INNOVATIVE TECHNOLOGY
Summary Report

DOE/EM-0626

In-Well Vapor StrippingTechnology

Subsurface Contaminants
Focus Area

Prepared for
U.S. Department of Energy
Office of Environmental Management
Office of Science and Technology

March 2002

INNOVATIVE TECHNOLOGY
Summary Report

In-Well Vapor StrippingTechnology

Tech ID #6

Subsurface Contaminants Focus Area

Demonstrated at
U.S. Department of Energy
Brookhaven National Laboratory
Upton, New York

INNOVATIVE TECHNOLOGY
Summary Report

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine whether a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, worker safety, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available on the OST Web site at www.em.doe.gov/ost under "Publications."

TABLE OF CONTENTS

SECTION 1
SUMMARY

Technology Summary

Problem

More than 1.7 trillion gallons of contaminated groundwater are targeted for remediation at U.S. Department of Energy (DOE) sites. At most of these sites, groundwater is contaminated with chlorinated organic solvents, including Volatile Organic Compounds (VOCs).

At the DOE Brookhaven National Laboratory (BNL), in Upton, New York, groundwater within a complex glacial aquifer is contaminated by various chlorinated organic solvents at a depth of approximately 150 to 230 feet below the surface. These chlorinated organics include: carbon tetrachloride (CCl_4) tetrachlorethene (PCE), trichlorethene (TCE), 1,1 dichlorethene (DCE), and 1,1,1 trichloroethane (TCA). Because BNL is situated over a sole-source aquifer, which provides potable drinking water for Long Island, New York, the U. S. EPA placed BNL on the National Priorities List in 1989. Subsequently, a Draft Federal Facilities Agreement, called an Interagency Agreement (IAG), was negotiated between DOE, EPA, and New York state. For the purposes of the IAG, BNL was divided into six Operable Units (Ous), which are the targets of remediation efforts by DOE. The OU 111 groundwater plume originates near the south central portion of the BNL site and extends beyond the site's southern boundary. The sources of contamination at OU 111 include a building transfer line and underground storage tanks; a Bubble Chamber area; the site sewage system; several buildings (including former chemistry buildings); and other facilities.

How It Works

In-well vapor stripping (IWVS) is an in situ remediation technology that integrates air stripping of volatile organic compounds (VOCs) in ground water by converting them to a vapor phase, which is then treated above-ground (Figure 1). IWVS is accomplished by establishing a groundwater circulation cell in a contaminated zone of an aquifer. Contaminants are continually drawn into the well, stripped from the aqueous to the vapor phase, and treated. The treated groundwater is discharged back into the aquifer. The circulating well concept is also known as groundwater circulating well technology (GCWT).

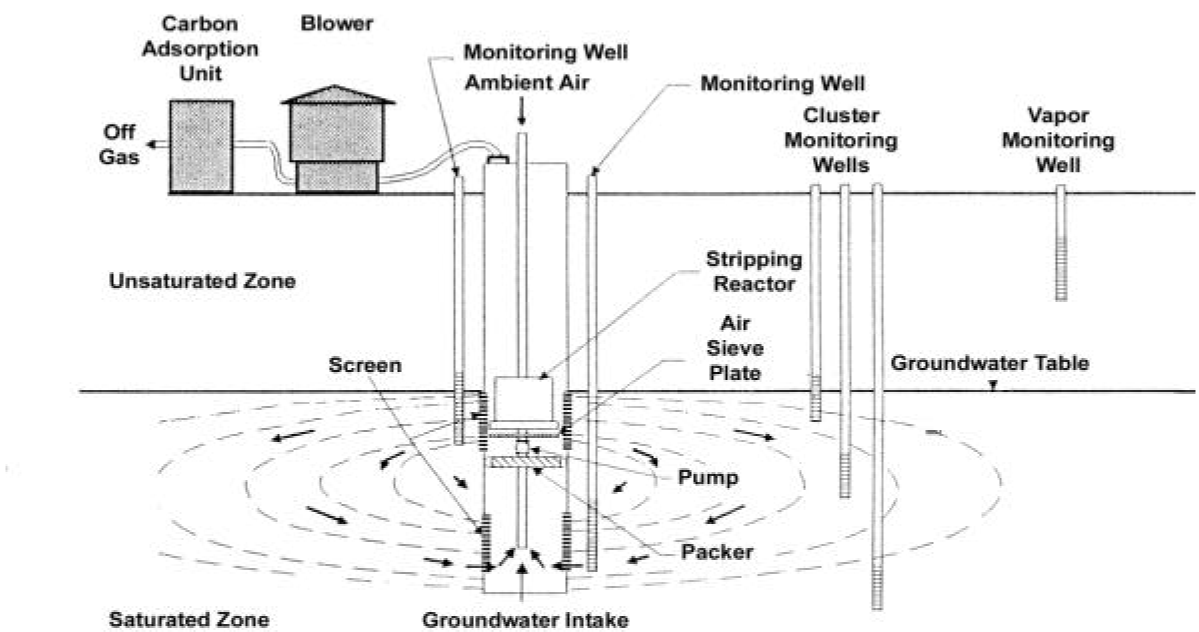


Figure 1. Conceptual picture of a typical UVB well.

IWVS occurs either within the well (in-well) or in the aquifer within the circulation zone by a variety of different methods. Treatment methods may include air stripping, activated carbon adsorption, in-well bioreactors, and in situ biodegradation. Air-lift pumping is commonly combined with IWVS, concurrent off-gas treatment, and re-injection into the vadose zone.

Candidate contaminants include VOCs and semi-volatile organic compounds (SVOCs), the nature and distribution of the contaminant is critical in determining the type of treatment system that should be employed with a IWVS. Contaminant properties such as solubility, partition coefficient, Henry's Law constant, and/or biodegradability are some factors that influence the likelihood of success.

Potential Markets

The potential markets for this technology includes DOE, DoD, and commercial sites that have moderately permeable, saturated zones contaminated with VOCs or SVOCs.

Advantages Over Baseline

- IWVS has cost advantages over pump and treat because significant energy reductions may be achieved, especially at sites with deep contamination, as groundwater need not be pumped to the surface for treatment.
- A single IWVS well can be used for treatment of both the vadose zone and the groundwater, whereas the baseline technology would require separate pump-and-treat and soil vapor-extraction wells. Also, the in-well stripping process combines the functions of the extraction pump and the air stripper blower, which results in additional cost savings.
- IWVS avoids handling contaminated water above the surface and disposing or storing of partially treated water. The elimination of liquid discharges can translate into significant cost savings. In addition, little above-ground space is needed, because remediation is accomplished in situ.
- IWVS accelerates remediation of the area within the recirculation zone, because groundwater within this zone flows perpendicularly through lower permeability zones, whereas with pump and treat systems, flow is predominantly horizontal.

Demonstration Summary

In the United States, four types of IWVS systems have been commercialized and are available through the original patent-holders or their licensees. The variations include the 1) NoVOCs™ system, 2) the Unterdruck-Verdampfer-Brunnen (UVB) Vacuum Vaporizer Well and Coaxial Groundwater Circulation (KGB) system, 3) the Density Driven Convection (DDC) system, and 4) the C-Sparger® system.

This report covers the deployment of a UVB System at Brookhaven National Laboratory (BNL), Upton, New York, in September 1999. At the BNL site, groundwater within a complex glacial aquifer is contaminated by various chlorinated solvents about 150-230 ft below grade. Seven UVB treatment wells were installed to target the portion of the OU III plume that had migrated beyond BNL's southern boundary toward Parr Industrial Park. Operation of the UVB system continues.

Key Results

- IWVS technology has been applied at numerous sites for in situ removal of petroleum hydrocarbons, non-petroleum hydrocarbons (methanol and isopropyl ether), polynuclear aromatic hydrocarbons (PAHs), and chlorinated hydrocarbons. Removal efficiencies of >90% have been achieved in several cases.
- At BNL, the IWVS system has performed as follows.
  - Influent and effluent concentrations from the seven treatment wells have decreased since system startup.

- — From September 1999 through March 2001, the IWVS system treated approximately 278 million gallons of groundwater, resulting in the removal of 300 pounds of mass. During the start-up period, the average removal efficiency was 95 percent.
- — Field data and numerical modeling techniques confirm that the system is capturing the full width of the OU III Off-Site plume.
- — Within the zone of influence of the re-circulation cell, groundwater rate (re-circulation rate) estimates for this system using field data range from 50 to 70 percent.

- Summaries of three other IWVS demonstrations are found in the Appendices to this report.

Contacts

Technical

UVB System – Eric Klingel, Ph.D., IEG-Technologies Corporation, phone/fax (704) 660-1673, email eklingel@juno.com or Jim Mueller, Ph.D., URS/Dames & Moore, (847) 228-0707, ext. 131, fax (847) 228-1115, email jim_mueller@urscorp.com.

NoVOCs™ System – Mr. Joe Aiken, MACTEC, Inc., (970) 204-0309, fax (970) 225-1781, email aikco@aol.com.

DDC System – Les Pennington, P.E., President or L. Boyd Breeding, Wasatch Environmental, Inc., (801) 972-8400, fax (801) 972-8459, email wei@wasatch-environmental.com.

C-Sparger® System – William B. Kerfoot, Ph.D., LSP, K-V Associates, Inc., (508) 539-3002, fax (508) 539-3566, email bill@kva-equipment.com.

Management

UVB System – Mr. Vinnie Racaneillo, Brookhaven National Laboratory, (631) 344-5436

James A. Wright, DOE-SR, Subsurface Contaminats Focus Area, (803) 725-5608

Licensing

UVB System – Eric Klingel, Ph.D., IEG-Technologies Corporation, phone/fax (704) 660-1673, email eklingel@juno.com.

NoVOCs™ System – Mr. Joe Aiken, MACTEC, Inc., (970) 204-0309, fax (970) 225-1781, email aikco@aol.com.

DDC System – Les Pennington, P.E., President or L. Boyd Breeding, Wasatch Environmental, Inc., (801) 972-8400, fax (801) 972-8459, email wei@wasatch-environmental.com.

C-Sparger®System – William B. Kerfoot, Ph.D., LSP, K-V Associates, Inc., (508) 539-3002, fax (508) 539-3566, email bill@kva-equipment.com.

Other

All published Innovative Technology Summary Reports are available on the OST Web site at www.em.doe.gov/ost under “Publications.” The Technology Management System (TMS), also available through the OST Web site, provides information about OST programs, technologies, and problems. The Tech ID for In-Well Vapor Stripping Technology is 6.

SECTION 2
TECHNOLOGY DESCRIPTION

Overall Process Definition

IWVS can be accomplished using any one of four GCWT systems. The theory behind IWVS is to remediate ground water and the vadose zone by creating a three-dimensional circulation system where groundwater flows from the targeted aquifer into a specially designed well and then discharges into the aquifer at a different point. The treatment of groundwater via this technology occurs either in the well (in-well), or in the aquifer within the circulation zone. Treatment methods may include air stripping, activated carbon adsorption, in-well bioreactors, and in situ biodegradation. The four commercially available groundwater re-circulation systems are described below. The UVB/KGB system uses an underground vault with an air stripper, while the C-Sparger™ system performs in situ air stripping through the injection of micro-encapsulated ozone (which performs chemical oxidation) and the NoVOCs™ system uses an overpressure concept (well within a well) to circulate water through the well.

UVB and KGB Systems

The UVB System consists of a specially designed well, a negative-pressure stripping reactor located in an air-tight, subsurface vault, an above-ground mounted blower, and an above-ground waste air decontamination system (Figure 2).

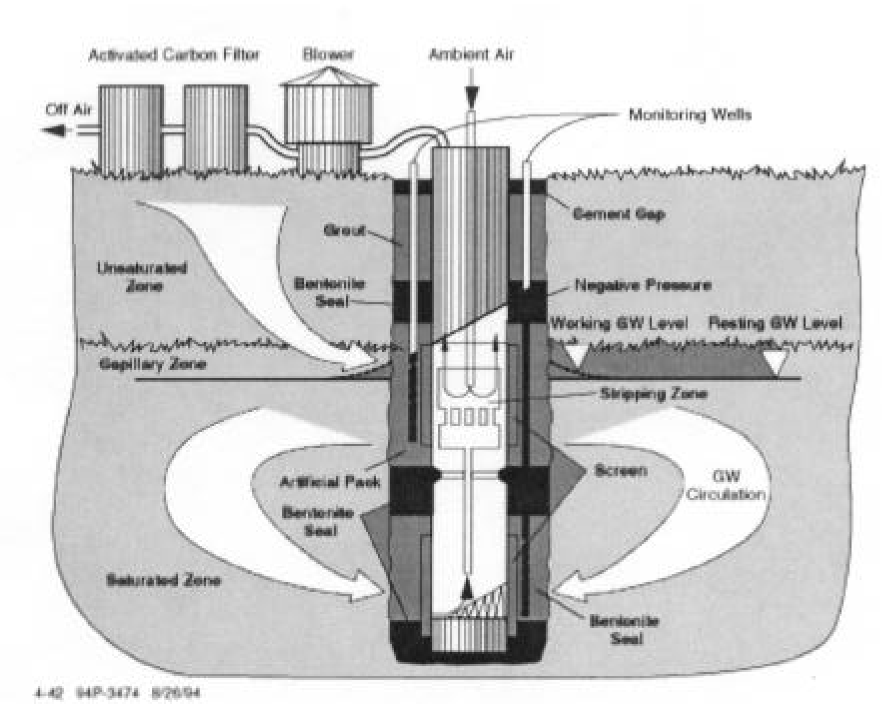


Figure 2. Schematic of the UVB system groundwater circulating well.

- A UVB well has at least two screened sections that are separated by solid casing. The lower screen is separated from the upper screen by a fixed or inflatable packer. The water level rises inside the well due to negative pressure generated by a blower applied to the air-tight vault. Through a pipe connected to the negative-pressure stripping reactor located within the vault, ambient air is drawn into the well, and the rising air bubbles act as an air-lift pump to enhance the suction effect at the well bottom. Thus, water is continually drawn into the well screen located at the bottom of the contaminated zone.

- The water is drawn to a stripping reactor above the water table, where VOCs are removed. As a result of the concentration gradient, contaminants vaporize into the air bubbles and are removed from the well by the air flow.
- After the vapor-phase separation, the cleaned groundwater is channeled through a pipe extending from the bottom of the stripper reactor through a packer separating the two screened intervals.
- A submersible pump may be added to the UVB System, to induce a specific flow direction, producing either an upward or a downward component to the vertical flow of groundwater within the well.
- UVB technology can also be modified as follows.
  - For thick aquifers, it is possible to create stacked vertical cells.
  - A former licensee had enhanced the UVB system by adding an in situ bioreactor and an above-ground vapor-phase bioreactor.

The KGB System, combining in situ air stripping and soil air venting, is designed to volatilize contaminants for extraction and above-ground treatment. KGBs are normally emplaced into artificially-packed boreholes and do not utilize well screens. The KGB system includes an air distributor and double-cased screen to permit bubble/water separation with sampling tubes that allow monitoring of both portions of the system. Via a compressor, air is injected into the air distributor, located at the bottom of the artificially-packed borehole, creating an air-lift pumping effect that serves as the stripping mechanism. The system headspace is kept under vacuum to draw off vapors stripped from groundwater and the vadose zone; off-gas treatment is typically accomplished via activated carbon canisters placed in series behind the vacuum system.

NoVOCsÔ System

This technology uses an over pressure concept to circulate water through the well and facilitate transfer of contaminants from the dissolved phase to the vapor phase. The system consists of a well within a well (Figure 3).

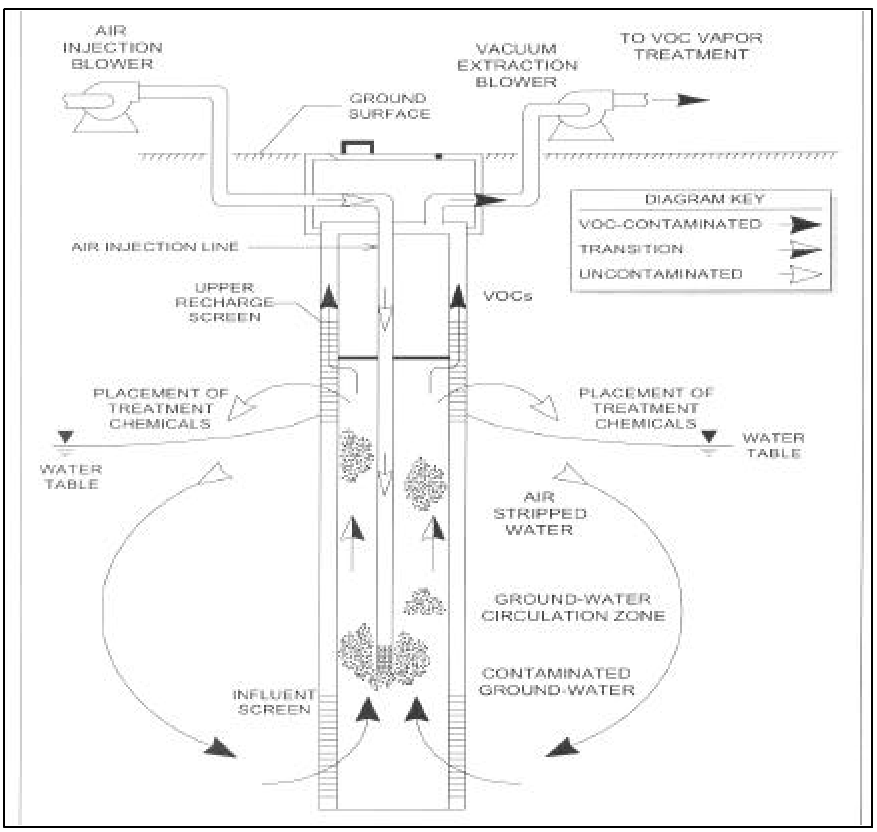


Figure 3. Schematic of the NoVOCsÔ in-well vapor stripping process.

In a vertical configuration, the inner well is installed from the ground surface to the bottom of the contaminated saturated zone, where the well casing is perforated (screened). The outer well extends from the ground surface through the vadose zone and may terminate above the water table. The outer well may be screened in the vadose zone, so it can be used for soil vapor extraction.

- A pressurized air-delivery line is placed within the inner well and configured to deliver a constant stream of air bubbles into the well at a level beneath the zone of contamination. The rising column of bubbles acts as an air lift pump.
- The mixed air and water in the well casing is less dense than the water column outside the well, causing water to enter the well to equilibrate the pressure differential that exists as a result of the weight differences between the two columns.
- VOCs vaporize and become a free vapor as the air bubbles and the water move up through the well.
- The inner well casing is sealed off with a deflector plate or packer at a point above the water table. The inner well casing is screened just below the deflector plate to allow the water and bubble mixture to escape into the annular space between the inner and outer well. The ground water reinfiltrates through the vadose zone, the air bubbles pop and are vacuumed off via a vacuum line extending from the ground surface into the annular space between the wells. The reinfiltrating water completes a toroidal circulation pattern, thus permitting a large portion of the water to be drawn back in and reprocessed.
- Off-gas treatment systems for the contaminated vapors are dictated by the type of contaminant treated, concentrations encountered, and flow rates.
- NoVOCs™ technology can also be modified for application in a confined aquifer, in a reverse flow configuration for light, non-aqueous phase liquid (LNAPL) applications, for shallow applications, for horizontal configurations, for free product removal, and shallow bedrock zones.DDC System

The DDC System is an in-well aeration technology based on a well design in which a 2- to 18-inch diameter well casing is screened across two separate intervals separated by a section of blank casing installed with a corresponding annular seal. Figure 4 shows a schematic of this system.

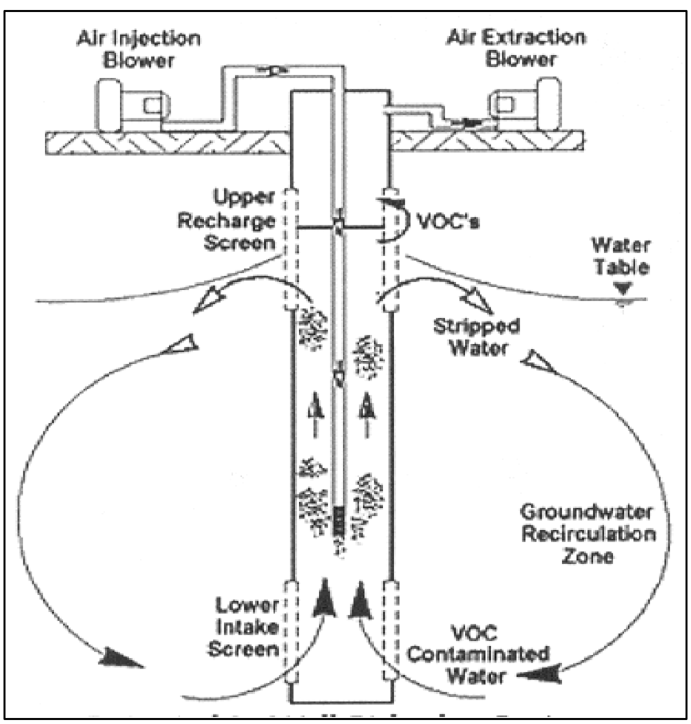


Figure 4. Schematic of the DDC system groundwater circulating well.

- The DDC wellbore is drilled to the bottom of the targeted treatment zone. Typically, in an unconfined aquifer, the upper screen is installed across the water table and the lower screen is installed near the bottom of the aquifer to be treated. In a confined aquifer, both screens are typically installed below the water table.

- An air line extends to the bottom of the well and a blower provides air under pressure. The air that enters the bottom of the well mixes with the water, reducing the density of the water column within the well, so that the air/water mixture rises and a flow of water is induced into the lower screen, in a similar manner to air-lift pumping. The air/water mixture rises to the top of the well, elevating the apparent water table before flowing laterally into the upper part of the aquifer. Eventually, a convection cell forms and the circulated water is pulled back into the lower screen.
- Dissolved VOCs are stripped from the groundwater as it flows through the well, and the vapors produced by the stripping action can be collected at a single point for treatment as necessary. In addition, bioremediation in the soil and groundwater surrounding the well is stimulated as stripped, oxygenated groundwater is circulated through the aquifer.
- Bioremediation in the vadose zone of unconfined aquifers may also be enhanced, as the DDC supplies oxygen to the surrounding soil.
- Soil vapor extraction (SVE) is an excellent complimentary technology, as the applied vacuum draws air through the vadose zone from the DDC well.

C-SpargerÒ System

C-Sparger® performs in situ air stripping with micro-encapsulated ozone that is injected periodically into a 2- to 4-inch PVC well with a pulsing pump. Each C-Sparger® System consists of a Master Unit and one or more in-well assemblies. Each Master Unit includes a gas generator, compressor, pump control, and timer, and can operate up to a total of three wells simultaneously. The in-well assemblies consist of a fixed packer, a Spargepoint®, a water pump, an air/ozone line, check valve, and fittings. Figure 5 depicts a schematic of the C-Sparger® system.

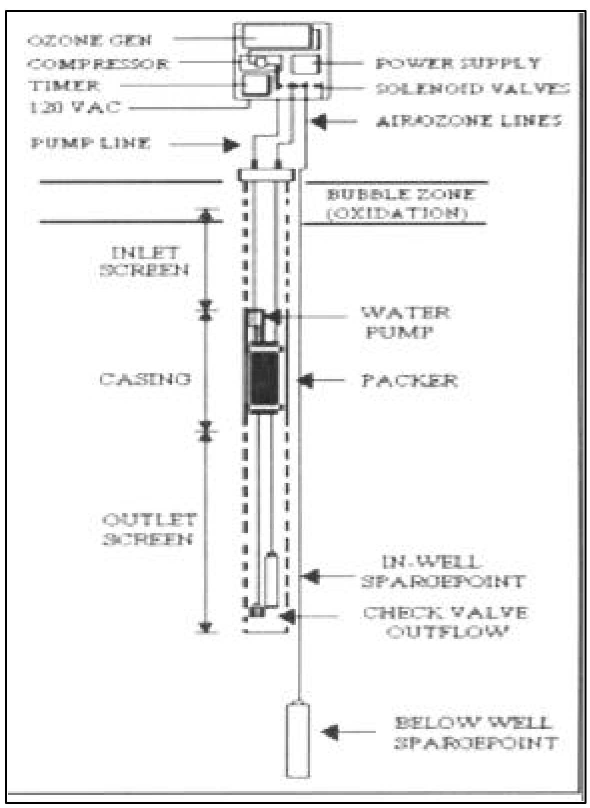


Figure 5. Schematic of the C-SpargerÒ master control unit.

- The C-Sparger® unit pumps an air/ozone mixture through a micro-channeled diffuser (Spargepoint®) into the soil at a point below the VOC plume and beneath the two screened intervals of a sparging well. A bentonite seal in the annulus, and an in-well expandable packer effectively isolate the two screened intervals of the sparging well.
- Within the core area of the plume, a second Spargepoint®combined with the intermittent operation of a submersible pump, displaces the vertically-moving bubbles sideways through the lower well screen to maximize dispersion and contact. The intermittent operation increases the circulation zone 3 to 10 times background conditions.
- The "microbubbles" produced by the Spargepoints® have a very high surface area to volume ratio, and contain ozone, an oxidizing gas. As the microbubbles rise within the column of water, they strip VOCs from groundwater. The VOCs enter the microbubbles and are rapidly oxidized.
- Vapor recovery is typically not necessary with the C-Sparger® System. The cleaned groundwater reenters the well through the upper screen, creating a groundwater recirculation cell.
- After a predetermined time, the submersible pump starts to agitate the water in the well. Agitation disturbs the usual inverted cone-shaped path of the bubbles through the formation and disperses them randomly, ensuring better contact between the oxidant (contained in each bubble) and the pollutant dissolved in the water. This action increases the efficiency and speed of the remediation process.

System Operation

Proper operation of IWVS systems will be aided, in most cases, by developing a system-specific operation and maintenance (O&M) plan. By following a detailed O&M plan, measurements associated with system operation and performance monitoring are conducted in accordance with the schedule.

- Operation details: closed-loop air system via single blower; two granular activated carbon units in series for off-gas treatment; dehumidification unit and duct heater to remove moisture from off-gas (condensate returned to UVB-4 stripping tray); and programmable logic controller in treatment building to regulate groundwater flow rates and air flow rates to wells. Sizing of system based on nominal hydraulic capacity of 60 gallons per minute (gpm) for each stripping tray (80 gpm max.) (Figure 6).

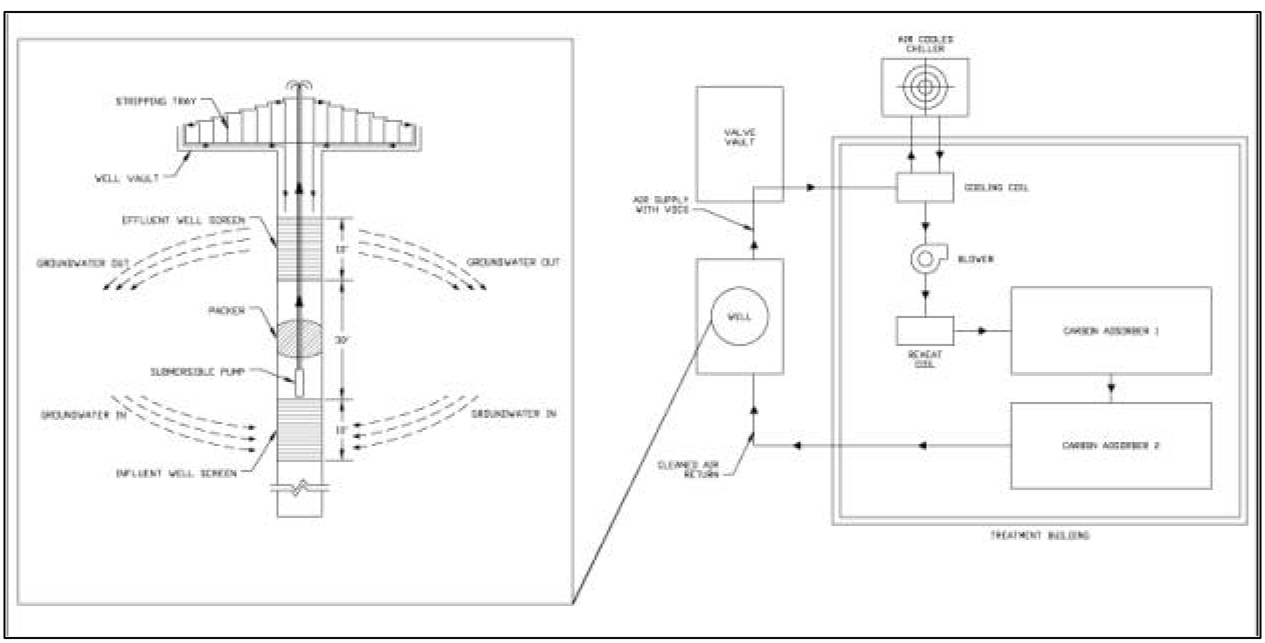


Figure 6. Treatment system schematic, BNL, Upton, New York.

- Typical system operating parameters may require frequent measure. Telemetry may aid in the long-term cost-effectiveness of data collection and system monitoring.
- Performance monitoring parameters must be collected at a frequency compatible with the system, site, and project requirements.
  - Monitoring of influent and effluent concentrations for individual treatment wells is needed for removal efficiency calculations.
  - Water-level monitoring in both treatment and monitoring wells is needed to allow determination of plume capture and verification of establishment of circulation cells.
  - Influent and effluent air samples are needed to evaluate off-gas treatment efficiency and performance.
  - Groundwater sampling of monitoring wells at various depths is necessary to determine operational impact to the contaminant plume(s).

SECTION 3
PERFORMANCE

Demonstration Plan

The four commercially available types of groundwater circulating well systems have been demonstrated and deployed at a variety of sites. Detailed performance data from one UVB system, that installed at BNL, is presented in this section. Appendix B provides one case study for each of the other three types of systems.

- UVB System at BNL:

  — The geology consists of Atlantic coastal plain sediments (Figure 7). The general hydrostratigraphic units are: 1) Upper Glacial aquifer (fine to coarse sand, trace clay, silt and gravel lenses) underlain discontinually by Gardiner's Clay; 2) Magothy aquifer. The upper Glacial aquifer is typically subdivided into three zones: water-table, mid-Glacial, deep-Glacial. The OU III plume is located in the deep-Glacial zone, about 150-230 ft below grade. Figure 7 depicts the plan view of the total VOCs in groundwater. Upper Glacial Aquifer hydrogeologic conditions include: transmissivity 114,048 to 200,789 gallons per day per foot (gpd/ft), hydraulic conductivity 633.6 to 1,115.5 gpd/ft2, and coefficient of storage 0.13 to 0.23. Groundwater flows nearly due south; the water table hydraulic gradient is 0.001 ft/ft; average horizontal groundwater velocity is 0.73 ft/day. Magothy aquifer parameters are similar except for average horizontal groundwater velocity is 0.18 ft/day.

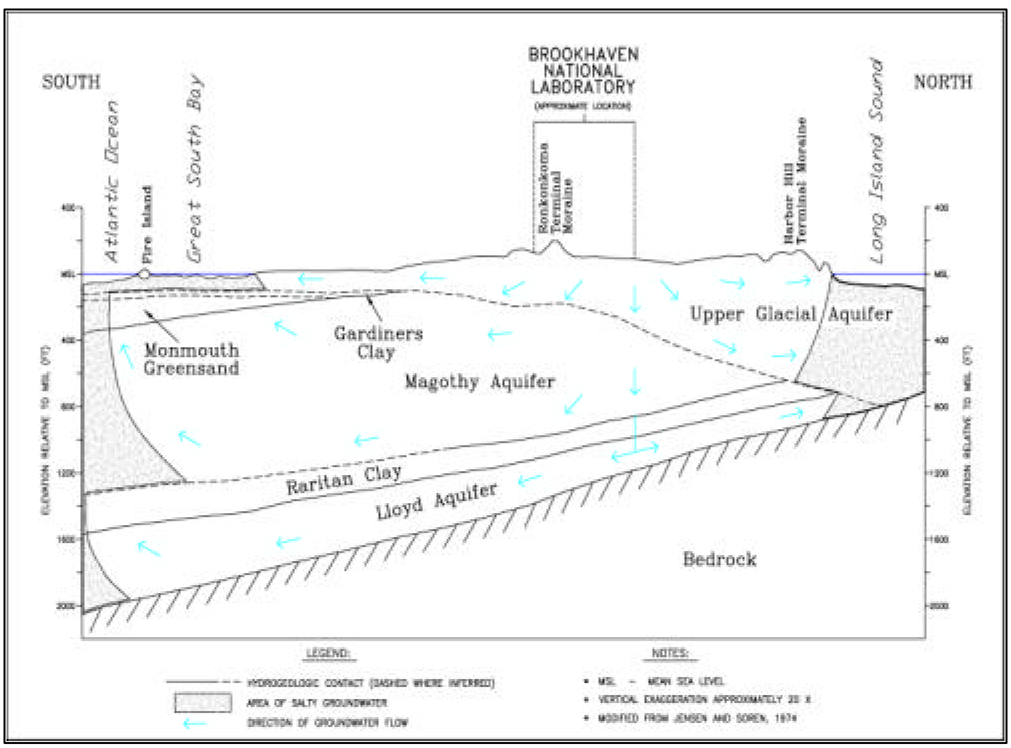


Figure 7. Generalized hydrogeologic cross-section and groundwater flow directions, BNL, Upton, New York.

  — Contaminants: CCl_4, PCE, TCE, DCE, and TCA. Maximum well influent concentrations (ug/L): Total VOC (TVOC) – 1900, CCl_4 - 1540, PCE – 330.

  — Seven UVB wells were installed perpendicular to the VOC plume immediately adjacent to but offsite of BNL; system operation was initiated September 29,1999. The OU III Off-Site Remedial Action targets the portion of the OU III plume that had migrated beyond BNL's southern boundary (Figure 8).

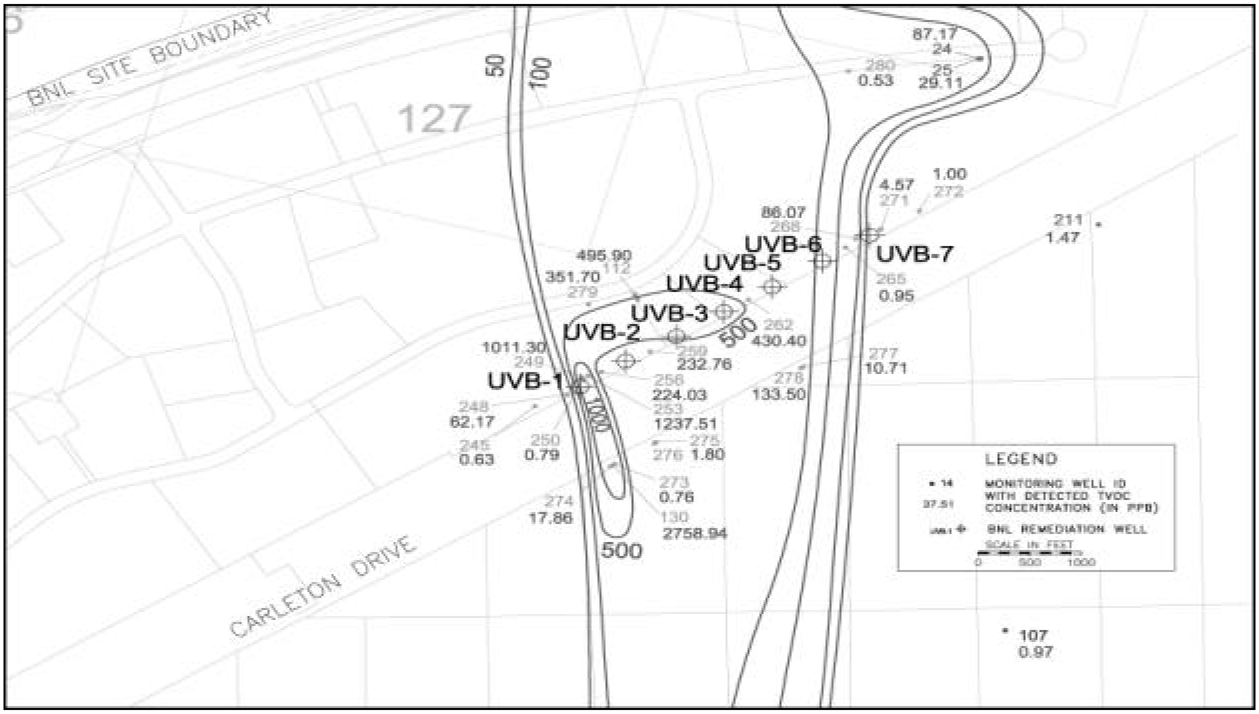


Figure 8. TVOC contours and UVB and monitoring well locations, BNL, Upton, New York.

— Treatment wells installed in Upper Glacial Aquifer, from west to east, designated as UVB-1 through UVB-7; each constructed with 8-inch diameter steel casing and two 20-foot long stainless steel screens separated by 25–35 ft. of casing and inflatable packer. Screen depths vary to optimize contaminant interception. One 3-hp submersible pump installed below the packer in each well draws groundwater into the lower screen; variable frequency drives for well pumps allowed independent flow-rate control.

— Thirty-four monitoring wells, screened within the Upper Glacial Aquifer, were used to monitor effectiveness at three depth intervals. Two were screened in the Magothy Aquifer.

— Operating parameters: UVB well instantaneous, daily average, and totalized water flows, blower and GAC instantaneous, daily average, and totalized air flows, temperature, relative humidity, and line pressures, clean-air relief port flow-rate, facility run time.

— Monitoring parameters: weekly depth to water in monitoring wells, weekly psig measurements converted to water levels in UVB wells, weekly system influent and effluent samples, weekly system air influent and effluent samples, condensate sump samples, groundwater samples from monitoring wells.

— System capture zone analyses were performed to determine if the UVB system was capturing the entire width of the VOC plume.

Results

— Removal efficiencies of TVOCs varied with the contaminant concentration and proportions of contaminants more highly susceptible to stripping at individual wells and pumping rates of the UVB wells. Average removal efficiencies of the seven UVB wells for TVOCs ranged from 88.06% to 96.54%; average system efficiency was 92.82% (Table 3).

— Pumping rate optimization, keeping air-flow rates constant and reducing groundwater flow rates, resulted in greater removal efficiencies at UVB-1 and UVB-2.

— From September 1999 through March 2001, IWVS (UVB) System treated approximately 278 million gallons of groundwater, resulting in the removal of 300 pounds of mass (Figure 9), with a system removal efficiency of approximately 93%. Influent groundwater concentrations in each well generally decreased, and effluent concentrations showed corresponding decrease; this was most apparent in wells UVB-1 and UVB-2, located in the area of highest TVOC concentration.

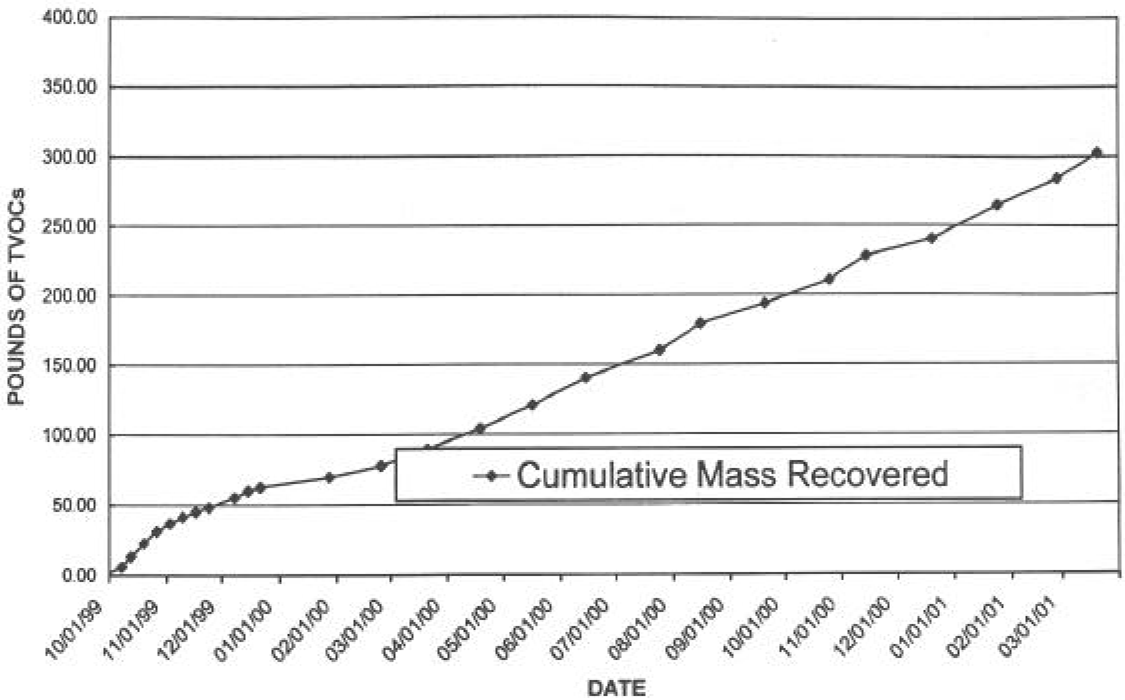


Figure 9. Cumulative mass removal of TVOCs vs. time.

— The current system configuration is capturing the entire width of the OU III plume, based on three independent analyses. Field data reveal drawdown 100 feet from UVB-7; mounding in monitoring wells screened at same interval as treatment wells effluent screen during recirculation; groundwater quality changes in monitoring wells adjacent to treatment well effluent screens; and, observed mounding, drawdown, and vertical gradient increases consistent with a working system. Analysis of data using the Herrling, et al, method concludes that the actual treatment-well spacing will yield 100 percent plume capture with a safety factor of 30 percent. Numerical modeling indicates the system achieves full capture under varying aquifer conditions. Recirculation rate estimates using field data range from 50 to 70 percent, within the expected range.

SECTION 4
TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Competing Technologies

- The baseline against which IWVS can be compared is pump and treat. Pump and treat technology generally requires long treatment times and has high operation and maintenance requirements and cost. Distinct advantages of IWVS over the baseline pump and treat technology include:
  - the IWVS system is an in situ technology that continuously removes VOCs from groundwater without pumping the water to the surface and eliminates the need to manage water discharges,
  - the IWVS system aerates the water and hence may promote aerobic biodegradation of hydrocarbons such as petroleum fuels,
  - the re-circulation created through IWVS optimizes the dissolution and transport of contaminants to the well and facilitates more complete removal of contaminants.
- Other competing technologies include air sparging, bioremediation, zero valent iron barriers, chemical treatment, and thermal technologies.
- IWVS is a more aggressive remediation technology than in situ air sparging or bioremediation. Its application at many sites may result in a faster cleanup, thereby reducing life-cycle remediation costs.
- IWVS can be used at sites where reactive barriers have not been applied to-date (e.g. at sites with contamination at depths greater than 40 feet).
- In situ chemical oxidation is similar to IWVS in cost and effectiveness of treatment, but may not be effective at sites that have a high natural oxygen demand. It may pose increased risks for worker safety, because workers must handle reactive chemicals.
- Thermal technologies generally have higher capital and operating costs than IWVS and pose greater worker exposure to safety risks.

Technology Applicability

- IWVS is best suited for sites with contaminants that are sufficiently mobile to be entrained within the circulation cell established by the well, and sufficiently volatile (Allmon et.al.1999).
- The site hydrogeologic setting coupled with well design comprise the critical determinant on whether IWVS can be employed successfully, as together, they govern the geometry of the circulation cell, including the area of influence of the treatment well.
- Targeted contaminants may be dissolved or sorbed in the saturated or vadose zones. Vadose zone remediation is often accelerated by coupling with SVE.
- Contaminants that have been treated with IWVS include petroleum hydrocarbons (TPH and BTEX); non-petroleum hydrocarbons (methanol and isopropyl ether); PAHs (naphthalene, and 2- and 3-ring PAHs), and chlorinated hydrocarbons (DCE, 1,1-dichloroethane, 1,2-dichloroethane, TCA, PCE, and TCE).
- Critical hydrogeologic factors influencing the horizontal area of influence include anisotropy (horizontal hydraulic conductivity/vertical hydraulic conductivity - K_h/K_v), and aquifer thickness. Well design parameters such as length and separation distance of the influent and effluent screen sections at the top and bottom of the treatment zone and pumping rate together with the site hydrogeology determine the area of influence of the treatment well.
- The vertical area of influence of the treatment well depends on aquifer anisotropy and on natural groundwater flow velocities, in conjunction with well design parameters such as degree of penetration of

the treatment well relative to aquifer thickness. In addition, presence of low-permeability layers between the influent and effluent screens of the treatment well may hinder the vertical component of circulation.

- Table 2 summarizes optimum parameters for which IWVS is best suited.

Table 2. Optimum parameters for IWVS of VOCs

Factor	Parameter	Limits/Desired Range
Contaminant	Volatility	>5 mm Hg, unless highly biodegradable
	Solubility	<20,000 mg/L
	Henry's Law	5E-04 atm-m^3/mole, unless biodegradable
	Biodegradability	Not required, but system performance will be enhanced for biodegradable compounds
Geology	Stratigraphy	No impermeable layers that reduce contaminated zones to thickness <3 m (Impermeable strata that divide the contaminated zone into one or more thin layers can present problems in discharging water into the vadose zone and may prevent efficient water recycle. Because the radius of the treatment zone is defined by the thickness of the conducting layer, thin zones may require an excessive number of treatment wells.)
	Hydraulic conductivity	>10^{-5} cm/s (e.g., clayey sand)
Physical	Thickness of vadose zone	>3 m, unless the vadose zone conductivity is >10 times the saturated conductivity. The vadose zone generally must be a minimum of 3 m thick to ensure circulated water can recharge without mounding to the surface. A vadose zone thickness of 9 m or more is optimum, and very thick vadose zones represent a specialty niche.
	Length of stripping zone in NoVOCs™ well	> 3 m

Patents/Commercialization/Sponsor

In the United States, four basic variations of GCWTs have been commercialized, and are available through the original patent holders or their licensees.

- **UVB System** was developed by IEG Technologies GmbH of Germany and is licensed in the U.S. by URS Corporation, Environmental Laboratories, Inc. and GZB.
- **The NoVOCs™ System** was patented by Stanford University of Stanford, California: U.S. patent 5,180,503, 5,389,627 (1993 and 1995 Gorelick, S.M., and H. Gvirtzman – In-situ Vapor Stripping for Removing Volatile Organic Compounds from Groundwater); and MACTEC, Inc., currently the exclusive licensee for NoVOCs™, has granted sublicenses to other companies, such as Metcalf & Eddy, Inc.
- **The DDC System** was patented and is marketed by Wasatch Environmental, Inc. of Salt Lake City, Utah: U.S. patent 5,425,598 (1995 Pennington L.H. – System for Sparging Ground Water Contaminants). There are four licensees for the DDC technology: Steve Willhelm & Associates, ATC Associates, Inc., Project Performance Corporation, and URS.
- **The C-Sparger® System** was patented and is marketed by K-V Associates (KVA) of Mashpee, Massachusetts: U.S. patent 5,855,775 (– Microporous Diffusion Apparatus); U.S. patent 6,083,407 (– Microporous Diffusion Apparatus and Process); and U.S. patent pending (2000 – Gas-Gas-Water Treatment System for Groundwater and Soil Remediation). Other U.S. and foreign patents are pending.

SECTION 5
COST

Methodology

The primary sources of cost information in this section are: 1) an analysis developed by MSE comparing the BNL UVB system to a pump and treat system, and 2) cost estimates prepared by technology vendors for a hypothetical scenario.

The UVB system installed at BNL consists of seven groundwater treatment wells, which provide hydraulic control and treatment of the off-site portion of the OU III VOC plume. The UVB system was started on September 29, 1999. The seven UVB wells extend to depths between 193 and 243 ft below grade. Each of the UVB wells was designed to operate at a nominal flow rate of 60 gpm with the capacity to operate at a maximum flow rate of 65-75 gpm. The combined nominal flow rate for the UVB system is 420 gpm with a maximum flow rate of 455-525 gpm. The average flow rate for the UVB system has met or exceeded the nominal design capacities during the recent months of operation. Each of the UVB wells has an air stripping tray designed to operate at 650 cubic feet per minute (cfm) with maximum flow rate of 900 cfm. During the startup period, the air flow rate for each of the UVB wells ranged from 425 to 791 cfm. The average contaminant removal efficiencies for each UVB well ranged from 88% to 97% during the startup period with the average UVB system removal efficiency at 93%.

A hypothetical baseline pump-and-treat system was compared to the actual UVB system at BNL. An equivalent pump-and-treat system would have to operate in the same range of flow rates to treat the same contaminant plume. The period of operation for the baseline technology was adjusted to the equivalent period of operations for the UVB system, FY99 to FY07. The real discount rate used in the analysis was 4% as recommended by OMB for cost-effectiveness analysis.

To further compare various IWVS systems with pump and treat, a hypothetical scenario was developed. Vendors submitted cost estimates for the hypothetical scenario. In addition, a pump-and-treat estimate was provided by TetraTech NUS of Pittsburgh, Pennsylvania and an anaerobic bioremediation using Hydrogen Release Compound (HRC) estimate was provided by Regenesis, Inc.

Cost Analysis

Table 3 provides the discounted cash flow analysis for the BNL UVB system and a baseline pump and treat system (MSE). The analysis does not take into consideration that the pump-and-treat operations would continue to operate well into the future. The MSE analysis shows the total discounted cash flow for IWVS (UVB) as $4.99M and $5.15M for pump-and-treat. The estimated cost savings for the UVB system over the period is $161,000. Although the cost savings estimated for the UVB system at BNL are small, BNL indicates that the public and regulatory acceptance of this innovative technology provides substantial benefit to BNL beyond cost savings.

Table 3. Potential cost savings analysis of UVB system and baseline pump-and-treat

UVB System FY 98–07	**FY 1998**	**FY 1999**	**FY 2000**	**FY 2001**	**FY 2002**	**FY 2003**	**FY 2004**	**FY 2005**	**FY 2006**
Contractor Costs		2,634,495	219,902	252,961	253,178	254,187	256,204	255,195	253,178
DAT Tech Support		9,215							
Administrative Support									
Community Relations Rep									
Computer Support Staff									
Field Engineer		53,016	53,854	21,800	21,670	21,757	21,930	21,843	21,670
Environmental Science Association		17,160							
Project Engineer									
Project Management		40,493	83,992	42,415	42,248	42,416	42,752	42,584	42,248
ERD Rad QA/QC									
ERD QA Representative									
Safety and Health Rep. – BNL		12,261							
Additional UVB Costs	569,179								
Total	569,179	2,766,640	357,748	317,176	317,096	318,360	320,886	319,622	317,096
Discounted Cash Flow @ 4%	547,288	2,557,914	318,037	271,123	260,630	251,605	243,847	233,545	222,787
Total DCF @ 4%	4,992,897								
Conventional Baseline FY 98–07	**FY 1998**	**FY 1999**	**FY 2000**	**FY 2001**	**FY 2002**	**FY 2003**	**FY 2004**	**FY 2005**	**FY 2006**
Capital	2,205,000	1,625,000							
O&M			246,000	246,000	246,000	246,000	246,000	246,000	246,000
Total	2,205,000	1,625,000	246,000	246,000	246,000	246,000	246,000	246,000	246,000
Discounted Cash Flow @ 4%	2,120,192	1,502,404	218,693	210,282	202,194	194,417	186,940	179,750	172,836
Total DCF @ 4%	5,153,897								
Total DCF @ 4% FY 98–07									
UVB System	4,992,897								
Conventional P&T Baseline	5,153,897								
Cost Savings	**161,000**								

The cost analysis comparing various IWVS systems is based on the following hypothetical scenario:

- Geology: Interbedded sediments (fine to coarse sand, trace clay, silt and gravel lenses) underlain by clay at 100 ft below ground surface (bgs). Contaminant zone 50 to 100 ft bgs.
- Hydrogeology: Unconfined aquifer with water table at 50 ft bgs; hydraulic conductivity of 1.0×10^{-3} cm/sec; hydraulic gradient of 0.001 ft/ft; average linear groundwater velocity of 2.5×10^{-6} cm/sec; anisotropy (K_h/K_v) 8.
- Contaminants: Maximum treatment well influent concentrations (ug/L): TCE - 500. Source remediation project with plume of area of 100 x 300 ft.

Vendors were requested to estimate the number of treatment wells necessary to capture the plume, individual and total pumping rates and air supply rates for treatment wells, off-gas production rate, and an itemized cost estimate for their particular system. In addition, the type and frequency of system operating parameters and performance monitoring parameters were also requested. It was assumed that 24 monitoring wells would be available to monitor effectiveness at three depth intervals (above adjacent treatment well effluent depth, at adjacent treatment well effluent depth, and at adjacent treatment well influent depth). The cost of monitoring well installation was not included in the estimates.

Capital costs and costs for one year of operation and maintenance (O&M) were requested. Extrapolation of the annual O&M costs by various increments without regard to predictions related to potential system performance were then conducted to compare long-term costs for the various technologies.

- The DDC cost estimate is based on the following assumptions (Table 4).
  - Two DDC wells installed to 100-ft depth, approximately 75 ft apart, through centerline of plume. (Drilling waste disposal included in well-installation capital costs).
  - Wells connected to a 15 HP rotary-vane positive-pressure blower staged in nearby equipment shed. (Assume that 200 ft. of trenching/piping is needed).
  - Off-gas would be treated via two 55-gallon carbon adsorption units and then vented to atmosphere.
  - Base estimate assumes that scaling is not a problem at the site.
  - Annual performance monitoring would include sampling of six monitoring wells and air samples.
  - Contingency covers potential acid treatment for scale accumulation.

Table 4. DDC cost estimate

Cost Element	Itemization	Cost ($K)
Capital Costs	Drilling, Treatment Well Construction	26
	Site Construction (Piping, Trench, etc.)	4
	Equipment (Blowers, Pumps, etc.)	11
	Above Ground Water Treatment System	0
	Off-Gas Treatment System	2
Subtotal		43
Annual Operation & Maintenance	Well Maintenance	4
	Power	3
	Consumables/Supplies (Carbon Changeout, etc.)	4
	NPDES Permit	0
Subtotal		11
Annual System Monitoring	Data Collection	1
	Data Analysis	1
Subtotal		2
Annual Performance Monitoring	Data Collection	12
	Data Analysis	2
Subtotal		14
Engineering and Reporting		8
Indirect and Profit		0
Contingency		4

- The C-Sparger® cost estimate is based on the following assumptions (Table 5).
  - A single recirculation well with an effective radius of influence of about 80 feet, so that two wells can treat the plume. (Drilling waste disposal not included in well installation capital costs).
  - The 500 ppb TCE concentration is primarily aqueous/adsorbed, (no dense non-aqueous phase liquid is present), and distributed mid-aquifer, and no additional split-spoon sampling is necessary.
  - Groundwater elevation is constant and groundwater velocity is 0.007 ft/day.
  - Only three downgradient wells are necessary to judge system performance (50, 75, and 90 foot depths). If a check of recirculation development is desired, five wells are used around the recirculation well and on top of the packer of the recirculation well. These five wells would include three depths upgradient of the recirculation well and two mid and deep near the recirculation system.
  - Capital costs include cost of a wall-mount unit (Model 3600), capable of a wide variety of flows and concentrations.
  - The air/ozone flow volume would be expected to fall within 2 to 6 cfm. No off-gas production rate, recovery blowers, or granular activated carbon draws is necessary. Off-gas treatment is not necessary because TCE vapors are adjusted to zero concentration in the air stream.
  - Measurement of dissolved oxygen and oxidation-reduction potential are sufficient to establish recirculation and radius of influence. Normally, a two-week (14-day) intensive test is conducted with granular carbon to determine rate of reaction and time/mass removal rate. Beyond this time, monitoring changes to weekly (first two months) then monthly.

Table 5. C-SpargerÒ cost estimate

Cost Element	Itemization	Cost ($K)
Capital Costs	Drilling, Treatment Well Construction	21
	Site Construction (Piping, Trench, etc.)	5
	Equipment (Blowers, Pumps, etc.)	25
	Above Ground Water Treatment System	Not necessary
	Off-Gas Treatment System	Not necessary
Subtotal - Capital Costs		
Annual Operation & Maintenance	Well Maintenance ($250/month)	3
	Power ($160/month)	2
	Consumables/Supplies (Carbon Changeout, etc.)	Not necessary
	NPDES Permit	Not necessary
Subtotal - O&M		5
Annual System Monitoring	Data Collection	20.8
	Data Analysis	8
Subtotal - ASM		28.8
Annual Performance Monitoring (3 wells - VOC)	Data Collection (22 days/$650/day)	14.3
	Data Analysis (chem. analysis)	4
Subtotal - APM		18.3
Engineering and Reporting		15
Indirect and Profit 10%		11.341
Contingency 10%		11.341

- The pump and treat cost estimate assumes the following (Table 6).
  - — Based on the MODFLOW model, one extraction well (90 ft deep) pumping at 0.5 gpm is sufficient to capture the plume. One treatment well (4-inch diameter) and a 1/3-h.p. submersible pump with controls is included under capital costs.
  - — Capital costs assume that electrical supply is already present at the site; only hookup is necessary.
  - — Capital costs assume 50 feet of pipe and trenching from the well to the treatment unit and 150 feet of pipe and trenching from the treatment unit to the point of disposal.
  - — Because flow rate is so small, no air stripper is included in treatment; all treatment is performed using carbon adsorption units.
  - — Treatment estimates assume that vinyl chloride or excessive iron in groundwater will <u>not</u> present a problem for the treatment system.
  - — Carbon sorption units will be very small and costs are included under annual O&M. Disposable 55-gallon drum units will be used. Each drum unit cost is $635. Disposal (regeneration) of used drum unit is estimated to be $1,000 each.
  - — Annual system monitoring assumes that carbon unit influent and effluent will be sampled and analyzed for VOCs monthly (total of 24 samples).
  - — Annual performance monitoring assumes that 12 wells with one duplicate and one trip blank will be sampled and analyzed for VOCs twice per year (28 samples total).
  - — Costs presented are rough estimates; actual costs could be more or less depending on site conditions, groundwater quality, regulatory requirements, and other variables.

Table 6. Pump and treat cost estimate

Cost Element	**Itemization**	**Cost ($K)**
Capital Costs	Drilling, Treatment Well Construction	6.95
	Site Construction (Piping, Trench, etc.)	6.97
	Equipment (Blowers, Pumps, etc.)	1.68
	Above Ground Water Treatment System	0
	Off-Gas Treatment System	0
Subtotal		20.6
Annual Operation & Maintenance	Well Maintenance	0.44
	Power	0.26
	Consumables/Supplies (Carbon Changeout, etc.)	5
	NPDES Permit	1
Subtotal		6.7
Annual System Monitoring	Data Collection	10
	Data Analysis	1
Subtotal		11
Annual Performance Monitoring	Data Collection	10
	Data Analysis	1
Subtotal		11
Engineering and Reporting		1
Indirect and Profit (15%)		6.8
Contingency (5%)		2.3

- The anaerobic bioremediation cost estimate assumes the following (Table 7).
  - — The contaminant plume is 300 ft wide (intersecting groundwater flow direction) and 100 ft long (parallel to groundwater flow direction.
  - — The treatment zone pore volume is 525,000 ft^3.
  - — The soil bulk density is 110 lb/cf, and the fraction of organic carbon is 0.01.
  - — A total of 10.47 lbs. of H_2 is required.
  - — A total of 140 HRC® delivery points are needed, with a total of 102 lbs. of HRC® injected at each point.

Table 7. Anaerobic bioremediation (HRCÒ) cost estimate

Cost Element	Itemization	Cost ($K)
Capital Costs	HRC® Cost	73
	Drilling, Treatment Well Construction	57
	Site Construction (Piping, Trench, etc.)	0
	Equipment (Blowers, Pumps, etc.)	0
	Above Ground Water Treatment System	0
	Off-Gas Treatment System	0
Subtotal		130
Annual Operation & Maintenance	Well Maintenance	0
	Power	0
	Consumables/Supplies (Carbon Changeout, etc.)	0
	NPDES Permit	0
Subtotal		0
Annual System Monitoring	Data Collection	0
	Data Analysis	0
Subtotal		0
Annual Performance Monitoring	Data Collection	8
	Data Analysis	12
Subtotal		20
Engineering and Reporting		10
Indirect and Profit		
Contingency		

Cost Conclusions

Table 8 is a summary of three IWVS technologies with pump and treat for a hypothetical scenario.

Table 8. Cost comparison summary ($K)

Cost Category	DDC	C-Sparger®	Pump and Treat	HRC®
Capital	43	51	21	130
Engineering/Indirect/ Contingency	12	38	10	10
Annual O&M and Monitoring	27	52	29	20

SECTION 6
OCCUPATIONAL SAFETY AND HEALTH

Summary

The baseline technology (groundwater pump-and-treat) presents an exposure risk to site workers from investigation-derived waste, groundwater monitoring well purge water, well-drilling equipment, and groundwater monitoring equipment. IWVS technology has similar exposure risks as pump and treat during the construction and sampling/monitoring phases, although the operational period for IWVS is believed to be significantly less than for pump-and-treat. During the operation of IWVS, exposure to site workers should be significantly reduced from the baseline technology.

Technology-Specific Health and Safety Risks

- There are no unusual health and safety issues related to the installation and operation and maintenance of IVWS systems.

Worker Safety

Health and safety issues for IWVS technology do not present significant hazards over conventional field remediation operations. Because liquids containing hazardous components are not pumped to the surface, the potential exposure of workers to hazardous materials is reduced. Routine site safety procedures for site remediation projects may include:

- Level D personnel protective clothing.
- Applicable OSHA training.
- Proper monitoring of off-gas treatment systems will minimize any potential for release of hazardous vapors.

Community Safety

- IWVS does not produce any routine release of contaminants, and no unique safety concerns are associated with the technology.
- Implementation of well-designed remediation systems in conjunction with system and performance monitoring will ensure worker and public safety.
- The potential risk of spills of liquids containing hazardous materials resulting in surface water contamination is eliminated.

Lessons Learned

All phases of the BNL IWVS deployment were conducted safely and according to all of the applicable guidelines of BNL's health and safety program. Although the IWVS process exposes workers to investigation and monitoring-derived waste and requires the use of well-drilling equipment, no accident occurred during the deployment.

SECTION 7
REGULATORY AND POLICY ISSUES

Regulatory Considerations

- Under the Comprehensive Environmental Responsibility Cleanup and Liability Act (CERCLA), the chemical-specific Applicable or Relevant and Appropriate Requirements (ARARs) pertinent to use of the technology are federal (40 Code of Federal Regulations (CFR) 141 and 40 CFR 143) and state groundwater standards.
- Federal and state location-specific ARARs may apply for specific aquifers, or in areas including wetlands, flood plains, and areas inhabited by endangered or protected species.
- Currently, New York State does not consider IWVS to involve reinjection. However, other states may have different underground injection well requirements and definitions. Treating groundwater in situ may eliminate the need for discharge permitting requirements, but it can not be assumed that this regulatory status is a certainty now and in the future.

Risks, Benefits, and Community Reaction

- IWVS does not produce any significant routine release of contaminants.
- No unusual or significant safety concerns are associated with IWVS.

Environmental Impacts

- No additional impacts beyond those anticipated as a result of site remediation will be produced.
- Well installation is required for both pump-and-treat technology and IWVS; therefore, drill cuttings and drilling fluids are produced, and well permits may be necessary. The zone of influence of remediation wells that use IWVS is dictated by both site properties and system configuration. If the zone of influence for IWVS wells is not very large for a particular site, more wells may be required for IWVS than for traditional pump-and-treat technology. Thus, a greater quantity of drill cuttings and drill fluids may be generated.
- Surface water, ground water rights, liquid holding tank monitoring, and liquid discharge issues are eliminated by IWVS because no liquids are brought to the surface for treatment.
- It may be necessary to collect, monitor and treat off-gases produced by the technology.

Socioeconomic Impacts and Community Perception

- IWVS has minimal economic or labor force impact.
- The general public has limited familiarity with this technology, however public support is likely due to elimination of contaminated liquid and reduction in remediation costs. At BNL, the public was extremely supportive of the use of IWVS technology.
- The Center for Public Environmental Oversight (CPEO) promotes and facilitates public participation in oversight of environmental activities, including hazardous waste site remediation. On their Web site, http://www.cpeo.org., CPEO lists several limitations or concerns with groundwater circulation wells and in-well air stripping:
  - potential vapor releases (untreated);

— potential increased contaminant mobility due to increased water in the soil, or raising of water table (without adequate monitoring);
— adequacy of radius of influence of each well;
— adequacy of design to prevent spread of contaminants and properly treat contaminants;
— effectiveness of process at sites with shallow aquifers;
— smearing of contaminants in area above groundwater level at non-aqueous phase liquid sites.

SECTION 8
LESSONS LEARNED

Implementation Considerations

The applicability of IWVS for a site is dependent upon the hydrogeological properties of the saturated and unsaturated zones, the geochemistry of aquifer, the nature of site contaminants, and prevailing regulatory requirements. Site characterization is therefore a critical step in evaluation of the potential success of the technology (Table 9).

Table 9. Data requirements applicable to selection and design of an IWVS system for a given site

General category	Effect	Data Required for Design
Site geology	Determines if the vadose zone characteristics will allow for recharge of treated waters into the unsaturated zone. If low permeability layers are present or aquifers are <3m, IWVS is not appropriate.	Soil type and stratigraphy in soil/aquifer horizons
		Depth to ground water
Hydrogeologic conditions	Determines the optimum pumping rate, the need for a given range of stripping efficiencies, and the probable radius of the treatment zone, hence, the number of wells required and the desired positioning of well screens.	Hydraulic conductivity of aquifer
		Aquifer thickness (saturated depth)
		Hydraulic gradient of aquifer
		Estimated anisotropic ratio; i.e., ratio of horizontal hydraulic conductivity to vertical hydraulic conductivity (K_h/K_v)
		Recharge characteristics of vadose zone
Water chemistry	Defines the nature and extent of contamination that directly affects the number and placement of wells. In addition, the presence of inorganic species (e.g., calcium carbonate) may lead to chemical fouling of the screens or formation.	Contaminated plume dimensions; length, width, and depth
		Plume concentration; range and distribution
		pH, alkalinity, calcium, dissolved iron, and total iron levels in site groundwater
Chemical properties of contaminants	Determines both the stripping efficiency that can be achieved at different air/water ratios and the time required to flush adsorbed chemicals out of the aquifer media.	Henry's law constant
		Organic carbon partition coefficient (K_{oc})
		Molecular weight
Regulatory requirements	Establishes the remediation criteria and the degree of removal required for both ground water and system off gas. Regulations may also impinge on well design and the need for various permits before operation.	Clean-up goal for contaminants
		Requirements for off-gas treatment
		Well and treatment system construction requirements

Table 10 provides a generalized view of individual factors influencing IWVS applicability, ranked by relative degree of suitability for technology implementation.

Table 10. Generalized applicability for groundwater circulation well technology

Parameter	**Applicability:** xxx good potential for success; xx moderate potential x limited or no potential
Contaminant Type	
VOCs	xxx
SVOCs	xxx
Metals	xx
Radionuclides	x
Clean-up Strategy	
Source treatment	xxx
Plume reduction	xx
Plume interception	xx
Unsaturated Thickness	
0-5 ft	x
5-1,000 ft	xx
Saturated Thickness	
0-5 ft	x
5-115 ft	xx
>115 ft	x
Aquifer Characteristics	
Porous media	xx
Fractured media	x
Karst	x
Background Flow Velocity	
Low (>0.001 ft/d)	xxx
Medium (0.001-1 ft/d)	xx
High (>1 ft/d)	x
Horizontal Hydraulic Conductivity	
Moderate (0.03-1 ft/d)	xx
High (>1 ft/d)	xxx
Ratio of Horizontal to Vertical Hydraulic Conductivity	
Anisotropic (K_h/K_v 3-10)	xx
Highly Anisotropic (K_h/K_v >10)	x
Aquifer Chemistry	
High iron in water	x
High calcium in water	x
High magnesium in water	x

Technology Limitations and Needs for Future Development

The critical aspect of IWVS that sets it apart from other technologies is the development of the three-dimensional circulation cell around the treatment well. The degree of anisotropy and the presence of thin low-permeability layers are some of the main technology limitations. The need to verify the circulation cell development and potential methods for doing so are stressed.

- Anisotropy (K_h/K_v) of the target aquifer must be within a range that allows the circulation cell to develop, generally between 3 and 10. If anisotropy is less than 3, the difference between horizontal and vertical conductivity is small, and the radius of influence of the treatment well will be very small. If anisotropy is greater than 10, the vertical flow will be limited, and the discharged water will flow beyond the radius of influence of the treatment-well intake. Thus, the quantity of water that is recirculated will be limited and the circulation cell will not properly develop. Many sites will exhibit anisotropies greater than 10, limiting the development of a recirculation cell, unless low hydraulic conductivities and/or adequate pumping rates counteract the less than optimum anisotropy.
- The presence of relatively thin, low-permeability layers within an otherwise highly permeable layer will cause the overall vertical hydraulic conductivity to decrease, and hence the anisotropy effect to increase. In addition to obtaining aquifer test and laboratory permeability data, a vertical model of the potential radius of influence (ROI) of a IWVS well should be developed to allow meticulous characterization of vertical hydraulic conductivity.
- Verification of the dynamics and geometry of the circulation cell is needed to allow better cost/benefit comparison to competing technologies, even though mass removal and concentration reductions may be noted as an indicator of successful remediation. Although the time for a circulation cell to develop can vary, case studies where groundwater concentration information shows continued contaminant decreases only near the discharge screen cause suspicion that the contaminant mass is simply being redistributed. Use of dye tracer studies have provided the best evidence of groundwater circulation to date, and dual tracer tests using both a convergent and divergent approach seem to hold the most promise. Table 11 summarizes potential methods for analyzing the circulation cell, with comments on their applicability and efficacy.

Table 11. Methods to document circulation cell development

Technique	Comment
Dye tracer studies	Dual tracer tests using both a convergent and divergent approach are effective. Costs to implement are currently high; results represent a single point in time.
Water level changes or Pressure changes (by transducers)	Head changes induced by the treatment well diminish rapidly with distance from the well; it may be difficult to distinguish treatment-well induced head changes from those caused by natural groundwater fluctuations.
Contaminant concentration charting	Reductions rarely seen throughout circulation cell; contaminant smearing by treatment well may cause fluctuations; background fluctuations may further complicate interpretation. Use of groundwater monitoring to verify circulation should be performed with an extensive array of vertically and horizontally distributed monitoring points upgradient, downgradient, and cross gradient from treatment wells.
Microbe counts DO increases Phosphorous or other nutrient changes Carbon isotope data Homogenization of electrical conductivity	Chemical and biological measurement techniques are limited by the short distance DO will travel in the circulation zone before it is utilized. Discontinuities of the magnitude needed for electrical conductivity homogenization may be lacking at typical sites, but can be so utilized where they do exist.
Flow sensors Colloidal bore-scope	Current methods for groundwater flow direction and velocity measurement currently lack the sensitivity needed to accurately measure the subtle flows induced away from the treatment well.

The efficiency of the single pass, in-well treatment process may also be a limiting factor in meeting site clean-up goals as less than 100% of the discharged water will be recirculated. A downgradient polishing process may be necessary. The continued ability to reinject the treated water is also of high importance, and it may be necessary to incorporate means of dealing with potential fouling agents into system design.

- Some IWVSs incorporate air-lift pumping and co-current air stripping (air and water flowing in the same direction in contrast to counter current stripping where these flows oppose each other). This innate treatment efficiency will generally result in VOC removal efficiencies of 99% or less, so that a single pass through the treatment well will not reach the cleanup goal when the contaminant concentrations are greater than one order of magnitude higher than the cleanup goal. Without 100% recirculation, some migration of contaminants may occur downgradient, perhaps necessitating additional downgradient treatment.
- Geochemical effects may adversely affect the efficacy of IWVS.
  - In-well stripping may reduce carbon dioxide from groundwater; the loss of buffering capacity may result in a pH increase and subsequent mineral precipitation at sites with a high mineral (calcium, etc.) content.
  - Iron precipitation may result from changes in redox potential, causing plugging of the recharge screen and recharge zone.
  - When groundwater recharged into the vadose zone is not in equilibrium with the soil chemistry (as in case of low ionic-strength groundwater being recharged into sodic (high sodium) soil), sodium may be displaced from soils, causing displacement of clay colloids, leading to clay colloid deflocculation or swelling, resulting in clogging or pore spaces.
- The capacity for reinjection at a site may be the limiting factor governing the flow rate of groundwater circulation wells; reinjection testing is recommended to assess recharge capacity.

Mechanical aspects may lead to inefficiencies if not properly addressed in design and operation.

- For applications that use an air compressor (>15 psi) in high temperatures, oil contamination and maintenance problems have been experienced. Rotary-vane blowers have proven effective in replacing air compressors for applications in high-temperature climates and where the pressure requirements are <15 psi.
- Condensate buildup in exhaust air hoses from the well can cause inlet airflow rate restrictions and, consequently, reduce the pumping rates of the system. To correct for condensation effects and to minimize the maintenance caused by condensation buildup, an in-line dryer or a water-dropout vessel is recommended for field applications. In addition, the reduction in moisture in the off-gas may extend the life of carbon off-gas treatment media.

Improvements in methods to characterize circulation cell dynamics and geometry could enhance system performance.

Field dye detection for tracer tests, increased sensitivity in pressure transducers to detect subtle flows and head differences, and other measurement methods should be investigated. In-well measurement methods should be further developed.

Technology Selection Considerations

Technology selection at a contaminated site is dictated by the contaminant type, initial concentration levels, clean-up requirements, clean-up schedules, site geology and hydrogeology conditions, soil and ground water chemistry, and remediation costs. IWVS should be considered for application because it offers efficient, in situ, and continuous treatment of groundwater, reduced capital costs, reduced energy demands, and elimination of liquid discharge requirements and permits. IWVS systems may more effectively flush contaminants bound to low permeability layers and provide superior contaminant mass removal to other technologies.

An overall summary of technology advantages and disadvantages is provided in Table 12.

Table 12. Groundwater circulation well technology advantages and disadvantages

Advantages/Disadvantages	Explanation
Advantages	
In situ treatment	Minimal above-ground space needs, water handling, or water discharge
Vertical flushing	Facilitates mobilization of contaminants bound in lower permeability layers
No reinjection permit needed	Current regulations do not require permit for subsurface reinjection
Low impact on groundwater levels	May be compatible with sensitive regimes such as wetlands, perennial springs, and sole source aquifers
Less process waste	Off-gas treatment may or may not be necessary; it is the main source of process waste
Deep contaminant cost effectiveness	Depth-dependent operation costs are limited, compared to pump and treat
Biodegradation enhancement	Higher DO in aquifer and nutrient delivery can enhance aerobic biodegradation
Technology compatibility/reagent delivery	Treatment wells can deliver a variety of chemicals to facilitate remediation (oxidants, surfactants, catalysts, nutrients, electron acceptors, etc.). Compatible with SVE for vadose zone remediation
Disadvantages	
Hydrogeologic sensitivity	High anisotropies are common and interfere with circulation cell development
Contaminant mobility	Flushing of vadose zone contaminants can add to contaminant mass in groundwater, and partially treated water could spread beyond radius of influence of treatment well if not properly designed
Treatment efficiency	Multiple circulations through well may be needed to meet clean-up goals, which may be difficult if co-current in-well stripping is only in-well treatment process
Geochemical effects	Distribution of chemicals (salts, carbon dioxide, metals) may affect groundwater geochemistry and potentially cause precipitation and plugging of reinjection zone
Well design and construction	Ineffective sealing along wellbores between influent and effluent screens, or internal packers with improper seal may cause short circuiting; slot size, screen length and placement are critical design elements
Thin target zones	The maximum radius of influence of a treatment well is two to three times the distance between the extraction and reinjection zone, so that thin target zones limit the radius of influence and hence cost effectiveness
Nonvolatiles	Nonvolatiles can not be removed with in-well stripping, so in-well treatment process must be compatible with contaminant

APPENDIX A
REFERENCES

Allmon, W.E., A.T. Lightner, B. Alleman, T.J. Boyd, and B.J. Spargo 1999. “Groundwater Circulating Well Technology Assessment.” Environmental Security Technology Certification Program (ESTCP), Naval Research Laboratory Environmental Quality Sciences, NRL/PU/6115—99-384, Naval Research Laboratory, Washington, DC, 74 pages.

Breeding, L. Boyd. Undated. “Density Driven Convection Achieves Remedial Action Objectives, Maxwell Air Force Base, Montgomery, Alabama,” included in company information provided by Wasatch Environmental, Inc. 2410 West California Avenue, Salt Lake City, UT 84104-4109, 9 pages.

K-V Associates, Inc. 2000. Company Provided Information. K-V Associates, Inc., Madaket Place – Unit B, 766 Falmouth Road, Mashpee, MA 02649

Kerfoot, W.B. 2000. “Ozone Microsparging for Rapid MTBE Removal,” K-V Associates, Inc. Technical Publication #115, to be presented at The Second International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, CA, May 22-25, 2000. Included in company information provided by K-V Associates, Inc., Madaket Place – Unit B, 766 Falmouth Road, Mashpee, MA 02649

MACTEC Environmental Technologies Company, L.L.C. 2000. Company Provided Information. MACTEC Environmental Technologies Company, L.L.C., 1000 Hobson Court, Fort Collins, CO 80526

P.W. Grosser Consulting Engineer & Hydrogeologist, P.C. 1998. “Final Remedial Design Work Plan for the OU III Off-Site Removal Actions.” Brookhaven National Laboratory Environmental Restoration Division, June 26, 1998, 7 sections plus tables and figures.

P.W. Grosser Consulting Engineer & Hydrogeologist, P.C. 2000. “Off-Site Removal Action System Start-Up Report”. Brookhaven National Laboratory Environmental Restoration Division, April 2000, 42 pages plus tables, figures, and appendices.

U.S. Department of Energy Draft Innovative Technology Summary Report. 1997. “In-Well Vapor Stripping Technology.” U.S. DOE Office of Environmental Management, Office of Science and Technology, April 1997, 20 pages.

Wasatch Environmental, Inc. 2000. Company Provided Information. Wasatch Environmental, Inc., 2410 West California Avenue, Salt Lake City, UT 84104-4109

APPENDIX B
Additional Case Studies

TCE Case Study

NoVOCsÔ System Installation at Edwards Air Force Base, TCE Case Study

- Site Descpription
  - — Hydrogeology: sandy silt/silty sand; low yield aquifer – 1 x 10^{-3} cm/sec; saturated thickness 23 feet; hydraulic gradient – 0.0047 ft/ft; vadose zone thickness – 27 ft
  - — Contaminant: TCE – 300 ppb initial
  - — Inorganic chemistry: alkalinity – 288 ppm as $CaCO_3$, groundwater is in equilibrium with calcite (strong potential for scaling)
- Operation: 3 –1.5 hp rotary vane blowers; closed loop operation – no air emissions; off-gas treatment with GAC; pH control – CO_2 addition to injected air; 6 monitoring wells to measure performance and radius of treatment zone; at 8 gpm – air to water ratio = 55:1
- Initial Results: Pumping rate – 3 to 8 gpm; period of operation – 7 mos.; radius of treatment zone - >50 ft, more than 2 x plume thickness; ave. concentration reduction at 4 mos. ~67%; max. concentration reduction - 97%
- Detailed results: 4 of 6 shallow zone monitoring wells reached 5 ppb MCL for TCE; average single pass removal through NoVOCs™ well of 90%; and, flow sensors showed significant hydraulic influence (changes in vertical and horizontal flow directions and velocities) at all point monitored (at least 35 feet from NoVOCs™ well).

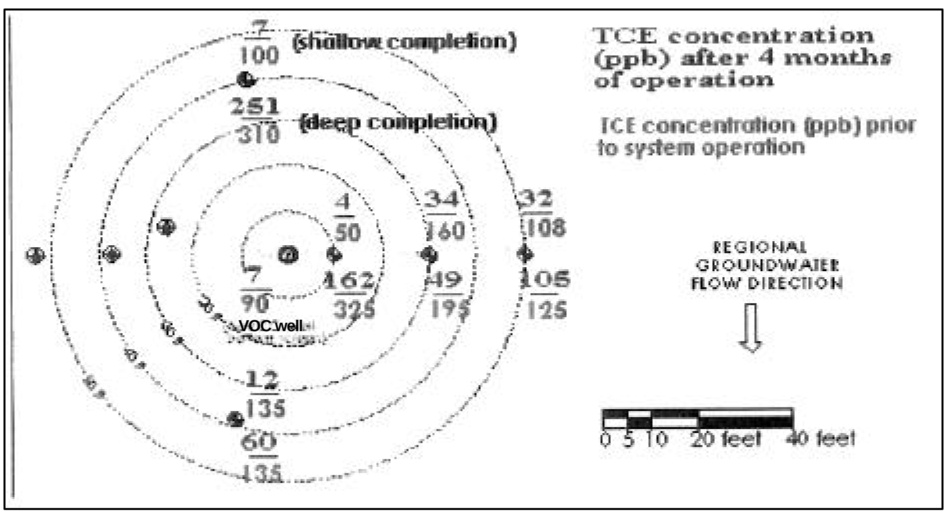


Figure B.1. Initial Concentration Reductions, NoVOCsÔ , Edwards AFB, CA.

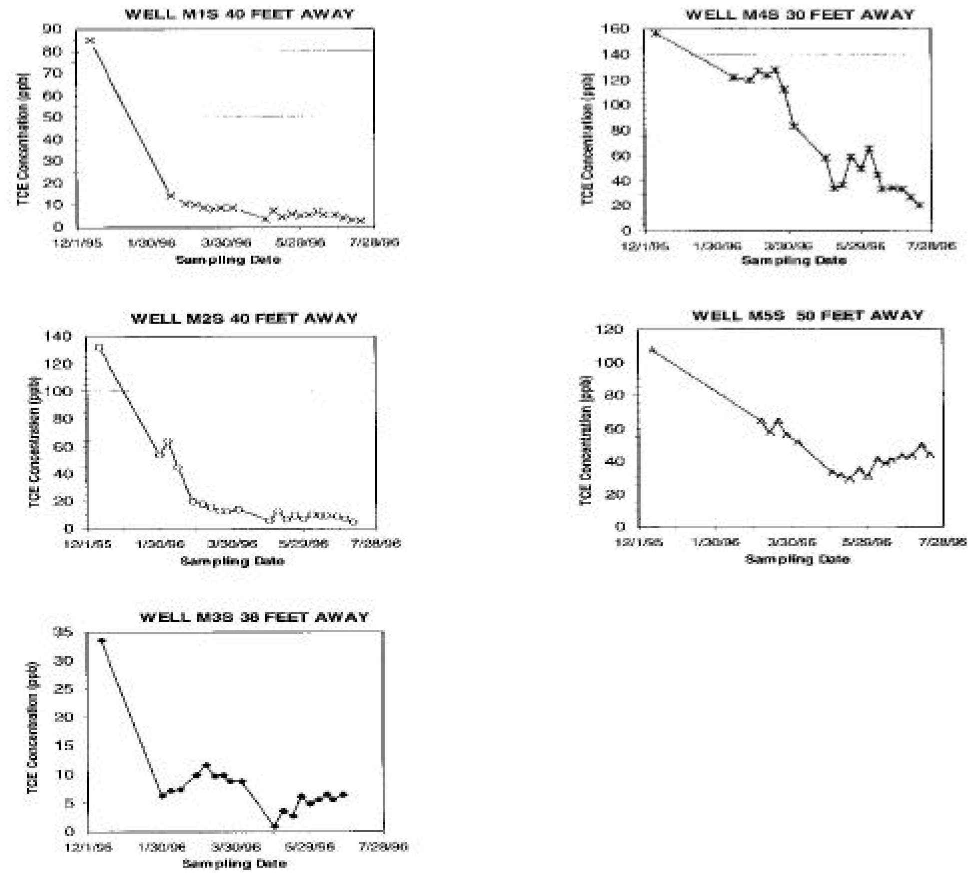


Figure B.2. Contaminant concentration reduction profiles, NoVOCsÔ, Edwards AFB, CA.

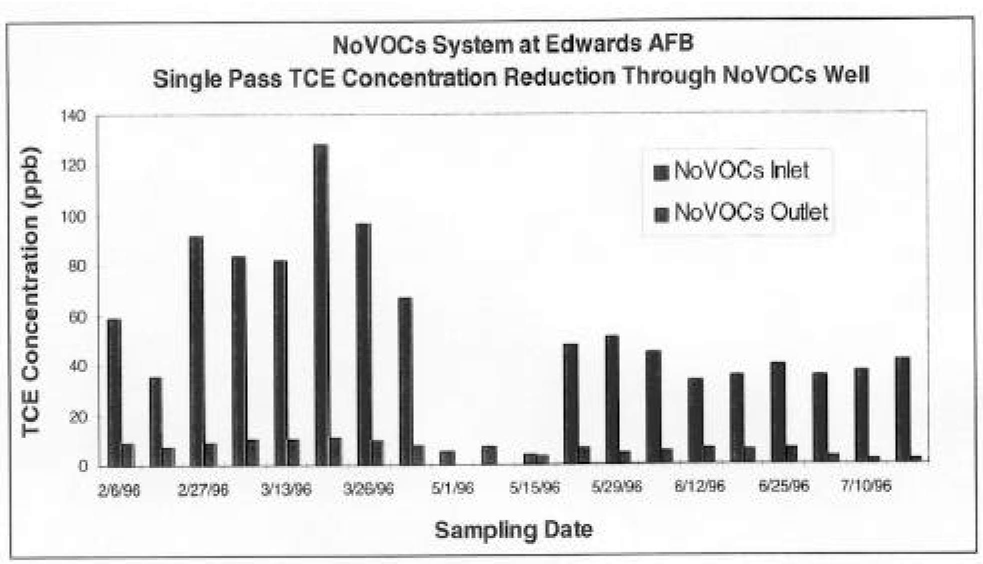
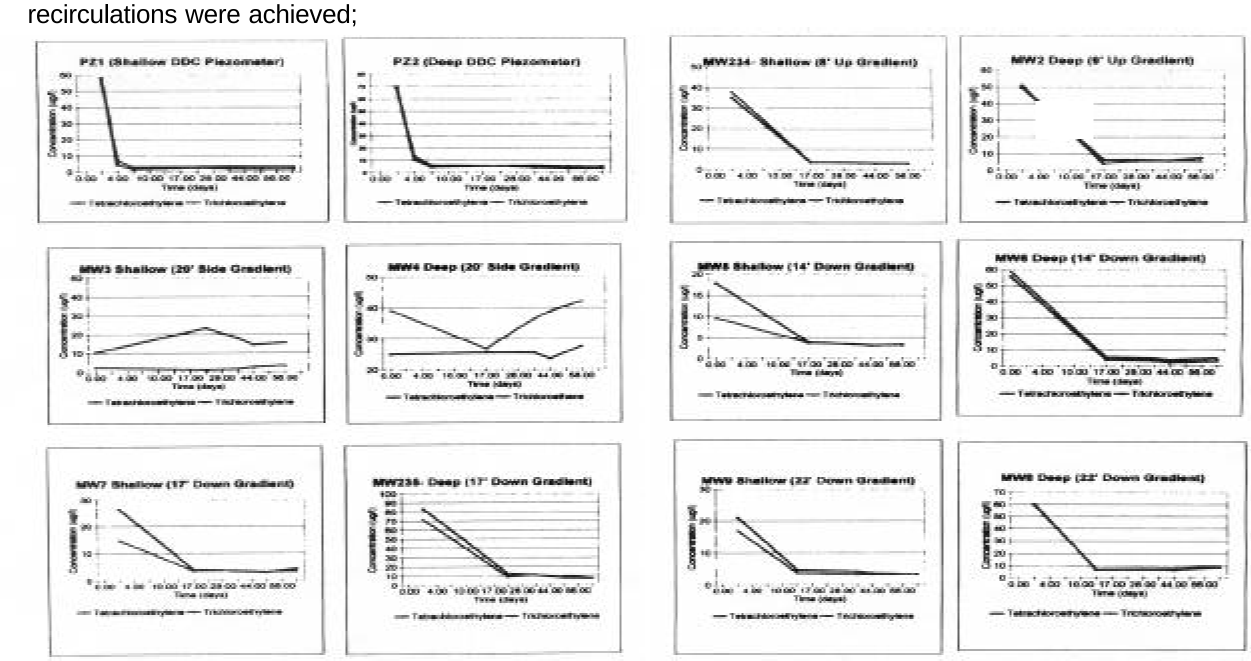


Figure B.3. In-well removal efficiency, NoVOCsÔ, Edwards AFB, CA.

PCE and TCE Case Study

DDC System Installation at Maxwell Air Force Base, PCE and TCE Case Study

- Site Description
  - Hydrogeology: Unconfined alluvial terrace deposit (sandy clay, poorly graded fine-grained sand and medium to fine-grained sand, gravelly sand); north-northeast groundwater flow; hydraulic gradient 0.003 ft/ft; water table 27 ft below the ground surface (bgs); saturated thickness 11 ft bgs; terrace deposits underlain by clay layer at 38 ft bgs.
  - Contaminant: <100 ug/L TCE and PCE.
- Operation: DDC well installed to 38 ft bgs – lower screen 32.5-37.5 ft bgs – upper screen 22.5-27.5 ft bgs; piezometers installed within same boring, screened adjacent to DDC screens. "S" monitoring wells screened 2 ft above and 8 ft below water table; "D" monitoring wells have 5 ft screens just above confining clay at 38 ft bgs. Air supply by oil-free rotary vane compressor; Air delivery to well via 0.5-inch drop tube. Pressure-relief valve downstream of blower outlet provided air flow regulation; Air injection rate into DDC well maintained at 15 cfm, confirmed with flow meter; air injection pressure maintained at 8 psi, as monitored at header near blower discharge.
- Groundwater Quality Results: Dissolved chlorinated solvent concentrations were reduced between 75 and 96%. Radius of effective treatment was about 17 ft, approximately 1.5 times the saturated thickness of the treatment interval. Six of ten monitoring wells show rapid PCE and TCE concentration decrease from baseline to MCLs. The majority of the monitoring well locations showed >85% reduction in first 20 days. Two wells showed reductions, but did not reach MCLs, and two wells were found to be outside the influence of the DDC well. Radius of influence found to be 17 ft sidegradient direction and 23 ft downgradient direction (Table B-1; Figure B-4).
- Stripping Efficiency: DDC well from piezometer sampling: TCE – 35-50% and PCE – 42-61%, both less than predictions of 66-77% for each, based on air to water ratio of 4.7 cfm/scfm. Lower efficiency likely due to decreased efficiencies as inlet concentration decreased, less than optimum air to water contact time, or higher groundwater flow rate through DDC than estimated. Despite lower than anticipated single-pass stripping efficiency, the multipass stripping efficiency was much greater and multiple recirculations were achieved;



modeling estimates suggest ratio of water flowing through DDC well to natural groundwater flow rate is about 23 to 1.

Figure B.4. TCE and PCE groundwater concentrations, DDC, Maxwell AFB, Montgomery, AL.

Table B.1. Summary of initial and final TCE and PCE concentrations in groundwater, DDC, Maxwell AFB, Montgomery, AL

Well	PCE Concentrations (ug/L)			TCE Concentrations (ug/L)		
	Initial	Final	% Reduction	Initial	Final	% Reduction
MW2D	49.6	0.22	99.56	51.3	5.7	88.89
MW3S	10.4	15.6	Outside of Radius	2.51	3.61	Outside of Radius
MW4D	25	27.6	Outside of Radius	39.2	42.2	Outside of Radius
MW5S	17.9	3.32	81.45	9.63	3.21	66.67
MW6D	55.4	3.03	94.53	58.7	4.89	91.67
MW7S	26.5	4.31	83.74	14.8	3.45	76.69
MW8D	60.4	8.73	85.55	59.7	8.99	84.94
MW9S	21	3.33	84.14	16.9	3.27	80.65
MW234S	35	2.89	91.74	37.9	3.23	91.48
MW235D	83.5	7.3	91.26	71.6	7.47	89.57
Overall Average			89.00			83.82

Notes:

Percent reductions are not calculated when initial concentration is below 1 ug/L.

Outside of Radius - Wells outside of the radius of influence of the DDC well.

BTEX and MTBE Case Study

C-SpargerÒ Installation at Gasoline Spill - Commercial Automotive Station, BTEX and MTBE Case Study

- Site Description
  - Hydrogeology: static groundwater at 3-6 ft bgs; stratigraphy: fill 0-2.5 ft bgs, silt 2.5-6 ft bgs, medium sand and gravel 6-20 ft bgs; soil permeability 10^{-3} to 10^{-7} cm/sec. groundwater pH – 7.0-8.5 and specific conductance 850-1,100 uS; hydraulic gradient 0.0036 ft/ft.
  - Contaminant: Total BTEX range – 5,000-24,000 ppb; BTEX concentration 19,220 ppb initial, MTBE concentration 520 ppb initial; contamination depth extended to 15 ft bgs, maximum; LNAPL was not observed; D.O. was <1 ppm in monitoring wells near the plume.
- Operation: Point source treatment; C-Sparger® unit equipped with an oxygen generator, allowing ozone concentrations between 100 and 300 ppmv, Recirculating well (CS-1) installed to ensure ozone mixing; Combined air/ozone flow to well was 2.2 cfm; System set to run 18 min. for lower Spargepoint®, 11 min. for in-well Spargepoint®, and 5 min. for submersible pump; System operated on 14 cycles of 34 min. during each 24 hr period; Dissolved oxygen (D.O.) and redox potential (ORP) monitored to determine radius of influence.
- Results: 94.8% reduction of BTEX (19,220 ppb to 1,004 ppb) and >99% reduction of MTBE (520 ppb to 6 ppb) within 18 ft of main injection well realized during 20-day test period. MTBE and toluene were reduced to one-half concentration in five days or less; benzene, ethylbenzene, and xylenes exhibited half-lives of seven to nine days; MTBE removal occurs primarily from the aqueous fraction.

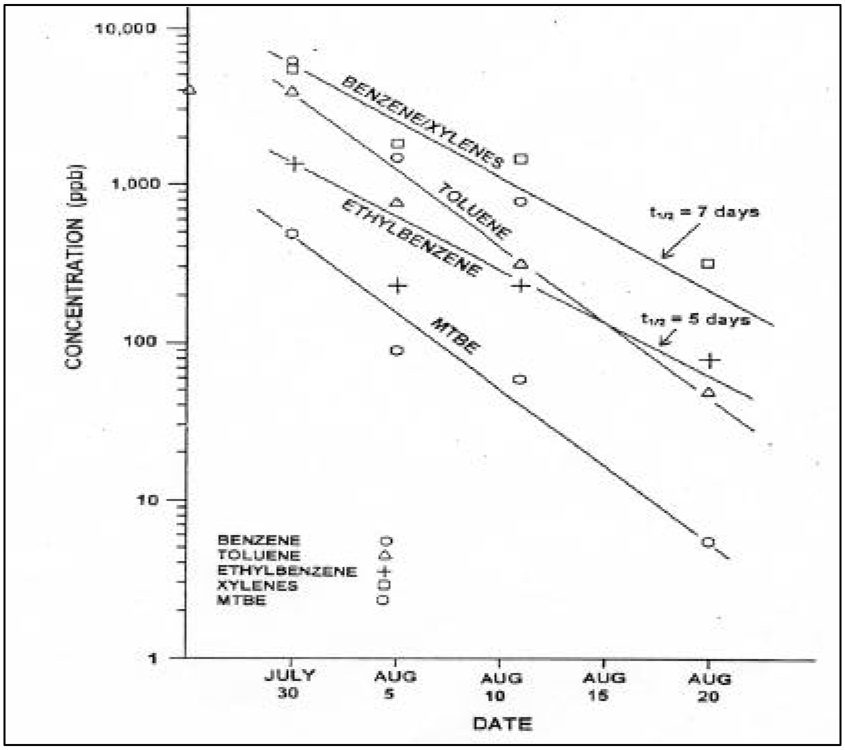


Figure B.5. Removal of MTBE and BTEX compounds at automotive service station, C-SpargerÒ.

APPENDIX C
ACRONYMS AND ABBREVIATIONS

ARAR	Applicable or Relevant and Appropriate Requirements
atm-m^3	atmospheric cubic meter
bgs	below ground (or grade) surface
BNL	Brookhaven National Laboratory
BTEX	benzene, toluene, ethylbenzene, xylene
CCl_4	carbon tetrachloride
CERCLA	Comprehensive Environmental Responsibility and Cleanup Liability Act
cfm	cubic feet per minute
cm/sec	centimeters per second
CPEO	Center for Public Environmental Oversight
DCE	dichloroethene
DDC	Density Driven Convection
DO	dissolved oxygen
fbg	feet below grade
ft msl	feet above mean sea level
GAC	granular activated carbon
GCW	groundwater circulating well
GCWT	groundwater circulating well technology
gpd	gallons per day
gpm	gallons per minute
GZB	Grundwasser-Zirkulations-Brunnen (Groundwater Circulation Well)
HP or hp	horsepower
IEG	Industrie-Engineering-GmbH
KGB	Koaxiale-Grundwasser- (Coaxial Groundwater Circulation)
K_h	horizontal hydraulic conductivity
K_{ow}	octanol-water partition coefficient
K_v	vertical hydraulic conductivity
KVA	K-V Associates
LNAPL	light, non-aqueous phase liquid
m	meter
mg/L	milligrams per liter
msl	mean sea level
MTBE	meth tert-butyl ether
NAPL	non-aqueous phase liquid
O&M	Operation and Maintenance
OU	Operable Unit
PAHs	polynuclear (polycyclic) aromatic hydrocarbons
PCE	tetrachloroethene
PLC	Programmable Logic Controller
ppb	parts per billion
ppm	parts per million
psi	pounds per square inch
psig	pounds per square inch gauge
RA	Remedial Action
ROI	radius of influence
scfm	standard cubic feet per minute
SDWA	Safe Drinking Water Act
SVE	soil vapor extraction
SVOCs	semi-volatile organic compounds
TCA	1,1,1-trichloroethane
TCE	trichloroethene
TPH	total petroleum hydrocarbons
TVOCs	total volatile organic compounds

ug/L	microgram per liter
UVB	Unterdruck-Verdampfer-Brunnen (Vacuum Vaporizer Well)
VOCs	volatile organic compounds