

Introduction

A nearly 3.2-km (2-mi) long trichloroethene (TCE) plume was identified in groundwater beneath Test Area North (TAN) at the Idaho National Engineering and Environmental Laboratory (INEEL) in the late 1980s and early 1990s. A Record of Decision (ROD) was signed in 1995 selecting groundwater pump and treat as the default remedy for the site (U.S. Department of Energy Idaho Operations Office [DOE-ID] 1995). The contaminants of concern identified were the chloroethenes TCE, cis-1,2-dichloroethene (DCE), trans-1,2-DCE, and tetrachloroethene (PCE), as well as several radionuclides. The other chloroethene, vinyl chloride (VC), was not identified as a contaminant of concern because it was never detected in groundwater. The primary risk driver for remediation of the site was TCE.

In situ bioremediation (ISB) was identified in the ROD as one of five innovative technologies to be evaluated for their potential to enhance or replace the default remedy. This paper describes the design of a 1-year field evaluation being performed from Fall 1998 to Fall 1999 to determine whether the degradation of TCE can be significantly enhanced using ISB. A description of enhanced ISB in general, and anaerobic reductive dechlorination specifically, is provided as background, and the basis for using the technology at TAN is discussed.

Technology Description

Bioremediation in the context of this paper is the destruction of organic contaminants to less harmful or more easily treated compounds through biochemical reactions mediated by microorganisms. The organic contaminant of interest at TAN is TCE because it poses the highest risk to human health and the environment (DOE-ID 1995 and Kaminsky et al. 1994). For contaminated groundwater, ISB refers to the destruction of the contaminant in place; i.e., extraction of the contaminated groundwater for treatment is not required. Microorganisms already present in the aquifer mediate the reactions necessary to facilitate degradation of contaminants. Enhanced ISB implies that the aquifer system is somehow manipulated to increase the degradation of contaminants by the indigenous microorganisms. In general, this manipulation includes the provision of substrates or nutrients necessary for microbial growth and alteration of groundwater flow patterns to prevent migration of contaminants outside the treatment area. The application of ISB at TAN for the field evaluation, described in detail below, will include both substrate addition in the high concentration source area to stimulate biological activity and pumping and injection to control groundwater flow.

Before discussing enhanced ISB in any detail, it is necessary to provide a brief discussion of the microbial processes responsible for biodegradation. Microorganisms obtain energy for new cells and for the maintenance of existing cells through the mediation of oxidation-reduction, or redox, reactions involving the transfer of electrons from an electron donor to an electron acceptor (Zehnder and Stumm 1988, Pirt 1975, and Bouwer 1994). In general, the electron donor is an organic compound while the electron acceptor is inorganic (Zehnder and Stumm 1988). The free energy yielded by redox reactions varies substantially depending upon the electron acceptor (Figure 1). During respiration, microorganisms will preferentially utilize the electron acceptors yielding the greatest free energy (Bouwer 1994). Figure 1 shows that the order of preference for the most common inorganic electron acceptors is oxygen, nitrate, manganese (IV), iron (III), sulfate, and carbon dioxide. It should be noted that this is based on thermodynamic considerations only and that the kinetics of a given redox reaction can also be important (Zehnder and Stumm 1988). Therefore, the dominant microbial community in aquifer systems is largely dependent upon the distribution of electron acceptors. Where oxygen is plentiful, aerobic bacteria will

Figure 1. Redox potentials for various redox reactions (modified from Bouwer 1994 and Wiedemeier et al. 1997).

predominate; where oxygen is depleted, but nitrate is plentiful, nitrate-reducing bacteria will predominate; and so on.

Wastewater treatment is one of the earliest applications of bioremediation. Bioremediation has traditionally been applied by providing organic contaminants to microorganisms as electron donors so that they are biooxidized to harmless compounds (Norris 1994 and Eckenfelder 1967). For organic compounds that are susceptible to oxidation, this process is easily induced because oxygen can be utilized as an electron acceptor providing ample energy for synthesis of cellular material from destruction of the organic contaminant. Bioremediation of fuel hydrocarbons through biooxidation has been observed intrinsically and enhanced in situ for several years now (Wiedemeier et al. 1995 and Norris 1994). Unfortunately, TCE and PCE are relatively oxidized compounds and biooxidation is generally not thermodynamically favorable (Vogel et al. 1987); DCE and VC are somewhat more susceptible to biooxidation. Largely because of this, TCE was considered to be nonbiodegradable until the early 1980s (McCarty and Semprini 1994). Some of the first field observations suggesting bioremediation of chloroethenes were reported by Roberts et al. (1982). Bower and McCarty (1983) confirmed biodegradation of PCE and TCE in the laboratory shortly thereafter.

Anaerobic Reductive Dechlorination

The observed biodegradation of PCE and TCE was different than traditional bioremediation because these organic contaminants were not biooxidized, but were reduced. In terms of the microbially mediated redox reactions discussed above, they acted as electron acceptors rather than electron donors. This reduction occurs only under anaerobic conditions because oxygen has a higher reduction potential than the chloroethenes (Table 1). Higher reduction potentials imply higher energy yields. When chloroethenes are reduced, a hydrogen atom replaces a chlorine atom. This process, illustrated for all of the chloroethenes in Figure 2, has come to be called anaerobic reductive dechlorination (ARD).

One of the major differences between ARD and bioremediation through biooxidation is that ARD is dependent upon an adequate supply of appropriate electron donors, while biooxidation is dependent upon an adequate supply of electron acceptors. The nature of the indigenous microbial population at a site and the electron donors available will determine the energy yielded by the reaction, and thus the rate. One reason the ARD process occurs is the energy yielded for many electron-donor chloroethene pairs is greater than the energy from using inorganic electron acceptors such as sulfate and carbon dioxide (Wiedemeier et al. 1997).

A major factor affecting the susceptibility of chloroethenes to ARD is the number of chlorine atoms on the molecule. The more chlorine atoms in a compound, the more oxidized the compound, and the more susceptible it is to ARD (Vogel et al. 1987). Thus, PCE is relatively easily reduced by ARD, while VC requires strongly reducing conditions. Investigations at many sites have shown that in situ conditions are sufficiently reducing to facilitate the complete ARD process shown in Figure 2, but at some sites the process stops at DCE or VC. While the lesser-chlorinated compounds are difficult to reduce, they are much more susceptible to biooxidation because of their reduced state, as illustrated in Figure 3. This has led to the concept of sequential anaerobic/aerobic systems for the complete treatment of chloroethenes to innocuous compounds such as carbon dioxide. These systems have been demonstrated successfully in the lab (Fathepure and Vogel 1991) and have been observed to occur naturally in the field (Chapelle 1996, Ellis et al. 1996, Wiedemeier et al. 1996a).

Table 1. Standard reduction potentials at 25°C and pH 7.^a

Electron Acceptor	Reduced Product	Potential (volts) ^b
Oxygen	Water	+0.82
Nitrate	Nitrogen	+0.74
PCE	TCE	+0.67
TCE	DCE	+0.54
Manganese (IV)	Manganese (II)	+0.52
DCE	VC	+0.37
Iron (III)	Iron (II)	-0.05
Sulfate	Hydrogen sulfide	-0.22
Carbon dioxide	Methane	-0.24

a. Modified from Bouwer 1994.

b. Data from Stumm and Morgan (1981) and Thauer et al. (1977). Values are for aqueous solution with pH = 7, $[\text{HCO}_3^-] = 0.001 \text{ M}$, and $[\text{Cl}^-] = 0.001 \text{ M}$.

Figure 2. Anaerobic reductive dechlorination pathways (Wiedemeier et al. 1997).

Figure 3. Relative rates of reduction and oxidation (modified from Vogel et al. 1987).

Conditions at TAN

Before applying enhanced ISB, or any in situ technology at a site, its suitability must be established. Some of the factors that must be considered are the geochemical conditions, the microbial populations, and the hydrogeologic conditions. The following discussion will focus on the first two of these factors at TAN because of their particular importance for enhanced ISB through ARD, but a great deal of hydrogeologic characterization has also been performed to support the field evaluation.

Geochemistry. With respect to the geochemical conditions, the most significant parameter for ARD is probably the redox potential of the groundwater. At a contaminated site such as TAN, the redox potential is generally a function of the contamination. Industrial and sanitary liquid wastewater with a high organic content including oils, sewage, and TCE were injected into Well TSF-05 at TAN (Figure 4) between the mid-1950s and 1972. As would be expected (Sewell and Gibson 1996), microbial utilization of the oxidizable organics has resulted in the creation of an anaerobic zone in the aquifer extending from Well TSF-05, downgradient about 152 m (500 ft) to Well TAN-29 (Bukowski and Sorenson 1998). Redox conditions are believed to range from nitrate reducing to methanogenic, well within the possible range for ARD identified in Figure 1. This is based on several observations: (1) dissolved oxygen is generally less than 1 mg/L throughout the area between Wells TSF-05 and TAN-29, (2) nitrate is generally less than 3 mg/L in the same area and is especially low in the immediate vicinity of Well TSF-05, and (3) low levels of methane have been detected in Well TSF-05. Sulfate concentrations generally range from 30 to 50 mg/L in the area, which is higher than would be expected if significant sulfate reduction or methanogenesis were occurring unless the sludge around Well TSF-05 represents a substantial source of sulfate.

Groundwater monitoring data collected during the last 9 years strongly suggest that ARD is occurring to some extent in the immediate vicinity of Well TSF-05 (Bukowski and Sorenson 1998 and Sorenson et al. 1998). Some of the evidence is the presence of significant concentrations of DCE (particularly notable is the predominance of the cis-DCE isomer), the absence of oxygen and nitrate as competing electron donors, the presence of low concentrations of VC and ethene, and the existence of a supply of electron donors (the organic sludge around Well TSF-05). Perhaps the most significant evidence is the relative concentrations of chloroethenes near Well TSF-05 (Figure 5). TCE is the primary contaminant in all of the wells; however, the relative concentrations of contaminants are not constant and appear to provide information regarding the fate of TCE. The fact that DCE, the second most prevalent chlorinated hydrocarbon at well TSF-05, is found primarily around the source and downgradient of the source, and that the isomer cis-1,2-DCE exhibits concentrations greater than trans-1,2-DCE and 1,1-DCE in every well at TAN where they have been detected suggests that the primary source of DCE is the reductive dechlorination of TCE. Figure 5 shows that DCE is relatively constant as a percentage of total contamination within 15 m (50 ft) of well TSF-05, and then decreases downgradient. It appears DCE is primarily generated near wells TSF-05, TAN-25, and TAN-26 where sufficient electron donors are available. At wells outside the more strongly reducing conditions near TSF-05, relative PCE concentrations are much higher, apparently indicating that reductive dechlorination is not as significant.

Microbiology. In addition to the geochemical conditions at TAN, the potential for indigenous microbes to carry out ARD has been investigated through laboratory studies. The laboratory studies essentially lay the groundwork for the field evaluation by demonstrating the feasibility of the technology at a small scale, and they also answer some important questions with respect to operation of the field-scale system. The laboratory work entailed the enrichment of mixed microbial cultures obtained from Well TAN-37 aquifer materials and evaluating their ability to biodegrade TCE through ARD.

Figure 4.

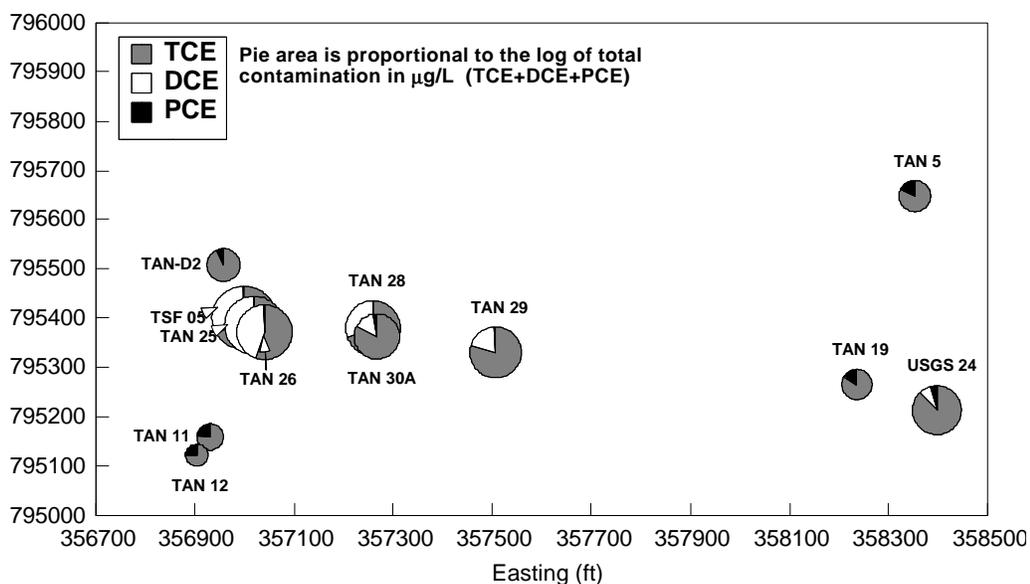


Figure 5. Distribution of chloroethenes near Well TSF-05.

After an incubation period of several months, 10 fed-batch bioreactors were studied for their ability to dechlorinate TCE with 3 different electron donors, 2 potential competing electron acceptors, and different TCE and DCE concentrations (Table 2). The bioreactors were pressurized and the pressure was monitored to ensure that no leakage of headspace gases was occurring. One reactor was maintained under abiotic conditions in order to account for any abiotic losses of TCE. After operating the reactors for about 2 months, it was apparent that Reactors 2, 4, and 8 from Table 2 were showing the best results so they were chosen for more detailed evaluation. These results seemed to indicate that glucose and methanol in the absence of lactate were not good electron donors for dechlorination, although some TCE removal was observed in Reactor 9. For this reason, and because of its success in other studies (e.g., DeBruin et al. 1992 and Gibson and Sewell 1992), lactate (in the form of sodium lactate) has been selected for use in the field evaluation. Also, the high levels of nitrate and sulfate in Reactor 6 appeared to inhibit dechlorination. It was not clear why Reactor 1 behaved differently than Reactor 4.

Figure 6 shows the TCE degradation in Reactor 8. The periodic spikes in TCE concentration correspond to feeding of the reactor, while the subsequent declines correspond to degradation. Although DCE was not observed to accumulate, ethene and ethane were generated. This is a significant result in that it indicates the potential for indigenous microorganisms at TAN to carry out complete ARD of TCE to innocuous products. Only one other study has shown degradation of PCE or TCE all the way to ethane with a single mixed culture (DeBruin et al. 1992). Other studies have shown that DCE did not accumulate when ARD proceeded to less chlorinated compounds (Vogel and McCarty 1985, and Freedman and Gosset 1989). Figure 7 shows TCE and ethene concentrations in the abiotic bioreactor for comparison to Figure 6. It is clear that abiotic TCE losses were minor.

The rates of TCE degradation in Reactors 2, 4, and 8 corresponded to half-lives of about 18 days during initial operations. While this rate is quite fast, it appeared to be limited by availability of lactate because of the very rapid lactate usage that was observed. Consequently further studies with these reactors

Table 2. Experimental conditions investigated in the bioreactors.

Reactor	TCE (mg/ L)	DCE (mg/L)	Lactate (mM)	Glucose (mM)	Methanol (mM)	SO ₄ (mg/L)	NO ₃ (mg/L)	NH ₄ H ₂ PO ₄ (mM)
1	10	—	2.5	—	—	Adjust 40	Adjust 1	0.5
2	10	—	2.5	—	—	—	—	0.5
3	5	5	2.5	—	—	—	—	0.5
4	10	—	1.5	1.0	5.0	Adjust 40	Adjust 1	0.5
5	10	—	1.5	1.0	5.0	—	—	0.5
6	10	—	1.5	1.0	5.0	192	310	0.5
7	10	—	—	2.0	—	—	—	0.5
8	5	—	5.0	—	—	—	—	0.5
9	5	—	—	1.5	7.0	—	—	0.5
10	10	—	—	—	—	—	—	—

Figure 6. TCE, ethene, and ethane levels in a bioreactor fed lactate.

Figure 7. TCE, ethene, and ethane levels in a bioreactor maintained under abiotic conditions.

were performed to evaluate the dependence of the rate of ARD on lactate availability. When the amount of lactate was increased so that it was available continuously at a concentration between 150 and 200 mg/L for a minimum period of 6 hours, the TCE degradation rate in all three reactors was observed to increase. The TCE half-life ranged between 2 and 15 days in six different experiments at the increased lactate levels. The half-life for DCE could only be estimated in Reactor 8 because concentrations remained so low in the other reactors. In five experiments with the increased lactate, the DCE half-life ranged from about 3 to 6 days. While it is somewhat surprising that DCE was degraded faster than TCE, this may explain the lack of any DCE accumulation in the bioreactors.

The results of the bioreactor studies demonstrate the feasibility of ARD of TCE by the indigenous microbes at TAN. In fact, they have shown that the mixed culture enriched from TAN aquifer materials appears to be among the best reported both in terms of the reaction extent (degradation all the way to ethane) and in terms of the reaction rate. A strong dependence of degradation rate on electron donor availability and some dependence on the nature of the electron donor were observed. These observations are consistent with other studies (Freedman and Gossett 1989, Hughes and Parkin 1991, DeBruin et al. 1992, McCarty 1996) and are important to consider for design and operation of the field-scale system. Finally, the results have led to the selection of lactate (in the form of sodium lactate) as the electron donor for the field evaluation.

Experimental Design and Operations

Both the geochemical and microbiological characterization have demonstrated that TAN may be an excellent site for the implementation of enhanced ISB. In fact it appears that ARD is already occurring to a limited extent and may be limited only by a shortage of electron donors. The overall objective of the 1-year field evaluation of enhanced ISB is to determine whether the biodegradation of TCE can be significantly enhanced by: 1) adding an electron donor to facilitate the reaction and 2) manipulating flow conditions in the aquifer. Several key issues pertinent to ARD have been considered in the design of the field evaluation and will affect its operation:

- In an engineered system it is critical to get the electron donors to the microorganisms in the presence of the chloroethenes to achieve ARD. The electron donors must be monitored as closely as possible so that their location and rate of utilization is understood to the extent possible.
- The aquifer redox conditions are an indicator of the suitability of the environment for the sequential steps of ARD to occur.
- Competing electron acceptors should be monitored to ensure that they are being reduced so that the reduction of chloroethenes can be maximized. Fully reducing the competing acceptors may in some cases exert a significant demand for electron donors.
- Chloroethene concentrations over time can be used to estimate the rate of ARD. The rates are necessary to predict long-term contaminant removal, and for evaluating the performance of different operating strategies.
- Reaction product concentrations including less chlorinated compounds, ethene, ethane, methane, carbon dioxide, and organic acids are very important because they provide information on the extent of the reactions and on the reaction pathways. These are crucial for evaluating system viability and performance, and for adjusting operations strategies.

The enhanced ISB field evaluation at TAN will entail the periodic injection of high concentrations of sodium lactate into Well TSF-05. The goal is to take advantage of the existing geochemical conditions in the vicinity of Well TSF-05 and to enhance the TCE degradation already occurring. It is believed that the continuous addition of electron donors can enhance degradation by increasing the rate and extent of dechlorination in the area where it is presently occurring, and by stimulating ARD further downgradient. As discussed previously, a strong dependence of dechlorination rates on electron donor type and availability has been observed in several studies. In addition to the provision of electron donors, the injection of biological nutrients such as nitrogen and phosphorous will be considered if they appear to be limiting.

In order to control the distribution and residence time of the electron donor and nutrients in the subsurface, it is desirable to induce a hydraulic gradient through pumping. An extraction well will be pumped continuously throughout the field evaluation to induce flow along the axis of the TCE plume, where the highest concentrations are present. The goal is to create an ARD treatment cell between Well TSF-05 and the extraction well, TAN-29 (Figure 4). It is very important to understand that the pumping that will occur during the field evaluation represents a significant change from existing conditions. This change in the flow conditions is likely to cause a corresponding change in the distribution of contaminants and other groundwater solutes and parameters of interest independent of electron donor addition. For this reason current and historical groundwater sampling results cannot be used as the basis for comparison when evaluating the effect of electron donor addition.

Start-up Period. In order to separate the effect of the new flow conditions on contaminant distributions from the effect of electron donor addition, it is necessary to operate and monitor the pumping and injection system for some period of time prior to lactate addition. This will allow a new baseline to be established for contaminant and other groundwater solutes and parameters of interest. The necessary time for this start-up period is at least one residence time. The residence time in this case is defined as the average time required for a groundwater “packet” to be transported from Well TSF-05 to the extraction well. Based on previous testing in the area, this is anticipated to require about 4 to 6 weeks. Chloroethenes, competing electron acceptors, redox potential, temperature, pH, conductivity, and nutrients will all be measured during the start-up period.

The start-up period will be used not only to establish the baseline for relevant parameter distributions, but also to establish the baseline for flow and transport in the aquifer under the conditions of the field evaluation. This will be accomplished by adding a conservative tracer, bromide, to the injection line at TSF-05 at the beginning of the start-up period. Measuring the tracer breakthrough at the monitoring wells to be used during the field evaluation will demonstrate the groundwater flow velocity and the aquifer dispersion. The aquifer pressure response will also be measured during the start-up period to aid numerical model calibration.

Performance of the Field Evaluation. The design of the field evaluation requires the flexibility to respond to changes in operations dictated by the field data. The constant input of information from field data analysis to process operations begins with the start-up period. Upon completion of the infrastructure construction and system checkout, the start-up period of pumping and injection without lactate addition will begin. The results of the tracer monitoring during this period will give a much better estimate of the residence time for the treatment cell than is currently available. If groundwater velocities are much slower or faster than expected, it may be necessary to adjust flow rates, particularly the injection flow rate at Well TSF-05. Depending on the dilution

of the injected tracer and the dispersivity observed, it may also be necessary to adjust the electron donor injection concentration. The results of the biological nutrient sampling during the start-up period may also affect the preliminary operations strategy.

Once the start-up period is completed and the necessary adjustments have been made to the operations strategy, sodium lactate addition will begin. The design average in situ lactate concentration will be 200 mg/L based on the results of the laboratory studies. The sodium lactate will be pulsed into a continuous 38-l/min (10-gal/min) potable water line at high concentrations two days per week. Pulsing will aid with in situ mixing and should help to prevent biofouling of the injection well because concentrations of sodium lactate in the injection line will be high enough to inhibit microbial growth. The pulsing frequency and concentration can be modified as dictated by the field data to improve the distribution of lactate in situ.

The nutrients required for biomass synthesis that will be considered for injection are nitrogen and phosphorous. In the bioreactor studies, these were added one time in the form of ammonium phosphate, but no further additions were required. Based on this observation, no addition of these nutrients is planned for the initial operations cycle; however, it is possible that sampling during the start-up period or during operations will reveal that one of these nutrients is limiting. In this event, the nutrients will be pulsed into TSF-05 during injection without lactate. Keeping the nutrient and lactate pulses separate should help prevent biomass growth in Well TSF-05 (McCarty and Semprini 1994). If nutrients are added, the carbon:nitrogen:phosphorous ratio of 100:10:1 (Norris 1994) will serve as a guideline for nutrient concentrations.

Monitoring. The monitoring network for the enhanced ISB field evaluation at TAN is shown in Figure 4. The primary monitoring locations are Wells TAN-25, TAN-37, TAN-28, and TAN-29. These wells are considered primary because they are located along the anticipated flow axis and they are completed in an interval similar to the completion of Well TSF-05. Well TAN-37 will be sampled at two depths above 91 m (300 ft) in order to take advantage of its open-hole completion. The secondary monitoring locations are Wells TAN-26, TAN-30A, and TAN-31. These wells are located along less direct flow paths and in the case of TAN-26 and TAN-30A are completed deeper than TSF-05. Finally Wells TAN-D2, TAN-10A, and TAN-27 are included in the monitoring network, but will be sampled much less frequently than the other wells because of their locations relative to the anticipated flow from Well TSF-05 to Well TAN-29.

All of the wells will be sampled using dedicated, low flow, submersible pumps at initial frequencies ranging from biweekly to monthly. The parameters to be monitored and their significance are given in Table 3. The sampling frequency and analyte list may change for a given well based on field data. For example if monitoring data in a given well shows no change after 2 months, sampling may be reduced to a subset of analytes on a less frequent basis.

Data Analysis

The overall objective of the enhanced ISB field evaluation is to determine whether the biodegradation of TCE through ARD can be enhanced through addition of an electron donor supply. The primary criterion established for demonstrating that biodegradation can be significantly enhanced at TAN is the observation of increases in the degradation rate for two consecutive quarters of groundwater monitoring with the final rate equaling or exceeding twice

Table 3. Data quality objectives for enhanced ISB field evaluation sampling.

Parameter	Data Need(s)	Analytical Method	Laboratory ¹	Precision
Bromide	Groundwater velocity, aquifer dispersivity	Ion-specific electrode	Field	±5 %
Water level changes	Aquifer hydraulic response	Pressure transducer and data logger	Field	±0.02 ft
Lactate	Time-varying electron donor concentrations	Ion chromatography	Fixed	±10 %
Acetate/propionate/butyrate	Initial and time-varying reaction product concentrations	Gas chromatography/flame ionization detector	Fixed	±10 %
Chloroethenes	Initial and time-varying chloroethene concentrations	Gas chromatography/electron capture detector	Fixed	±10 %
Chloride	Initial and time-varying reaction product concentrations	Colorimetric	Field	±1%
Ethene/ethane/methane	Initial and time-varying reaction product concentrations	Gas chromatography/flame ionization detector	Fixed	±10 %
Temperature/pH/conductivity	Initial and time-varying reaction product concentrations	Hydrolab probe in flow-through cell	Field	±5% ±3 % ±1 %
Tritium	Initial and time-varying tritium concentrations	Liquid scintillation	Fixed	
Dissolved oxygen	Initial and time-varying electron acceptor concentrations	Hydrolab probe in flow-through cell	Field	±2 %
Nitrate/sulfate/iron	Initial and time-varying electron acceptor concentrations	Colorimetric	Field	±8 % ±1 % ±1 %
Redox potential	Initial and time-varying redox conditions	Hydrolab probe in flow-through cell	Field	±2 %
Carbon dioxide/alkalinity	Initial and time-varying biomass indicator parameter values	Titrimetric	Field	±1 % ±1 %
Chemical oxygen demand	Initial and time-varying biomass indicator parameter values	Colorimetric	Field	±3 %
Phosphate/ammonia as nitrogen	Initial and time-varying biological nutrient concentrations	Colorimetric	Field	±4 % ±20 %

1. Distinguishes between parameters to be measured in the field and those to be measured in a fixed laboratory.

the baseline rate. The biodegradation rate will be estimated using several first-order methods including: graphical extraction, the Buscheck and Alcantar (1995) analytical approach, and the Wiedemeier et al. (1996b) tracer-corrected approach. A numerical model will also be utilized to estimate the rates through inverse modeling.

In addition to the quantitative evaluation criterion, many other qualitative parameters have been identified which will aid in the interpretation of the field evaluation results. In particular the time variations of the following parameters are expected to contribute to the overall analysis: chloroethene concentrations, electron donor concentrations, reaction product concentrations, electron acceptor concentrations, redox potential, biomass indicators, and micro-nutrient concentrations. Performance of the field evaluation will also demonstrate whether the ISB system can be adequately monitored and will provide information that can be used to estimate long-term operations cost. All of this information will be used to make a recommendation regarding the use of enhanced ISB for the final remedial action at TAN. Of course much of the information gathered will also be valuable for evaluating enhanced ISB of chloroethenes at other sites.

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