

Demonstration of a Microbiologically Enhanced Vertical Ground Water Circulation Well Technology at a Superfund Site

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Abstract

A full-scale ground water circulation well (GCW) system was installed and operated to demonstrate in situ remediation of soil and ground water impacted with a mixture of chlorinated and nonchlorinated organic compounds at a Superfund site in upstate New York. System performance and applicability under site-specific conditions were evaluated based on the system's ability to meet the New York State Department of Environmental Conservation (NYSDEC) cleanup goals for target compounds in ground water and soil. Contaminants from the unsaturated zone were mobilized (volatilized) by one-way vacuum extraction, and treated via enhanced biodegradation (bioventing). In the saturated zone, contaminants were mobilized by soil flushing (solubilized) and treated by a combination of air stripping and biodegradation. An in situ aqueous phase bioreactor, and an ex situ gas phase bioreactor, were integrated into the system to enhance treatment via bioremediation. After 15 months of operation, the mass of target contaminants in soil and ground water combined had been reduced by 75%. Removal by biological mechanisms ranged from 35% to 56% of the total observed mass reduction. The in situ and the ex situ bioreactors mineralized 79% and 76%, respectively, of their target biodegradable contaminant loads. Results indicate that some mass reduction in target contaminants may have been from aerobic and anaerobic processes within the circulation cell. Nonchlorinated compounds were relatively easy to mobilize (volatilize, solubilize, and/or transport) and treat when compared to chlorinated compounds. The data collected during the 15-month study indicate that remediation could be accomplished at the Sweden-3 Chapman site using the technology tested.

Introduction

Technologies broadly defined by the term "In Situ Air Sparging" have found many applications for in situ treatment of contaminated ground water in recent years (Schrauf and Pennington 1995; Gvirtzman and Gorelick 1992; Hinchee 1992). These technologies work by bubbling air into a contaminated aquifer to strip the volatile organic compounds (VOCs). The resulting VOCs-laden air is then extracted for aboveground treatment using blowers. In general, these processes induce a circulating ground water flow in the saturated zone, facilitate stripping of VOCs, and achieve biodegradation of VOCs, semi-volatile organic compounds (SVOCs), and nonvolatile organic compounds (NVOCs) by distributing terminal electron acceptors such as oxygen and nutrients in the aquifer.

Although effective, conventional air sparging techniques are limited in their ability to control the flow of ground water which is essential in maintaining an optimum air-to-water ratio, to maximize the stripping or aeration efficiency. In addition, stripping is achieved by injecting pressurized air into the formation (aquifer) which, due to channeling effects, can be inefficient. The operating costs are also high because air is sparged at the bottom of the impacted zone in the aquifer, which in most cases is fairly deep. Finally, conventional air sparging techniques do not incorporate in-well

bioreactors which can significantly enhance the in situ biotreatment process.

In contrast, the UVB (UVB is an acronym for vacuum vaporizer well or Unterdruck-Verdampfer-Brunnen in German), is a GCW technology that allows variations in the air-to-water ratio using a submersible pump, and can be built with in-well bioreactors. Air stripping is done in the well casing (not in the formation) by pumping the ground water to a specially designed in-well air stripper (not an air sparger) to maximize the stripping efficiency. The operating costs are low because a blower is used for both injection of fresh air, as well as for extraction of VOCs-laden air. Finally, the energy required to overcome the water column head is minimized by positioning the stripper plate to only 1 to 2 feet (0.3 to 0.6 m) below the water table.

The formation of a circulating ground water flow pattern is an important aspect of the UVB technology. Processes that inject microorganisms, nutrients, and oxygen delivery sources (hydrogen peroxide and calcium peroxide), as well as those that set up reactive barriers (Mueller et al. 1996; Norris et al. 1993) in the aquifer, depend on diffusional properties and slow ground water flow to achieve treatment. The UVB, however, generates velocities that are two to 10 times the natural ground water velocity and, consequently, reduces the treatment time by mobilizing the contaminants at a faster rate.

Vertical GCW technology has distinct advantages over conventional pump-and-treat (PAT) systems. An obvious advantage of the GCW is that it accomplishes treatment without ground water extraction, hence no surface treatment is required for ground water. Only limited surface treatment is required for the vapor phase. The GCW creates a three-dimensional flow with a vertical component which actively flushes contaminants from the soil matrix in the entire zone of influence (ZOI). Alternatively, PAT systems create only a radial flow in a plane determined by the size and location of the extraction screen. A PAT system also requires separate wells for injection of treated ground water.

The primary objectives of this demonstration were to determine the effectiveness of the UVB technology in reducing the concentrations of select organic contaminants in soil and ground water. The compounds of interest included toluene, acetone, methylethyl ketone (MEK), 4-methyl 2-pentanone (MIBK), cis-1,2 dichloroethene (cis-1,2 DCE), trans-1,2 dichloroethene (trans-1,2 DCE), trichloroethene (TCE), tetrachloroethene (PCE), vinyl chloride (VC), and 1,1,1 trichloroethane (TCA). Specifically, the remediation goals were to meet 90% of the NYSDEC cleanup criteria for these target contaminants in a 50 feet \times 50 feet (15.2 m \times 15.2 m) test plot after six months (later extended to 15 months) of operation, and show that at least 51% of mass reduction in target contaminants was due to microbiological mechanisms.

Experimental

Site Background

Under the Multi-Vendor Biotreatability Demonstration Program sponsored by the NYSDEC, a full-scale field demonstration of a microbiologically enhanced UVB technology was conducted at the Sweden-3 Chapman Superfund Site, Brockport, New York. The Sweden-3 Chapman site is an inactive landfill that was used to dispose of construction/demolition debris and hazardous wastes between 1970 and 1978. Preliminary site investigations conducted in 1987 indicated that on-site soil and ground water were contaminated with elevated levels of TCE, methylene chloride, PCE, MEK, MIBK, toluene, xylenes, acetone, various VOCs, and SVOCs (NYSDEC 1993).

Technology Description

Vertical ground water circulation is established by creating a pressure differential across a specially constructed double screened well using a mechanical or an air-lift pump. This double screened well can simultaneously mobilize and treat contaminants from the unsaturated zone, capillary fringe, and the saturated zone (U.S. Patent Office 1990; U.S. Patent Office 1992a; U.S. Patent Office 1992b). Removal of hydrocarbons from the unsaturated zone is achieved by one-way vacuum extraction through the upper screen which straddles the upper portion of the aquifer, the capillary fringe, and part of the unsaturated zone. Mobilization and treatment in the saturated zone is achieved by a combination of soil flushing, air stripping, and bioremediation.

In a standard circulation mode (like the one used in this study), ground water enters the well through the lower screen and leaves through the upper screen (Herrling et al. 1993). In a reverse circulation mode, ground water enters the well through the upper screen and leaves through the lower screen. Between its travel from one screen to the other, ground water passes through one or more in-well treatment systems which, for example, may include an air stripper/aerator and an in situ bioreactor, depending on the type of contaminants being treated. In addition, ground water leaving the treatment well can be supplemented with nutrients, dissolved oxygen (DO), and co-substrates to further facilitate in situ biodegradation of contaminants in the aquifer.

Site Geology and Hydrogeology

Effective operation of the UVB depends primarily on the hydrogeologic conditions of the impacted aquifer. The capture zone, as well as the ZOI of the UVB, depend on site-specific conditions such as aquifer heterogeneity, anisotropy, hydraulic conductivities, thickness of the saturated zone being treated, and natural ground water velocities. Design factors such as screen lengths and positions, and air and ground water

flow rates can be adjusted to optimize system performance.

In general, the soil composition at the Sweden-3 Chapman site could be described as 19% gravel, 24% sand, and 57% silt/clay. The average horizontal hydraulic conductivity ranged from 3.3×10^{-6} to 2.3×10^{-7} ft/sec (1.0×10^{-6} to 7.0×10^{-8} m/sec), and the average vertical hydraulic conductivity ranged from 3.3×10^{-7} to 1.6×10^{-8} ft/sec (1.0×10^{-7} to 5.0×10^{-9} m/sec). The average horizontal hydraulic gradient was 0.054, and the average Darcian velocity was calculated to be 9.3×10^{-6} ft/sec (2.8×10^{-6} m/sec). The seasonal water table fluctuated between 8 to 10 feet (2.4 to 3.1 m) bgs. Regional ground water flow was reported to be in the northeasterly direction (NYSDEC 1993).

Well Construction and Design

Figure 1 shows an as-built diagram of the UVB treatment well. The well consisted of a 1.4-foot (0.4 m) I.D. steel casing set at a depth of 25.9 feet (7.9 m) bgs. The lower screen (bridge slot) was 3.3 feet (1.0 m) in length, and the upper screen (double cased) was 6.6 feet (2.0 m) in length. A 1.4-foot (0.4 m) O.D. fixed packer was installed between the two screens at a depth of 22 feet (6.7 m) bgs to physically separate the upper and lower chambers of the well. A submersible pump was connected to a 2-inch (5 cm) OD high-density polyethylene (HDPE) pipe, the open end of which was positioned below the packer to pump water from

the lower screen. The discharge of the pump was attached to the inlet of a bioreactor with a 2-inch (5 cm) O.D. HDPE pipe. The bioreactor was 7 feet (2.1 m) high and 1 foot (0.3 m) in outer diameter, and was constructed of HDPE. To the outlet of the bioreactor was attached an aerator/stripper with an aboveground ambient air intake pipe. The entire well was completed 2 feet (0.6 m) aboveground and was sealed airtight with a flange. The top of the well was connected to a blower to create a vacuum in the upper chamber of the well, and at the same time to pull in ambient air through the aerator/stripper. The pressure side of the blower was connected to the off-gas treatment system.

Ground water entering the lower screen was first pumped through the bioreactor. Untreated contaminants leaving the bioreactor effluent were then air stripped as the water flowed through the stripper/aerator. The aerated and oxygen rich water was then discharged through the upper screen at the water table. As the circulation cell developed, this water returned to the lower screen providing dissolved oxygen to the bioreactor for aerobic degradation. The VOCs-laden air exiting the well was processed in an off-gas treatment system consisting of gas phase bioreactors and granular activated carbon (GAC) drums.

In Situ Bioreactor

The in situ bioreactor was a packed bed, fixed-film type reactor containing GAC (Model TIGG 5D, 0.1-inch [3 mm]) pellets) as a biosupport media for native microorganisms. Knowing that toluene present in ground water would stimulate cometabolism of TCE (Nelson et al. 1987), the objective here was to create an environment (high surface area, high DO, readily available carbon source) for the native microorganisms to achieve higher mineralization rates. Due to its ability to provide a large surface area, activated carbon has been used in many bioreactor applications (Andrews and Chi Tien 1981; Fan et al. 1987), where it provides sites for microorganisms to attach on the surface, and develop a biofilm. Influent and effluent sampling ports were installed on the bioreactor to collect water samples for analysis of VOCs and DO. GAC samples from the bioreactor were analyzed for microbial plate counts before, during, and after the demonstration to determine biofilm development.

Gas Phase Bioreactor

The gas phase bioreactor consisted of one or several spiral cartridges fabricated from a polyvinyl chloride (PVC) silica-based biosupport. Description of the physical and chemical properties of the biosupport and construction of the spiral cartridge are provided elsewhere (Lakhwala et al. 1990; Shim et al. 1995). During the first six months of operation, a single cartridge bioreactor was used. The initial reactor was later replaced with two reactors in parallel containing a total of 14 cartridges. The total biosupport surface area for both reactors was 500 square feet (46.5 m²).

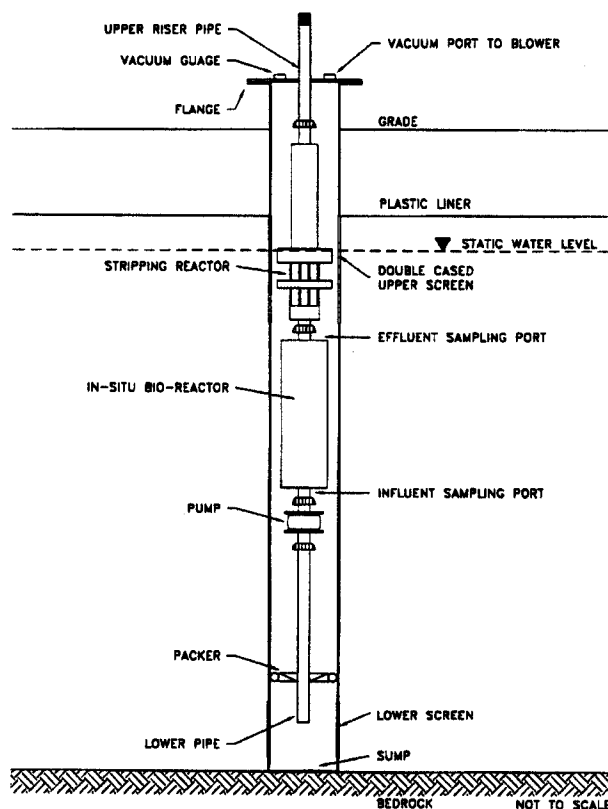


Figure 1. Schematic diagram of UVB-400 well.

Unlike the in situ bioreactor, the gas phase bioreactor was inoculated with bacterium *Burkholderia* (formerly *Pseudomonas*) cepacia strain G4, a constitutive TCE degrader that can use compounds such as benzene, toluene, phenol, and lactate, among others, as its primary source of carbon (Shields and Reagin 1992). This strain has been used extensively to study the degradation mechanisms of TCE and its daughter products. A 1 L culture of 10^8 cells/mL was grown in the laboratory on phenol as the primary carbon source. This was used as an inoculum for a 3.5 ft³ (0.1m³) reactor in the field. Cells were grown on sodium acetate in the field to a final concentration of 108 cells/mL. The cells were then pumped through the bioreactor cartridges, where they were immobilized on the biosupport (Lakhwala et al. 1990). The mechanisms of immobilization by surface attachment are described by van Loosdrecht et al. (1987). The bioreactors were supplemented with a 1 L solution of sodium acetate (20 mM) and urea (1 mM) every week during the course of the study.

Monitoring and Sampling

A Quality Assurance Project Plan (QAPP) (SAIC 1994) was prepared to describe the sampling and analytical procedures. These procedures were designed in accordance with the United States Environmental Protection Agency (U.S. EPA) protocols to ensure that sampling frequency, sample size, sample locations, and analytical methods were adequately selected to realize the goals and objectives of the demonstration.

Figure 2 shows a layout of the UVB well and the associated ground water monitoring wells. A total of 13 monitoring wells (six shallow and seven deep) were installed around the UVB well. In addition, two annulus wells (one deep and one shallow) were installed within the annular space of the UVB well borehole and the UVB casing. All monitoring wells were constructed of 2-inch (5 cm) I.D. PVC. Shallow monitoring wells were installed to a depth of 12 feet (3.7 m) bgs, while the deep monitoring wells were installed to a depth of 22 feet (6.7 m) bgs. All monitoring wells were sampled on a weekly basis to determine water levels, DO, pH, and temperature.

The UVB well parameters monitored included ground water recirculation rate, influent and effluent air flow rates, and the well vacuum. Two ground water recirculation flow rates of 8 gpm (0.03 m³/min) and 22 gpm (0.09 m³/min) were investigated. These flow rates were measured using an in-line flowmeter (SIGNET, Model 2535, Birmingham, Alabama). Influent air flow through the aerator/stripper varied between 70 to 250 ft³/min (2 to 7 actual m³/min). Air flow rates were measured with a vane anemometer (TESTO, model 400, Flanders, New Jersey).

Ten ground water sampling events were conducted to determine the dissolved concentration of target contaminants. Samples were collected from all 15 monitoring wells. In addition, samples were collected from the influent and effluent sampling ports of the in situ biore-

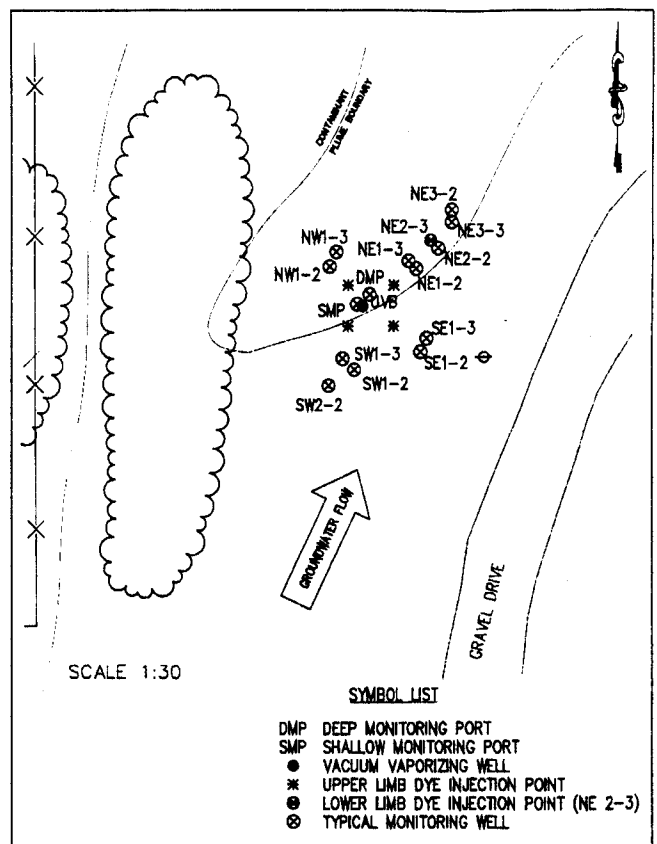


Figure 2. UVB well-400 and monitoring wells layout.

actor. These samples were analyzed for a series of critical (VOCs), and noncritical (total organic carbon, total N, total P, biochemical oxygen demand, chemical oxygen demand, TCE degraders, and total heterotrophic bacteria) parameters described in the QAPP.

Five soil sampling events (baseline, and after three, six, 10, and 15 months of operation) were also conducted. Twenty-five soil borings were performed during each sampling event within the test plot. Soil samples were collected from both saturated and unsaturated zones to determine the concentrations of target VOCs. In addition, noncritical parameters (total organic carbon, total N, NO₃-N, NH₃-N, NO₂-N, total P, TCE degraders, and heterotrophic bacteria) were also measured (SAIC 1994).

Influent and effluent air samples across the gas phase bioreactors were collected periodically to determine the VOC removal efficiency of the bioreactors. Two sampling and analytical methods were used. On a more frequent basis, a known volume of air (0.42 ft³) was pumped through tubes containing activated carbon (Solvent Desorption Tubes, SUPELCO, Bellefonte, Pennsylvania) to adsorb the contaminants. The contaminants were desorbed by extraction using carbon disulfide, and then analyzed by gas chromatography for target VOCs using a method recommended by SUPELCO. On a quarterly basis air samples were collected in Summa cans (0.2 ft³ volume) and analyzed using U.S. EPA method TO-14.

Results and Discussions

Ground Water Circulation Cell Flow Dynamics

During the design phase, mathematical modeling (Herrling and Stamm 1992) employing site-specific data indicated that the effective radius of influence of the UVB would be in the range of 30 to 40 feet (9.1 to 12.2 m). Dye trace experiments were conducted in the field, along with piezometric head measurements in surrounding monitoring wells, to verify the dynamics and the dimensions of the circulation cell. These tests verified the modeling results, and indicated that the effective radius of influence was in the range of 30 to 50 feet (9.1 to 15.2 m) (SBP Technologies Inc. 1996). It was estimated that the quantity of new ground water captured in the upgradient capture zone ranged from 1.4 to 4.3% of the ground water within the circulation cell. Also, it is important to note that the UVB well was positioned at the fringe of the estimated plume boundary with the majority of the contamination on its downgradient side. Consequently, it was assumed that essentially no contaminants migrated into the circulation cell from areas upgradient, and that the amount of fresh water moving into the cell (1.4 to 4.3%) did not significantly dilute the concentration of contaminants.

In Situ Bioreactor Performance

After one month of operation (to allow for breakthrough of the GAC and biofilm development), periodic collection of bioreactor influent and effluent ground water samples was initiated. Influent and effluent concentrations of target contaminants across the bioreactor were averaged over block days of operating periods for mass balance purposes (Table 1). Percent removal of target contaminants was low (26 to 33%) during the first three months of operation, probably due to an initial lag or acclimation phase of the microorganisms. As the biofilm of the indigenous microflora stabilized and developed, the removal efficiency of the bioreactor was maintained at an average value of 70% during the next 12 months of operation. A switch in ground water flow rate from 8 gpm (0.03

m³/min) to 22 gpm (0.09 m³/min) was done after eight months of operation when it was certain that a stable biofilm and a high treatment efficiency was attained. In all, 68 pounds (31 Kg) of target contaminants were biologically degraded by the in situ bioreactor which accounted for 79% of the total load (mass of target contaminants mobilized and delivered to the system over 15 months).

Virgin, unused carbon has a density of 30 to 31 lb/ft³ (0.48 to 0.50 g/cc) (TIGG Corp., Pittsburgh, Pennsylvania). A test performed on the spent carbon from the in situ bioreactor showed that the density was 31 to 32 lb/ft³ (0.51 to 0.52 g/cc). According to the manufacturer, a completely spent carbon should weigh 36 to 38 lb/ft³ (0.58 to 0.60 g/cc), indicating that the adsorption capacity of GAC was not exhausted, and that the removal of contaminants across the bioreactor was not due to adsorption on GAC. Less surface area is available on the GAC for adsorption of contaminants after the biofilm has been created, and in fact the microorganisms use the adsorbed contaminants over time. This observation was similar to that seen in another UVB study where GAC was used as a biosupport for degradation of triazine (Sick et al. 1993), indicating that biological activity was the preferred path for pesticide removal in the in situ bioreactor.

Bacterial biofilm development on the in situ bioreactor GAC was confirmed visually, microscopically, and via microbial plate counts to enumerate culturable aerobic bacteria on the surface of the GAC. On average, there were 2 log and 3 log increases in total heterotrophic bacterial counts per mg of GAC after 10 and 15 months of operation, respectively. Also, a ten-fold increase in bacterial counts from the top to the bottom of the bioreactor was observed. Presumably, this was due to the fact that the bottom portion of the bioreactor was more oxygen rich than the top.

Reduction of Target Contaminants in Ground water

Reductions in concentrations of target contaminants in ground water were viewed as a prime indicator of the treatment systems' efficiency. However, during

Table 1
In Situ Bioreactor Performance

Operating Period	Days	Flow (gpm)	Influent	Mass (g) Effluent	Biodegraded	Percent Change
8/15/94 to 8/31/94	17	8	900.42	600.48	299.94	-33%
9/15/94 to 9/26/94	12	8	317.52	233.33	84.19	-26%
10/6/95 to 3/10/95	115	8	29420.93	5636.40	23784.53	-81%
4/13/95 to 6/15/95	54	22	2671.80	133.00	2538.80	-95%
6/16/95 to 7/30/95	45	22	1552.76	232.15	1320.61	-87%
8/1/95 to 9/30/95	61	22	3946.20	1138.31	2807.89	-71%
10/1/95 to 10/23/95	23	22	499.62	431.71	67.91	-14%
Total	327		39309.25	8405.38	30903.87	-79%

All mass calculations are based on eight target compounds except PCE and 1,1,1-TCA, which are not degraded aerobically.

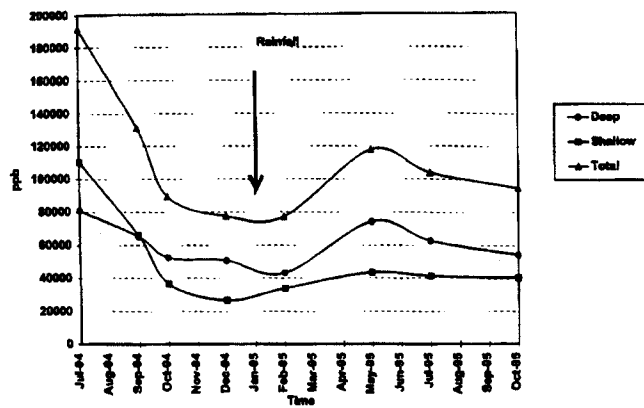


Figure 3. Variation in concentration of target contaminants in ground water within the circulation cell: Deep and shallow monitoring wells.

the 15-month operation, both decreases and increases in the concentrations of target VOCs were observed in ground water. The pathways that could have caused a decrease in concentration were dilution, stripping, biodegradation across the in situ bioreactor, biodegradation in the aquifer, and convective transport away from the circulation cell. The pathways that could have caused an increase in concentration were convective transport into the cell from highly contaminated areas, soil flushing followed by dissolution of contaminants, and transport by diffusion into the cell from the contaminated capillary fringe and unsaturated zone soils.

Figure 3 shows a concentration profile of target contaminants (a total of chlorinated and nonchlorinated) in deep and shallow monitoring wells within the minimal 30 feet (9.1 m) effective radius of influence of the circulation cell. On average, the concentration of target contaminants decreased by 58% during the first six months. The decrease in shallow monitoring wells was 76%, and in the deep monitoring wells the decrease was 40%. Excessive rainfall after six months resulted in a 4-foot (1.2 m) rise in the local static water table, creating favorable conditions for contaminants from outside the predicted ZOI to migrate into the circulation cell. The rising water table also mobilized and transported contaminants from the highly contaminated vadose zone into the ground water circulation cell. In addition, a high water table increased the total height of the saturated zone and increased the ZOI of the circulation cell by 24 feet (7.3 m) (SBP Technologies Inc. 1996), thereby pulling into the circulation cell contaminants from unmonitored areas. The quantitative effect of this was an increase in the concentrations of target contaminants within the circulation cell by 52% during the next six months. Of the overall 52% increase, 26.5% increase was in the deep wells, and 27.5% increase was in the shallow wells (Figure 3). Such variability is not uncommon for field studies (Pritchard et al. 1993).

After 15 months, the concentration of target contaminants in the circulation cell had decreased by 45% from their baseline values. Overall, a 28% decrease in the deep wells and a 62% decrease in the shallow wells

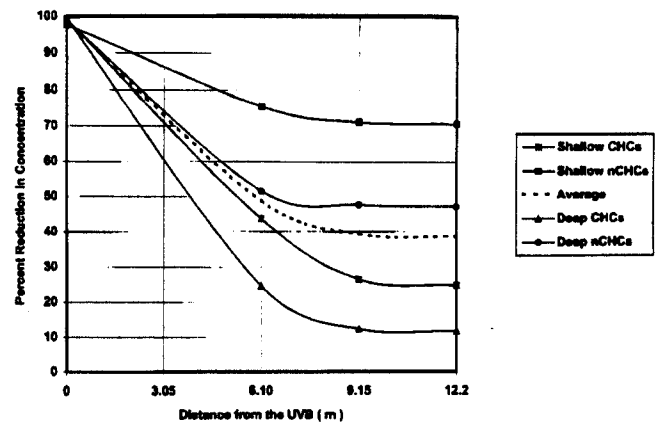


Figure 4. Reduction in concentration of target CHCs and nCHCs in deep and shallow monitoring wells as function of distance from the UVB.

was seen during this period. With the UVB system operating in a standard circulation mode, these results were expected because treated water is released in the shallow portion of the aquifer, where it further dilutes the contaminated water.

A similar trend was observed in concentration profiles of target chlorinated hydrocarbons (CHCs) and target nonchlorinated hydrocarbons (nCHCs) in ground water samples. The concentration of target CHCs decreased by 48% and that of target nCHCs decreased by 68% during the first six months. This indicated that the solubilization and transportation of target CHCs was slower relative to the target nCHCs, and probably influenced by factors such as solubility, biodegradability, and partitioning. After the rains, the concentration of target CHCs increased by 48%, while that of target nCHCs decreased by 30%. Target CHCs accounted for 95% of the total contaminants that migrated into the circulation cell after the rains. Consequently, at the end of the study the concentration of target CHCs had been reduced by only 21%, while that of target nCHCs had reduced by 69% from their baseline levels.

Figure 4 shows a best fit curve of percent reduction in concentration of target CHCs and target nCHCs in deep and shallow wells as a function of distance from the UVB during the 15-month operation. The percent reduction in all cases followed an exponential decay with respect to distance from the UVB, and also showed that the circulation cell developed as far out as 40 feet (12.2 m) from the UVB well. The figure also indicates that the removal of target nCHCs was higher when compared to the removal of target CHCs at every location (except the UVB). Some of this could be attributed to a large influx of target CHCs after six months as described earlier. In general, the removal and treatment of target contaminants was higher in the shallow wells when compared to that in the deep wells. On average, the percent reduction in ground water of target contaminants was 96% at the UVB well, 44% at a distance of 20 feet (6.1 m), and 30% at a distance of 30 feet (9.1 m) from the UVB. This trend is in agree-

Table 2
Change in Mass of Target Contaminants
in Ground Water Within the Circulation Cell
During 15 Months of Operation

Compound	Mass (g)		Change	Percent Change
	Initial	Final		
Acetone	1165	5	-1160	-99.6%
MEK	6233	0	-6233	-100.0%
MIBK	279	5	-274	-98.2%
Toluene	3637	2982	-655	-18.0%
Target nCHCs	11314	2992	-8322	-73.6%
cis-1,2-DCE	10770	8449	-2321	-21.5%
trans-1,2-DCE	95	1	-94	-98.9%
PCE	141	62	-80	-56.4%
TCE	8234	6174	-2059	-25.0%
Target CHCs	19240	14686	-4554	-23.7%
Total (Less (TCA & VC)	30554	17678	-12876	-42.1%
TCA	2487	3219	732	29.4%
Vinyl chloride	955	1845	889	93.1%

ment with the operation of the UVB, wherein the number of pore volumes flushed through the zone closer to the UVB is higher than that flushed through the zone distant from the UVB.

Table 2 shows mass reduction of individual target contaminants in ground water. Contaminant mass was calculated by averaging the concentrations of the first two sampling events and reporting them as baseline concentrations. This data normalization seemed reasonable and offered a conservative analysis of target contaminant removal. Out of 10 target compounds, the masses of eight compounds had decreased, while that of TCA and VC had increased by 29.4% and 93.1%, respectively, at the end of the study.

Mass of VC increased presumably, due to its production from anaerobic degradation of PCE and TCE in the anaerobic regions of the circulation cell. Eighty percent of the total mass of VC present in ground water was seen in monitoring wells outside the 40-foot-diameter (12.2 m) aerobic zone, indicating that, outside

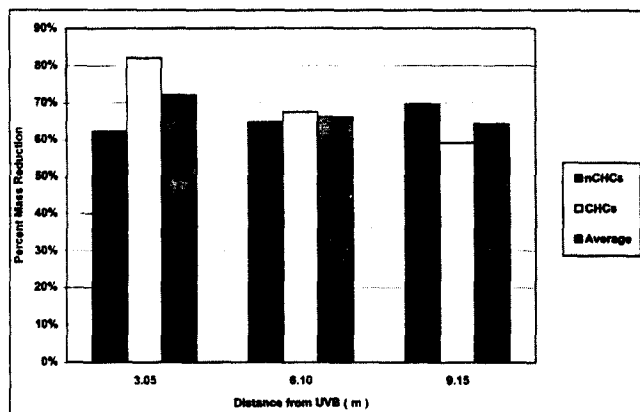


Figure 5. Percent reduction in mass of target contaminants in soils as a function of distance from the UVB.

Table 3
Change in Mass of Target Contaminants
in Soils Within the Circulation Cell
During 15 Months of Operation

Compound	Mass (g)		Change	Percent Change
	Initial	Final		
Acetone	3895	953	-2942	-75.5%
MEK	7923	2089	-5834	-73.6%
MIBK	2834	444	-2390	-84.3%
Toluene	75555	7422	-68133	-90.2%
Target nCHCs	90205	10908	-79297	-88.0%
cis-1,2-DCE	2867	1208	-1659	-57.9%
trans-1,2-DCE	349	80	-269	-77.1%
TCE	4836	3155	-1681	-34.8%
PCE	1943	351	-1592	-81.9%
Target CHCs	9995	4794	-5201	-52.0%
Total	100200	15702	-84498	-84.3%

the aerobic zone, PCE and TCE were anaerobically transformed in appreciable quantities. Since TCA is not a daughter product of the mineralization processes of PCE or TCE, an increase in mass of TCA was strictly due to its mobilization from unmonitored areas outside the ZOI. Sixty-two percent of the total mass increase in TCA was observed in monitoring wells outside the 40-foot-diameter (12.2 m) zone indicating that it was pulled in from areas outside of the anticipated ZOI as a result of changes in the water table.

Not accounting for the increases in TCA and VC, the total mass reduction in ground water of the eight target compounds was approximately 29 pounds (13 Kg) or 42% from the baseline levels.

Reduction of Target VOCs in Soils

Concentrations of most target contaminants in soil increased from their baseline values during the first sampling event after three months, which is due to the ability of the circulation cell to flush and mobilize the contaminants. Consequently, concentrations from the first two sampling events (0 and three months) were averaged and reported as initial concentrations. Once again, this data normalization seemed reasonable and offered a conservative analysis of target contaminant removal. Although samples were collected for both the 7- to 11-foot (2.1 to 3.4 m bgs) unsaturated zone and the 11- to 15-foot (3.4 to 4.6 m bgs) saturated zone separately, the reported data were combined because the unsaturated zone remained saturated for most of the study due to a rise in the water level following excessive rains.

Table 3 shows the percentage mass and absolute mass reductions of target contaminants in soil during the 15-month study in the test plot. The reductions for target CHCs varied from 35% for TCE to 82% for PCE, with an average of 52%, while that of target nCHCs varied from 74% for MEK to 90% for toluene, with an average of 88%. Once again, the target nCHCs

appeared to be mobilized and treated or removed with a higher efficiency than the target CHCs. Toluene accounted for 75% of the total contaminant mass present in soil at start, and 81% of the total contaminant mass removed at the end of the study. TCE accounted for 5% of the total contaminant mass present in soil at start, and 2% of the total contaminant mass removed at the end of the study. Percent reduction of TCE was the least at 35%, and that for toluene was the highest at 90%. The total mass of target contaminants within the 50 feet × 50 feet × 8 feet (15.2 m × 15.2 m wide, and 2.5 m thick) zone was reduced by 187 pounds (85 Kg) after 15 months, which accounted for 84% reduction from baseline levels.

Figure 5 shows percent reduction in mass of target CHC and target nCHC contaminants in soil as a function of radial distance from the UVB. The mass of target nCHCs decreased by 62%, 65%, and 70% in zones 10, 20, and 30 feet (3.1, 6.1, and 9.1 m) away from the UVB, respectively, indicating that the mobilization and treatment of target nCHCs in soils was consistent in the entire circulation cell. The mass of target CHCs decreased by 82%, 67%, and 59% in zones 10, 20, and 30 feet (3.1, 6.1, and 9.1 m) away from the UVB, respectively, indicating that the mobilization and treatment efficiency of target CHCs in soils decreased with distance from the UVB well. The average mass of all target contaminants (both nCHCs and CHCs) decreased by 72%, 66%, and 64% in zones 10, 20, and 30 feet (3.1, 6.1, and 9.1 m) away from the UVB, respectively. The trend in decreasing removal efficiency with distance from the UVB relates to the number of pore volume flushes achieved per unit time. It was estimated that time required for one pore volume flush through the ZOI (30 feet or 9.1 m radius) would be six months. In the same time the zone near the UVB well (10 feet or 3 m radius) would go through at least 10 pore volume flushes.

Gas Phase Bioreactor Performance

As explained earlier, two bioreactor configurations were used to treat off-gases from the UVB well. The gas phase bioreactors were operated for a total of 222 days. A mass balance was performed by averaging the concentration of contaminants between two sampling events to determine the average daily concentration for the days between the two sampling events. The amount of VOCs in the UVB effluent air was determined to be approximately 42 pounds (19 Kg), of which 33 pounds (15 Kg) were biologically degraded at a removal efficiency of 79% (Table 4). The mass calculations did not account for PCE and 1,1,1-TCA, which are not degraded under aerobic conditions.

At the end of the study, the bioreactors were flushed by recirculating 3.5 ft³ (0.1 m³) of water at a flow rate of 2 ft³/min (0.06 m³/min) for three hours. Water samples from these bioreactors and from an unused bioreactor (control) were analyzed for heterotrophic bacterial counts. Results indicated that there was a 3 log and a 4 log increase in bacterial counts in the first and second bioreactor configurations, respectively.

Mass Balance

Mass calculations for contaminants in soil were based on the volume of soil sampled in a boring test. The concentrations of target contaminants were corrected for soil density and moisture content to determine contaminant mass on a dry weight basis. Mass of target contaminants in ground water at any sampling event was based on the volume of water in the circulation cell at the time of sampling.

From analytical results, the baseline and final mass of target contaminants in soil and ground water combined were 289 pounds (131 Kg) and 73 pounds (33 Kg), respectively. This correlated to an apparent reduc-

Table 4
Gas Phase Bioreactor Performance

Operating Period	Days	Flow (acfm)	Mass of Target VOCs (g)			Percent Change
			Influent	Effluent	Biodegraded	
One Bioreactor System						
8/15/94 to 8/31/94	17	12	199.51	57.36	142.16	-71%
9/15/94 to 9/26/94	12	12	5.71	2.13	3.58	-63%
10/6/94 to 10/31/94	26	8	4.55	0.99	3.55	-78%
11/1/94 to 12/31/94	21	8	1.37	0.21	1.16	-85%
Bioreactor taken off-line from 1/95 to 5/95						
Two Bioreactor System						
6/1/95 to 6/30/95	30	180	3737.95	2014.20	1723.75	-46%
7/1/95 to 7/31/95	31	220	4153.28	445.43	3707.85	-89%
8/1/95 to 9/8/95	40	200	3066.18	335.08	2731.10	-89%
9/8/95 to 9/23/95	16	240	2631.96	200.93	2431.03	-92%
9/24/95 to 10/2/95	9	230	1061.96	450.37	611.59	-58%
10/3/95 to 10/22/95	20	225	4499.56	1207.95	3291.61	-73%
Total	222		19362	4715	14647	-75%

tion of 216 pounds (98 Kg) or 75% of the total mass of target contaminants within the circulation cell. Of the 216 pounds (98 Kg) observed mass reduction, 68 pounds (31 Kg) were treated in the in situ bioreactor, 32 pounds (14.5 Kg) in the gas phase bioreactor, and 10 pounds (4.5 Kg) were vented, for a total of 110 pounds (50 Kg). The balance of 106 pounds (48 Kg) were either mobilized to areas where monitoring wells were not present, transported by natural ground water flow to areas outside the circulation cell, or biologically mineralized within the circulation cell.

Due to the complex, nonhomogeneous and varying test environment of the site, it was difficult to quantify every removal pathway occurring in the aquifer to perform a more accurate mass balance. Stable isotope monitoring methods (Borchert et al. 1996) developed as part of another study could possibly be used to quantify these in future efforts. Consequently, results from DO monitoring, microbial plate counts, nutrient measurements, and mineralization by-products were used as qualitative indicators to assess the extent of in situ bioremediation in the aquifer.

Monitoring of DO indicated that enhanced aerobic conditions were established within a 30-foot-diameter (9.1 m) zone surrounding the UVB, even though physically the circulation cell extended 60 to 80 feet (18.3 to 24.4 m) in diameter. On average, the DO levels ranged from 1 to 3.5 mg/L in deep wells, and from 1 to 5.5 mg/L in shallow wells within the 30-foot-diameter (9.1 m) zone around the UVB. Outside this zone, the DO levels were detected at less than 0.5 mg/L in all deep and shallow wells. By design, the cell recirculated water in the zone nearest to the UVB well more times than in the zone away from the UVB well, and consequently, mobilized and transported contaminants, nutrients, oxygen, etc. in the zone nearest to the well in a more efficient manner than in the zone away from the UVB well.

In soil, the concentrations of $\text{NH}_3\text{-N}$, $\text{NO}_3\text{-N}$, $\text{NO}_2\text{-N}$, and ortho-phosphate decreased by 88%, 89%, 50%, and 99%, respectively. In ground water, the concentrations of $\text{NH}_3\text{-N}$ and $\text{NO}_3\text{-N}$ decreased by 64% and 96%, respectively, whereas the concentrations of $\text{NO}_2\text{-N}$, and ortho-phosphate remained unchanged. Microbial enumeration of heterotrophic bacteria and TCE degraders in soil provided mixed results. Average counts for TCE degraders decreased from 1.6×10^5 cfu/g soil at start to 1.1×10^4 cfu/g soil after 15 months, while that for heterotrophic bacteria increased from 5.8×10^4 cfu/g soil at start to 4.0×10^5 cfu/g soil after 15 months. Finally, a 93% increase in mass of VC (an intermediate) also indicated enhanced anaerobic activity in outermost areas of the circulation cell.

All of the aforementioned data suggested that within a reasonable margin of error at least half (53 pounds or 24 Kg) of the unaccounted 106 pounds (48 Kg) of mass reduction may be due to aerobic and/or anaerobic in situ bioremediation in the aquifer. The two bioreactors combined treated 100 pounds (45.5 Kg) of target compounds, which at a minimum accounted for 35% reduction (in soil and ground water

combined) from baseline strictly due to biodegradation. Considering this, the removal by microbiological mechanisms may have ranged from 35 to 56%.

Conclusions

Results from this field-scale demonstration indicated that the microbiologically enhanced UVB technology was able to mobilize and remove contaminants from the aquifer at the Sweden-3 Chapman Site. The technology did not meet the NYSDEC cleanup criteria for all the target compounds, but it did meet the practical cleanup criteria by reducing the combined concentrations of target contaminants by 75% in 11 months of actual operation. Mobilization and treatment of target CHCs appeared to be lower than the target nCHCs, presumably limited by chemical and biological factors. Biological transformation of target compounds was due to aerobic as well as anaerobic pathways, but neither could be quantified. An estimated 35 to 56% of the total observed mass reduction was achieved by microbiological mechanisms. All considered, it can be stated that the GCW technology relied more on the activity of the in situ bioreactor than on the stimulation of indigenous biota within the ZOI to achieve treatment of target contaminants. Hence, simple oxygenation would not be as effective as the integration of the in-well bioreactor.

Acknowledgments

This work was performed under the U.S. EPA's, Superfund Innovative Technology Evaluation (SITE) Program with participation from the NYSDEC, and the New York State Center for Hazardous Waste Management (NYSCHWM). Mention of trade names and technologies does not constitute an endorsement by the U.S. EPA, NYSDEC, or NYSCHWM. Research was performed, in part, in association with the U.S. EPA's National Health and Environmental Effects Research Laboratory (NHEERL) under the terms of the Cooperative Research and Development Agreement between SBP Technologies Inc. and the U.S. EPA (Contract # FTTA-003). The bacterial strain *Burkholderia cepacia* was obtained from Dr. Malcolm Shields, Center for Environmental Diagnostics and Bioremediation, University of West Florida, Pensacola, Florida. The authors would like to thank the staff at SAIC, NYSCHWM, U.S. EPA, NYSDEC, and IEG for their assistance during this project, as well as the reviewers of *Ground Water Monitoring and Remediation* for their constructive comments.

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