Full-Scale Bioaugmentation to create a Passive Biobarrier to Remediate a TCE Groundwater Plume

Michael S. Kovacich (mkovacich@geotransinc.com), David Beck, Tammy Rabideau, Erin Pettypiece, and Kevin Smith (GeoTrans, Inc., Ann Arbor, Michigan)
Michael Noel (GeoTrans, Inc., Brookfield, Wisconsin)
Michael J. Zack and Michael T. Cannaert
(Visteon Corporation, Van Buren Twp., Michigan)

ABSTRACT: The goal of this paper is to assess the interim results of a full-scale bioaugmentation biobarrier. The biobarrier is designed to treat a trichloroethene (TCE) plume along the downgradient property boundary of an industrial facility. The biobarrier is 381 meters long perpendicular to the groundwater flow direction. The aquifer was conditioned with 27,215 kilograms (kg) of an emulsified vegetable oil (EVO) electron donor using direct-push techniques. Three groundwater extraction wells were used to supply make-up water to three different portions of the biobarrier. The make-up water was used to prepare a 20% EVO solution, which was delivered to the subsurface. The central extraction well was located in an area where a viable bacterial population persisted from an earlier bioaugmentation pilot test. The EVO donor solution prepared from this water successfully "pre-seeded" the central portion of the biobarrier. Two months following donor addition, 330 liters (L) of dechlorinating bacterial culture (KB-1) was applied to the entire length of the biobarrier including the pre-seeded area. Subsequently, ten months of very positive dechlorination trends have been observed at every inoculation point and local down-gradient monitoring wells and complete dechlorination has been observed in one down-gradient well.

INTRODUCTION

Enhanced in-situ anaerobic groundwater treatment technologies offer advantages over other remedial methods due to complete mineralization of contaminants in situ and relatively lower costs (Parsons, 2004). This Site has a relatively large TCE plume emanating from multiple potential source locations throughout a 148,644 square meter manufacturing plant. A passive biobarrier was selected to create a treatment zone along the down-gradient property boundary that would eliminate future offsite migration. The goal of this paper is to assess the results of this full-scale bioaugmentation implementation and to track the overall success of this passive biobarrier.

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 this 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 gravels 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 9 meters near the western margin of the channel to greater than 37 meters 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 336 meters wide, 2170 meters long and the impact depth in the area of the biobarrier is 15 meters (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

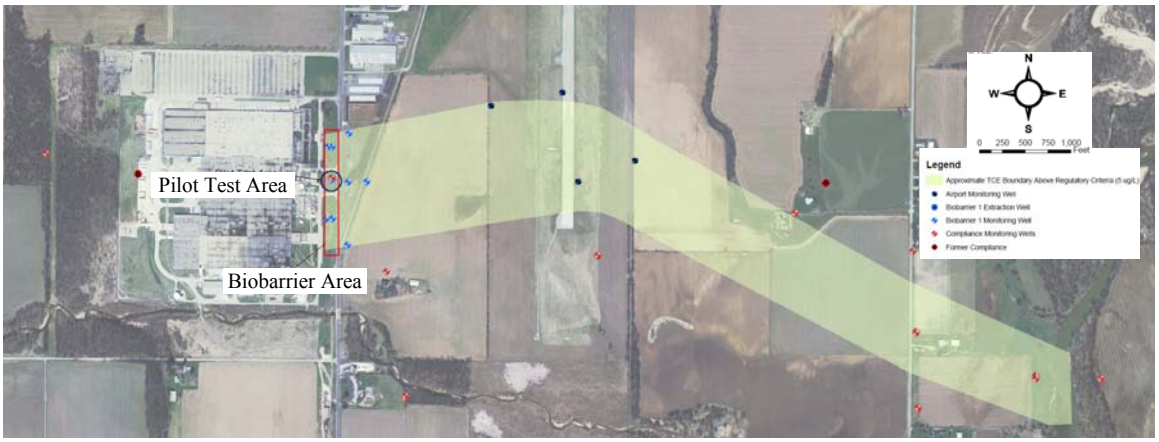

Figure 1. Site Layout

be 0.074 cm/sec. The groundwater flow velocity in the area of the biobarrier is approximately 0.61 meters per day.

Bench and Pilot Testing. Genetic testing and microcosm studies were conducted during the design stage to determine if dechlorinating bacteria were present at the Site and whether biostimulation would be adequate to achieve complete dechlorination, or if bioaugmentation would be necessary. Results indicated that dechlorinating bacteria may be present in Site soil, but at very low concentrations and were not detected in Site groundwater. Biostimulation of Site soils in mirocosms 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 performed to determine if the bench test results could be replicated at the site. The pilot test design was based on experience at the Bachman Road Site (Lendvay, 2003) but with a significantly larger test plot to address potential scaling issues due to the planned application at the Site. The pilot 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 12 meters by 30 meters with the longer dimension parallel to groundwater flow. Approximately 200 kg 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 were changed.

An EVO donor product was introduced to the circulation cell via temporary direct-push points to condition the aquifer prior to bioaugmentation. The circulation system continued to operate at approximately 8 gpm and about 1,700 kg 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 throughout 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) was observed after one year. The deeper monitoring wells exhibited significant reductions in the concentration of TCE and DCE isomers, and VC, but complete dechlorination was not observed. Genetic testing confirmed that *Dehalococcoides (Dhc)*, the primary halorespiring 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 (Kovacich, 2006). Based on the results of this study the Indiana Department of Environmental Management approved the full-scale application of this technology for the Site.

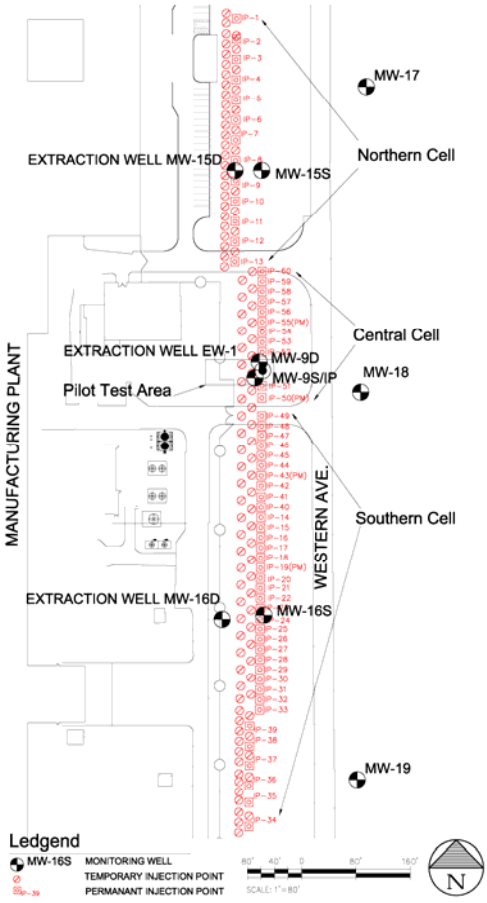

Figure 2. Biobarrier Layout

MATERIALS AND METHODS

The biobarrier was divided into three areas, referred to as the northern cell, the central cell and the southern cell. Three separate extraction wells (EW-1, MW-15d and MW-16d) provided the source water for donor delivery in each cell. Two layouts were used to determine the number of injection points and spacing. The layouts are referred to as the "plume margins" and the "plume heart". The plume margin layout consists of the northern 122 meters and southern 61 meters of the biobarrier, and the heart layout was the central 198 meters, for a total length of 381 meters (Figure 2). All of northern cell was installed using the plume margin layout, the central cell was installed using plume heart layout and the southern cell was installed using a combination of both layouts.

Plume Margin Layout. The plume margin layout consisted of two rows of injection points. The up-gradient row included temporary injection points, spaced 4.6 meters apart. The second row included alternating temporary and permanent injection points, spaced 14.6 meters apart. A second row was installed 4.6 meters down gradient but was offset 2.3 meters. All injection points within the plume margin layout were screened over the entire saturated thickness (approximately 7.6 to 13.7 meters bgs). This layout was installed in the margins of the plume where TCE concentrations were generally less than 1,000 µg/L.

Plume Heart Layout The heart of the biobarrier consisted of three rows of injection points. The most up-gradient row consisted of temporary points spaced 7.6 meters apart and screened over the entire saturated thickness. The middle row was installed 7.6 meters down gradient and offset 3.8 meters. The points were temporary and only screened from approximately 10 to 14 meters bgs. The down-gradient row consisted of permanent points, spaced 7.6 meters 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 and Donor Delivery System. 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. Approximately 131 kg (144 L) of EOS® at a 20% solution was applied to points with 7.6-meter spacings. Approximately 215 kg (235 L) of EOS® at a 20% solution was applied to points with 7.6-foot spacings. In total, approximately 27,215 kg of EOS® was applied to the biobarrier to condition the aquifer. Immediately following donor addition at each injection 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. The approximate volume of fresh water used for the 7.6- and 3.8-meter spacings, was 7,570 L and 18,168 L per injection point, respectively.

Temporary points consisted of 1-inch stainless steel with 0.020-inch slot, wire-wrapped screens. A total of 108 temporary points were used for donor delivery. Permanent points consisted of 1-inch PVC with 0.020-inch mill slot screens with flush grade covers. The permanent points provided locations for inoculation and additional donor when needed. A total of 60 permanent points were installed in the biobarrier. All injection points were installed with direct-push methods and the donor was injected with a Dosatron® DI520 Water Powered Metering System with water supplied from the corresponding extraction well (Beck, 2006).

Bioaugmentation. Results of the pilot test indicated that relatively high bacterial populations [14-37% *Dhc* with $3x10^{-7}$ organisms per liter (org./L)] were present in the former pilot test area near EW-1 (Kovacich, 2006). Prior to donor injection, genetic testing was completed on water samples collected from four points (IP-19, IP-43, IP-50 and IP-55) to confirm that dechlorinating bacteria were not present in central cell just beyond the former pilot test area or in the southern cell. The genetic testing indicated that bacteria were not present at the method detection limit. Two bioaugmentation injection events were conducted once the aquifer was properly conditioned by donor addition.

For the first injection event, approximately 295,230 L of groundwater from the former pilot test area were withdrawn by EW-1, mixed with donor and placed into the 25 permanent and temporary injection points located in the central cell. Genetic testing at IP-50 and IP-55 was completed one month and two months following placement to determine whether it was possible to inoculate or seed an area by extracting water from another area known to contain a healthy and viable microbial population.

For the second injection event, 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. Genetic testing at IP-19, IP-43, IP-50 and MW-16S was completed two months following inoculation and then at down-gradient wells, MW-15S and MW-16S after 8 months.

Biobarrier Performance Monitoring. In addition to genetic testing, nine monitoring wells located in the vicinity of the biobarrier were sampled over a 10-month period following donor addition. Each well was monitored regularly for dissolved oxygen, dissolved iron, nitrate, ORP and volatile organic compounds and intermittently for methane, ethane, ethene, volatile fatty acids and total organic carbon.

RESULTS

The aquifer was adequately conditioned within two months of donor delivery. ORP measurements in all 60 permanent injection points were less than –120 mV and a significant reduction of nitrate and sulfate was observed. Additionally, TCE was completely converted to cis-DCE in the injection points tested. Ten months of analytical results from select wells from each cell are discussed in the following sections.

North Circulation Cell. Table 1 summarizes the key parameters from MW-15S and MW-17 in this area. MW-15S is located approximately 13.7 meters down gradient of the nearest injection/inoculation point. Favorable redox conditions persist within this portion of the biobarrier. There was an increase in total mass of VOCs 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 but, ethene was not been detected. Five months after bioaugmentation, PCE and TCE were no longer detected, cis-DCE and VC were significantly reduced, and ethene was detected. Ten months following bioaugmentation, complete dechlorination was observed at MW-15S. MW-17 is located approximately 61 meters down gradient of the biobarrier. After 5 months, ORP dropped and methane and cis-DCE were detected. After 10 months, TCE has remained unchanged, but ORP continues to drop and VC and ethene were detected.

Table 1. North Circulation Cell Data.

MW-15S		2/15/06	5/22/06	8/16/06	11/8/06	2/5/07
PCE	(ug/L)	8.4	4.2	1.8	ND	ND
TCE	(ug/L)	545	64	9.0	ND	ND
cis-DCE	(ug/L)	3.2	974	330	8	ND
VC	(ug/L)	ND	4.4	41.3	6	ND
ethene	(ug/L)	ND	ND	ND	77	54
methane	(ug/L)	ND	--	1,780	10,000	6,870
ORP	(mV)	94	-33	-117	-140	-101
MW-17		2/15/06	5/22/06	8/16/06	11/8/06	2/5/07
PCE	(ug/L)	ND	ND	ND	ND	ND
TCE	(ug/L)	58	47	50	49	47
cis-DCE	(ug/L)	ND	ND	ND	28	33
VC	(ug/L)	ND	ND	ND	ND	0.7
ethene	(ug/L)	ND	ND	--	ND	15
methane	(ug/L)	ND	ND	--	4,440	7,070
ORP	(mV)	95	10	19	-10	-43

Central Circulation Cell. Table 2 summarizes the key parameters from IP-50, IP-55 and MW-18 in this area. IP-50 and IP-55 were injection points used to apply the donor and inoculate the biobarrier. Favorable redox conditions persist within at these points. TCE and cis-DCE have been significantly reduced and VC and ethene are still being produced but at lower concentrations. Recently, there has been TCE rebound that correlates to elevated methane and lower ethene concentrations. MW-18 is located 40 meters feet down gradient of the biobarrier. Analytical results from this well indicate that breakdown products from the biobarrier have reached the well but dechlorination may not be occurring at this location. Recently, the ORP has drop below zero for the first time and suggests conditions that are favorable for dechlorination may exist in the future.

Table 2. Central Circulation Cell Data.

IP-50		4/23/06	5/23/06	6/20/06	8/16/06	11/8/06	2/5/07
PCE	(ug/L)	ND	ND	ND	ND	0.8	0.7
TCE	(ug/L)	1,200	ND	ND	ND	208	208
cis-DCE	(ug/L)	ND	1,400	1,900	450	334	246
VC	(ug/L)	ND	10	80	70	29	32
ethene	(ug/L)	ND	ND	10	100	89	105
methane	(ug/L)	30	50	310	3,000	12,400	7,980
ORP	(mV)	--	-78	-127	-100	-102	-112
IP-55		4/23/06	5/23/06	6/20/06	8/16/06	11/8/06	2/5/07
PCE	(ug/L)	ND	ND	ND	ND	ND	ND
TCE	(ug/L)	3100	ND	ND	ND	2	195
cis-DCE	(ug/L)	340	4200	2400	40	108	204
VC	(ug/L)	ND	50	530	40	61	103
ethene	(ug/L)	ND	ND	440	600	282	235
methane	(µg/L)	30	140	1900	3900	11700	7640
ORP	(mV)	na	-110	-140	-110	-95	-122
MW-18		2/14/06	5/22/06	6/20/06	8/16/06	11/8/06	2/5/07
PCE	(ug/L)	4.0	4.3	--	4.2	3.9	3.3
TCE	(ug/L)	2,570	2,840	--	2,220	2,050	1,760
cis-DCE	(ug/L)	1,250	985	--	1,120	1,150	867
VC	(ug/L)	ND	ND	--	117	100	79
ethene	(ug/L)	ND	ND	--	478	339	260
methane	(µg/L)	ND	--	--	1,650	6,840	3,920
ORP	(mV)	94	10	--	58	37	-47

Southern Circulation Cell. Table 3 summarizes the key parameters from IP-19, IP-43, MW-16S and MW-19 in this area. IP-19 and IP-43 were injection points used to apply the donor and inoculate the biobarrier. MW-16 is approximately 1.5 meters down-gradient of the biobarrier and MW-19 is located approximately 44 meters down gradient of the biobarrier. Favorable redox conditions exist in every well in this area except MW-19. TCE is no longer present at IP-19 but has been observed at very low concentrations at the other wells in this cell. IP-19 exhibits nearly complete dechlorination. Cis-DCE, VC and ethene were detected at all of the wells in this area. Elevated methane (5 to 10 mg/L) was observed in

Table 3. Southern Circulation Cell Data.

IP-19		4/8/06	5/23/06	6/20/06	8/16/06	11/8/06	2/5/07
PCE	(ug/L)	ND	ND	ND	ND	ND	ND
TCE	(ug/L)	3,100	ND	ND	ND	ND	ND
cis-DCE	(ug/L)	480	5,100	7,000	1,400	492	2.8
trans-DCE	(ug/L)	ND	30	60	20	14	10
VC	(ug/L)	ND	40	50	490	263	137
ethene	(ug/L)	10	ND	ND	350	522	653
methane	(ug/L)	60	30	350	350	14,000	14,900
ORP	(mV)	-66	-95	-123	0	-114	-128

this area a may indicate that methanogens are consuming the EVO at the expense of the *Dhc* (Parsons, 2004).

Table 3. Southern Circulation Cell Data. (continued)

IP-43		4/19/06	5/23/06	6/20/06	8/16/06	11/8/06	2/5/07
PCE	(ug/L)	ND	ND	ND	ND	ND	ND
TCE	(ug/L)	1800	370	ND	ND	ND	26.8
cis-DCE	(ug/L)	ND	2800	4200	670	173	125
VC	(ug/L)	ND	20	40	200	104	35.1
ethene	(ug/L)	30	0	40	320	325	297
methane	(ug/L)	ND	30	ND	1600	9940	13500
ORP	(mV)	-26	-63	-120	-105	-124	-131
MW-16S		2/15/06	5/24/06	6/20/06	8/16/06	11/8/06	2/5/07
PCE	(ug/L)	7.4	ND	--	ND	ND	ND
TCE	(ug/L)	5,160	10	--	ND	1.8	ND
cis-DCE	(ug/L)	329	5,790	--	1,700	1,280	1,000
VC	(ug/L)	1.4	33	--	20	107	300
ethene	(ug/L)	ND	ND	--	478	339	260
methane	(ug/L)	ND	--	--	760	5,000	5,000
ORP	(mV)	73	-91	--	-120	-122	-147
MW-19		2/14/06	5/24/06	6/20/06	8/16/06	11/8/06	2/5/07
PCE	(ug/L)	ND	ND	--	ND	ND	ND
TCE	(ug/L)	32	13	--	5.8	2.3	3.9
cis-DCE	(ug/L)	1.9	0.7	--	35	17	15
VC	(ug/L)	ND	ND	--	ND	ND	ND
ethene	(ug/L)	ND	ND	--	--	16	15
methane	(ug/L)	ND	ND	--	--	2,520	4,350
ORP	(mV)	82	-14	--	14	16	35

Genetic Testing. SiREM performed all of the genetic testing for this phase of the study. A summary of the results are presented in Table 4. *Dhc* was not detected in any sample prior to donor addition. However, after one month *Dhc* was detected at very low levels in the central cell were water from the former pilot test was used to prepare the donor solution. Significant increases in the number of organisms and their percentage of the total bacterial population occurred after one month in the central cell. In addition, a very low detection of bacteria was observed at IP-43 in the southern cell. IP-43 is over 18 meters away from the nearest injection point where water from the former pilot test was used to prepare the donor. Very high bacterial populations (10^7 – 10^9 orgs./L) were observed two months after inoculation with 330L of KB-1™ in each of the inoculation points tested. Adequate bacterial populations (10^6 – 10^7 orgs./L) were observed eight month after inoculation in two down-gradient monitoring well MW-15S and MW-16S.

Table 4. Genetic Testing Data

Location	Analysis	Units	4/23/06	5/23/06	6/20/06	8/16/06	2/5/07
MW-15S	Dhc	(orgs./L)	--	--	--	--	3×10^6/L
	% Dhc	(%)	--	--	--	--	2 - 7
IP-43	Dhc	(orgs./L)	ND	ND	6×10^3/L	1×10^9/L	--
	% Dhc	(%)	--	--	0.0002	51	--
IP-19	Dhc	(orgs./L)	ND	ND	ND	1×10^9/L	--
	% Dhc	(%)	--	--	--	48	--
MW-16S	Dhc	(orgs./L)	--	--	--	4×10^7/L	3×10^7/L
	% Dhc	(%)	--	--	--	11	21 - 51
IP-55	Dhc	(orgs./L)	ND	5×10^4/L	7×10^8/L	--	--
	% Dhc	(%)	--	0.01	15	--	--
IP-50	Dhc	(orgs./L)	ND	2×10^4/L	1×10^7/L	3×10^8/L	--
	% Dhc	(%)	--	0.002	0.7	45	--

CONCLUSIONS

The use of EVO and direct-push methods adequately conditioned the aquifer within two months of delivery and sufficient donor has persisted for over ten months. Results from the installation of the central cell suggest that a viable anaerobic bacteria population can be transferred from one biologically active area within an aquifer to another properly conditioned area using a closed loop extraction – injection system. The second bioaugmentation event conducted at this Site significantly increased the bacterial population of *Dhc* throughout the entire length of biobarrier. Strong evidence of dechlorination has been observed throughout the biobarrier and complete dechlorination has been observed at one location. Elevated methane concentrations may correlate to the recent rebound in TCE at some locations. As donor is consumed, we expect the aquifer conditions to become less methanogenic indicating more favorable conditions for dechlorination. Additional monitoring data will be collected to continue monitoring the long-term success of this remediation approach.

REFERENCES

Books and Reports

Parsons Corporation. August 2004. *Principles and Practices of Enhanced Anaerobic Bioremediation of Chlorinated Solvents*. Prepared for the U.S. Air Force Center for Environmental Excellence, the U.S. Naval Facilities Engineering Service Center, and the U.S. Environmental Security Technology Certification Program.

Chapter or Article on Book or Proceedings

Kovacich, M., D. Beck, P. Rich, M. Zack and M. Cannert, 2006. "Direct-Push Injection and Circulation Biobarrier to Remediate a TCE Groundwater Plume," In: The Proceedings of the 5th International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, California, May 2006, Battelle Press, Columbus, OH.

Beck, D., M. Kovacich, T. Rabideau, M. Zack and M. Cannert, 2006. "Full-Scale Installation of a Passive Biobarrier to Remediate a TCE Groundwater Plume," In: The Proceedings of the 1st International Conference on DNAPL Characterization and Remediation, Pittsburg, Pennsylvania, September 2006, Redox Technologies, Inc., London, Ontario.

Journal Articles

Lendvay, J.M., M.J. Barcelona, G. Daniels, M. Dollhopf, B.Z. Fathepure, M. Gebhard, R. Heine, R. Hickey, R. Krajmalnik-Brown, F.E. Löffler, C.L. Major, Jr., E. Petrovskis, J. Shi, J.M. Tiedje and P. Adriaens. 2003. "Bioreactive Barriers: A Comparison of Bioaugmentation and Biostimulation for Chlorinated Solvent Remediation." *Environmental Science and Technology 37*: 1422-1431.

Maps

Gray, H.H. 2000. *Physiographic Divisions of Indiana, Indiana Geological Survey Special Report 61, Plate I.*