presented below.

- Volatile organics at part per billion levels to 1% NAPLs
- Semivolatile organics at part per billion to 1,000-ppm levels
- Total solids at up to 5% by weight

Waste streams that can be treated by HVEA’s E-beam technology include the following:

- Landfill leachates
- Contaminated groundwater
- Contaminated soil
- Industrial wastewaters from chemical, petrochemical, agricultural, metal finishing, automobile, wood finishing, paint, and pulp and paper plants
- Drinking water sources

#### **A.6 Cost Considerations**

The cost of treatment using an HVEA E-beam system depends on many factors such as the initial concentrations of organic contaminants, treatment objectives, the dose required to obtain the desired destruction, the volume of waste to be treated, the size of the treatment facility, the length of treatment, and the manner in which capital recovery is handled. The cost of treatment using HVEA systems in various industrial waste and groundwater applications has ranged from \$2.00 per 1,000 gallons to \$0.50 per gallon. Because of this wide range of possible costs, the three-phase approach described in Section 4 should be used to estimate treatment costs for a specific application. These costs may decrease as a result of economies of scale when more treatment systems are produced in the future.

To reduce the required capital investment, HVEA offers turn-key lease options that, for a monthly fee, include equipment, maintenance, and technical services. The minimum lease period is usually 5 years renewable annually, but purchase options are also available. HVEA’s leasing arrangements allow for flexibility in responding to changing regulations and changing water quality over the life of a remediation project.

#### **A.7 Summary**

HVEA’s E-beam system offers an innovative, cost-effective, and flexible technology for treatment of industrial and hazardous wastewaters. The technology can treat waters with varying contaminant and feed compositions. The HVEA E-beam treatment system produces a high-quality effluent, destroys complex mixtures of organic pollutants, and can handle waste streams containing solids. This technology has been well demonstrated and is now commercially available for the treatment of a variety of hazardous wastewaters.

**Table A-1.** Capabilities of HVEA's E-Beam Treatment Systems

Specific Capabilities	Demonstrated Results	Comparison to Conventional Technology
High RE for complex mixtures of organic pollutants	Routinely reduces organic pollutant concentrations by 99%; higher removals achieved for specific pollutants	Biological treatment has high REs for biodegradable compounds only; pollutants such as PCBs are not removed
Process can accommodate suspended materials present at concentrations up to 5%	Presence of suspended Kaolin clay has no effect on removal efficiency	Ultraviolet treatment is limited to solutions that are transparent to the ultraviolet source
Significant flexibility to handle changes in feed flow rate and composition	Process is not sensitive to changes in feed pH, temperature, and solids content (up to 5%)	Most treatment systems cannot handle changes in feed composition and still produce a high-quality effluent
Minimal post-treatment needed	E-beam process results in destruction of organic contaminants, which are usually mineralized to CO <sub>2</sub> , H <sub>2</sub> O, and inorganic salts	Activated carbon and air stripping transfer the contaminants to other media, usually carbon, which have to undergo secondary treatment as hazardous waste

**Table A-2.** Contaminants and Pollutants Treatable by HVEA's E-Beam Treatment Systems and Other General Uses of the Systems

Treatable Organics	General Uses of the Systems
Aroclors	Color removal
BTEX	Odor control
Chemical warfare agents	Bacterial disinfection
Explosives and energetics	Halogenated volatiles
Halogenated semivolatiles	Disinfection byproduct removal
Nonhalogenated volatiles	TOC reduction
Nonhalogenated semivolatiles	Chemical oxygen demand and biochemical oxygen demand reduction
Nonvolatile organics	
Organic cyanides	
Organic pesticides and herbicides	
Phenol and phenolics	
PAH	
Solvents	

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## A.8 Bibliography

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## Appendix B

### Case Study

In December 1994, HVEA's trailer-mounted E-beam treatment system was transported to a technology demonstration site in Halle-Dieskau, Germany. At this site, HVEA performed several treatability studies on waters contaminated with various hazardous waste constituents. This case study summarizes one of the treatability studies performed using process wastewater from a petroleum refinery. The wastewater contained phenol, BTEX, and PAH. Site conditions, HVEA system performance, and estimated treatment costs are summarized below.

#### B.1 Site Conditions

HVEA was informed that process wastewater from a petroleum refinery routinely exceeded German wastewater regulatory limits for phenol, BTEX, and PAH (see Table B-1) and that the German government was actively seeking innovative technologies with the capability of destroying such complex contaminant mixtures to meet German regulatory limits.

To determine the effectiveness of HVEA's E-beam technology, about 270 gallons of the process wastewater was shipped to the demonstration site. The trailer-mounted E-beam treatment system was used to treat the wastewater in recirculation mode at a

flow rate of 25 gpm and a beam current of 40 mA for about 45 minutes. Samples were collected at regular intervals to evaluate the HVEA system's performance as a function of time.

#### B.2 System Performance

Table B-1 summarizes the highest REs and corresponding effluent concentrations achieved by HVEA's E-beam system. The E-beam system achieved REs of 99.10%, >99.92%, and >99.51% for phenol, total BTEX, and total PAH, respectively, and met the German regulatory limits for all the compounds involved.

#### B.3 Estimated Costs

To meet German regulatory limits, HVEA recommended a 75-kW unit (HVEA-T75W-48S) to treat the wastewater at 35 gpm in a continuous flow mode. The O&M costs for the system recommended included electricity and general maintenance costs. The cost of electricity per 1,000 gallons treated is estimated to be \$3.75, based on a rate of \$0.07 per kWh. The cost of required maintenance and treatment services is estimated to be \$1.02 per 1,000 gallons treated. The total estimated treatment cost is \$4.77 per 1,000 gallons treated.

**Table B-1.** Case Study Results for HVEA's Trailer-Mounted E-Beam Treatment System

Compound	Initial Concentration (µg/L)	Effluent Concentration (µg/L)	RE (%)	German Regulatory Limit (µg/L)
Phenol	2,230	20	99.10	20.0
Benzene	6,200	3.5	99.94	5.0
Toluene	498	<1	>99.80	20.0
Ethylbenzene	118	<0.5	>99.58	— <sup>a</sup>
m/p/o-xylene	201	<0.5	>99.75	20.0
Total BTEX	7,017	<5.5	>99.92	20.0
Naphthalene	15.207	<0.020	>99.87	—
Fluorene	0.728	<0.020	>97.25	—
Phenanthrene	0.048	<0.010	>79.17	—
Anthracene	0.138	<0.010	>92.75	—
Fluoranthene	0.086	<0.010	>88.37	—
Pyrene	0.056	<0.005	>91.07	—
Benzo-(a)-anthracene	0.012	<0.005	>58.33	—
Total PAH	16.275	<0.080	>99.51	0.200

<sup>a</sup> — = Not available