

## Full-Scale Installation of a Passive Biobarrier to Remediate a TCE Groundwater

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### ABSTRACT

The goal of this study was to use results from a biobarrier pilot test to design a full-scale biobarrier to treat a trichloroethene (TCE) plume approximately 1,100 feet wide. The full-scale passive biobarrier was installed along the downgradient property boundary and extended 1,250 feet perpendicular to the groundwater flow direction. The biobarrier consisted of two rows of electron donor injection points at the northern and southern margins of the plume and three rows in the central part of the plume installed using direct push techniques. A total of 60,000 pounds (lbs) of an emulsified vegetable oil (EVO) product was used as the electron donor and applied evenly throughout the aquifer to condition it for bioaugmentation. Two months following the completion of the donor application, the aquifer was adequately conditioned for bioaugmentation with oxidation-reduction potentials (ORP) of -100 to -150 millivolts (mV). At that time, 330 liters (L) of dechlorinating bacterial culture was applied to the biobarrier. Within two months of bioaugmentation, dechlorination products including ethene were observed within and downgradient of the biobarrier.

### INTRODUCTION:

**Site Description.** The Site is located in the New Castle Till Plains and Drainage Ways physiographic region of Indiana [Gray (1)]. Historic use of TCE at a manufacturing plant has impacted an unconfined aquifer. The aquifer is part of a north-south trending glacial outwash channel. The outwash deposits are composed of coarse-grained sands and gravel with occasional interbeds of silty sand and silt that generally coarsen toward the center of the channel. The bedrock surface is located at depths ranging from 30 feet near the western margin of the channel to greater than 120 feet near the center. A plume consisting primarily of TCE has migrated from west to east across the Site toward a regionally significant river located at the center of the outwash channel. The plume is approximately 1,100 feet wide, 7,200 feet long and the impact depth in the area of the biobarrier is 50 feet (Figure 1).

The properties of the aquifer were characterized by grain size distributions, an eight-hour pump test and a sodium bromide tracer test. The specific yield was estimated to be 0.28, and the hydraulic conductivity was calculated to be 204 feet per day. The groundwater flow velocity in the area is approximately 2 feet per day.

**Pilot Test.** Genetic testing and microcosm studies were conducted during the design stage to determine if dechlorinating bacteria were present at the Site and biostimulation would be adequate to achieve complete dechlorination, or if bioaugmentation would be necessary. Results indicated that dechlorinating bacteria were present in Site soil at very low concentrations but were not detected in Site groundwater. Biostimulation of Site soils in microcosms with lactate yielded dechlorination of TCE to cis-1,2-dichloroethene (cis-DCE); however, dechlorination

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**Figure 1. Site Layout**

beyond cis-DCE was not observed. Bioaugmentation of the microcosms with halorespiring bacteria inoculum resulted in complete dechlorination of TCE to ethene. A circulation system pilot test was designed to determine if the bench test results could be replicated at the site. The design was based on our experience at the Bachman Road Site [Lendvay (2)] but with a significantly larger test plot to address scaling issues as we apply the technology to this site.

The pilot test circulation area was located in the center of the plume, where the highest concentration of TCE (4,500  $\mu\text{g/L}$ ) was observed. The circulation area was 40 feet by 100 feet with the longer dimension parallel to groundwater flow. Soil data collected during the installation of the circulation system indicated sandy-silty clay from the ground surface to 5 feet below surface grade (bsg), silty sand and gravel from 5 to 10 feet bsg, medium sand from 10 to 47 feet bsg and dry, tight, glacial till at approximately 47 feet bsg. Groundwater was observed at approximately 23 feet, indicating an aquifer thickness of 24 feet.

Approximately 440 lbs of sodium lactate was injected over 9 months, but constant biofouling of the injection wells limited effective delivery. As a result, the delivery method and donor was changed. EVO product was introduced to the circulation cell via temporary direct-push points. The circulation system continued to operate at approximately 8 gpm. Approximately 3750 lbs of EVO with 5% lactate was applied to the pilot test cell through 14 injection points. Approximately 10 days after direct injection of EVO, the ORP dropped to -200 mV at a monitoring well within the pilot test cell. That well was inoculated with 20 L of halorespiring bacterial culture, bypassing the injection wells. The circulation system continued to operate for 4.5 months distributing the donor and bacterial culture through out the circulation area.

All wells located in the pilot test cell exhibited convincing evidence that dechlorination of TCE had occurred. In a shallow monitoring well, where most of the donor was applied, complete dechlorination with no detections of TCE, DCE isomers or vinyl chloride (VC) after one year. The deeper monitoring wells exhibited significant reductions in the concentration TCE and DCE isomers, and VC, but complete dechlorination has not been observed. A rebound in the

concentration of TCE from 10% of the original concentration to 50% was observed at a deeper interval 11 month following the conclusion of the pilot test.

Genetic testing confirmed that *Dehalococcoides*, the primary halo-respiring bacteria in the inoculum, were present in every well tested within the pilot test area. The highest bacterial counts were present in the shallow interval. The circulation system was very successful at distributing the inoculum from the single inoculation point throughout the entire test cell creating the biobarrier.

The VOC, genetic testing and geochemical results from the pilot test suggested that a combination of direct injection and a circulation system can be used to establish a biobarrier and completely circumvent problems with biofouling. The application of donor primarily in the shallow interval has biased the results of the pilot test. The direct injection of EVO with 5% lactate provided superior results when compared to lactate-only additions previously conducted at the site. Additional donor will be required in the deeper intervals to sustain the halo-respiring bacteria and continue the dechlorination mechanism to completely dechlorinate TCE in those intervals.

**Full-scale.** Based on the results of this study the Indiana Department of Environmental Management approved the full-scale application of this technology for the Site, the subject of this paper. Based on the results of the pilot test, key design changes were made to improve donor delivery techniques. Although a circulation system was used during the pilot test, a passive biobarrier was constructed for the full-scale application due to the required treatment width and required infrastructure.

## MATERIALS AND METHODS

**Biobarrier Layout.** A combination of two layouts was used for the locations and spacing of the injection points. These layouts are referred to as the “wings” and the “heart” of the biobarrier. The northern 400 feet and southern 200 feet of the biobarrier are the wings, and the central 650 feet is the heart, for a total length of 1,250 feet (Figure 2). The biobarrier consisted of three extraction/injection cells. One 6-inch

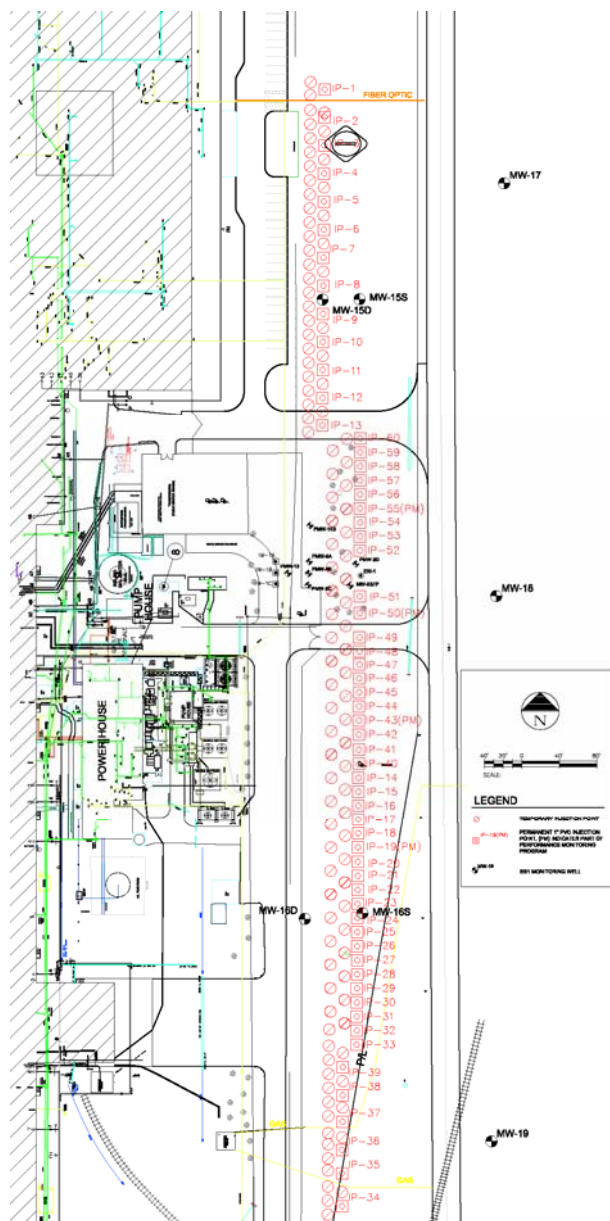
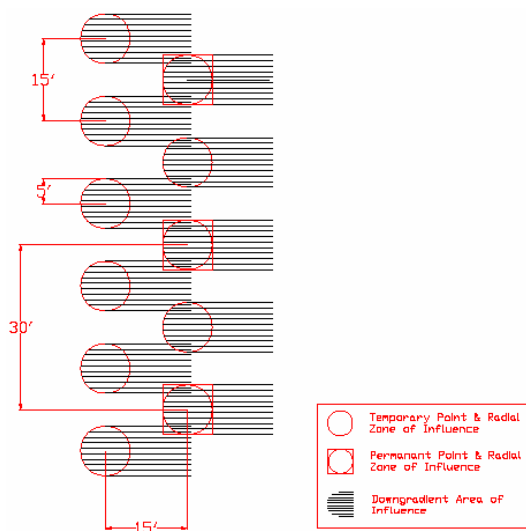


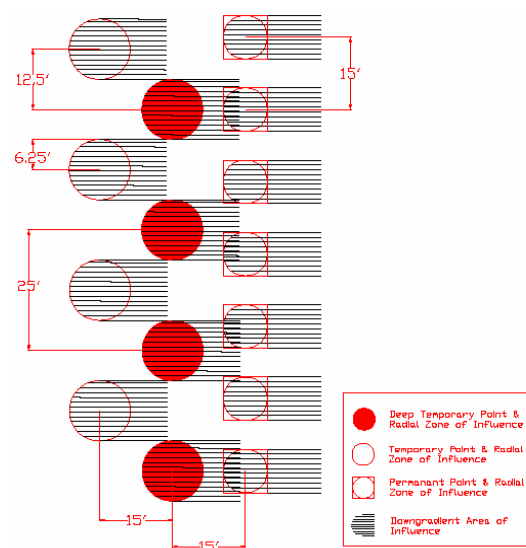
Figure 2. Biobarrier Layout

extraction well was located within each cell. Each extraction well provided the source of the water for the donor delivery. A key component of the design was that the central circulation cell used *Dehalococcoides*-containing water from the pilot test extraction well as discussed in the central circulation cell section below.

The layout of the wings consisted of two rows of injection points. The upgradient row had all temporary injection points and was spaced 15 feet apart. A second row of points with spacings of 15 feet apart was installed 15 feet downgradient. This downgradient row was offset 7.5 feet, as demonstrated in Figure 3a. Additionally, the downgradient injection points consisted of alternating temporary and permanent points. All injection points within the wings were screened over the entire saturated thickness (approximately 25 to 45 feet bsg). This layout was installed in the margins of the plume where TCE concentrations were generally less than 1,000 µg/L.



**Figure 3a. Biobarrier Wings Injection Layout**



**Figure 3b. Biobarrier Heart Injection Layout**

The heart of the biobarrier consisted of three rows of injection points (Figure 3b). The upgradient-most row had temporary points spaced 25 feet apart and screened over the entire saturate thickness. The middle row was installed 15 feet downgradient and offset 12.5 feet. The points were temporary and only screened from approximately 35 to 45 feet bsg. This was one of the most significant changes from the pilot test where better results were observed in the shallower portion of the aquifer. We concluded that insufficient delivery pressure and preferential flow out of the upper portion of the screen prevented donor from reaching the lower portion of the aquifer. The downgradient row consisted of permanent points, spaced 15 feet apart and screened over the entire saturated thickness. This layout was installed in the central part of the plume where concentrations were greater than 1,000 µg/L.

**Donor Delivery System.** Temporary points were 1-inch stainless steel with 0.020-inch slot, wire-wrapped screens. The stainless steel material provided durability for the repeated installation and removal of these points. A total of 108 temporary points were utilized for biobarrier construction. Permanent points were 1-inch PVC with 0.020-inch mill slot screens. These points were finished flush with grade. The permanent points provided locations for

inoculation, once the aquifer was conditioned and for future donor injections when donor depletion is observed. A total of 60 permanent points were installed in the biobarrier.

All injection points were installed with a Geoprobe® 6600 direct-push rig utilizing hollow 2.125-inch rods. Drill rods were advanced to the appropriate depth, and the 1-inch injection points were installed using standard well installation techniques. Following the donor injection and water flush, the temporary points were extracted using a Geoprobe® 54LT. This allowed the 6600 to continuously install points without stopping to return to extract well casing and screen. The screens from the extracted points were thoroughly cleaned using a pressure washer to remove bentonite smear and sand pack from the openings.

A 5-horsepower, 75 gpm submersible pump was installed in the extraction wells. A 2-inch steel drop-pipe was connected to an in-line bag filter with a 200 U.S. sieve size filter. A pressure regulator was installed to ensure the maximum rated pressure of the 2-inch PVC hose was not exceeded. The 2-inch hose had a maximum length of 500 feet to an injection manifold, depending on the location of the injection points in relation to the extraction well.

The injection manifold had two branches. One branch was for the donor injections and the other branch was for the fresh water injections that immediately followed the donor. The donor injection side of the manifold was reduced to 1-inch and had four 1-inch hoses extending up to 50 feet to the donor intake and metering system. The 1-inch line was reduced to ¾-inch with a pressure regulator and in-line flow restrictor before the Dosatron® DI520 Water Powered Metering System. Each line had a check valve after the Dosatron® to prevent water hammer. A standard garden hose connected each Dosatron® to the individual injection points. The fresh water side of the manifold was reduced to five ¾-inch lines with a total flow meter on each line. The lines were connected to the injection points with a standard garden hose.

EOS® 598 B42 was the electron donor used for the biobarrier. This donor is emulsified soybean oil with 4% sodium lactate and a vitamin B12 supplement. Several studies have shown that growth of dechlorinating microorganisms may be enhanced by providing these bacteria with amino acids and /or vitamins [Deweerd et al. (3), Holliger et al. (4), and Maymo-Gatell et al. (5)]. Approximately 290 pounds (38 gallons) of EOS® at a 20% solution was applied to points with 15-foot spacings. Approximately 474 pounds (62 gallons) of EOS® at a 20% solution was applied to points with 25-foot spacings. In total, approximately 60,000 pounds of EOS® was applied to the biobarrier to condition the aquifer.

Immediately following the injection of donor into a point, the EOS® B12 supplement was added just before the injection of fresh water. The fresh water injections were completed to achieve specific radii of influence at each point, depending on point spacing. For points spaced 15 feet apart, a radius of influence target was 7.5 feet because rows were offset 7.5 feet. This prevented the need to achieve a radius of influence of 15 feet. Similarly, for points with 25-foot spacings, an effective radius of influence of 12.5 feet was required. The calculated volumes to achieve these radii of influence were 2,000 gallons and 4,800 gallons, respectively. All plumbing, including piping, hoses and electrical supply, were temporary. The only infrastructure visible at the Site after the completion of the donor applications was the flush to grade well covers for the

permanent injection points, extraction wells and monitoring wells. Figure 4a and 4b show the Site during and after donor application, respectively.



**Figure 4a. Site During Donor Application Activities**

permanent injection points using SiREM's protocol and procedures. A total of 330 L of culture was applied to the biobarrier. As of October 2006, this was the largest application of KB-1™ at any site.

Results of the pilot test indicated that high populations of dechlorinating bacteria were present near the pilot test extraction well. Prior to donor injections in the central circulation cell (served by the pilot test extraction well), genetic testing was completed on water samples from points in that area but outside the influence of the pilot test to confirm dechlorinating bacteria were not present.



**Figure 4b. Site One Month After Donor Application**

**Bioaugmentation.** The aquifer was adequately conditioned within two months of donor delivery. ORP measurements in the permanent injection points were less than  $-120$  mV and significant reduction of nitrate and sulfate was observed. Additionally, TCE was completely converted to cis-DCE in the injection points. Approximately 5.5 L of KB-1™ Dechlorinator culture from SiREM was applied to each of the 60 permanent injection points using SiREM's protocol and procedures. A total of 330 L of culture was applied to the biobarrier. As of October 2006, this was the largest application of KB-1™ at any site. Results of the pilot test indicated that high populations of dechlorinating bacteria were present near the pilot test extraction well. Prior to donor injections in the central circulation cell (served by the pilot test extraction well), genetic testing was completed on water samples from points in that area but outside the influence of the pilot test to confirm dechlorinating bacteria were not present. The sampling confirmed the absence of dechlorinating bacteria. As part of this study we wanted to determine whether it is possible to inoculate or seed an area by extracting water from another area known to contain a healthy and viable microbial population.

**Biobarrier Performance Monitoring.** Monitoring wells were placed at key locations along the biobarrier to assess the success of the remedy. Two shallow (screened over the top 10 feet of saturation) monitoring wells were located 40 feet and 5 feet downgradient of the injection points, MW-15S and MW-16S, respectively. The extraction wells in the north and south circulation cell are also used as monitoring well. The submersible pump was removed following donor application. The north extraction well, MW-15D, is within the biobarrier. Ideally, the extraction well would be located upgradient, but existing utilities prevented this. The south extraction well, MW-16D, is located approximately 15 feet upgradient of the biobarrier. Four of the permanent injection points (IP-19, IP-42, IP-50 and IP-55) were included in the monitoring until bacteria establishment was observed. Three monitoring wells (MW-17, MW-18 and MW-19) are located significantly down-gradient of the biobarrier at 175, 130 and 145 feet, respectively.

Dissolved oxygen, dissolved iron, nitrate, ORP and volatile organic compounds are parameters monitored regularly. The following parameters are monitored intermittently to reduce costs: methane, ethane, ethene, volatile fatty acids, total organic carbon and *Dehalococcoides* population.

## RESULTS

The data discussed in this section was collected 4 months after donor application and two month after bioaugmentation.

**Table 1. North Circulation Cell Data.**

<b>MW-15S</b>		<b>2/15/06</b>	<b>5/22/06</b>	<b>8/16/06</b>
<b>PCE</b>	<b>(ug/L)</b>	8.4	4.2	1.8
<b>TCE</b>	<b>(ug/L)</b>	545	64	9.0
<b>cis-DCE</b>	<b>(ug/L)</b>	3.2	974	330
<b>VC</b>	<b>(ug/L)</b>	ND	4.4	41.3
<b>ethene</b>	<b>(ug/L)</b>	ND	ND	ND
<b>ORP</b>	<b>(mV)</b>	94	-33	-117
<b>MW-15D</b>		<b>2/15/06</b>	<b>5/22/06</b>	<b>8/16/06</b>
<b>PCE</b>	<b>(ug/L)</b>	2.1	0.7	ND
<b>TCE</b>	<b>(ug/L)</b>	585	204	420
<b>cis-DCE</b>	<b>(ug/L)</b>	4.3	459	120
<b>VC</b>	<b>(ug/L)</b>	ND	2.4	ND
<b>ethene</b>	<b>(ug/L)</b>	ND	ND	ND
<b>ORP</b>	<b>(mV)</b>	76	-68	-51
<b>Dhc</b>	<b>(orgs./L)</b>	--	--	6 x 10 <sup>4</sup> /L
<b>% Dhc</b>	<b>(%)</b>	--	--	0.004
<b>MW-17</b>		<b>2/15/06</b>	<b>5/22/06</b>	<b>8/16/06</b>
<b>PCE</b>	<b>(ug/L)</b>	ND	ND	ND
<b>TCE</b>	<b>(ug/L)</b>	58	47	50
<b>cis-DCE</b>	<b>(ug/L)</b>	ND	ND	ND
<b>VC</b>	<b>(ug/L)</b>	ND	ND	ND
<b>ethene</b>	<b>(ug/L)</b>	ND	ND	--
<b>ORP</b>	<b>(mV)</b>	95	10	19

**North Circulation Cell.** Table 1 summarizes the key parameters in this area. Favorable redox conditions persist within this portion of the biobarrier. There was an increase in total mass of VOCs by 2.5 times immediately after donor application, likely due to desorption of contaminants from soils. Most of the mass was converted from TCE to cis-DCE. Two months after bioaugmentation, the total mass returned to pre-donor total; however, no TCE was observed and cis-DCE concentration was reduced by 70%. Ethene has not been detected at MW-15S. An increase in the TCE concentration occurred at MW-15D. MW-15D provided the water for the installation of the barrier in this area. During pumping, EVO previously injected around MW-15D may have been stripped from the soil leaving the area with insufficient donor. No effects of the biobarrier are observed in MW-17, 200 feet downgradient of the biobarrier.

**Central Circulation Cell.** Table 2 summarized the key parameters in this area. Very favorable redox conditions persist within this portion of the biobarrier. TCE has been completely

**Table 2. Central Circulation Cell Data.**

<b>IP-50</b>		<b>4/23/06</b>	<b>5/23/06</b>	<b>6/20/06</b>	<b>8/16/06</b>
<b>PCE</b>	<b>(ug/L)</b>	ND	ND	ND	ND
<b>TCE</b>	<b>(ug/L)</b>	1,200	ND	ND	ND
<b>cis-DCE</b>	<b>(ug/L)</b>	ND	1,400	1,900	450
<b>trans-DCE</b>	<b>(ug/L)</b>	ND	10	20	ND
<b>VC</b>	<b>(ug/L)</b>	ND	10	80	70
<b>ethene</b>	<b>(ug/L)</b>	ND	ND	10	100
<b>methane</b>	<b>(ug/L)</b>	30	50	310	3,000
<b>ORP</b>	<b>(mV)</b>	--	-78	-127	-100
<b>Dhc</b>	<b>(orgs./L)</b>	ND	2 x 10 <sup>4</sup> /L	1 x 10 <sup>7</sup> /L	3 x 10 <sup>8</sup> /L
<b>% Dhc</b>	<b>(%)</b>	--	0.002	0.7	45
<b>IP-55</b>		<b>4/23/06</b>	<b>5/23/06</b>	<b>6/20/06</b>	<b>8/16/06</b>
<b>PCE</b>	<b>(ug/L)</b>	ND	ND	ND	ND
<b>TCE</b>	<b>(ug/L)</b>	3,100	ND	ND	ND
<b>cis-DCE</b>	<b>(ug/L)</b>	340	4,200	2,400	40
<b>trans-DCE</b>	<b>(ug/L)</b>	ND	30	20	ND
<b>VC</b>	<b>(ug/L)</b>	ND	50	530	40
<b>ethene</b>	<b>(ug/L)</b>	ND	ND	440	600
<b>methane</b>	<b>(ug/L)</b>	30	140	1,900	3,900
<b>ORP</b>	<b>(mV)</b>	--	-110	-140	-110
<b>Dhc</b>	<b>(orgs./L)</b>	ND	5 x 10 <sup>4</sup> /L	7 x 10 <sup>8</sup> /L	--
<b>% Dhc</b>	<b>(%)</b>	--	0.01	15	--
<b>MW-18</b>		<b>2/14/06</b>	<b>5/22/06</b>	<b>8/16/06</b>	
<b>PCE</b>	<b>(ug/L)</b>	4.0	4.3	4.2	
<b>TCE</b>	<b>(ug/L)</b>	2,570	2,840	2,220	
<b>cis-DCE</b>	<b>(ug/L)</b>	1,250	985	1,120	
<b>VC</b>	<b>(ug/L)</b>	ND	ND	117	
<b>ethene</b>	<b>(ug/L)</b>	ND	ND	478	
<b>ORP</b>	<b>(mV)</b>	94	10	58	

eliminated in this area, and there has been a 99.96% reduction in mass of cis-DCE and VC at IP-55. IP-55 is a biased location that served as both a donor injection and inoculation point. MW-18 is approximately 150' down-gradient of the biobarrier and shows stable concentrations of TCE and cis-DCE and increasing concentrations of VC and ethene. Given the groundwater velocity in this area, we do not expect to observe significant geochemical changes at MW-18 from the full-scale operation. However, MW-18 is somewhat downgradient of the pilot test and the fluctuations of VOC concentrations may represent effects from the pilot test.

Prior to donor application in the central circulation cell, *Dehalococcoides* was not observed in points outside the influence of the pilot test, IP-50 and IP-55. Concentrations regarding *Dehalococcoides* are expressed in terms of organisms per liter. One month following donor application, *Dehalococcoides* were observed at concentrations of 2 × 10<sup>4</sup>/L and 5 × 10<sup>4</sup>/L, respectively. An increase three to four orders of magnitude in *Dehalococcoides* was observed two months following donor application and prior to bioaugmentation, with concentrations of 1 × 10<sup>7</sup>/L and 7 × 10<sup>8</sup>/L, respectively.

**Table 3. South Circulation Cell Data**

<b>IP-43</b>		<b>4/19/06</b>	<b>5/23/06</b>	<b>6/20/06</b>	<b>8/16/06</b>
PCE	(ug/L)	ND	ND	ND	ND
TCE	(ug/L)	1,800	370	ND	ND
cis-DCE	(ug/L)	ND	20	4,200	670
trans-DCE	(ug/L)	ND	20	30	ND
VC	(ug/L)	ND	ND	40	200
ethene	(ug/L)	30	30	40	320
methane	(ug/L)	ND	30	ND	1,600
ORP	(mV)	-26	-63	-120	6.9
Dhc	(orgs./L)	ND	ND	6 x 10 <sup>3</sup> /L	1 x 10 <sup>9</sup> /L
% Dhc	(%)	--	--	0.0002	51
<b>IP-19</b>		<b>4/8/06</b>	<b>5/23/06</b>	<b>6/20/06</b>	<b>8/16/06</b>
PCE	(ug/L)	ND	ND	ND	ND
TCE	(ug/L)	3,100	ND	ND	ND
cis-DCE	(ug/L)	480	5,100	7,000	1,400
trans-DCE	(ug/L)	ND	30	60	20
VC	(ug/L)	ND	40	50	490
ethene	(ug/L)	10	ND	ND	350
methane	(ug/L)	60	30	350	350
ORP	(mV)	-66	-95	-123	0
Dhc	(orgs./L)	ND	ND	ND	1 x 10 <sup>9</sup> /L
% Dhc	(%)	--	--	--	48
<b>MW-16S</b>		<b>2/15/06</b>	<b>5/24/06</b>	<b>8/16/06</b>	
PCE	(ug/L)	7.4	ND	ND	
TCE	(ug/L)	5,160	10	ND	
cis-DCE	(ug/L)	329	5,790	1,700	
VC	(ug/L)	1.4	33	20	
ethene	(ug/L)	ND	ND	20	
ORP	(mV)	73	-91	-120	
Dhc	(orgs./L)	--	--	4 x 10 <sup>7</sup> /L	
% Dhc	(%)	--	--	11	
<b>MW-16D</b>		<b>2/15/06</b>	<b>5/24/06</b>	<b>8/16/06</b>	
PCE	(ug/L)	6.4	5.6	5.6	
TCE	(ug/L)	6,500	5,350	4,930	
cis-DCE	(ug/L)	820	334	374	
VC	(ug/L)	3.3	0.5	ND	
ethene	(ug/L)	ND	ND	--	
ORP	(mV)	74	-66	30	
<b>MW-19</b>		<b>2/14/06</b>	<b>5/24/06</b>	<b>8/16/06</b>	
PCE	(ug/L)	ND	ND	ND	
TCE	(ug/L)	32	12.8	5.81	
cis-DCE	(ug/L)	1.9	0.7	35.2	
VC	(ug/L)	ND	ND	ND	
ethene	(ug/L)	ND	ND	--	
ORP	(mV)	82	-14	14	

**South Circulation Cell.**

Table 3 summarized the key parameters in this area. Very favorable redox conditions exist in this area. TCE is not detected in any of the monitoring points and significant ethene has been observed. MW-16D is up-gradient of the biobarrier and is likely representative of groundwater that is entering the biobarrier in this area. MW-16S is 5 feet down-gradient of the injection points and is effectively 30 feet into the biobarrier. Comparing the concentrations observed in MW-16D with the concentrations observed in MW-16S suggests a reduction in mass of TCE, DCE and VC of 42%. We believe that this data may be representative of the biobarrier as a whole.

**CONCLUSIONS**

The use of direct push techniques to install and extract injection points was very effective and efficient. By completing the donor applications concurrently with injection point installation, significant labor costs were saved. The 1-inch points were more than adequate for the required volume of water injected into each point. Installation of a passive biobarrier using 1-inch point will not work at all sites, but the highly transmissive formation at this Site made this design and cost savings possible.

A very important preliminary result has already been observed at this biobarrier. The extraction and re-injection within the central circulation cell successfully demonstrated that viable dechlorinating bacteria from a biologically active area can be transferred through a temporary closed extraction/injection system to successfully create a biobarrier. By using a phased approach, an initial seed cell could be created. Once that cell had a sustained population, the biobarrier could be expanded several hundred feet in any direction. Results from this Site indicate that the *Dehalococcoides* in the immediate area of the injection points reached an adequate population ( $10^8$  organisms per L) in approximately two months. With this approach, it may take on the order of six months to a year to establish a biobarrier comparable in size to this Site.

The biobarrier continues to display favorable redox conditions suggesting that donor is still present in the biobarrier. Reductions in the total VOC mass between 99% and 42% have been observed across the biobarrier. It is important to keep in mind that this biobarrier is very young, only four months post-donor application and two months post-bioaugmentation. Additional monitoring data will be collected to determine the long term success of this remediation approach.

## REFERENCES

- (1) Gray, H.H. *Physiographic Divisions of Indiana, Indiana Geological Survey Special Report 61*. **2000**. Plate I.
- (2) Lendvay, J.M.; Barcelona, M.J.; Daniels, G.; Dollhopf, M.; Fathepure, B.Z.; Gebhard, M.; Heine, R.; Hickey, R.; Krajmalnik-Brown, R.; Löffler, F.E.; Major, Jr., C.L.; Petrovskis, E.; Shi, J.; Tiedje, J.M. and Adriaens, P. *Environ. Sci. Technol.* **2003**. 37, 1422-1431.
- (3) DeWeerd, K. A.; Concannon, F. and Suflita, J. M. *Appl. Environ. Microbio.* **1991**. 57, 1929–1934.
- (4) Holliger, C., D. Hahn; Harmsen, H.; Ludwig, W.; Schumacker, W.; Tindall, B.; Vazquez, F.; Weiss, N. and Zehnder, A.J. *Arch. Microbiol.* **1998**. 169, 4, 313-321.
- (5) Maymo-Gatell, X.; Chien, Y., Gossett, J.M. and Zinder, S.H. *Science*. **1997**. 276, 1568-1571.

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