

Direct-Push Injection and Circulation Biobarrier to Remediate a TCE Groundwater Plume

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ABSTRACT: The goal of this study was to determine if direct-push drilling methods combined with a circulation system could be used to establish a passive biobarrier in a very transmissive aquifer to treat trichloroethene (TCE). The Site is located in central Indiana, where historic use of TCE has impacted an unconfined aquifer. A plume consisting primarily of TCE has migrated from west to east across the Site toward a regionally significant river. The plume is approximately 1,100 feet wide, 6,300 feet long, and up to 50 feet deep. The horizontal groundwater flow velocity is estimated to be 2.0 to 5.0 feet/day. Site geochemical and volatile organic compound (VOC) data did not indicate the natural attenuation of TCE. A bench test indicated that bioaugmentation could be successfully applied at the site. Direct push injection of emulsified vegetable oil with 5% lactate was applied at 14 drive points in the upgradient portion of a circulation cell. Very positive results were observed within weeks suggesting that the combination of direct injection and circulation accelerated the establishment of the biobarrier. Halorespiring bacteria have been quantified in the circulation area using Real-Time Polymerase Chain Reaction (PCR) techniques. Recent VOC, geochemical and microbial data indicate that the biobarrier continues to persist in the circulation zone more than six months since system shut-down. Based on these results the Indiana DEM approved the work plan for full-scale implementation of biobarriers at the Site.

INTRODUCTION

Site Description. The Site is located in the New Castle Till Plains and Drainage Ways physiographic region of Indiana (Gray, 2000). 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, 6,300 feet long, and up to 50 feet deep.

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 ft/day. Non-pumping and pumping groundwater flow velocities in the circulation area were approximately 2 and 5 feet per day, respectively.

Bench Testing. Soil samples were collected from the targeted test circulation cell area for genetic tests and microcosm studies. The genetic tests and microcosm studies

demonstrated 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 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.

Pilot Test - Phase I Summary. The test circulation area was located in the center of the plume where the highest concentration of TCE (4,500 µg/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 a 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 roughly 23 feet, indicating an aquifer thickness of 24 feet.

Sodium lactate was used initially to condition the aquifer but constant biofouling of the injection wells limited the delivery of lactate. Between January 28 and November 5, 2004, approximately 200 kg of lactate was added to the aquifer via the injections wells. During this time, approximately 3.05 million gallons of groundwater were circulated through the system. Lactate addition converted most TCE to cis-DCE and created the following changes in the geochemistry in several monitoring wells located within the circulation area: oxygen was reduced from a range of 0.5 to 2.2 mg/L to 0.0 mg/L, nitrate was reduced from a range of 3.3 to 17.6 mg/L to a range of 1.5 to 3.5 mg/L, dissolved iron increased from 0.0 to a range of 0.0 to 0.3 mg/L, sulfate remained unchanged at a range of 49 to 63 mg/L and ORP was reduced from a range of +33 to +87 to a range of -50 to +50 mV. Bioaugmentation was attempted during this period but was unsuccessful due to inadequate aquifer conditioning.

Pilot Test - Phase II Objectives. The primary purpose of the circulation cell was to create an anaerobic zone where a pilot-test-scale biobarrier could be established. Once the anaerobic zone was established, bioaugmentation would be performed. The resulting biobarrier would convert TCE to ethene through reductive dechlorination, as demonstrated at many sites across the nation (Parsons, 2004). The purpose of this phase of the study was to determine if a one time direct injection of emulsified oil with 5% lactate followed by a period of circulation would help avoid problems with biofouling, facilitate a successful bioaugmentation and successfully establish a persistent pilot-test-scale biobarrier.

MATERIALS AND METHODS

The size of the circulation system was established based on three dimensional numerical groundwater modeling results, dechlorination rates observed during the completion of the Bachman Road project (Lendvay et al., 2003) and design considerations for a full-scale application. The circulation system included one extraction well, three injection wells and six monitoring wells as presented in Figure 1. The extraction well had 30 feet of screen set across the entire saturated thickness and the

three injection wells had 10 feet of screen set in the following intervals: 22 to 32 feet bsg (A), 31 to 41 feet bsg (B), and 40 to 50 feet bsg (C). Each injection well and monitoring well has been labeled with a corresponding depth interval. Generalized daily particle tracking results from the numerical model for the B interval at 20 gpm is included on Figure 1 for reference. Monitoring well PMW-10B was installed outside the expected circulation area to serve as a control point. MW-9D was installed below the lower clay unit as part of the compliance monitoring program and was not sampled as part of the pilot test.

Geochemical data collected during the initial pilot test (lactate conditioning) indicated that the A interval was the least reduced. As part of Phase II of the pilot test direct push injection of emulsified vegetable oil with 5% lactate was applied at 10 drive points screened in the A interval, 2 drive points in the B interval and 2 drive points in the C interval (Figure 1). A total of 122 kg of emulsified vegetable oil with 5% lactate was mixed with system water at a 5:1 ratio using a mixer/dispenser and added to each drive point. The

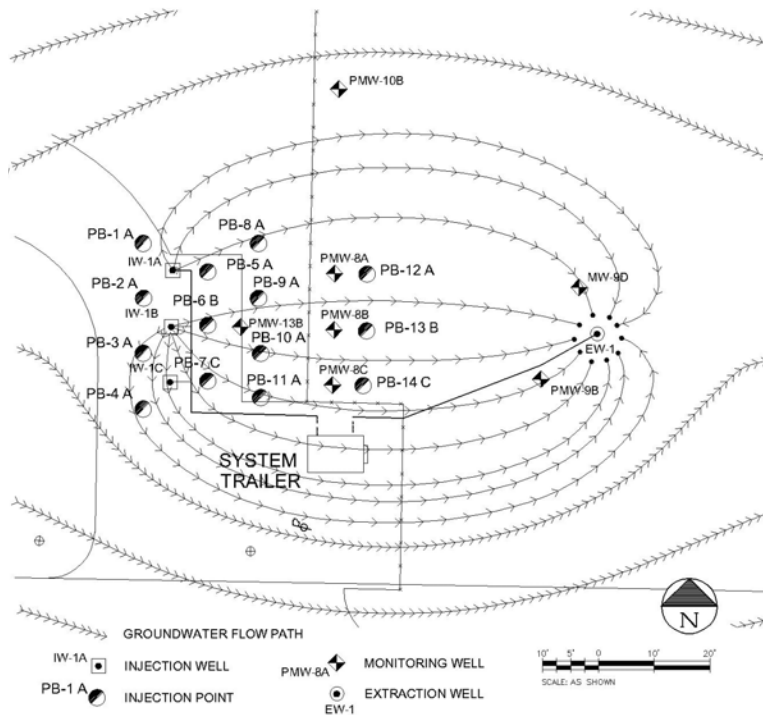


FIGURE 1. Study Area

The circulation system was used to distribute the donor through out the test plot at 15 gallons per minute. Six days after donor addition, donor was visibly observed in groundwater samples collected from the injection wells. The donor seemed to affect the injection wells' ability to recirculate water. As a result, the circulation system was reduced to approximately 8 gallons per minute.

Approximately 10 days after direct injection of donor, the ORP dropped to -200 mV at PMW-13B. At that time, the site was inoculated with 20 liters of halo-respiring bacterial culture via PMW-13B, bypassing the injection wells. The supplier's inoculation protocols were strictly followed. The circulation system continued to operate for 4.5 months distributing the donor and bacterial culture through out the circulation area.

Upon inoculation, system performance groundwater sampling was completed at time intervals of three weeks, 2 months, 5 months and one year. Select monitoring wells were sampled and analyzed for selected parameters from the following list of analytes: VOCs, dissolved hydrocarbon gases, TOC, volatile fatty acids, ORP, oxygen, nitrate, dissolved iron, sulfate and genetic tests. Standard EPA laboratory analytical methods were used for

all parameters except, dissolved oxygen, nitrate and dissolved iron which were analyzed in the field by colorimetric methods.

RESULTS AND DISCUSSION

Key analytical results including perchloroethene (PCE), TCE, cis-DCE and trans-1,2-DCE, vinyl chloride (VC), ethene, methane and genetic testing from the performance groundwater monitoring are presented in Table 1. Geochemical results from laboratory and field analysis including pH, specific conductivity, ORP, oxygen, nitrate, dissolved iron, sulfate and total organic carbon (TOC) are included in Table 2. No significant changes in the water chemistry were observed at PMW-10B, confirming that it was out of the influence of the circulation cell and serves as a useful control point. All wells located in the circulation cell exhibit convincing evidence that dechlorination of TCE has occurred. PMW-8A in the upper 10 feet of the barrier, where most of the donor was applied, exhibits complete dechlorination with no detections of TCE, DCE isomers or VC after one year (Figure 2). The other monitoring wells set in the B and C intervals exhibit significant reductions in the concentration TCE and DCE isomers, and VC, but complete dechlorination has not been observed.

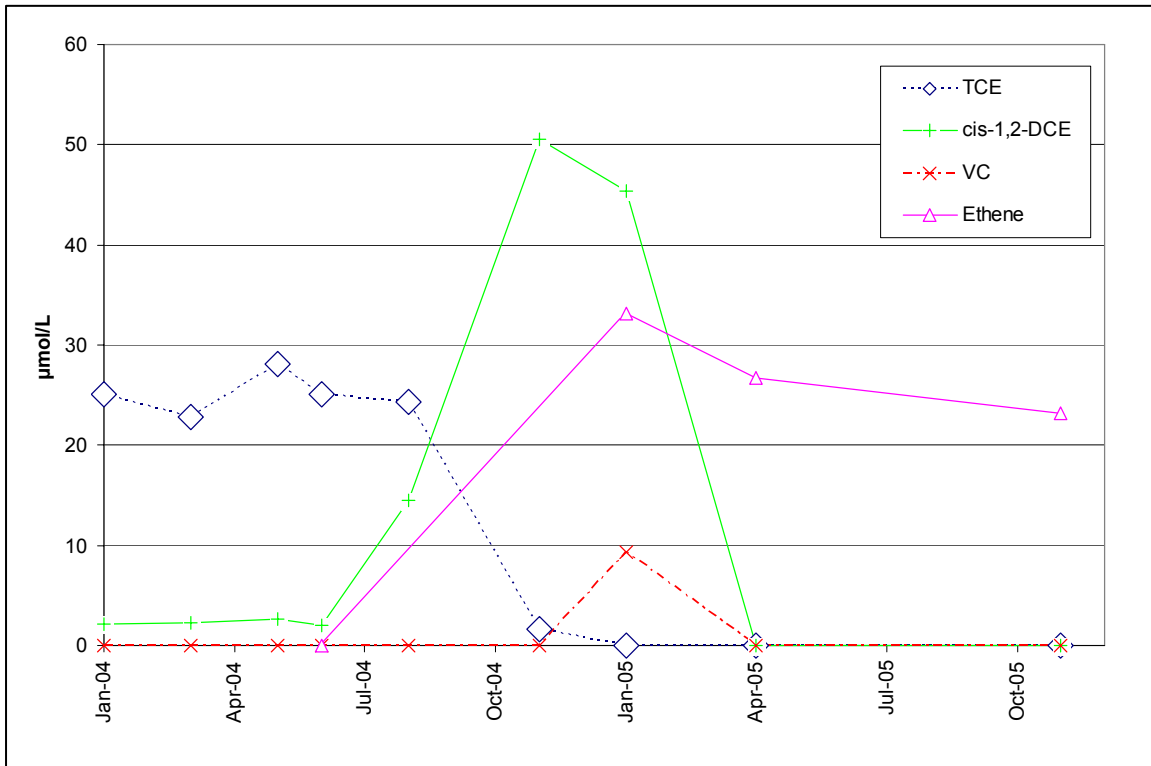


FIGURE 2. PMW-8A VOCs over Time

One unexpected result was the concentration of TCE at PMW-8B that increased from 275 µg/L in January 2005 to 1,200 µg/L in November 2005. An increase in the TCE concentration was also observed at EW-1, which is screened over all three intervals. PMW-13B and IW-1B are located up-gradient of PMW-8B and EW-1 and the November 2005 TCE concentrations from these two wells were non-detect and 2 µg/L, respectively. One possible explanation for the increase at PMW-8B may be the difference in the

groundwater flow direction under pumping and non-pumping conditions. The extraction well has been shut down for over 8 months, TCE impacted groundwater may be migrating in from the sides of the test plot.

The geochemical results are generally consistent with the VOC results described above. More than one year after donor addition, all monitoring wells located in the circulation area including EW-1 exhibit ORP values less than -97 millivolts. Dissolved oxygen concentrations continue to remain below the detection limit, nitrate concentrations are between 0.0 to 0.6 mg/L, dissolved iron concentrations are between 0.3 to 12 mg/L (over equipment range at PMW-8A), and sulfate concentrations are between 0.0 and 60 mg/L. PMW-8B exhibited the highest sulfate concentration, consistent with the highest TCE concentration. These results indicate that most of the donor injected in the A interval was adsorbed by A interval soils. Thus, less donor was available for re-circulation to the deeper intervals. Overall, geochemical data indicates that the A interval is the most reduced (Figure 3) and the B interval is the least reduced but all intervals should support anaerobic bacteria.

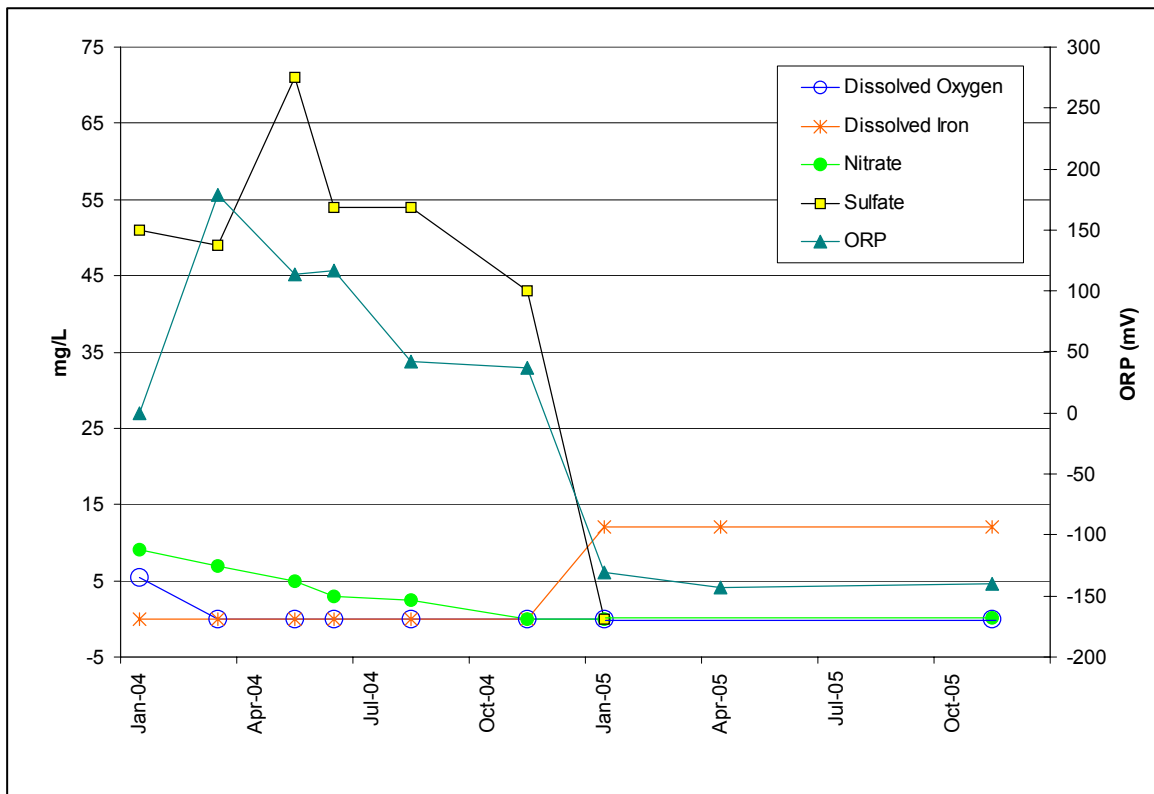


FIGURE 3. PMW-8A Inorganics over Time.

TABLE 1. VOC and Genetic Testing Results

Parameters	Well	PMW-8A			PMW-8B			PMW-8C		
	Date	11/04	01/05	11/05	11/04	01/05	11/05	11/04	01/05	11/05
PCE	µg/l	ND	ND	ND	ND	ND	ND	ND	ND	ND
TCE	µg/l	220	ND	ND	860	275	1,200	650	270	220
cis-1,2-DCE	µg/l	4,900	4400	ND	4,900	4350	210	4,900	5600	230
trans-1,2-DCE	µg/l	42	ND	ND	45	55	ND	48	ND	10
Vinyl Chloride	µg/l	ND	580	ND	ND	65	40	ND	150	70
Ethene	µg/l	na	930	649	na	49	49	na	11	194
Methane	µg/l	na	1300	15400	na	22	642	na	0.68	420
% <i>Dehalococcoides</i>	% <i>Dhc</i>	na	na	7-20%	na	0.06%	5-13%	na	na	2-7%
<i>Dehalococcoides</i>	<i>Dhc</i> /l	na	na	9 X 10 ⁷	na	5.40 X 10 ⁴	1 X 10 ⁶	na	na	3 X 10 ⁶

Parameters	Well	PMW-10B			PMW-13B		EW-1			IW-1B
	Date	11/04	01/05	11/05	01/05	11/05	11/04	01/05	11/05	11/05
PCE	µg/l	ND	ND	1.9	ND	ND	ND	ND	ND	ND
TCE	µg/l	2,100	2,000	2,140	ND	ND	3,100	220	750	2
cis-1,2-DCE	µg/l	110	120	52.2	2400	90	3,000	6200	880	264
trans-1,2-DCE	µg/l	ND	ND	0.68	35	ND	ND	ND	ND	12.7
Vinyl Chloride	µg/l	ND	ND	ND	640	80	ND	69	70	323
Ethene	µg/l	na	na	na	570	640	na	16	137	349
Methane	µg/l	na	na	na	1	3300	na	0.74	514	13800
% <i>Dehalococcoides</i>	% <i>Dhc</i>	na	na	na	23%	7-20%	na	na	14-37%	na
<i>Dehalococcoides</i>	<i>Dhc</i> /l	na	na	na	1.11x 10 ⁷	7 X 10 ⁷	na	na	3 X 10 ⁷	na

Notes:
 ND - not detected above the laboratory reporting limit
 na - not analyzed

TABLE 2. Inorganics Results

Parameters	Well	PMW-8A			PMW-8B			PMW-8C		
	Date	11/04	01/05	11/05	11/04	01/05	11/05	11/04	01/05	11/05
pH	S.U.	7.4	7.0	6.9	7.4	7.3	7.0	7.4	7.3	7.2
Specific Conductance	µS/cm	1,361	1,560	1,490	1,352	1,516	1,790	1,362	1,310	1,480
ORP	mV	37	-131	-150	-30	-74	-97	-67	-127	-147
Dissolved Oxygen	mg/l	ND	ND	ND	ND	ND	ND	ND	ND	ND
Nitrate as NO ³	mg/l	ND	ND	0.1	ND	ND	0.3	ND	ND	0.7
Sulfate	mg/l	43	ND	na	45	2.0	52	47	1.4	na
Dissolved Iron	mg/l	ND	12	12.6	ND	0.3	0.2	0.3	2.6	3.2
TOC	mg/l	na	na	na	na	2.5	2.2	na	na	na

Parameters	Well	PMW-10B			PMW-13B		EW-1			IW-1B
	Date	11/04	01/05	11/05	1/05	11/05	11/04	01/05	11/05	11/05
pH	S.U.	7.4	7.1	7.0	7.3	7.2	7.3	7.2	7.1	6.7
Specific Conductance	µS/cm	1,676	1,779	2,090	1,556	1,289	1,371	1,513	1,420	1,394
ORP	mV	15	5.3	41	-159	-145	72	-151	-105	-150
Dissolved Oxygen	mg/l	ND	ND	ND	ND	ND	ND	ND	ND	ND
Nitrate as NO ³	mg/l	5.9	17.6	1.0	ND	0.1	1.3	ND	0.2	ND
Sulfate	mg/l	na	63	na	0.33	na	50	18	47	na
Dissolved Iron	mg/l	ND	ND	ND	3.7	1.8	ND	1.5	1.3	1.0
TOC	mg/l	na	na	na	na	na	na	4.4	1.9	na

Notes:
 ND - not detected above the detection limit
 na - not analyzed

Genetic testing confirms that *dehalococcoides*, the primary halo-respiring bacteria in the inoculum, are present in every well tested within the circulation area. The highest bacterial counts are present in PMW-8A, the interval where most of the electron donor was applied. The second highest bacterial counts were in PMW-13B, which was the

inoculation point, and the lowest bacterial counts were present at PMW-8B. The circulation system was very successful at distributing the inoculum from PMW-13B throughout the entire test cell creating the biobarrier.

CONCLUSIONS

The VOC, genetic testing and geochemical results from this study suggest 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 this study. The A interval, which has the highest bacterial population, exhibits the most reduced geochemistry and, as a result, VOCs are no longer detected. The results indicate that most of the donor injected in the A interval sorbed to the A interval soils. The existing circulation system was very successful at distributing the inoculum through out the entire biobarrier. PMW-10 was not affected by the test and provided adequate control during the study. The direct injection of emulsified vegetable oil with 5% lactate provided superior results when compared to lactate-only additions previously conducted at the site. Additional donor will be required in the B and C intervals to sustain the halorespiring bacteria and continue the dechlorination mechanism to completely dechlorinate TCE in those intervals.

Based on the results of this study the Indiana Department of Environmental Management approved a full-scale application of this technology for the site. Biobarriers will be constructed at the site to create treatment zones at key locations along the axis of the plume. At this time a full-scale biobarrier is under construction in the vicinity of the existing circulation cell. The barrier will be located along the down gradient property boundary and will be approximately 1200 feet long. The biobarrier will be constructed from 139 direct push temporary injection points, 62 permanent injection points and three extraction wells. The donor and bacterial culture described in this paper will be used in the full-scale application.

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