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# Innovative Subsurface Remediation

## Field Testing of Physical, Chemical, and Characterization Technologies

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## Chapter 12

# Performance Assessment of In-Well Aeration for the Remediation of an Aquifer Contaminated by a Multicomponent Immiscible Liquid

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A pilot-scale test to evaluate the performance of a vertical recirculation well equipped with an in-well air stripper was conducted at Hill AFB, Utah, in an aquifer contaminated with petroleum and chlorinated solvents. During the two months of operation, the air stripping system was found to remove more than 26% of the combined mass of ten representative contaminants from water passing through the well. The cell-wide performance was evaluated by comparing the contaminant concentrations for aquifer core samples collected before and after the test and by comparing the average immiscible liquid saturations determined with partitioning tracer tests conducted before and after operation. The net magnitude of remediation was low (<1%) due to the low aqueous concentrations of the predominant treatable contaminants at the site and the impact of the vertical gradients on immiscible liquid mobilization.

Most sedimentary aquifers are composed of predominantly horizontal layers of differing hydraulic conductivities. Attempts to extract contaminants from such systems using horizontal flushing (e.g., typical pump and treat) are inhibited by preferential flow through the higher permeability layers, which limits the remediation of the lower permeability layers. Thus, removal of contaminants from these layers is often dependent on diffusive mass transfer, which can be significantly rate limited. It is possible to enhance contaminant removal in such systems by inducing flow perpendicular to the strata. This may be accomplished with a vertical circulation well (VCW).

Vertical circulation wells are single wells screened at two or more separate intervals. Water is extracted at one interval and injected into another. In systems without a confining layer between the screens, water flows from one screen to the other along parabolic flow lines. A higher ratio of horizontal to vertical conductivity and greater distance between screens have been shown to extend the flow-lines farther from the well *(1, 2)*. More complicated VCW systems include the addition of multiple wells *(3)*.

Researchers at the University of Oklahoma conducted model simulations, column studies, and a field demonstration of enhanced removal of TCE, PCE, and recalcitrant jet fuel components using a vertical surfactant flush *(4, 5)*. They recovered 95% of the injected surfactant while increasing PCE removal 40 fold and that of jet fuel components 90 fold compared to the horizontal-flow pump-and-treat systems at the site. In conjunction with the vertical circulation well, four other wells were used for monitoring and hydraulic control.

The injection of air into a well can drive circulation through the well, strip volatile contaminants from the water, and increase the dissolved oxygen content of recirculated water, which may enhance the potential for aerobic biodegradation as a secondary means of remediation. Researchers with the USEPA from 1982 to 1985 evaluated several options including airlift pumping with and without in-well diffused aeration (sparging) and electrical submersible in-line pumps coupled with in-well defused aeration for remediation of groundwater contaminated by volatile organic compounds *(6)*. They found that the combination of the submersible pump coupled with in-well aeration was effective in removal of volatile organic compounds and that aeration may provide a useful treatment technique on a short-term emergency basis for vital production wells.

If contaminants are treated within the well, the treated water can be reinjected into the aquifer, thereby creating a vertical recirculation system. Treating contaminated water within the recirculation well offers an alternative to more common techniques involving above-ground treatment of extracted groundwater. One method for separating volatile contaminants from water that is adaptable to recirculation wells is air stripping. The coupling of an air-stripping reactor within a vertical recirculation well has been termed a vacuum vaporizer well (UVB) or in-well aeration (IWA). Less common in-well treatment systems include bioreactors, activated carbon adsorption, and the use of materials such as contact resins and iron filings.

Vertical recirculation systems have been applied to more than 300 sites world wide because of its advantages of in-situ treatment, low operational costs, and ease of use. Herrling et al. *(1, 7)* describe the use of UVB systems to remediate aquifers contaminated by gasoline and chlorinated solvents. Herrling et al.*(8)* discuss the potential uses of vertical circulation wells for free product recovery, soil vapor extraction, bioventing, and soil flushing.

This report presents the results of a test conducted to evaluate the ability of a vertical recirculation well, equipped with an IEG Technologies 150 mm canister in-well aeration system, to remediate a portion of the aquifer at Operable Unit 1 of Hill Air Force base in Utah. The system was operated from July 26 to September 23, 1996. This test was part of a large project designed to evaluate the performance of several innovative remediation technologies *(9)*.

## Methods

Operable Unit 1 at Hill AFB has a history of disposal and periodic burning of used solvents and jet fuel in unlined pits. This has contaminated the surficial unconfined aquifer with chlorinated compounds, jet fuel components, and high molecular weight poly nuclear aromatic hydrocarbons (PAHs). Cell 2 is thought not to be located directly beneath the former chemical disposal pits, but within the migratory paths of aqueous and free-phase contaminants.

The aquifer is composed primarily of sand, with gravel and cobbles mixed with clay and silt stringers. It is underlain by a regional clay aquitard at 8 to 8.5 meters (m) below ground surface. A 3 by 5 meter rectangle of sheet piling was emplaced through the aquifer into the clay aquitard. A vertical recirculation well was installed in the center of the test cell accompanied with other wells and multilevel samplers to evaluate performance (see Figure 1). Pre-remediation coring within cell 2 determined that the depth to clay on the south side was 7.8 m below ground surface (bgs), 8.2 m bgs in the middle, and 8.3 m bgs on the north side. The static ground water level was 6.7 to 6.9 m bgs outside the cell and was elevated to 5.8 m bgs inside the cell.

The basic instrumentation of the cell is similar to others at the site *(9)*. Four injection wells at the southern end and three extraction wells at the northern end of the cell were installed for conducting horizontal partitioning tracer experiments common to all test cells. All of these wells are screened from 4.9 to 7.9 meters below ground surface (bgs). The four wells nearest the corners of the cell are 6.4 cm internal diameter and the other three are 5.08 cm. Twelve multi-level sampling systems (MLSs) were installed between the injection and extraction wells. Each MLS has five sampling points spaced every 0.46 meters from 5.8 to 7.6 meters bgs, which provides a three-dimensional sampling array of 60 points.

The IWA well was installed with a hollow stem auger. The auger had an inside diameter of 24 centimeters and an outside diameter of 31 centimeters. The location of the IWA was previously cored and backfilled with sand. Placing this required core at the same location as the IWA minimized the disturbance of the aquifer system and provided a pilot hole for the larger auger used to drill the IWA borehole.

The vertical recirculation well, which contained two screened intervals, has an inner diameter of 15.5 centimeters. The screens of the vertical recirculation well have a 15.2 cm (6 inch) internal diameter and are wire wrapped screens fabricated of galvanized low-carbon steel with round wire (Irragator model, Johnson of Minneapolis, Minnesota). The openings between the wires are 8mm giving 0.18 $m^2$ opening per meter of screen. The top screen is 0.61 m long, the middle casing is 1.07 m long, and the bottom screen is 0.46 m long, and rests atop a 0.15 m deep sump. The top screen starts at 5.5 m bgs and the bottom screen ends at 7.6 m bgs. The total coverage of saturated aquifer is 2.14 meters. A solid casing made of schedule 40 high density polyethylene connects the top screen to the surface. Two PVC monitoring wells, 2.54 cm inside diameter, were placed within the same borehole as the VCW, one at each screen. Based on experience at the site, 20-40 sand was used for backfill around the screens to enable a productive interface with the aquifer. Micro-bentonite chips were placed surrounding the middle casing between the layers of sand to deter vertical flow within the borehole.

The IWA system employed at OU1 was designed and built by the IEG Technologies Corporation (Charlotte, North Carolina). A schematic of the in-well system is shown in Figure 2. Initial modeling studies were conducted to optimize the size of the IWA and the position of the vertical recirculation well within the test cell. A small pilot-scale IWA system of only 150 mm in diameter was used because of the small size of the test domain (3x5x2 m). This demonstration-scale system may be inherently less efficient in removing contaminants from recirculated water than the

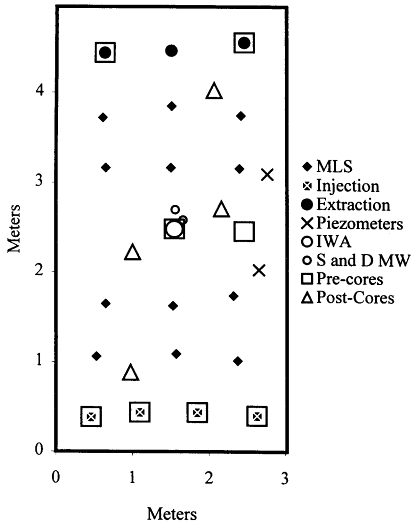

Figure 1 Cell Instrumentation and Coring Locations

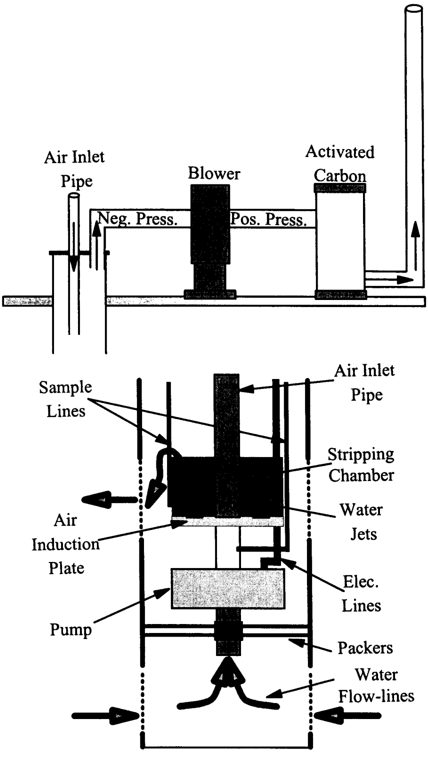

Figure 2 Above Ground and In-well Systems

normal full-sized systems currently used. An in-line pump was used to withdraw water from the lower portion of the aquifer into the lower screen, and up through a pipe within the solid casing separating the two screens. This pipe was surrounded by dual rubber packers to limit recirculation of water within the well. After passage through the pump, the water continued up through three pipes into a stripping chamber. The treated water then spilled over the edge of the stripping chamber, and exited into the top portion of the aquifer through the top screen. This design is a "standard flow" IWA, in which air and water flow concurrently upward within the casing.

A schematic of the above ground system is presented in Figure 2. Air flow through the system is induced via a blower, which withdraws air from the well casing. The resulting negative pressure causes air to flow through the air-stripping chamber from an in-take pipe in the well cap. Air enters through a pinhole plate at the bottom of the cylindrical (45cm deep and 10cm wide) stripping chamber. Water from the pump enters the chamber through three 1 cm diameter jets and mixes with the air. The vacuum created within the well casing by the blower is sufficient to force atmospheric air to overcome the weight of the column of water within the stripping chamber and induce flow through the intake pipe. Air and contaminated water turbulently mix within the stripping chamber, stripping volatile contaminants from the water into the air. The contaminated air is drawn to the surface due to the negative pressure within the well-casing. The contaminated air exits the blower, under pressure greater than atmospheric, and is flushed through a drum of activated carbon for treatment. The contaminant-depleted air is vented to the atmosphere through a 3.8 meter high stack.

Of the many detectable organic compounds at the site, twelve were chosen for use in assessing technology performance. The twelve include common chlorinated solvents such as TCA and TCE, fuel components such as the aromatics, benzene and toluene, and alkanes such as decane and undecane. These compounds have large differences in aqueous solubilities, volatilities, biodegradation potential, and other characteristics (see Table I). The potential remedial performance of the IWA is limited to those compounds with suitable aqueous solubility and volatility. Thus, compounds such as benzene and TCE are potentially more easily removed than decane. The actual removal effected for any specific compound will be further mediated by the complex nature of the physical, chemical, and biological interactions occurring within the aquifer.

## Results

**Characterization of Groundwater Entering and Exiting the IWA.** Thirty pairs of samples were taken from the IWA well to measure the target contaminant concentrations entering and leaving the well during the technology demonstration. Samples were collected from a sampling line located just prior to the air stripper and a sampling line located after the stripper (see Figure 2). The majority of the target concentrations within these samples were near method detection and quantifiable thresholds. For the purposes of determining mean concentrations entering and exiting the IWA, samples with measured target concentrations below detection levels are given the value of the detection level and samples with measured concentrations above the detection level, but below the quantifiable level are assigned the quantifiable level. This is a conservative approach to determining performance because more exiting samples have target concentrations within these ranges. Because the samples were not taken at

**Table I. Target Contaminant Results**

| *Target Contaminants* | *Aqueous Solubility*[a] | *Henry's Coeffeicents*[a] | *Theoretical stripping efficiency*[b] | *Initial Coring* | | *Final Coring* | | | *Initial Static Aqueous*[d] | | | *Final Static Aqueous*[d] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | *Air Out/ Water In* | *Avg.*[c] | *St. Dev.*[c] | *Avg.*[c] | *St. Dev.*[c] | *Div.* | *Avg.*[c] | *St. Dev.*[c] | *St./Equ* | *Avg.*[c] | *St. Dev.*[c] | *St./Equ* |
| | *(mg/L)* | *(atm-m3/mol)* | *g/g* | *ug/g* | *ug/g* | *ug/g* | *ug/g* | *F./I.* | *ug/L Est.* | *ug/L Est.* | | *ug/L Est.* | *ug/L Est.* | |
| Benzene | 1790 | 0.00548 | 98.2% | 0.008 | 0.007 | 0.010 | 0.007 | 125% | 1.4 | 1.3 | 0.39 | 0.9 | 0.4 | 0.27 |
| TCA | 1550[a] | 0.016 | 99.4% | 0.019 | 0.042 | 0.028 | 0.023 | 148% | 4.5 | 3.3 | 1.00 | 4.7 | 6.1 | 0.92 |
| TCE | 1100 | 0.0099 | 99.0% | 0.044 | 0.130 | 0.023 | 0.016 | 53% | 2.1 | 1.7 | 0.27 | 2.2 | 1.7 | 0.70 |
| Toluene | 515 | 0.0067 | 98.5% | 0.142 | 0.179 | 0.110 | 0.096 | 77% | 1.2 | 0.6 | 0.07 | 0.6 | 0.3 | 0.06 |
| o-Xylene | 152 | 0.0053 | 98.1% | 1.65 | 1.43 | 1.43 | 1.20 | 87% | 0.6 | 0.7 | 0.01 | 0.3 | 0.1 | 0.01 |
| p-Xylene | 180 | 0.007 | 98.6% | 0.681 | 0.696 | 0.871 | 0.615 | 128% | 0.9 | 1.4 | 0.04 | 0.4 | 0.4 | 0.02 |
| Ethyl-Benzene | 152 | 0.0066 | 98.5% | 0.242 | 0.209 | 0.321 | 0.217 | 133% | 0.5 | 0.7 | 0.07 | 0.2 | 0.2 | 0.03 |
| DCB | 137 | 0.0012 | 92.1% | 0.704 | 0.582 | 0.919 | 0.458 | 131% | 12.6 | 23.8 | 0.92 | 1.4 | 1.2 | 0.10 |
| Tri-Methyl- | 57 | 0.0057 | 98.2% | 3.50 | 2.34 | 4.22 | 1.78 | 120% | 0.5 | 0.8 | 0.01 | 0.2 | 0.2 | 0.01 |
| Naphthalene | 31.7 | 0.00046 | 81.8% | 1.15 | 1.19 | 1.71 | 1.10 | 149% | 12.0 | 20.0 | 1.92 | 0.7 | 0.3 | 0.09 |
| Decane | 0.009 | 0.187[a] | 99.9% | 42.3 | 32.0 | 48.6 | 15.9 | 115% | | | | | | |
| Undecane | | | | 77.5 | 85.3 | 99.3 | 51.6 | 128% | | | | | | |
| Total | | | | 127.9 | | 157.5 | | 123% | 36.3 | | 0.5 | 11.7 | | 0.2 |

[a] Reference *(17)* :Aqueous Solubility and Henry's Coefficients, TCA solubility range 900-4500 at 20C, Decane's Henry's coef. is calculated

[b] Theoretical Equilibrium Volatilized calculated from Henry's Coefficients, Vapor Pressure, and the flux, temperature, and pressure values for Air and Water for the Air Stripping Chamber.

[c] Core and Static Aqueous contaminant concentrations are arithmatic means and standard deviations of all samples.

[d] Initial and Final Static Aqueous Concentrations are from the same locations: 9 samples from 6.9 m bgs and 10 samples from 7.8 m bgs.

equal intervals, a time-weighted mean concentration was computed. TCA is the only target for which a significant fraction of samples had concentrations above detection limits. The results for the other compounds are strongly biased in that only a few of the thirty samples are above the quantifiable threshold. These few highly concentrated samples occurred early and late in operation and contributed more than 75% of the computed mass entering the IWA, but account for less than 10% of the total time of operation.

The percent of each target volatilized was computed by subtracting from unity the result of dividing the exiting mean concentration by the entering mean concentration. Using the mean of the measured air flux, temperature, and pressure conditions, the estimated water flux of 5 L/min, and assuming that air entering the stripping chamber contains no target compounds, a theoretical maximum amount volatilized can be computed (Table I):

$$\text{Stripping Eff.} = \frac{M_{\text{air out}}}{M_{\text{water in}}} = \frac{1}{1 + \dfrac{V_w RT}{V_{air} K_H}}$$

where $V_w$ is the estimated volumetric water flow rate ($m^3$/hr) passing through the IWA, $V_{air}$ is the averaged measured volumetric air flow rate ($m^3$/hr) passing through the IWA, R is the gas constant ($8.21 \times 10^{-5}$ atm $m^3$ $mol^{-1}K^{-1}$), T is the average temperature in degrees kelvin, $K_H$ is Henry's constant scaled for air pressure (atm $m^3$ $mol^{-1}$). Water temperature is assumed to be equal to air temperature due to the large air-to-water volume ratio within the chamber (238 to 1).

The theoretical maximum amount volatilized is greater than the computed values for all the targets except naphthalene, for which theoretical and computed values are nearly the same. TCA, which is considered the most reliable target for measuring stripping efficiency because it has the lowest coefficient of variation of the ten measured targets, has a computed volatilization of 11% compared to a theoretical maximum of 99.4%. This translates into a stripping efficiency of 11.4% for TCA, indicating that air and water do not reach equilibrium within the chamber for TCA. Figure 3 shows the entering and exiting concentration versus time for the study.

An estimate of the time required for the system to remove the target contaminants from the cell is useful to evaluate potential performance. An initial mass of each target can be estimated from initial core concentrations and aquifer properties. The removal of individual contaminants from the cell can be estimated by combining the average influent water concentration, the average stripping efficiency, the estimated water flow rate through the cell, and the total time of operation. If TCA removal continued at the same average rate as occurred during the study, it would take more than two years of operation of the IWA to completely remove TCA from the treatment zone.

**Characterization of Air Entering and Exiting the IWA.** Air flow was monitored periodically at the air inlet pipe, before and after the blower, and within the stack. Pressure within the air ducts was monitored with pressure gauges while temperature, relative humidity, and flow rate were monitored with the model 452 Instant Action Anemometer (Testo Incorporated, Flanders, New Jersey). Combining the measurements of volumetric flow-rate, temperature, pressure, and relative humidity generates a calculation of water flux for each measurement location. These results indicated the net removal of 17 ml/min of water, or more than 600 liters during the time of operation.

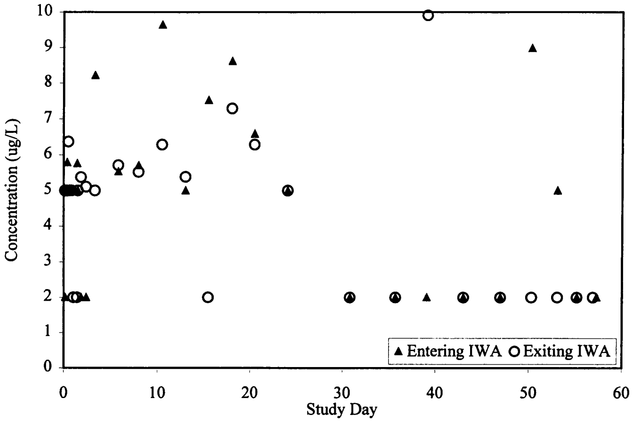

Figure 3 TCA Aqueous Fluxes Through the IWA

The contaminant load in the air was monitored with a portable photo-ionization detector (PID). The PID was calibrated with a reference gas of 100 mg/L iso-butanol and the local atmosphere approximately thirty meters from the site to negate potential background interferences. Results of monitoring of the air stream by the PID are shown in Figure 4. Because the PID is calibrated solely to iso-butanol (MW = 124 grams/mole), the concentration has been combined with flow rate, pressure, and temperature to yield contaminant mass flow measurements as equivalent grams of iso-butanol per day. To estimate overall mass removed, calculations are made as per day for a single measurement by assuming each reading is an average condition for the time period that spans halfway between the previous and subsequent samples. Although humidity and temperature naturally fluctuate with the hour of the day, these influences were relatively small and precautions were taken to limit biases.

Table II shows the total equivalent mass of iso-butanol measured at each sample point along with the average for each sample. The intake concentration rarely rose above zero, with more than 2/3 of the readings taken from the intake being zero. Based on these data, approximately 18 g of equivalent iso-butanol (EIB) is estimated to have entered the cell through the air inlet. The measurements after the blower, which are believed to be more accurate because it is under positive pressure and therefore less subject to dilution, provide a value of 303 grams of EIB mass removed. Subtracting the influent from the effluent air contaminant loads produces a calculated net mass removal of 285 grams in equivalent mass of iso-butanol.

**Characterization of Core Samples Before and After IWA Operation**. Contaminant concentrations present in cores collected before and after operation were used as one method to evaluate the performance of the IWA system. During coring, soil samples were placed into vials containing methylene chloride (extractant) and acid. They were analyzed at the Environmental Laboratory at Michigan Technological University by a gas chromatograph (GC) mass spectrometer. Table I lists the average and standard deviation of the concentrations for the twelve target compounds for both pre- and post-remediation coring. Initial conditions were determined from eight cores collected with the installation of wells (see Figure 1 for locations). The initial amount of each target contaminant is roughly inversely proportional to its aqueous solubility. For example, the two most insoluble targets, decane and undecane, compose 33% and 60% respectively of the total mass of target compounds. Except for TCE, the target compounds were distributed predominantly from 5.64 to 7.16 meters below ground, with diminishing amounts below this level. Assuming the data obtained from pre-remediation cores accurately reflect the distribution of contaminants within the cell, the total mass of the twelve targets within the cell is calculated to be 6.3 kg.

The post-cores were collected from locations closer to the middle of the cell (see Figure 1). Due to limited recovery from the coring process, only 14 samples exist from the treatment zone. Samples were taken from the four cores at 5.8, 6.4, 7.0, and 7.6 meters bgs depths. Averaging the concentration of each target for each depth profile produces a relatively uniform distribution for most contaminants in the post-cores.

Samples from similar depths are used to compare the pre- and post-coring results. These include samples from 5.8, 6.4, 7.0, and 7.6 meters bgs for the post and samples from 5.6, 5.9, 6.2, 6.6, 7.0, 7.3, and 7.6 meters bgs depths for the pre-remediation coring. Comparisons indicate that the final average concentration is greater

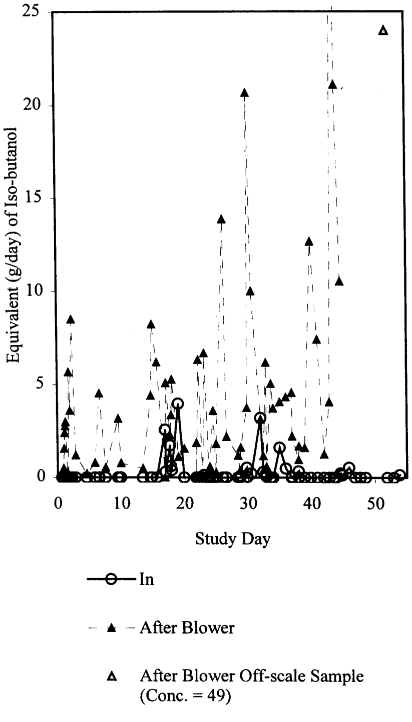

Figure 4 PID Fluxes

than the initial average concentration for nine of the 12 compounds. Post-remediation cores have lower average concentrations for TCE, toluene, and o-xylene.

**Table II. IWA Air Stream Parameters**

| *Sampling Location* | *In* | *Out of Well* | *After Blower* | *Stack* |
|---|---|---|---|---|
| Num. of Samples | 75 | 76 | 76 | 72 |
| Avg. Flowrate (L/min) | 1189 | 1864 | 1318 | 1227 |
| Avg. Flowrate (Std L/min) | 1103 | 1588 | 1163 | 1118 |
| Avg. Temp (°C) | 25.9 | 24.1 | 43.6 | 32.4 |
| Avg. Pressure (kPa) | 94.2 | 84.3 | 95.2 | 94.2 |
| Avg. Humidity (%RH) | 30.4 | 79.6 | 27.1 | 48.8 |
| Avg. Water Flux (ml/min) | 32.9 | 106.3 | 50.1 | 48.2 |
| Avg. PID (ppm EIB)[a] | 0.24 | 1.82 | 3.01 | 1.75 |
| Total (g EIB)[a] | 18 | 255 | 303 | 180 |
| Total (ml EIB)[a] | 14 | 205 | 244 | 145 |

[a]EIB is Equivalent mass as Iso-butanol

The fact that the post-cores appear to be generally more contaminated than the pre-remediation cores indicates a non-uniform distribution of contamination within the cell. Most of the pre-cores were close to the cell perimeter whereas the post-cores were collected from the center of the cell. Given that the center of the cell received the greatest treatment, the best direct comparison would be the two pre- and two post-remediation cores located near the middle of the cell. The two pre and post-cores are located within 0.4 meters of the treatment well. For these two sets of cores, the number of targets experiencing reductions in concentrations increases to five of the twelve, but there is no significant pattern showing greater removal.

During the operation of the IWA, the hydraulics of the vertical recirculation system mobilized and redistributed immiscible liquid. For example, the flow away from the top screen of the IWA moved large quantities of floating immiscible liquid to wells 2252 and 2253, where it was not previously observed. More than 7 liters of the immiscible liquid was collected from the two wells. Accumulation was also observed at other wells within the cell, but in thicknesses less than 2 cm. It is possible that the mobilization and smearing of the immiscible-liquid influenced contaminant distributions during the study, thereby obscuring contaminant removal associated with operation of the IWA system.

**Partitioning Tracer Tests.** Interwell partitioning tracer studies were performed in cell 2 before and after the operation of the in-well aeration system. Through the chromatographic separation of chemical species, these tracer tests allow both the detection and estimation of an immiscible-liquid saturation ($S_n$) located within the swept-zone of a porous medium *(11-15)*. The tracers used in the test are either preferentially retained by the immiscible-liquid phase or behave conservatively. Using the travel times and immiscible-liquid/water partition coefficients of these tracers, an effective immiscible-liquid saturation can be calculated for the targeted portion of contaminated porous medium. Comparisons of the preliminary and post estimated immiscible-liquid saturations indicates the amount of immiscible liquid solubilized and removed by the IWA. These studies allow a much larger volume of aquifer to be characterized, compared to other method such as soil cores and groundwater sampling.

As seen in Table III, the results of the cell 2 pre-remediation partitioning tracer test demonstrate a relatively uniform immiscible-liquid distribution across the cell (from wells 2251 to 2253). The $S_n$ values range from 7.4 to 9.7% for the three wells, with a swept-volume weighted averaged of 8.9%. This value translates to 525 L of NAPL and 5366 L of water within the flow field for the pre-remediation study. Table III gives the pore volume, travel times for the conservative tracer (bromide), $S_n$, and immiscible-liquid volumes for both the pre- and post-remediation partitioning tracer tests.

**Table III. Cell 2 NAPL Partitioning Tracer Tests**

| | *Pre-Partitioning Study* | | | | *Post-Partitioning Study* | | | |
|---|---|---|---|---|---|---|---|---|
| Extraction Well | *2251* | *2252* | *2253* | *Wt. Avg. or Total* | *2251* | *2252* | *2253* | *Wt. Avg. or Total* |
| Pore Volume (L) | 1800 | 2050 | 1520 | 5370 | 1500 | 2780 | 1270 | 5550 |
| Travel Time (days) | 1.24 | 1.41 | 1.04 | 1.25 | 1.03 | 1.92 | 0.87 | 1.44 |
| Partitioning ($S_n$%) | 9.7 | 9.3 | 7.4 | 8.9 | 16.7 | 7.7 | 14.0 | 11.6 |
| NAPL Volume (L) | 193.4 | 210.2 | 121.5 | 524.6 | 300.7 | 231.9 | 206.7 | 728.3 |
| Tracer | bromide (370), ethanol (997), pentanol (988), 2,2-dimethyl-3-pentanol (395), hexanol (945) | | | | bromide (307), ethanol (1107), pentanol (522), 2,2-dimethyl-3-pentanol (406), hexanol (991), 6- methyl-2-heptanol (477) | | | |

The post-partitioning tracer test was conducted after the operation of the IWA system. The flow rate and depth to the water-table were essentially identical to those used in the pre-remediation study. Comparisons of the results indicate an increase in $S_n$ from the pre-study to the post-remediation study. This apparent increase may originate from the redistribution of immiscible liquid within the cell as discussed above, and an increase in size of the pore volume observed for the post-partitioning tracer test. Similar apparent increases in immiscible liquid saturation from the pre- to post-partitioning tracer studies were observed for the air sparging test at OU1 *(16)*.

**Characterization of Groundwater Prior to and After the IWA Operation.** To evaluate the ability of the system to remove specific contaminants, aqueous groundwater samples were collected from the aquifer before and after operation of the IWA. Static conditions were maintained for 72 hours in an attempt to establish equilibrium distributions of the target compound within the cell. To determine the initial groundwater concentrations, 10 samples were drawn from the MLSs at 5.9, 6.9, and 7.8 m bgs just prior to operation of the IWA.

Table I shows the results of the initial static sampling, including the average and standard deviation of the aqueous concentration of the ten most soluble targets. To evaluate if the static aqueous samples are in equilibrium with the immiscible-liquid contamination in the cell, the average static concentration is divided by the expected equilibrium concentration, which is estimated by *(10)*:

$$X_i = \frac{C_i \rho_b V_c MW_n}{S_n \theta \rho V_c MW_i}$$

where $X_i$ is the mole fraction of the component of the NAPL, $S_i$ is the aqueous solubility, $C_i$ is the average core concentration (initial cores are used for comparison with initial statics), $\rho_b$ is the bulk density, which is best approximated at 1.6 g/cm$^3$, $V_c$ is the cell volume(which cancels out), $MW_n$ is the average molecular weight of the NAPL, which based on the work of McCray and Brusseau *(10)*, is best approximated to be 180 g/mole for this site, $S_n$ is the NAPL saturation, $\theta$ is the porosity (0.18), $\rho_n$ is the NAPL density (extracted NAPL from cell 2 had a density of 0.885 g/ml), and $MW_i$ is the molecular weight of the target of concern. The results of these calculations are presented in Table I as the ratio of average static to computed equilibrium concentration.

The ratio of measured to expected shows that the three major constituents in the pre-remediation static samples, naphthalene, DCB and TCA, appear to be close to equilibrium. Conversely, the five alkyl benzenes have very small ratios. This result may not mean, however, that these compounds are actually far from equilibrium. The low concentrations could reflect preferential biodegradation of these more labile compounds. The larger aromatic and the chlorinated target compounds are likely to be less prone to biodegradation than the alkyl benzenes. The intermediate ratios observed for TCE and benzene, which are generally less biodegradable than the alkyl benzenes, may result from volatilization losses during sampling and storage.

The mean aqueous concentrations measured for the 19 post-remediation static samples were lower than those of the initial static samples for eight of the ten detectable target contaminants. The comparison of measured to expected concentration are similar to the initial static data, with the exception of DCB and naphthalene, of which showed apparent nonequilibrium for the final samples. As a result, the distribution of the contaminants changed from the initial samples. In the final static round, the three most soluble, benzene, TCA, and TCE, comprise the majority (67%) of the total dissolved load, whereas DCB and naphthalene did for the initial statics.

## Conclusions

The operation of the In-well aeration system at OU1 removed small amounts of contamination from the aquifer. Monitoring of dissolved target contaminants entering and exiting the recirculation well showed a net reduction in the ten contaminants that could be detected. Monitoring of the air stream with a portable photo ionization detector (PID) showed that contaminants in the water entering the well partitioned into the air stream. Combining the readings of the PID, which was calibrated to iso-butanol (124 grams per mole), with temperature, pressure, and flow-rate measurements of the air stream resulted in calculated values of 18 and 303 grams of contaminant mass entering and exiting the IWA, respectfully. Further, the air concentrations did not decrease over the two months of operation, indicating that the system was still removing mass. If the calibration of the PID to iso-butanol accurately reflects the contaminant load within the off gas air stream, then the total mass removal of contaminants is approximately 285 grams. This amount is nearly 24 times more than the amount of the target compounds calculated to have been volatilized by air stripping. However, not including decane and undecane which could not be detected in aqueous samples, the target contaminants are estimated to compose less than 0.1% of the total contaminant mass within the treatment zone. Thus, the higher PID air stream mass removal calculations are not unexpected because many other volatile and semi-volatile compounds were likely removed during air stripping.

To measure the net effect on contamination within the cell, aquifer coring, partitioning tracer-test data, and groundwater samples were collected before and after operation of the IWA. The partitioning tracer tests and core comparisons show increases in contamination present within the treatment zone. The total of the average concentration of the twelve target contaminants increased 27% from pre- to post-remediation cores measurements. The $S_n$ estimated from the post-remediation partitioning tracer test was 31% greater than that from the pre-remediation partitioning tracer, which corresponds well to the increase determined with the core samples.

The strong vertical gradient in the center of the cell created by operation of the IWA appears to have mobilized and redistributed immiscible liquid within the cell. Comparisons between immiscible-liquid residual for the three extraction wells showed relatively uniform distribution for the pre-remediation study and a nonuniform distribution for the post study. During operation of the recirculation well, large quantities of floating immiscible liquid appeared in all wells and the shallowest MLSs. More than 7 L of immiscible liquid was collected from wells 2252 and 2253. This redistribution is most likely responsible for the contaminant-mass increases measured in the post-cores and post-partitioning tracer tests. Thus, while contaminant mass was removed with operation of the IWA, this amount is negligible compared to the impact of the immiscible-liquid redistribution.

The purpose of the studies conducted at OU1 of Hill AFB was to compare the performances of several remediation technologies. Hence, the tests were designed to be conducted in a manner as similar as possible. While the design worked well for the horizontal flushing technologies, it was not optimal for the IWA system. Thus, we expect IWA systems may be more successful in systems for which their use is optimized.

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