

Enhanced In Situ Bioremediation

Subsurface Contaminants
Focus Area



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Enhanced In Situ Bioremediation

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Subsurface Contaminants
Focus Area

Demonstrated at
Idaho National Engineering and
Environmental Laboratory
Idaho Falls, Idaho

INNOVATIVE TECHNOLOGY

Summary Report

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine whether a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, worker safety, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available on the OST Web site at www.em.doe.gov/ost under "Publications."

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SECTION 1 SUMMARY

Technology Summary

Problem

Half a century of nuclear weapons production and energy research has left the U. S. Department of Energy (DOE) with a legacy of contaminated soils and groundwater that will cost many billions of dollars to remediate. At many DOE, other government, and commercial sites, chlorinated organic compounds have been used in industrial applications as solvents, cleaners, and degreasing agents. As a result of spills and past disposal practices, these compounds are now found as contaminants in soils and groundwater. Organic contaminants in groundwater are often laterally dispersed over large areas and vertically dispersed to depths hundreds of feet below ground surface. These groundwater contaminants are difficult to treat; the baseline technology of pump and treat is very expensive over the life of the project, often projected to require more than 30–200 years.

At the Idaho National Engineering and Environmental Laboratory (INEEL) Test Area North (TAN), liquid wastes containing sewage, solvents, and radionuclides were injected into the Snake River Plain Aquifer, a sole source aquifer, between 1953 and 1972. Contamination of TAN groundwater was first discovered in 1987 when trichloroethylene (TCE) and tetrachlorethylene (PCE) were detected in drinking water supply wells. Subsequent observations confirmed the presence of TCE, PCE, and 1,2-dichloroethene (DCE) and radionuclides above risk-based concentrations. The groundwater contaminant plume is about two miles long, at a depth of 200-450 ft. Concentrations of TCE in groundwater at TAN range from about 100 milligrams/L (mg/L) in the source zone (approximately 100-ft radius) to 5 micrograms/L ($\mu\text{g/L}$) at the distal end of the plume.

How It Works

The in situ bioremediation (ISB) process (Figure 1) is one that enhances the ability of native microorganisms to degrade subsurface contaminants through biochemical processes. For chlorinated organic compounds, aerobic bioremediation refers to the process of nutrient injection to accelerate aerobic co-metabolism (the contaminants are fortuitously degraded by microbial enzymes without yielding energy or carbon to the microorganisms). Anaerobic ISB, as used at INEEL, involves the use of nutrient injection to accelerate reductive dechlorination reactions to convert chlorinated organic compounds

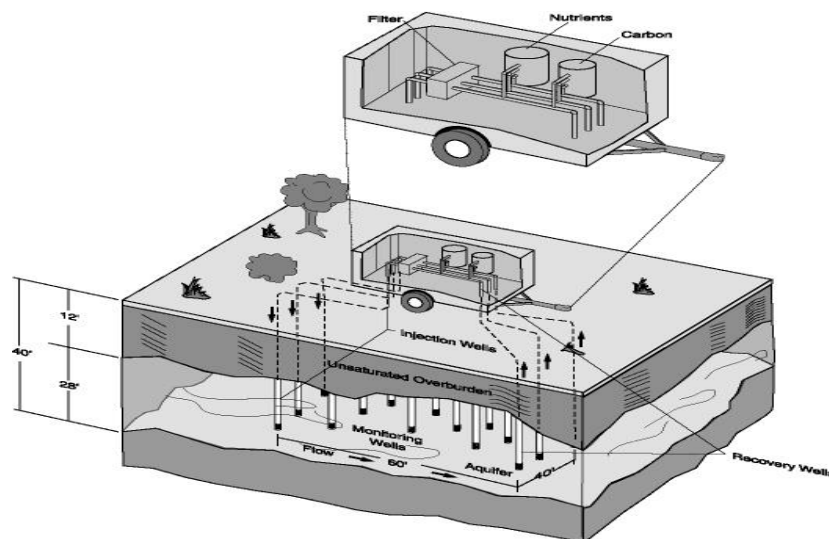


Figure 1. Conceptual picture of in situ bioremediation process.

(chloroethenes in this case) to ethenes. This accelerated reductive dechlorination (ARD) is realized through the addition of nutrients, e.g. sodium lactate, into the contaminant source zone through injection wells to promote ARD.

During the reductive dechlorination process, the chlorinated ethenes act as electron acceptors and thus assist in the respiration process of the microorganisms. The respiration process is carried out in the presence of an appropriate electron donor (food source), providing microorganisms with the energy for growth and cell maintenance. As electrons are transferred to chloroethenes through the microbially-mediated reactions, chlorine atoms are sequentially replaced with hydrogen atoms under anaerobic conditions. Thus, PCE is reduced to TCE, which is reduced to 1, 2-DCE, which is reduced to vinyl chloride, which is reduced to ethene as shown in the following pathway. A sufficient electron donor source (e.g., lactate) is the primary requirement to facilitate this reaction. The technology can be implemented in two ways: in a source area to remove contaminant mass or as a barrier to prevent ongoing migration of a contaminant plume.

PCE ® TCE ® DCE ® VC ® ethene

At INEEL, an ISB system consisting of ARD in the source zone was combined with monitored natural attenuation (MNA) in the dissolved plume. At the INEEL TAN site, an injection system mixed food-grade sodium lactate with potable water to be injected into the aquifer via the former wastewater injection well. Periodic lactate injections are made to accelerate ARD in the source zone.

Down-gradient within the dissolved plume, only groundwater monitoring is performed to confirm the progress of contaminant destruction using natural biodegradation processes performed by indigenous bacteria. A pump-and-treat system was operated down-gradient of the source zone to provide hydraulic containment. Groundwater was extracted and treated with above-ground air stripping.

Potential Markets

The potential markets for this technology includes DOE, DoD, and commercial sites that have moderately permeable, saturated zones contaminated with chlorinated organic compounds.

Advantages over Baseline

ISB has the potential to be a more efficient and cost-effective treatment of contaminated source zones than the baseline pump-and-treat technology. In addition to reducing the cleanup costs and timeframe, ISB destroys the contaminants in situ, thereby eliminating 1) management of secondary waste streams 2) the potential for additional worker or environmental exposure, 3) air emissions, and 4) large, aboveground facilities.

Demonstration Summary

This report covers a 1999–2000 demonstration to treat the source area of the groundwater contaminant plume at the TAN area of the INEEL with in situ bioremediation and the more dilute dissolved plume with natural attenuation. The demonstration was part of an evaluation of five innovative technologies, which could be selected as alternatives or enhancements to the baseline pump-and-treat, in accordance with a Record of Decision (ROD), for Operable Unit 1-07B at INEEL. The ISB field operations consisted of three major activities: electron-donor (lactate) injection, groundwater monitoring, and groundwater pumping and above-ground air stripping.

The deployment site for the one-year operating campaign was the TAN at INEEL in a deep, fractured basalt aquifer. The contaminated aquifer in this area of the INEEL is located between about 210 and 410 ft below land surface and the contaminant source area is about 200 ft in diameter. Groundwater flow is controlled primarily by the distribution of interflow zones consisting of highly vesicular, fractured basalt. The demonstration site characteristics are described in more detail in Section 3, Performance.

Key Results

- At the end of the one-year operating campaign, a report was submitted to the Idaho Department of Environmental Quality and U.S. EPA Region 10, which now have approved the combined ISB/MNA remedy as an alternative to pump-and-treat for remediation of the majority of the plume. An amendment to the ROD is now being reviewed.
- A reduction of TCE to non-detectable levels has been shown in a number of wells, including the original injection (disposal) well and the three monitoring wells where TCE concentrations had been the highest. Continued groundwater monitoring has shown no rebound.
- Analysis of stable carbon isotopes in the TCE showed that the signature of the TCE changed, suggesting that the process directly impacted the source material.
- Monitoring data from the dissolved plume show that TCE is being degraded via MNA with an effective half-life of 10 to 20 years under aerobic conditions, independent of dispersion.
- TCE was observed to be disappearing from the plume faster than both tritium and PCE.
- Characterization of indigenous microorganisms revealed that three physiological groups that have been shown to degrade TCE co-metabolically were present.

Commercial Availability/Status

- The use of sodium lactate (or other similar electron donors) at high concentrations for its ability to enhance bioavailability as well as its electron donor properties is novel and is the subject of the patent. This is being marketed as Bioavailability Enhancement Technology™, or BET™.
- The electron donors used to date (sodium Lactate) are not proprietary; however, the process is. By buying sodium lactate through the licensed distributor, one automatically obtains a “license” to use that material for the proprietary process.
- Separate licenses are not required to use the technology when sodium lactate or other electron donors are purchased from JRW Technologies, Inc., the licensed electron donor distributor.

Contacts

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Other

All published Innovative Technology Summary Reports are available on the OST Web site at www.em.doe.gov/ost under “Publications.” The Technology Management System (TMS), also available through the OST Web site, provides information about OST programs, technologies, and problems. The Tech ID for Enhanced In Situ Bioremediation is 2410.

SECTION 2 TECHNOLOGY DESCRIPTION

Overall Process Definition

The ISB system includes injection and extraction wells, a nutrient injection system, and a groundwater sampling system. The ISB system used for the one-year operating campaign consisted of: a 492 ft-long treatment cell created by one injection well (TSF-05); one extraction well continuously extracting groundwater at a rate of 190 liters/minute located approximately 492 ft downgradient; a nutrient injection system; and eleven monitoring wells. The in situ treatment cell encompassed the original source zone, was approximately 210 ft thick, and was bounded on the bottom by a clay aquitard. Two of the eleven monitoring wells allowed the lower half of the zone to be sampled.

- The first two months of field operation were used to establish baseline conditions of the source zone to refine the injection and extraction parameters.
- A bromide tracer test was conducted to determine the hydraulic communication between the injection well and the monitoring wells.
- The system was designed to operate so that there would be sufficient residence time for degradation of chlorinated organic compounds, and that the nutrient concentration in the injected water would be adequate to facilitate degradation of chlorinated compounds within a sufficient area downgradient of the injection well (Figure 2).

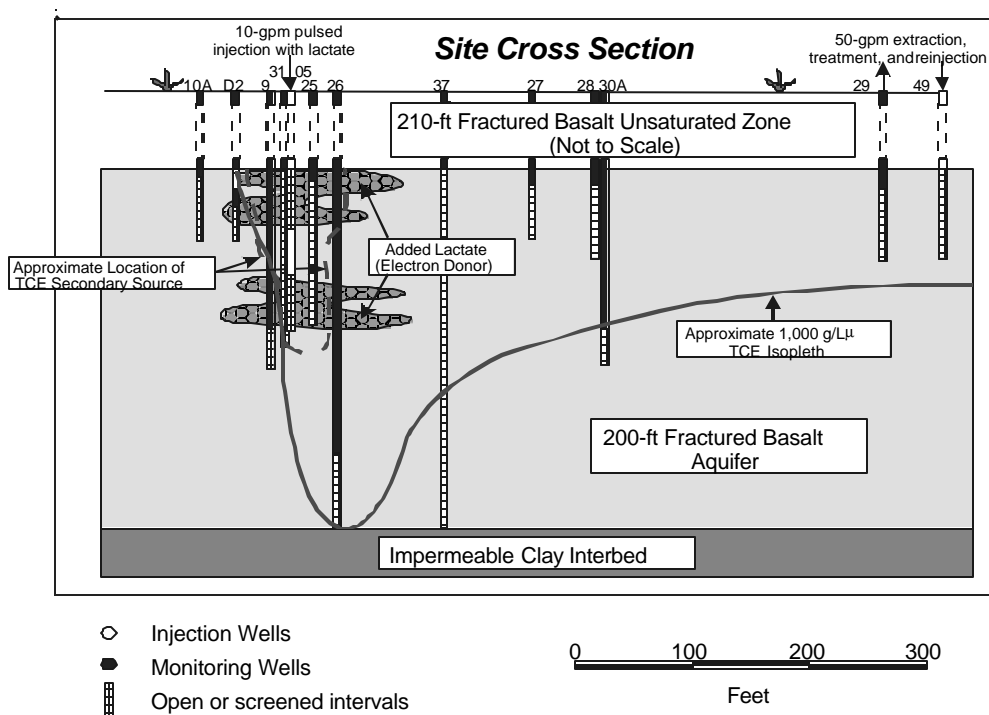


Figure 2. Cross section of the bioremediation field evaluation at TAN.

System Operation

ISB field operations consisted of three major activities: sodium lactate (electron donor) injection, groundwater monitoring, and groundwater pumping and aboveground air stripping and reinjection downgradient.

- Weekly lactate injections occurred from January to September 1999. Four different injection solution concentrations were used, each successive injection becoming more dilute.
- The raw electron donor solution used was food-grade sodium lactate, 60% by weight.
- No lactate was injected from September 1999 to February 2000, because electron donor had accumulated in the aquifer. Following this period, a pulsed injection scheme with bi-monthly injection was found to be sufficient to facilitate ARD. This injection scheme has continued into 2001.
- The initial strategy for injecting lactate was continuous injection of potable water at 10-gpm lactate into the injection well. Potable water injection was discontinued approximately one year after startup, due to a significant reduction in chloroethenes near the injection well.
- During system operation, the groundwater sampling schedule consisted of bi-weekly samples at eight locations with three additional locations sampled on a monthly basis. The analytes for each sample included electron donors, chlorinated ethenes, biological activity indicators, redox parameters, and general water-quality parameters.
- Compliance monitoring ensured that the air-stripper system associated with the pump and treat system reduced VOC concentrations to acceptable levels and that the activated carbon off-gas treatment operated within regulatory limits. Water samples were analyzed for chlorinated ethenes and gross alpha and beta. Air samples were analyzed for chlorinated ethenes.

SECTION 3 PERFORMANCE

Demonstration Plan

Performance of the technology is based upon the one-year demonstration at the TAN of the INEEL.

- The site of the ISB campaign overlies a relatively small region near the source of a two-mile long TCE plume in a fractured basalt aquifer, which lies between approximately 200 and 400 ft below ground surface. Concentrations of TCE in groundwater samples range from 100 mg/L in the source zone (within a 100-ft radius) to five $\mu\text{g/L}$ at the distal end of the plume (Figure 3). The residual source area of contamination is approximately 200 ft in diameter. Vertically, the contamination appears to be isolated between the water table at 210 ft below the ground surface and a continuous, areally-extensive sedimentary interbed located about 410 ft below ground surface.
- Regional groundwater flow at INEEL is generally toward the south-southwest. Locally, in the TAN area, the aquifer appears to be unconfined, although locally confined conditions may exist. Most of the aquifer is composed of numerous, relatively thin basaltic flows with interbedded sediments extending to depths of about 3,500 ft below land surface. Most of the groundwater migrates horizontally through fractured interflow zones that occur at various depths. Water also migrates vertically along joints and the interfingering edges of interflow zones. The effective thickness of the contaminated aquifer at TAN ranges from 200 ft to more than 300 ft.
- The vadose zone extends from the land surface down to the regional water table at a depth of approximately 200 ft. This complex zone at the INEEL consists of surface sediments (primarily clay with silt, with some sand and gravel) and numerous, relatively thin basaltic flows with some sedimentary interbeds.
- Groundwater flow velocity along the plume axis ranges from 0.35 to 0.79 ft/day.
- A bromide tracer test was used effectively to establish baseline conditions within the treatment cell, and to determine the hydraulic communication between the injection well and the observation wells.
- Laboratory studies (using core samples) were demonstrated to be an accurate predictive technique for assessing the presence of indigenous organisms needed for dechlorination.

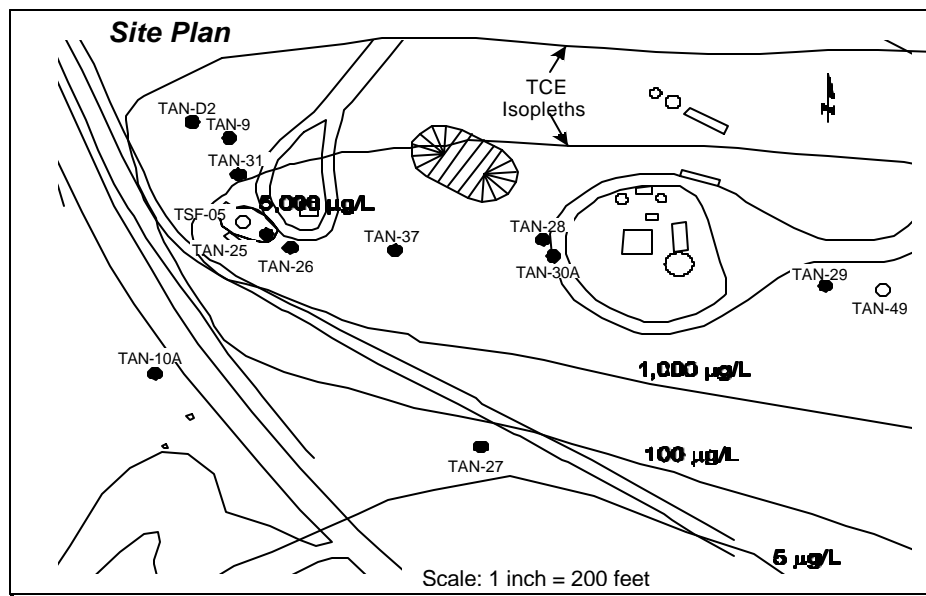


Figure 3. Site plan, including monitoring locations at TAN of the INEEL.

Results

- The operating campaign at TAN demonstrated that reductive dechlorination of TCE can be significantly enhanced by the addition of an electron donor, lactate.
- Figure 4 indicates that Chemical Oxygen Demand (COD) provides a good qualitative indicator of electron donor concentrations over time; redox conditions were successfully manipulated, as measured by concentrations of ferrous iron, sulfate, and methane; and the transformation of TCE to ethene occurred during the campaign.

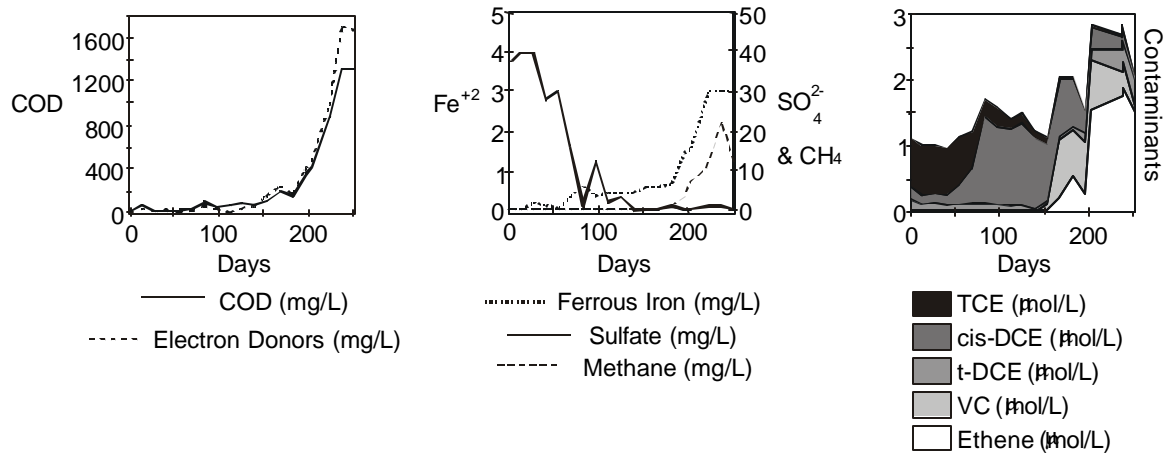


Figure 4. Data monitored in well TAN-31 over 200 days of operation.

- ARD has begun remediation of the TCE source zone, as shown in the before and after maps of TCE in groundwater in Figure 5.

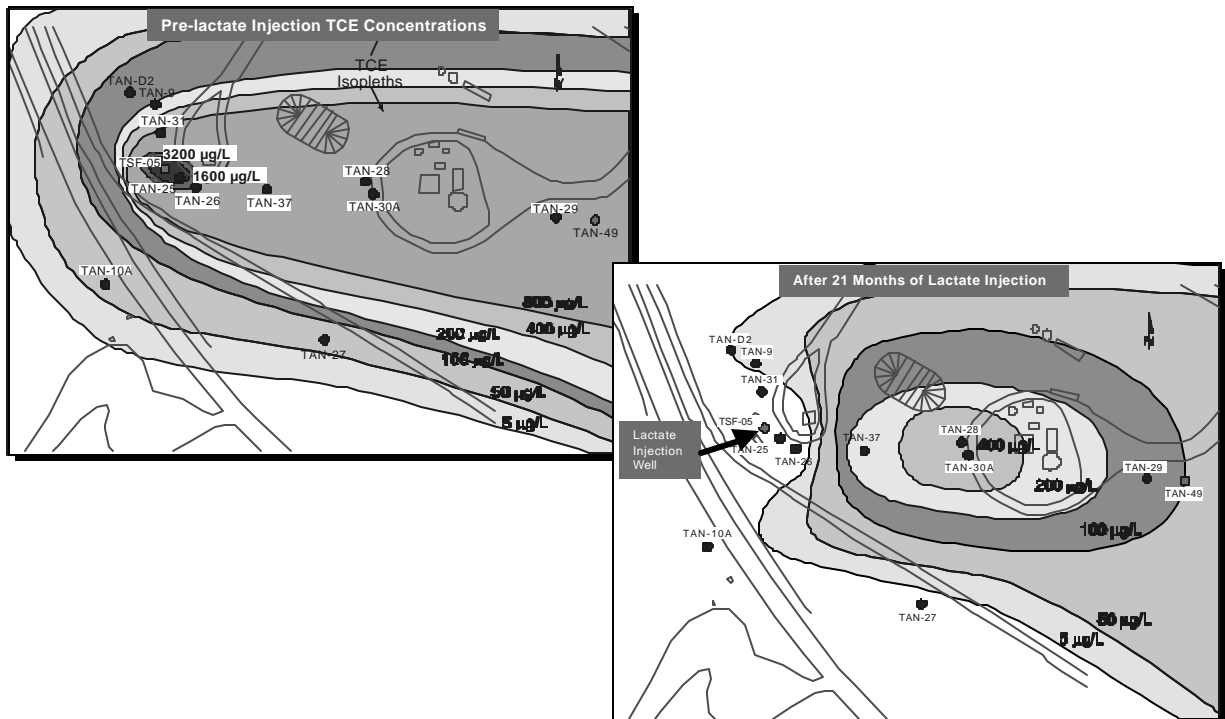


Figure 5. Plume maps of TCE in groundwater before and after one year of ARD operations at TAN.

- Monitoring wells placed both inside and outside the source zone provided a complete assessment of the effectiveness of the remediation.
- The observation of ethene as the final byproduct of the ISB is important, because it demonstrates that the microorganisms are degrading TCE completely to harmless byproducts without accumulation of vinyl chloride.
- In addition to degrading contaminants in the aqueous phase near the source, results indicate that the injection of sodium lactate has accelerated degradation of source material (separate-phase DNAPL). This is an important finding regarding performance of ARD.
- Evaluation of groundwater monitoring data from the dissolved plume indicates that TCE is being degraded with an effective half-life of 10 to 20 years, independent of dispersion under aerobic conditions.
- TCE was found to disappear from the plume faster than both tritium and PCE.
- Characterization of the indigenous microorganisms showed that three physiological groups that have been shown to degrade TCE were present.
- The regulatory agencies have selected MNA as the final remedy for the vast majority of the dissolved plume, based upon the analysis of groundwater monitoring data (Figure 6).

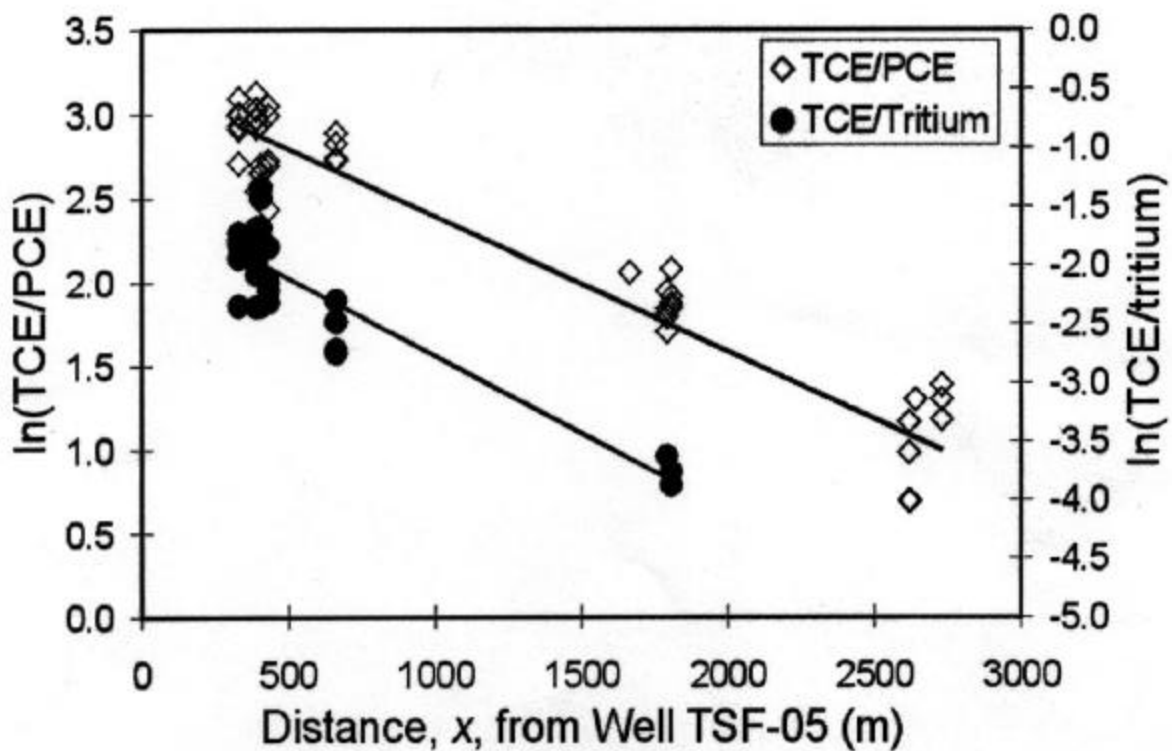


Figure 6. Comparison of TCE concentrations to PCE and corrected tritium along the axis of the plume (after Sorenson, et al., 2000).

SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Competing Technologies

- ISB with aqueous nutrient injection is competitive in cost with the conventional baseline pump-and-treat technology. ISB has been more effective in source remediation at TAN than pump-and-treat.
- Other innovative technologies with potential application for treatment of groundwater contaminated with VOCs and/or DNAPLs include in well vapor stripping, in situ thermal technologies, and in situ oxidation. A summary of attributes of these alternative technologies is presented in Table 1.
 - In Well Vapor Stripping is best suited for sites with contaminants that are sufficiently mobile. The presence of low permeability layers limits the applicability of this technology.
 - In Situ Oxidation can provide relatively rapid reaction and treatment times at sites with hydraulic conductivity greater than 10^{-8} centimeters per second, a depth to groundwater of greater than 5 ft and less than 6 inches of free product on the water table (DOE, 1999). This technology is not applicable at sites with greater than 6 inches of free product, with high organic carbon content, or where the pH is greater than eight (DOE, 1999).
- Accelerated in situ anaerobic bioremediation was successfully demonstrated at the DOE Hanford Site in Washington state in 1995 and 1996.
- Accelerated in situ anaerobic bioremediation was successfully demonstrated at Dover Air Force Base, Delaware from 1996 to 1998.

Table 1. Comparisons of alternative technologies

Technology	Capital Cost	Operating Cost	Waste Mgmt. Cost	Potential Worker or Environmental Exposure?	Contaminant Transfer or Destruction?	Applicable to Source Areas?	Applicable to Large NAPL Volumes?	Applicable to Dissolved Phase?	Potentially Hazardous Materials or Energy?	Risk of Detrimental Source Mobilization?
Pump and Treat	Medium	Low to Medium	Low to Medium	Yes	Transfer	No (except containment)	No	Yes	No	No
Thermal (Steam or Electrical)	High	High	Medium to High	Yes	Both	Yes	Yes	No	Yes	Yes
Chemical Oxidation	Low to Medium	Low to Medium	Low	No	Destruction	Yes	Yes	No	Yes	No
Surfactant or Cosolvent Flooding	Medium to High	Medium	High	Yes	Transfer	Yes	Yes	No	No	Yes
Aerobic Bioremediation	Medium	Low to Medium	Low	No	Destruction	No	No	Yes	Yes	No
Conventional Anaerobic Bioremediation	Low to Medium	Low to Medium	Low	No	Destruction	No	No	Yes	No	No
Anaerobic Bioremediation with Bioavailability Enhancement	Low to Medium	Low to Medium	Low	No	Destruction	Yes	No	Yes	No	No

Technology Applicability

- ISB is effective for remediation of groundwater contaminated with VOCs, including DNAPLs. ISB technology is being deployed at Lawrence Livermore National Laboratory and has been selected for deployment at the Oak Ridge Y-12 site. It is also being deployed at numerous sites outside the DOE complex.

- ISB requires distribution of nutrients within the treatment zone, so low permeability zones may not be treated.
- Aquifer conditions must be suitable to support microbial growth. A microbial community able to degrade chlorinated solvents either anaerobically or aerobically with the addition of appropriate nutrients is preferred for application of ISB.
- ISB with MNA has been shown to treat both the source area and the dissolved plume.

Patents/Commercialization/Sponsor

- The INEEL is working with commercial companies to accelerate application of this technology. A patent application was filed in FY00 for the ISB lactate-injection system (a description of the patent rationale is presented in Section 1).

SECTION 5 COST

Methodology

A preliminary cost analysis was developed by the INEEL using data from the ISB operating campaign at TAN. In order to provide a direct comparison between ISB and a pump-and-treat system, it must be assumed that both must provide source containment. The ISB system will provide this capability through the ARD process, while the pump-and-treat system (New Groundwater Treatment Facility [NGWTF]) will provide this capability by providing a hydraulic containment system with reinjection of the effluent upgradient of the contaminant zone (DOE, 2000).

- The primary assumption regarding ISB is that it degrades the source material and therefore will significantly reduce the operating lifetime that is required for the system (approximately one-half of the lifetime required for the NGWTF [DOE, 2000]). According to studies at TAN, the NGWTF will not remove source material as effectively as ISB and will therefore require a much longer time period for groundwater treatment.
- The ISB treatment system will be comprised of equipment and controls to properly inject the proposed nutrients throughout the hotspot area, including the equipment and piping needed to inject nutrients into five wells. The system will mix sodium lactate with potable water, then inject the nutrient into any of the connected wells. A large nutrient-holding tank, controls and data logging equipment that will automatically distribute the nutrients, metering pumps for nutrient injection, a new enclosure to house the nutrient-holding tanks, and an expanded distribution system are included in this ISB life-cycle cost evaluation.
- The ISB treatment system will be able to continuously distribute the nutrients into the hot spot, and will have freeze protection and heated interior spaces for freeze protection. The system will operate unmanned 24 hours per day, seven days per week.
- The NGWTF will consist of the equipment and piping needed to: pump water from four wells and remove VOCs from the groundwater using an air stripper flow system at a flow rate of 50 gpm. The treated water will be reinjected into the aquifer using one existing well and one new well. The extracted groundwater will be considered Resource, Conservation, and Recovery Act (RCRA) F001 listed waste and all components of the system will meet secondary containment requirements of RCRA.
- The NGWTF will include a 5,000-gallon surge tank, a bag filter system, and an air stripper. A standard model, low-profile air stripper will be used to remove VOCs at an efficiency of at least 99.99% when processing water at 50 gpm. Air Pollution Control (APC), using a carbon filtration system, will be incorporated into the design of the system, although normal operations will not likely require use of the APC. A new building will house the surge tank, air stripper, APC equipment, backwash water tank, pumps, and associated piping.
- The NGWTF will extract groundwater from any of the four wells or a combination of wells at various pumping rates. The total cumulative flow from all four wells will be approximately 50 gpm.
- Because the NGWTF will not remove a significant quantity of the contaminant source, it is anticipated that the system will operate indefinitely. For this Life Cycle Cost comparison, the NGWTF is assumed to be intended for a 30-year operating life, and operation costs are estimated for a period of 30 years. All components within this system will have double containment including external piping.

Cost Analysis

- Capital costs for ISB are estimated to be substantially less than for the NGWTF (Table 2), using either a 1999 or Net Present Value basis. These cost estimates are based upon a ROD amendment.

Table 2. Cost comparisons between original pump-and-treat baseline and ISB/MNA

Cost Basis 1999 Dollars		
Cost Category	Baseline	ISB/MNA
Capital Cost	\$7,300,000	\$3,909,000
Operations Cost	\$55,054,000	\$44,943,000
D&D	2,145,000	\$701,000
TOTAL	\$64,500,000	\$49,544,000
Cost Basis Net Present Value		
Cost Category	Baseline	ISB/MNA
Capital Cost	\$5,910,000	\$3,750,000
Operations Cost	\$36,814,000	\$31,508,000
D&D	281,000	\$152,000
TOTAL	\$43,005,000	\$35,410,000

Cost Conclusions

The estimated Net Present Value cost of implementing ISB at the TAN facility for 15 years would be \$35,410,000 compared to a 30 year Net Present Value cost of \$43,005,000 for the NGWTF, yielding an estimated cost savings of \$7,595,000.

SECTION 6 OCCUPATIONAL SAFETY AND HEALTH

Summary

The baseline technology (groundwater pump-and-treat) presents an exposure risk to site workers from investigation-derived waste, groundwater monitoring well purge water, well-drilling equipment, and groundwater monitoring equipment. ISB technology has similar exposure risks during the initial construction of the injection/withdrawal and monitoring well systems, and similar exposure risks during sampling/monitoring, although the operational period for ISB is significantly less than for pump and treat. During the operation of ISB, exposure to site workers should be significantly reduced from the baseline technology.

Technology-Specific Health and Safety Risks

- There is no unusual health and safety issues related to the installation and operation and maintenance of in situ bioremediation.

Worker Safety

ISB technology does not require any unusual health and safety measures. Routine site safety procedures for site remediation projects may include:

- Level D personnel protective clothing
- applicable OSHA training

Community Safety

- ISB does not produce any significant routine release of contaminants.
- No unusual or significant safety concerns are associated with the transport of equipment, samples, waste, or other materials associated with ISB.

Lessons Learned

All phases of the INEEL ISB field operations were conducted safely and according to all of the applicable guidelines of INEEL's health and safety program. Although the ISB process exposes workers to investigation and monitoring-derived wastes and requires the use of well-drilling equipment, no accident occurred during the field operations.

SECTION 7 REGULATORY AND POLICY ISSUES

Regulatory Considerations

Permits required to deploy ISB depend on the specific application and on state and/or federal requirements. Early and continuous discussions with regulators will encourage expedited permitting and implementation of the technology.

- No specific permits were required for the ISB operational campaign at the TAN area of INEEL.
- The operating campaign at TAN was completed as part of a required evaluation of five innovative technologies as alternatives or enhancements to the baseline pump-and-treat technology under a 1995 CERCLA RI/FS Record of Decision (ROD).
- An amendment to the INEEL OU 1-7B ROD has been submitted to the regulatory agencies for approval to incorporate ISB as the final remedy for the source area and MNA as the final remedy for the distal zone.

Risks, Benefits, and Community Reaction

- ISB does not produce any significant routine release of contaminants.
- No unusual or significant safety concerns are associated with the transport of equipment, samples, waste, or other materials associated with ISB.
- No harmful microbes were detected at the TAN site after biostimulation.
- The public comments on the Proposed Plan that described the ROD amendment selecting ISB and MNA were overwhelmingly in favor of the replacement of pump-and-treat with the innovative technologies.

Environmental Impact

- Surface disturbance from ISB is minimal.
- The biomass in groundwater and the COD are significantly increased during implementation of ISB, but both will naturally decrease once nutrient addition ceases at the conclusion of the cleanup.
- Nutritional enrichment does not promote the growth of harmful microbes at the TAN site.

Socioeconomic Impacts and Community Perception

- ISB has minimal economic or labor force impact.
- ISB is viewed by the public as a preferred and acceptable technology.

SECTION 8 LESSONS LEARNED

Implementation Considerations

- The electron donor (sodium lactate) was distributed well beyond the source area, but the distribution was not uniform. This distribution must be improved for long-term operations. At TAN, a second injection location is being added to solve this problem. A primary objective of pre-design ISB studies must be to develop a cost-effective method for optimizing distribution of nutrients (electron donors) in the treatment zone.
- At TAN, a combination of field and laboratory analyses (rather than using more expensive EPA methods) provided near real-time data collection needed to optimize nutrient injection strategies. Comparison of the TAN monitoring to three existing protocols for ARD showed that some analytes specified in the protocols could be omitted and that equivalent data for others could be obtained using less expensive, real-time, field methods.
- For any in situ remediation approach, distribution of amendments (i.e., heat, steam, oxidants, etc.) throughout the residual source is a key issue.
- Monitoring wells should be located both within and outside the source area to evaluate the effectiveness of the remediation.

Design Issues

- Site geology (particularly permeability and heterogeneity), concentrations of native nutrients (such as native total organic carbon), and natural oxidation potential of the subsurface (i.e. aerobic or anaerobic conditions) are critical factors that will determine injection protocols, remediation system siting, and monitoring requirements.
- The frequency and mass of nutrient addition required for long-term operations must be estimated prior to ISB system design.
- Injection of nutrients in a pulsed manner was found to be more effective than continual injection in facilitating ARD.

Technology Limitations and Needs for Future Development

- Better mechanisms for effective distribution of nutrients into low-permeability zones of an aquifer are required to broaden the applicability of ISB remediation.
- The results of the INEEL ISB demonstration may not be directly applicable to other sites with appreciably different microbial populations or contaminant characteristics.

Technology Selection Considerations

- This technology can yield significant economic and efficiency gains over the baseline pump-and-treat technology for source remediation of groundwater contaminated with VOCs.
- Laboratory and pilot-scale studies must first be conducted to evaluate the ability of native microbial populations to degrade the target contaminant of concern.

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APPENDIX B
ACRONYMS AND ABBREVIATIONS

APC	Air Pollution Control
ARD	Accelerated Reductive Dechlorination
COD	Chemical Oxygen Demand
DCE	1,2 Dichloroethene
DNAPL	Dense, Non-aqueous Phase Liquid
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
EM50	DOE Office of Science and Technology
EPA	U.S. Environmental Protection Agency
INEEL	Idaho National Engineering and Environmental Laboratory
ISB	In Situ Bioremediation
mg/L	Milligrams Per Liter
MNA	Monitored Natural Attenuation
NGWTF	New Groundwater Treatment Facility
OST	Office of Science and Technology
PCE	Perchloroethylene
RCRA	Resource, Conservation, and Recovery Act
ROD	Record of Decision
TAN	Test Area North
TCE	Trichloroethylene
TMS	Technology Management System
µg/L	Micrograms Per Liter
VC	Vinyl Chloride
VOC	Volatile Organic Compounds