

**Pilot-Scale Evaluation of the Iron-Enhanced Dechlorination Technology for
Remediation of Contaminated Groundwater**

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Abstract

The iron-enhanced dechlorination technology was evaluated under the U.S. Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) program at a contaminated site in New Jersey... This paper describes the ability of this technology to destroy chlorinated volatile organic compounds (VOCs) in contaminated groundwater. Specifically, this paper discusses performance and economic data from a demonstration of the technology.

The technology involves oxidation of iron and reductive dechlorination of chlorinated VOCs in aqueous media. During reductive dehalogenation, VOCs are converted to hydrocarbons and inorganic chlorides. The process can be used for either in situ or ex situ groundwater treatment.

This process was demonstrated using a pilot-scale, aboveground treatment reactor containing the reactive iron medium. A flow rate of about 0.5 gallons per minute was maintained throughout a 13-week demonstration period; about 60,800 gallons of groundwater were treated. During the demonstration of the aboveground reactor, water samples were collected at influent, intermediate, and effluent sampling locations and analyzed for VOCs and inorganic parameters (e.g., concentrations of dissolved metals, chloride, sulfate, total inorganic carbons; pH; Eh). VOCs present in influent groundwater or generated as degradation by-products were considered critical analytes for the SITE demonstration.

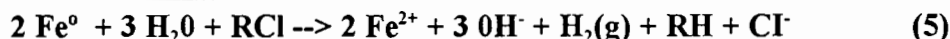
The analytical results indicated that influent groundwater was contaminated with (1) trichloroethene (TCE) at concentrations ranging from 54 to 590 micrograms per liter ($\mu\text{g/L}$); (2) tetrachloroethene (PCE) at concentrations ranging from 4,100 to 13,000 $\mu\text{g/L}$; and, (3) cis-1,2-dichloroethene (cDCE) at concentrations ranging from 35 to 1,600 $\mu\text{g/L}$. Vinyl chloride (VC) was not detected in the influent groundwater. Analytical results for the effluent samples indicated that the iron-enhanced dechlorination process significantly reduced the total concentrations of chlorinated VOCs in water treated, and consistently achieved the demonstration effluent target level of 1 $\mu\text{g/L}$ for TCE and PCE. During the last two weeks of the demonstration the process did not consistently achieve the effluent target levels of 2 $\mu\text{g/L}$ for VC and 5 $\mu\text{g/L}$ for cDCE. Although some cDCE was present in the influent groundwater, most of the cDCE and VC appears to have formed through the degradation of PCE and TCE. The incomplete dechlorination of cDCE and VC in the latter portion of the SITE demonstration may have been caused by PCE persisting to greater depths within the reactor than anticipated. These factors may have resulted from a gradual reduction in the iron's reactive surface area through formation of precipitates.

Based on information obtained from the SITE demonstration, groundwater remediation costs for an aboveground reactor using the iron-enhanced dechlorination process are estimated to be about \$91 per 1,000 gallons treated. This cost was estimated based on data from a pilot-scale system operating at a flow rate of 0.5 gpm extrapolated to a 30-years operational period.

Introduction

Common technologies (e.g., air sparging/soil vapor extraction with carbon adsorption) for remediating groundwater contaminants with chlorinated solvents, involve the transfer of contaminants from water to another medium. As regulatory requirements for the treatment of the contaminated medium become more stringent and more expensive to comply with, the iron enhanced technology may offer a major advantage over other treatment technologies because it destroys hazardous substances rather than transferring them to another medium.

The iron-enhanced dechlorination technology involves oxidation of iron and reductive dechlorination of chlorinated VOCs in aqueous media. Although aluminum, copper, brass, standard steel, and zinc have also been shown to promote reductive dechlorination of VOCs (O'Hannesin and Gillham, 1992), metallic iron has been chosen for use in large-scale applications of the technology. Metallic iron is readily available, inexpensive, and induces rapid dechlorination of organic compounds. The technology induces conditions that cause substitution of chlorine atoms by hydrogen atoms. Equations (1) through (5) may describe the reactions that take place in the presence of water, zero-valent iron (Fe^0), and a chlorinated hydrocarbon (RCl) (Gillham and O'Hannesin, 1994):



The overall reaction that takes place (Equation 5) results in the formation of Fe^{2+} , hydroxyl ions (OH^-), hydrogen gas [$\text{H}_2(\text{g})$], nonchlorinated hydrocarbons (R-H), and chloride ions (Cl^-).

This technology can be installed and operated in either an aboveground reactor or in situ as a permeable treatment wall (EPA, 1995). An aboveground, pilot-scale reactor was used for the Superfund Innovative Technology Evaluation (SITE) demonstration at a contaminated site in New Jersey. The pilot-scale reactor was designed to evaluate the technology's suitability for full-scale remediation at this site, and to gather data regarding full-scale system design and operating parameters.

The primary purpose of the SITE Program is to advance the development and demonstration, and thereby establish the commercial availability, of innovative treatment technologies applicable to Superfund and other hazardous waste sites. The SITE Program was established by the U.S. Environmental Protection Agency (EPA) Office of Solid Waste and Emergency Response (OSWER) and Office of Research and Development (ORD) in response to the Superfund Amendments and Reauthorization Act of 1986 (SARA), which recognized the need for an alternative or innovative treatment technology research and demonstration program.

This process has shown very effective for the dechlorination of various VOCs (e.g., chlorinated methanes, ethanes, and ethenes) (Gillham and others, 1993) over a wide range of concentrations in laboratory-scale tests. However, its effectiveness, possible problems and cost for a large scale treatment has not been evaluated. This paper describes the results of a pilot-scale demonstration under natural conditions. These results can be used for control, modification, and optimization of design and operating parameters for either the above-reactor or in situ permeable wall.

Experimental

Groundwater at the demonstration site was treated in a reactor (see Figure 1). The reactor was a 9-foot-high, 8-foot-diameter fiberglass-reinforced plastic tank containing a 5.5-foot-thick layer of reactive granular iron. The reactive iron rested on top of a layer of coarse silica sand, referred to as "well sand," placed in the bottom of the reactor. The well sand in the bottom of the reactor prevented granular iron from washing out into the effluent pipe. Pea gravel or well sand can also be placed on top of the reactive iron to act as a prefilter, but was not used during the SITE demonstration as the reactor feed line was equipped with an in-line 5-micron prefilter. Eliminating the upper filter layer also allowed observation of and direct access to the top of the iron. The top of the reactor was equipped with a passive gas vent to prevent accumulation of excess pressure, and a manhole with a sightglass to allow observation of the reactive iron surface and access to the vessel interior.

The influent groundwater fed to the reactor was collected from the shallow, unconsolidated zone and the underlying, fractured bedrock aquifer (PRC, 1994). Two trenches passively collected contaminated groundwater from the shallow zone. The trenches drained to a common sump; water was pumped directly from the sump to the feed line for the reactor. Two pumping wells extracted groundwater from the bedrock aquifer. Water from these wells flowed to a common pipe, and then directly into the reactor feed pipe. The influent groundwater contained TCE at concentrations ranging from 54 to 590 $\mu\text{g/L}$, PCE at concentrations ranging from 4,100 to 13,000 $\mu\text{g/L}$, and cDCE at concentrations ranging from less than 25 to 1,200 $\mu\text{g/L}$.

The influent groundwater passed through an air eliminator, a 5-micron water filter (to remove suspended solids, which may inhibit flow through the reactive iron medium), and then entered the reactor. Water was pumped into the reactor at a sufficient rate to maintain a 2-foot-deep layer of water ponded above the iron at all times, to prevent rust from forming on the iron surface and to minimize variations in volumetric flow through the reactor. The water then flowed through the reactive iron layer by gravity. The treated water flowed to a perforated pipe in the well sand, and then out through an effluent pipe. The volumetric flow rate, flow velocity and residence time were controlled by the thickness, porosity, and permeability of the iron layer and the configuration of the effluent piping. A flow rate of about 0.5 gpm was maintained throughout the SITE demonstration period. The estimated residence time of 27.5 hours equates to a vertical flow velocity of about 4.8 feet per day, based on an assumed iron porosity of about 40 percent (Vogans and others, 1995).

The operating parameters (system design and flow rate) were determined with laboratory column tests using the groundwater from the site. The SITE program evaluated the treatment reactor's effectiveness over a period of 13 weeks. During this period, three types of data were

collected: 1) analytical data for water samples collected from the reactor; 2) analytical data for samples of other media (reactive iron and air); and 3) operating data and observations, such as cumulative volume treated, flow rate, and electrical consumption.

The total amount of iron placed in the reactor was 42,920 pounds. The total volume of reactor space filled by the iron was 277 cubic feet; therefore, the iron's bulk density after settling was 155 lbs/ft³. During the demonstration: the flow rate (through the reactor), cumulative volume treated, and electrical power consumption were recorded; and groundwater samples at the reactor's influent (I1), control (R1), intermediate (R2 through R5), and effluent (E1) sampling locations (Figure 1). Sampling locations I1 and E1 were taps on the reactor's influent and effluent lines, respectively. The other locations (R1 through R5) consisted of slotted stainless steel tubes that extended to the reactor's interior. The tubes were capped when not in use; to obtain samples, the tubes were uncapped, and water flowed out into the sample containers. Sampling locations R2 through R-5 were spaced at various depths through the layer of reactive iron, to evaluate changes as water passed through the reactive medium.

The influent and effluent water were collected weekly during the demonstration to determine and monitor the concentrations of various chlorinated hydrocarbons. These include tetrachloro ethene (PCE, trichloro ethene (TCE), 1,1-dichloro ethene (1,1-DCE), cis-1,2-dichloro ethene (cDCE), and vinyl chloride (VC). During weeks 1, 5, 9, and 13 of the demonstration, water samples from locations R1, R2, R3, R4, and R5, as well as the influent and effluent locations were collected. In addition to the aforementioned chlorinated hydrocarbons, the dissolved metals, chloride, sulfate, and total inorganic carbons were also analyzed for these collected water samples. Field measurements of dissolved oxygen (DO), temperature, specific conductance, pH, and Eh. Were conducted on all the water samples collected. In addition to water, air gas samples from the headspace of the reactor interior during weeks 5, 9, and 13 were also collected. The concentrations of PCE and TCE in the gaseous samples were analyzed.

The first sampling event (week 1) was performed after about three pore volumes of groundwater had passed through the treatment reactor. One pore volume equals the volume of pore space of the reactive iron medium and is estimated by the developer as about 40 to 45 percent of the total volume of the reactive iron medium. Based on the volume of iron in the reactor, the pore space was about 110 cubic feet, indicating that the pore space of the iron probably held approximately 827 gallons of water at any given time during the demonstration.

Results and Discussion

Table 1 presents a summary of the concentrations of chlorinated VOCs detected in samples collected at the influent and effluent sampling locations during weeks 1 through 13. Figures 2 through 5 summarizes concentrations of these VOCs detected at all (influent, control, intermediate, and effluent) sampling locations during weeks 1, 5, 9, and 13.

The relatively high PCE concentrations in the influent groundwater necessitated dilution of some samples to bring the PCE concentrations within the quantifiable range. In diluted samples the detection limits were adjusted for the dilution factor. For this reason, it is possible that relatively small amounts of cDCE, VC, and possibly other VOCs, were present in the diluted samples and were not detected. No effluent samples required dilution; therefore, the detection limits achieved for these samples were all lower than the applicable effluent target levels.

Applicable effluent target levels for all VOCs detected are summarized in Table 1. Compliance with the target levels was evaluated by comparing the effluent VOC concentrations with the most stringent effluent target levels.

The analytical results shown in Table 1 indicate that the TCE and PCE were detected in the influent during all weeks of testing; however, the influent concentrations of PCE and TCE were variable. Influent TCE concentrations ranged from 54 to 590 $\mu\text{g/L}$, and influent PCE concentrations ranged from 4,100 to 13,000 $\mu\text{g/L}$. The types and concentrations of VOCs in the influent may have varied due to the effects of mixing of groundwater from the two different zones (the shallow zone and the bedrock aquifer), which typically contain different concentrations of the various contaminants.

Based on comparison of influent and effluent samples, the iron-enhanced dechlorination process significantly reduced the total chlorinated VOC concentrations in groundwater treated by the reactor. Concentrations of PCE and TCE in the effluent were consistently below the detection limit of 0.9 $\mu\text{g/L}$ during all weeks of testing, and thus were also below the applicable target effluent level of 1 $\mu\text{g/L}$ for both compounds. As shown in Figures 2 and 3, PCE and TCE concentrations at intermediate sampling locations generally increased over the demonstration period, but were reduced to below detectable levels before exiting the reactor in all weeks of testing.

cDCE was not detected in influent groundwater during weeks 1 to 5, or during weeks 7 and 9. cDCE was detected in the influent groundwater in weeks 6, 8, 10, 11, 12, and 13. The detection limit for VOCs (including cDCE) in the influent groundwater samples was 25 $\mu\text{g/L}$ for all weeks except weeks 1 and 7; for these 2 weeks the influent detection limits were 250 $\mu\text{g/L}$ and 50 $\mu\text{g/L}$, respectively. The detection limit of 1.0 $\mu\text{g/L}$ for cDCE was achieved for effluent samples during all weeks. cDCE was not detected in the effluent during the first 8 weeks of the demonstration, but was detected in the effluent during weeks 9 through 13. The technology achieved the NJDEP site-specific discharge limit of 5 $\mu\text{g/L}$ for cDCE for all weeks except week 13. Although cDCE was detected in the influent groundwater during some weeks, during weeks 1, 5, 9, and 13 the highest cDCE concentrations were detected at the intermediate locations, indicating that cDCE was also introduced as a by-product of the dechlorination of PCE and TCE (see Figure 5). Generally, the concentrations of cDCE in the effluent groundwater increased consistently from 1.3 $\mu\text{g/L}$ during week 9 to 37 $\mu\text{g/L}$ during week 13 (see Figures 4 and 5).

Table 1 Chlorinated VOC Concentrations at Influent and Effluent Sampling Locations

VOC	Week 1		Week 2		Week 3		Week 4		Week 5		Week 6		Week 7		Target Effluent Levels	
	I	E	I	E	I	E	I	E	I	E	I	E	I	E	Federal MCL	NJDEP Discharge Limit
PCE	5,900	<0.9	9,800	<0.9	9,700	<0.9	9,800	<0.9	13,000	<0.9	7,200	<0.9	6,900	<0.9	5	1
VC	<250	<1	<25	<1	<25	<1	<50	<1	<50	<1	<25	<1	<50	<1	2	5
TCE	110 ^a	<0.9	69	<0.9	130	<0.9	120	<0.9	110	<0.9	350	<0.9	54	<0.9	5	1
cDCE	<250	<1	<25	<1	<25	<1	<50	<1	<50	<1	1,200	<1	<50	<1	70	5

VOC	Week 8		Week 9		Week 10		Week 11		Week 12		Week 13		Target Effluent Levels	
	I	E	I	E	I	E	I	E	I	E	I	E	Federal MCL	NJDEP Discharge Limit
PCE	5,900	<0.9	8,900	<0.9	7,300	<0.9	4,100	<0.9	7,100	<0.9	7,900	<0.9	5	1
VC	<25	<1	<25	<1	<25	1.4	<25	1.2	<25	2.8	<25	8.4	2	5
TCE	79	<0.9	54	<0.9	110	<0.9	590	<1	99	<0.9	180	<0.9	5	1
cDCE	65	<1	<25	1.3	67	2.4	1,600	2.8	35	2.3	330	37	70	2

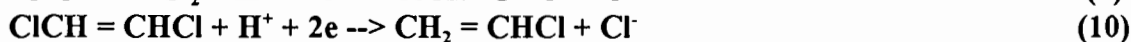
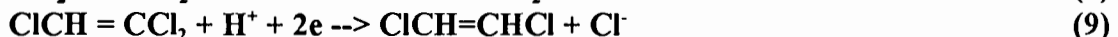
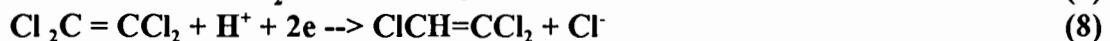
Notes:

All analytical results are presented in $\mu\text{g/L}$.
 I = Influent groundwater
^a Value estimated without sample reanalysis

< = Less than the detection limit shown.
 E = Effluent groundwater

VC was not detected in the influent groundwater during the SITE demonstration. Because the detection limits were adjusted for dilutions, it is possible that VC was present in the influent samples at low concentrations and was not detected. However, past groundwater monitoring data do indicate that VC is typically present in site groundwater at significant concentrations. VC was detected in the effluent samples collected during weeks 10, 11, 12 and 13. The effluent concentrations of VC during these weeks increased from 1.2 $\mu\text{g/L}$ during week 10 to 8.4 $\mu\text{g/L}$ during week 13 (see Figure 5). VC concentrations in the effluent exceeded the applicable maximum contaminant level (MCL) of 2 $\mu\text{g/L}$ during weeks 12 and 13, but were relatively low (2.8 $\mu\text{g/L}$ during week 12 and 8.4 $\mu\text{g/L}$ during week 13). VC is a common by-product of PCE, TCE, and cDCE dechlorination. Because VC was not detected in the influent groundwater it was probably formed during the reductive dechlorination of PCE, TCE, and cDCE.

Based on the demonstration results, the following reaction mechanism is suggested (Chen, 1995):



During the early part of the SITE demonstration, the iron was still very reactive and was able to rapidly reduce all by-products (TCE, cDCE, and VC) generated as PCE degraded. However, as the demonstration progressed, the reactivity of the iron decreased and the produced TCE could not be immediately reduced, leading to increases in TCE concentrations and incomplete dechlorination of cDCE and VC. For this reason, during this demonstration the dechlorination of multi-chlorinated VOCs appeared to be continuous and sequential, rather than occurring in one precipitous step.

Table 2 presents the pH values measured at the influent and effluent sampling locations during all weeks of testing. Table 3 shows the pH values measured at all locations during weeks 1, 5, 9, and 13. Generally, the pH increased progressively as groundwater moved through the reactor during all weeks except week 13. Equations 1 through 4 may explain the increase in pH. In these reactions, H^+ is consumed so that the pH rises and significant amounts of OH^- ions appear.

Sulfate concentrations were measured to evaluate, in part, the potential for sulfate-reducing bacterial growth and precipitation of metal sulfates. Table 2 shows that, except during week 1, the concentration of sulfate did not change significantly during or after treatment. During week 1, the influent sulfate concentration was 27.3 mg/L, and the effluent sulfate concentration was less than 5 mg/L. However, even during week 1 the decrease in sulfate concentration did not progress consistently through the reactor.

For Table 2 pH at all locations

Sampling Location	I1	R1	R2	R3	R4	R5	E1
RI Distance(inches)	--	0	12	24	42	60	66
Week 1	7.52	7.30	7.36	7.89	8.14	8.32	8.72
Week 5	7.52	7.43	8.75	8.48	10.72	10.96	10.69
Week 9	7.66	7.77	7.78	7.92	9.17	9.04	9.36
Week 13	8.90	8.63	8.74	8.81	Not measured	8.73	8.91

Note: R1 Distance = Distance through reactive iron.

Table 3 pH at Influent and Effluent Sampling Locations

Week	pH at I1:	pH at E1:
1	7.52	8.72
2	7.67	8.63
3	7.90	8.72
4	8.42	10.82
5	7.52	10.69
6	7.58	9.57
7	8.11	9.63
8	7.73	9.69
9	7.66	9.36
10	7.57	9.37
11	7.17	9.76
12	7.66	9.60
13	8.90	8.91

these reasons the sulfate data provide no evidence of metal-sulfate precipitation or bacterial growth.

Chloride concentrations were determined because they may correlate with dechlorination of VOCs. However, because the background chloride concentrations are relatively high compared to the VOC concentrations, no significant trends in chloride concentrations were noted during treatment as a result of VOC dechlorination.

TIC concentrations generally decreased from concentrations measured at the influent and control sampling locations as the groundwater moved through the reactor (see Table 4). This decrease in TIC concentration may be caused by the precipitation of metal carbonate compounds.

Precipitation of calcium carbonate (CaCO_3) (as well as iron carbonates) may be attributed to the removal of CO_3^{2-} . The OH^- produced from the dissolution of water as described in equation 2 may react with bicarbonate ions (HCO_3^-) in the groundwater to produce carbonate ions

Table 4 *Summary of Inorganic Analyte Data*

Week 1

Analyte:	Concentration at Sampling Location:						
	I1	R1	R2	R3	R4	R5	E1
Chloride	85.8	73.7	75.9	76.4	78.7	73.2	73.7
Sulfate	27.3	33.3	30.4	46	8.12	U	U
Aluminum	U	U	U	U	U	U	2.16
Barium	0.311	0.258	0.171	0.230	0.192	0.125	U
Calcium	76.1	63.1	48.6	34.8	23.1	19.4	33.4
Iron	0.114	U	U	U	U	U	1.05
Magnesium	25.1	19.2	21.5	15.7	2.55	1.32	10.9
Manganese	0.012	0.037	0.812	0.246	0.278	0.099	U
Potassium	U	9.36	2.58	4.17	6.12	6.92	16.6
Sodium	11.8	15.7	11.8	12.6	17.5	21.6	29.1
Zinc	0.043	0.043	0.041	0.031	0.024	0.023	0.025
TIC	40	36	18	4.0	1.0	1.0	1.0

Week 5

Analyte	Concentration at Sampling Location:						
	I1	R1	R2	R3	R4	R5	E1
Chloride	77.7	78.1	81.1	84.7	82.9	82.8	82.9
Sulfate	34.1	34.6	34.2	34.4	35.6	34.7	33.8
Aluminum	U	U	U	U	U	U	U
Barium	0.299	0.297	0.038	0.034	0.102	0.136	0.148
Calcium	72.1	71.7	34.3	28	24.3	24	25.5
Iron	U	U	0.091	U	U	U	U
Magnesium	22.8	22.5	21.8	21.9	19.2	19.1	17.9
Manganese	U	U	0.311	1.40	0.270	0.025	0.135
Potassium	1.05	U	U	1.11	1.36	1.26	1.45
Sodium	9.28	9.70	9.27	9.06	9.11	9.49	9.43
Zinc	U	0.012	U	U	0.012	U	U
TIC	38	39	18	12	4.8	3.2	3.7

Notes: All concentrations in milligrams per liter (mg/L)
 U = Analyte not detected TIC = Total inorganic carbon

Table 4 Summary of Inorganic Analyte Data (Continued)

Week 9

Analyte	Concentration at Sampling Location:						
	I1	R1	R2	R3	R4	R5	E1
Chloride	70.9	69.9	74.4	76.6	75.7	72.9	76.2
Sulfate	30.2	30.5	31.2	28.8	25.2	23.6	26.8
Aluminum	U	U	U	U	U	U	U
Arsenic	0.0211	0.0169	0.0117	0.0135	U	0.0121	0.0160
Barium	0.298	0.255	0.0356	0.0347	0.0313	0.0653	0.0639
Calcium	68.8	66.3	37.0	28.7	24.6	23.1	21.1
Iron	U	U	0.557	U	U	U	U
Magnesium	22.6	21.1	20.8	18.4	15.7	13.8	15.2
Manganese	U	0.0449	0.166	0.470	0.883	0.222	0.0781
Potassium	U	1.74	1.86	2.34	2.95	3.14	3.04
Sodium	9.71	13.1	13.6	14.2	15.9	16.0	16.0
Zinc	U	U	U	U	U	U	U
TIC	18	18	14	11	6.5	4.7	5.3

Week 13

Analyte	Concentration at Sampling Location:						
	I1	R1	R2	R3	R4	R5	E1
Chloride	83.3	78.7	81.1	81.9	N/A	83.7	83.5
Sulfate	32.0	31.5	32.7	30.2	N/A	31.7	31.9
Aluminum	U	U	U	U	N/A	U	U
Barium	0.327	0.322	0.0715	0.0306	N/A	0.0454	0.0259
Calcium	77.6	74.8	54.2	39.3	N/A	25.8	26.8
Iron	U	U	2.11	.228	N/A	U	U
Magnesium	24.8	23.7	23.7	23.6	N/A	20.7	23.1
Manganese	0.0260	0.0165	0.142	0.284	N/A	0.213	0.649
Potassium	U	1.24	U	U	N/A	1.29	3.27
Sodium	10.5	10.3	10.2	10.9	N/A	10.3	10.5
Zinc	U	U	U	U	N/A	U	U
TIC	40	37	31	19	N/A	5.3	8.3

NOTES: All results in milligrams per liter (mg/L)

TIC = Total inorganic carbon

U = Analyte not detected; associated value is quantitation limit

N/A = Sample not collected - sampling location R4 inaccessible during week 13

The concentrations of dissolved calcium, magnesium, and barium generally decreased as water moved through the reactor (see Table 2). During weeks 1, 5, and 9, the decrease in concentrations of these metals coincided with an increase in measured pH values, suggesting that geochemical conditions were conducive to decreased solubility and increase precipitation of some metal compounds. The decreasing concentrations of barium, calcium, and magnesium as water moved through the reactor are probably indicative of metal compounds such as calcium carbonate precipitating from the water.

The cost for using the iron-enhanced dechlorination technology, in an aboveground reactor, to treat contaminated groundwater is estimated. The cost estimates are based on a reactor designed to treat the types and concentrations of chlorinated VOCs observed at the demonstration site, and were based on data compiled during the SITE demonstration. Costs for this technology are highly variable and are dependent on the types and concentrations of the contaminants present, regulatory cleanup requirements, and other site-specific factors. Estimates for total cost and cost per gallon of water treated are also heavily influenced by assumptions regarding the duration of the treatment program and the cumulative volume treated. The purpose of the pilot-scale system was to determine the optimal design and operating parameters for a full-scale system; differences between the capabilities of the pilot-scale and full-scale systems could significantly affect costs. For these reasons, costs for full-scale systems designed for optimal performance at other sites may vary significantly from estimates presented herein.

Due to the numerous factors that potentially affect the cost of using this technology, various assumptions were necessary to prepare the economic analysis. Some of the most significant assumptions were (1) the aboveground reactor is identical to the pilot-scale reactor used at the demonstration site (2) the reactor will treat water contaminated with PCE, TCE, cDCE, and VC at concentrations observed during the demonstration (3) the reactor operates at 0.5 gpm, as demonstrated. Also, the cost evaluation is based on data obtained during the SITE demonstration, extrapolated to a 30-year operational period. The 30-year timeframe was selected for consistency with cost evaluations of other innovative technologies evaluated by the EPA SITE Program, and because it facilitates comparison to typical costs associated with conventional, long-term remedial options.

Costs have been distributed among 12 categories applicable to typical cleanup activities at Superfund and RCRA sites (Evans 1990). Costs are presented in July 1995 dollars and are rounded to the nearest 100 dollars. These factors include: (1) treatability study, (2) system design, (3) site preparation, (4) permitting and regulation, (5) Mobilization and startup, (6) capital equipments, (7) demobilization, (8) supplies, (9) utilities, (10) treatment and disposal of effluent and residual waste, (11) analytical services and (12) equipment maintenance. After operating for 30 years, the total costs of the groundwater remediation scenario presented in this analysis are \$714,700. Costs were not adjusted for inflation. A total of nearly 7.9 million gallons of groundwater would be treated over this time period. Based on these criteria, the total cost per 1,000 gallons treated is \$91, or roughly 9.1 cents per gallon.

Conclusion

The SITE demonstration of the iron-enhanced dechlorination technology produced the following key findings:

- The iron-enhanced dechlorination process significantly reduced the total concentrations of chlorinated VOCs present in the water treated. The effluent water met the target concentration of 1 $\mu\text{g/L}$ for TCE and PCE during each of the 13 weeks of testing. No cDCE or VC was detected in the effluent during weeks 1 through 8; however, low concentrations of cDCE and VC were detected in the effluent in the latter part of the demonstration. The effluent groundwater met the target levels of 2 $\mu\text{g/L}$ for VC during weeks 1 through 11, and 5 $\mu\text{g/L}$ for cDCE during weeks 1 through 12. VC concentrations during weeks 12 and 13 (2.8 $\mu\text{g/L}$ and 8.4 $\mu\text{g/L}$, respectively) and cDCE concentrations during week 13 (37 $\mu\text{g/L}$) exceeded the target levels.
- The PCE removal efficiencies were consistently greater than 99.9 percent during each week of testing. Results from weeks 1, 5, 9, and 13 indicate that PCE concentrations increased at the intermediate sampling locations, suggesting that PCE was persisting to increasingly greater depths as the demonstration progressed.
- The concentrations of chloride and sulfate did not change significantly as water moved through the reactor. The groundwater TIC concentration decreased as a function of reactor depth.
- The concentrations of dissolved metals such as calcium, magnesium, and barium changed as groundwater moved through the reactor, apparently as a result of pH increase induced by the process. Generally, the decrease in concentrations of calcium, magnesium, and barium coincided with an increase in pH. Iron concentrations were higher at intermediate sampling locations than iron concentrations in the influent and effluent samples, also possibly due to the effects of pH on solubility of iron compounds.
- The main operating problem observed during the demonstration was the deposition precipitated. A hard, crust-like layer formed in the upper few inches of the reactive iron, which according to the developer was primarily carbonate compounds that had been produced during the dechlorination process. The crust was periodically manually broken up during the demonstration to maintain unrestricted flow through the reactor.
- Precipitates may also have affected the reactor's performance by blocking the iron surfaces available for reaction, thereby reducing the reactivity of the upper portion of the iron. This may have contributed to the increasing persistence of PCE over the demonstration period and the incomplete dechlorination of cDCE and VC in the latter part of the demonstration.

Costs for using the iron-enhanced dechlorination process are highly dependent on site-specific factors, and highly variable. The cost estimate assumed that groundwater was contaminated with the same types and concentrations of chlorinated VOCs present in groundwater at this demonstration site, and assumed that design and operating parameters for the treatment system were the same as for the pilot-scale system at this site. Based on these assumptions, the total costs directly related to the metal-enhanced dechlorination process are estimated to be \$91 per 1,000 gallons of groundwater treated. Due to potential differences between the capabilities of pilot-scale systems and full-scale systems designed for optimal

performance, and varying site-specific factors, costs per gallon treated could be significantly less for a full-scale application of the metal-enhanced dechlorination process at other sites.

References

- Chen, Chien T. 1995a. "Iron Enhanced Dechlorination of Chlorinated Hydrocarbons", 21st Annual Research Symposium Abstract Proceedings, April, pp 74-78
- Chen, Chien T. 1995b. Excerpts from Presentation Titled "Iron Reactive Wall." Innovative Site Remediation Workshop, Sturbridge, Massachusetts, Sept. 13-14.
- EnviroMetal Technologies, Inc. Report on Performance of Test Reactor, former SGL Printed Circuits Facility, Wayne, New Jersey. September 28.
- Gillham, Robert W., and others. 1993. "Metal Enhanced Abiotic Degradation of Halogenated Aliphatics: Laboratory Tests and Field Trials." Paper Presented at the 1993 HazMat Central Conference. Chicago, Illinois. March 9-11.
- Gillham, Robert W., and Stephanie F. O'Hannesin. 1994. "Enhanced Degradation of Halogenated Aliphatics by Zero-Valent Iron." *Ground Water*. Vol. 32, No. 6, pp. 958 - 967.
- O'Hannesin, Stephanie F., and Robert W. Gillham. 1992. "A Permeable Reaction Wall for In Situ Degradation of Halogenated Organic Compounds." Paper Presented at the 1992, 45th Canadian Geotechnical Society Conference. Toronto, Ontario, Canada. October.
- PRC Environmental Management, Inc. (PRC). 1994. EnviroMetal Technologies, Inc. "Metal Enhanced Abiotic Degradation Technology Demonstration Final Quality Assurance Project Plan." Submitted to EPA ORD, Cincinnati, Ohio. October.
- EPA. 1995. Metal-Enhanced Dechlorination Technology, Demonstration Bulletin, EPA/540/MR-95/5100, May.
- Vogan, John L., and others. 1995. "Site-Specific Degradation of VOCs in Groundwater Using Zero-Valent Iron." Preprint Extended Abstract. Presented Before the Division of Environmental Chemistry. American Chemical Society (ACS). Anaheim, California.
- Yamane, C.L., and others. 1995. "Installation of a Subsurface Groundwater Treatment Wall Composed of Granular Zero-Valent Iron." Preprint Extend Abstract Presented before the Division of Environmental Chemistry, American Chemical Society. Anaheim, California.

Figure 1
Schematic of Aboveground Reactor Design

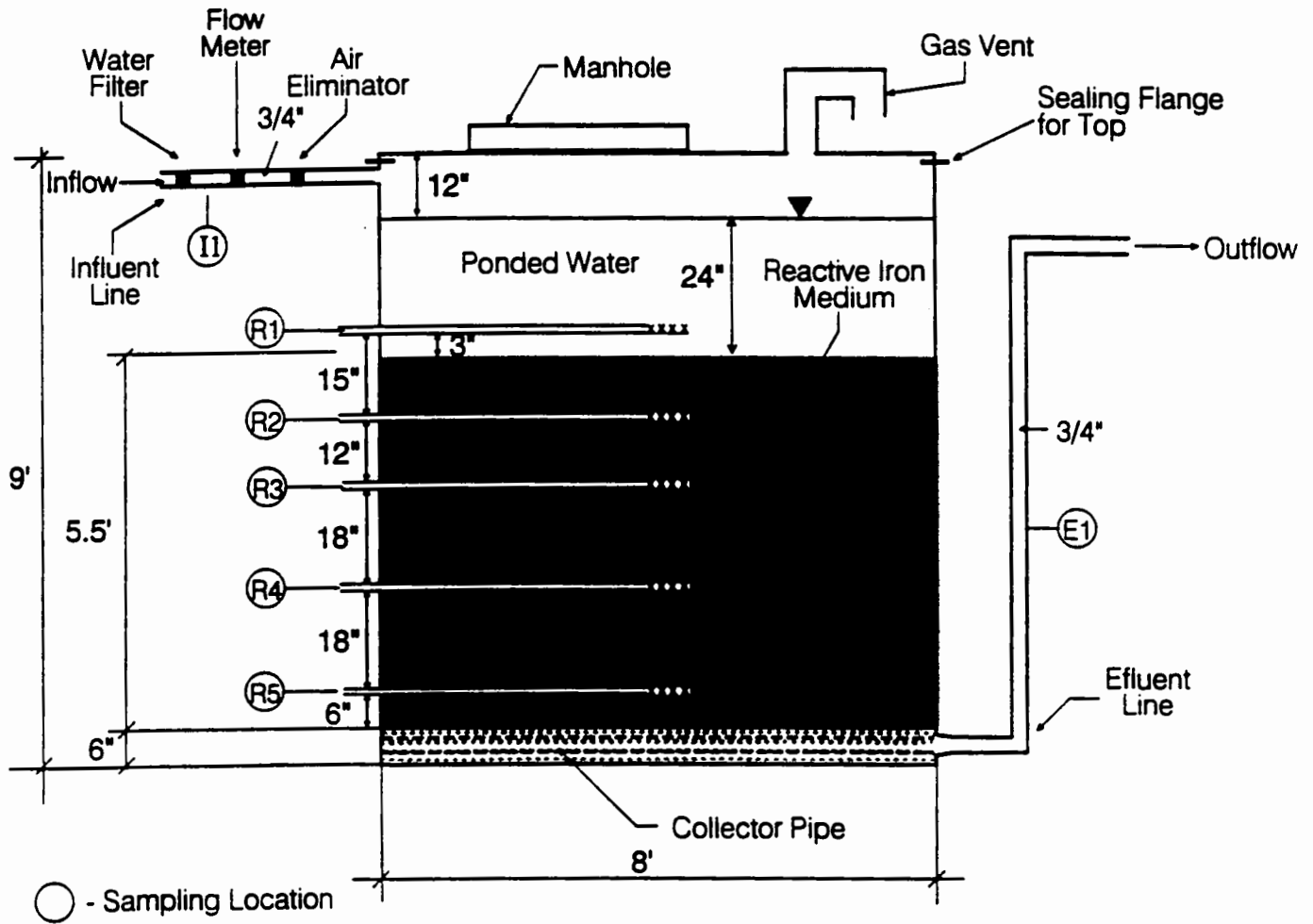
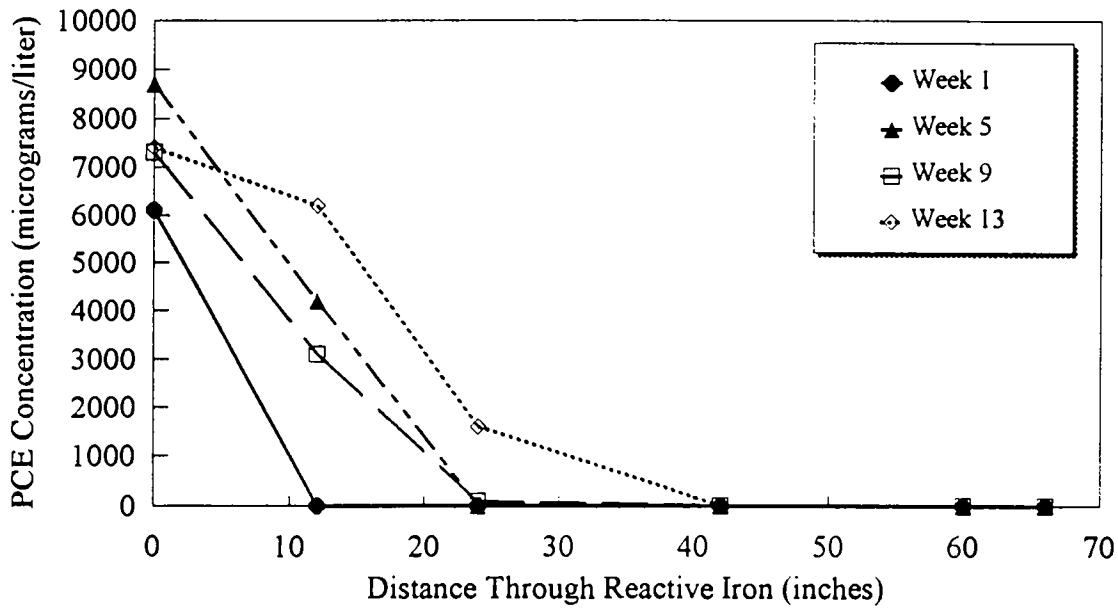
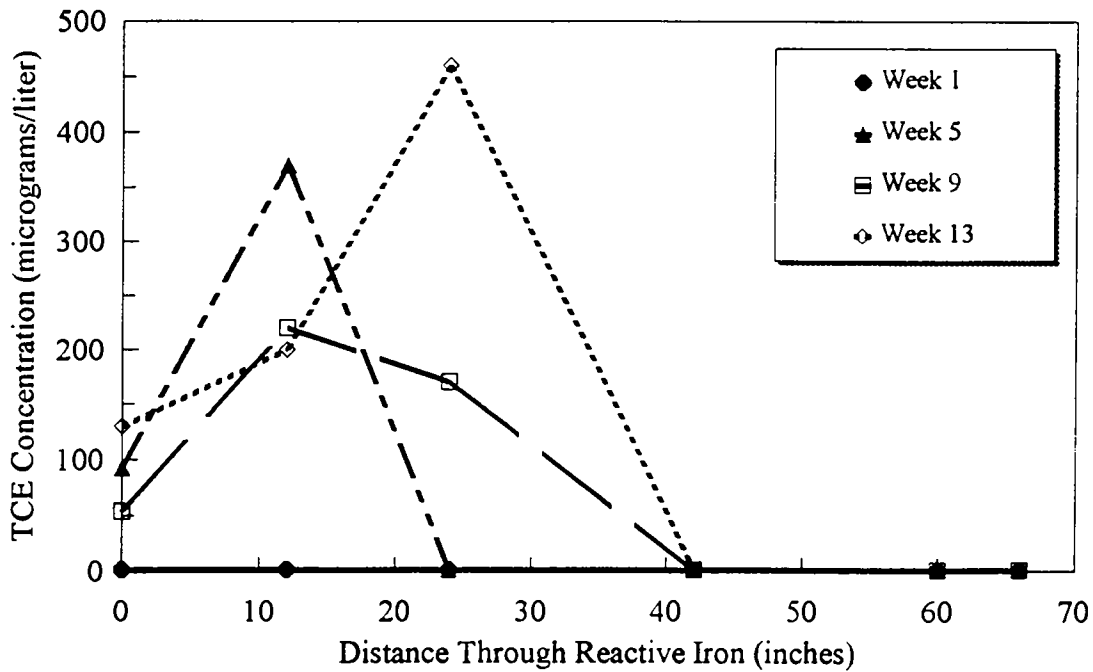


Figure 2
PCE Concentration vs. Distance through Reactive Iron



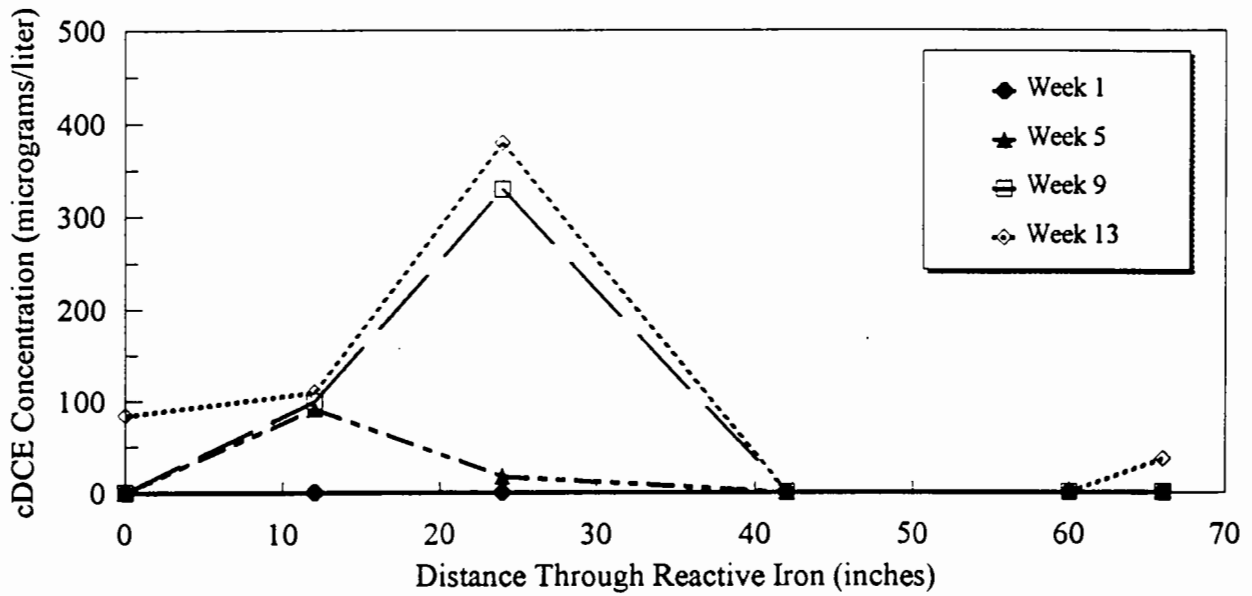
Notes: 1) Sampling location R1 used as distance $x = 0$ inches. 2) Sampling location R4 (42 inches) not sampled during week 13. 3) All non-detect values assumed to be 0 for plotting purposes.

Figure 3
TCE Concentration vs. Distance through Reactive Iron



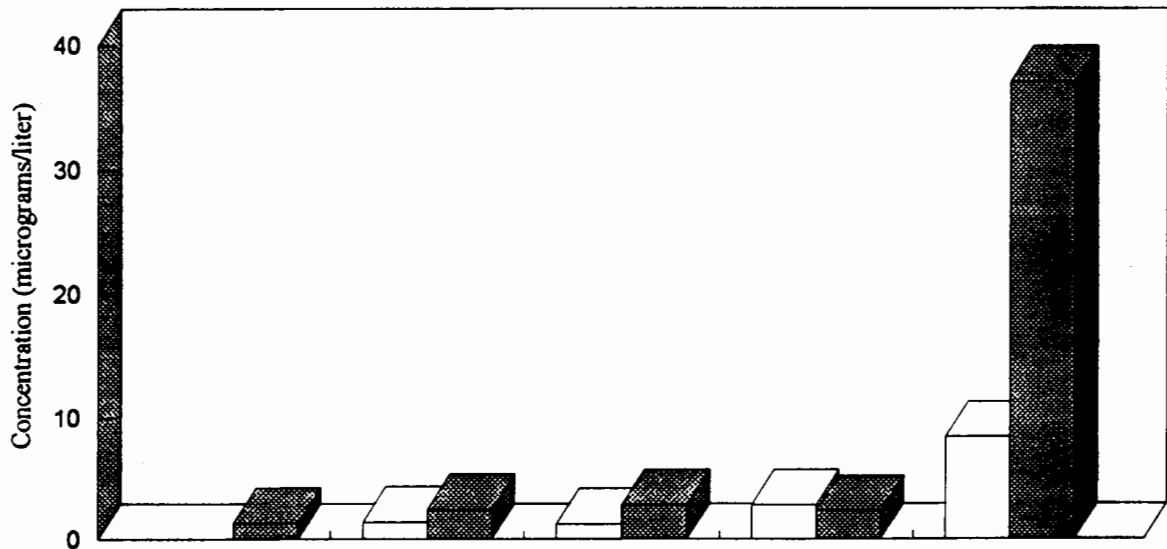
Notes: 1) Sampling location R1 used as distance $x = 0$ inches. 2) Sampling location R4 (42 inches) not sampled during week 13. 3) All non-detect values assumed to be 0 for plotting purposes.

Figure 4
cDCE Concentration vs. Distance through Reactive Iron



Notes: Sampling location R1 used as distance $x = 0$ inches.
 Sampling location R4 (42 inches) not sampled during week 13.

Figure 5
Effluent Concentrations of VC and cDCE



Week of Testing	9	10	11	12	13
□ VC	<1	1.4	1.2	2.8	8.4
■ cDCE	1.3	2.4	2.8	2.3	37.0

Note: Only concentrations greater than applicable detection limits are plotted.

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TECHNICAL REPORT DATA

(Please read instructions on the reverse before completing)

1. REPORT NO. EPA/600/A-97/063	2.	3. RECL.
4. TITLE AND SUBTITLE Pilot-Scale Evaluation of the Iron-Enhanced Dechlorination Technology for Remediation of Contaminated Groundwater	5. REPORT DATE 10/15/96	
	6. PERFORMING ORGANIZATION CODE	
7. AUTHOR(S) C.T. Chen, US EPA, UWMB, Edison, NJ 08837	8. PERFORMING ORGANIZATION REPORT NO.	
9. PERFORMING ORGANIZATION NAME AND ADDRESS PRC	10. PROGRAM ELEMENT NO. TD1Y1A	
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15. SUPPLEMENTARY NOTES Project Officer: Chien T. Chen (908) 906-6895		
16. ABSTRACT <p>The iron-enhanced dechlorination technology was evaluated under the U.S. Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) program at a contaminated site in New Jersey...This process was demonstrated using a pilot-scale, aboveground treatment reactor containing the reactive iron medium. A flow rate of about 0.5 gallons per minute was maintained throughout a 13-week demonstration period; about 60,800 gallons of groundwater were treated.</p> <p>Analytical results for the effluent samples indicated that the iron-enhanced dechlorination process significantly reduced the total concentrations of chlorinated VOCs in water treated, and consistently achieved the demonstration effluent target level of 1 µg/L for TCE and PCE. During the last two weeks of the demonstration the process did not consistently achieve the effluent target levels of 2 µg/L for VC and 5 µg/L for cDCE. Most of the cDCE and VC appears to have formed through the degradation of PCE and TCE. The incomplete dechlorination of cDCE and VC in the latter portion of the SITE demonstration may have resulted from a gradual reduction in the iron's reactive surface area through formation of precipitates.</p> <p>Based on information obtained from the SITE demonstration, groundwater remediation costs for an aboveground reactor using the iron-enhanced dechlorination process are estimated to be about \$91 per 1,000 gallons treated. This cost was estimated based on data from a pilot-scale system operating at a flow rate of 0.5 gpm extrapolated to a 30-years operational period.</p>		
17.	KEY WORDS AND DOCUMENT ANALYSIS	
a. DESCRIPTORS ion enhanced dichloroethene tetra-chloroethene tri-chloroethene cis-1,2-dichloroethene vinyl chloride	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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