

# U.S. EPA TECHNICAL SUPPORT PROJECT TECHNICAL SESSION SUMMARY

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Technical Support Project

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## U.S. EPA TECHNICAL SUPPORT PROJECT CO-CHAIRS

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Sharon Hayes, Region 1 • William Rothenmeyer, Region 8 • Neil Thompson, Region 10

### Ground-Water Forum:

Richard Willey, Region 1 • Bernie Zavala, Region 10

### Federal Facilities Forum:

Stacie Driscoll, Region 3 • Jim Kiefer, Region 8 • Chris Villarreal, Region 6

## TABLE OF CONTENTS

Welcome and Introductions .....	1
Thermal Remediation: Mechanisms, Principles, and Case Studies Eva L. Davis, U.S. EPA, Ground Water and Ecosystems Restoration Division - Ada .....	1
Wyckoff Superfund Site–Thermal Remediation Pilot Study Maryjane Nearman, RPM, U.S. EPA Region 10, and Kathy LeProwse, U.S. Army Corps of Engineers, Seattle District, and Gorm Heron, SteamTech .....	2
DNAPL Characterization Overview Bernie Kueper, Queen’s University .....	7
Options for DNAPL Source Area Containment John Guswa, GeoTrans, Inc. ....	9
Chlorinated Solvent DNAPL Source Area Remediation–East Gate Disposal Yard, Fort Lewis, Washington Richard Smith and Kira Lynch, U.S. Army Corps of Engineers, Seattle District .....	10
In-Situ Flushing Technologies Michael Annable, University of Florida .....	13
In-Situ Chemical Oxidation: Theoretical and Practical Considerations Scott Huling, U.S. EPA, Ground Water and Ecosystems Restoration Division - Ada .....	15
Enhanced Bioremediation for Treatment of Chlorinated Solvent Source Areas—Case Studies and Implications Kent Sorenson, North Wind, Inc. ....	17
Performance Assessment and Forecasting Lynn Wood, EPA, National Risk Management Research Laboratory-Cincinnati .....	19
Forecasting Benefits of Flushing Remediation Carl Enfield, EPA, National Risk Management Research Laboratory-Cincinnati .....	20
DNAPL Source-Zone Remediation: What Is the Case for Partial Source Depletion? Suresh Rao, Purdue University .....	21
Western Region—Hazardous Substances Research Center Dr. Lewis Semprini, Oregon State University .....	22
Interstate Technology & Regulatory Council Ana Vargas Arizona Department of Environmental Quality, Mike Smith Vermont Department of Environmental Conservation, and George Hall, ITRC Program Adviser .....	24
Superfund Basic Research Program: A Program Update Larry Reed, National Institute of Environmental Health Sciences .....	25

Microbial Transformation of TCE in Anaerobic Ground Water  
    Jennifer Fields, Oregon State University ..... 26

PARTICIPANTS LIST ..... 27

## **Welcome and Introductions**

Neil Thompson (Engineering Forum co-chair, Region 10) and Bernie Zavala (Ground Water Forum co-chair, Region 10) welcomed TSP members and friends to the spring 2003 meeting of the Technical Support Project (TSP). Neil and Bernie introduced three senior managers from Region 10 who provided opening remarks.

Janis Hastings (Director, Office of Environmental Assessment, Region 10) welcomed the TSP to Seattle and noted that Region 10 is proud to host and support the TSP. She stressed how important the three forums are to facilitating technology transfer between and among the Regions, Headquarters, and the EPA laboratories. The forums help the technical staff in the Regions do their jobs better. Janis noted that the issue papers produced by the forums are extremely useful tools for Regional staff.

Rick Albright (Director, Office of Waste & Chemicals Management, Region 10) remarked that his job is made easier when trained staff use the proper tools to conduct sound science. His staff's interactions with the Technology Innovation Office (TIO), the TSP, and EPA laboratories help place the proper tools in the right hands. He highlighted the importance of technology transfer by briefly discussing how the TSP provided critical support to his office at two sites in Region 10, one of which had indoor air issues. He also acknowledged the TSP's contributions to the monitored natural attenuation guidance and added that the TSP helps Regional managers and technical staff make better decisions.

Mike Gearheard (Director, Office of Environmental Cleanup, Region 10) indicated that he has not had the pleasure of doing "hands on" technical work like many members of the TSP, but he nonetheless has great admiration for the work the forums undertake. EPA always wins when hard decisions are made using sound science, and the TSP often provides the foundation for that sound science. Mike noted that the Wyckoff Superfund site on Bainbridge Island has presented Region 10 with fascinating technical challenges. He was pleased that the forums were going to witness first-hand the complexities of the site. In addition to NAPL problems at Eagle Harbor, the Region as a whole must deal with many other difficult emerging issues, including radiation, sediments, solvents, perchlorates, and, most recently, homeland security.

## **Thermal Remediation: Mechanisms, Principles, and Case Studies**

Eva L. Davis, U.S. EPA, Ground Water and Ecosystems Restoration Division - Ada, OK

Eva Davis provided an overview of thermal remediation technologies and introduced subsequent presentations on steam injection and electrical heating methods. Thermal technologies are considered aggressive techniques that have been found effective for addressing volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs). They have been applied successfully to recover non-aqueous phase liquid (NAPL) in diverse lithologies and fractured bedrock settings. The application of thermal technologies depends on the physical properties of the contaminants, such as density, viscosity, vapor pressure, and solubility. For VOCs, the increase in vapor pressure with temperature is the most important mechanism for recovery during thermal remediation, while for SVOCs the viscosity reduction and displacement are the most important recovery mechanisms.

VOCs recovery from the subsurface will be enhanced by steam distillation and steam stripping. Steam distillation occurs when two liquid phases are present. Because both phases contribute to the vapor pressure, the boiling point of the combined liquids is less than that of either individually. When a VOC NAPL and water are present, they will boil at a temperature less than that of water. Steam stripping facilitates the separation of dissolved phase VOCs from the water. Rapid volatilization of dissolved-phase contaminants occurs due to their high Henry's constants. Boiling off small amounts of water can

reduce dissolved phase concentrations of VOCs by orders of magnitude. Mechanisms for recovering VOCs include vaporization (the most important), solubilization, reduced adsorption, and increased diffusion from low permeability zones, while recovery of contaminants such as creosote occurs through NAPL mobilization (the most important), vaporization, and increased dissolution.

Steam injection has the added recovery mechanism of displacement—both of liquid- and vapor-phase contaminants—and can be used for both VOCs and SVOCs. The contaminated area is surrounded by injection wells which force contaminants toward extraction wells in the center. Steam injection is effective both above and below the water table, but is favored by deep injections and bulk soil hydraulic conductivities greater than  $10^{-5}$  cm/s. To mitigate the potential downward movement of DNAPL, a hot floor can be established below the DNAPL (to volatilize VOCs that might move downward) or air can be co-injected with steam to eliminate the condensation front and thus the DNAPL bank. Dr. Davis described a steam injection test conducted at the Loring AFB Quarry Site, a site with complex fractured bedrock and no overburden. Extensive characterization of the bedrock and contaminant distribution was carried out, and based on this a steam injection and extraction system was designed. This characterization effort showed that the bedrock had a much lower permeability and frequency of fractures than expected, and thus steam injection rates were low, and the area was not heated completely. The maximum temperature measured in the subsurface was 47°C. Despite the low temperatures, significant increases in the rate of extraction of contaminants in both the liquid and vapor phase were achieved during the short term demonstration, showing the potential for steam injection remediation of VOCs in fractured limestone.

Electrical resistance heating is a thermal technology that relies on electrical resistance of soils to produce heat. Traditional six-phase heating is conducted through six electrodes, typically installed in a 15- to 40-foot array, with a seventh neutral electrode centered within the array. All of the electrodes can also serve as vents. Heating temperatures are limited to the boiling point of water; if the water boils off, the soil can't carry the electric current. Heated contaminants are volatilized and are collected at the vent as vapors. Full-scale application of this technology now more commonly uses three-phase heating methods. It is applicable to low-permeability soils. Heating occurs most rapidly in zones of low permeability when applied in areas with a range of soil permeabilities. Dr. Davis described a pilot test of electrical resistance heating in a highly contaminated area at the Silresim Superfund site. The results showed a 94% reduction in VOCs without causing contaminations to migrate downward.

Dr. Davis concluded by explaining when laboratory treatability studies for thermal remediation technologies should be used and summarized the results of the treatability study for steam injection at the Wyckoff Superfund site. The study was particularly successful for naphthalene, a prevalent contaminant at the site.

**To view Dr. Davis' presentation for more details, click here.**

### **Wyckoff Superfund Site—Thermal Remediation Pilot Study**

Maryjane Nearman, RPM, U.S. EPA Region 10, and Kathy LeProwse, U.S. Army Corps of Engineers, Seattle District, and Gorm Heron, SteamTech

Mary Jane Nearman (Region 10) has been an EPA RPM for 16 years but has only recently been named RPM for the Wyckoff/Eagle Harbor Superfund site. She explained the history of contamination at the site. Wyckoff is a 50-acre former wood-treating site located at the mouth of Eagle Harbor on Bainbridge Island, Washington. The Wyckoff facility began operating in the early 1900s and continued treating wood until it closed in 1988. As a result of the wood treatment process and the use of large

creosote lagoons, surface and subsurface soils as well as ground water were contaminated with creosote and other compounds. An estimated total of 1,000,000 gallons site wide of product remain in the soil and ground water beneath the site, with 60,000 gallons of creosote in the pilot area.

In July 1987, EPA listed Wyckoff as a Superfund site. A ground-water extraction and treatment system was constructed at the site and has been operating since 1988. A 1997 remedial investigation found elevated levels of PAHs, pentachlorophenol (PCP), and dioxins in soil and ground water, and in seeps on adjacent beaches. These contaminants are present in dissolved form, as light non-aqueous phase liquids (LNAPLs), and as dense non-aqueous phase liquids (DNAPLs). The most severe contamination detected is in the upper aquifer. Contaminant concentrations in the lower aquifer are low, but data is limited and this area is not well characterized.

The initial cleanup proposal for the site called for traditional containment with pump and treat. The State of Washington, however, became concerned that long-term O&M costs would be too high. At the request of the community, EPA looked at steam injection—an in-situ thermal remediation technology that actively treats the soil and ground water by removing mobile contaminants. Steam injection is also expected to enhance biodegradation of contaminants so that residual contaminant concentrations will not adversely impact the marine environment. The pilot project, which covers an approximate 1-acre area, began in October 2002 and ran six months. Complications involving the onsite water and vapor treatment plant have suspended operations until the system can be redesigned.

Kathy LeProwse (USACE), who has been working at Wyckoff since 1993 when a portion of the sediments in Eagle Harbor were capped, summarized earlier work at the site. The Wyckoff/Eagle Harbor site is divided, for program purposes, into four operable units: West Harbor, East Harbor, Wyckoff Soil, and Wyckoff Ground Water. In 1995-96, all tanks and buildings on the Wyckoff site were removed with the exception of the water treatment facility. The following year, four dock structures were removed. A year later, the 800-ft. long west dock was removed. In 2000, an additional cap was put in place. Along the eastern edge of the property, four major seep areas have been identified. In the seep at the former log rafting area, divers have removed 1,500 gallons of free product over the years. A sheet pile containment wall has been installed around the perimeter of the site (as deep as 95 feet), allowing for the restoration of an intertidal beach on the west side of the property. The sheet pile components, which were installed using vibratory and impact hammers, are up to 104-feet long with no splices at the deepest locations. USACE began the design phase of the in-situ thermal remediation project in 2000. With the help of several thermal design consultants, including SteamTech, they designed the pilot study with two goals: 1) to determine if thermal technologies will work at Wyckoff; and 2) to collect data for use in a full-scale design for the site.

Gorm Heron (SteamTech) described the steam injection system constructed for the Wyckoff pilot. Steam is injected into 16 injection wells and removed via seven extraction wells. When fully operational, the system injects approximately 12,000 pounds of steam per hour into the ground. The maximum liquid extraction rate is 80 gpm, and the vapor extraction rate is 300 scfm. Dr. Heron mentioned that electrical resistance heating (ERH) of the underlying aquitard was considered, but was not attempted during the first phase of the pilot because modeling indicated that ERH was not necessary to obtain steam contact with the aquitard. He said the team might consider ERH to heat the aquitard in the future.

Once extracted, the vapor and liquid (including mobilized NAPL) are transferred to an effluent treatment system. The vapors are transferred either to a Thermox unit or to the boiler where they are heated to 1500-1600°F and destroyed. The water is treated by induced air floatation and biological

treatment, followed by multi-media filters and activated charcoal filtration. Following treatment, NAPL is transported to a hazardous waste disposal area, while the treated water is discharged to Puget Sound. A vapor cap consisting of a gravel layer, a gravel layer with perforated piping, a geomembrane, and another gravel layer was installed inside the pilot area for safety and visual reasons and to reduce odors. In addition, 60-70 fiber optic temperature sensors, thermocouples and pressure transducers were installed across the pilot area and just outside the pilot area to monitor subsurface conditions.

The performance expectations for the pilot were to demonstrate the removal of mobile product and to demonstrate that ground-water concentrations at the point of compliance will not exceed marine water quality limits or sediment standards. Currently, the effect of the tides on the mobile product is to pull creosote into Puget Sound twice a day. This has been slowed temporarily by the installation of a sheet pile wall.

The operational strategy of steam injection is to disturb the NAPL equilibrium so that both mobile and immobile NAPL can be moved by steam. Operation targets include establishing hydraulic and pneumatic control, heating the target volume, optimizing mass removal until NAPL recovery drops off, optimizing vaporization and mixing through pressure cycling (turning off steam to reduce pressure so that sand grains release energy and boil water so that the gas phase exerts a push out), and conducting a controlled cool down and transition to a polishing technique.

After six months of operation, the pilot was stopped. Monitoring had indicated that the steam temperatures were not well distributed along the edges of the pilot area, and higher temperatures were needed across the site. The measured anisotropy factor was closer to 5:1, rather than the 20:1 factor used in modeling, so it was clear that higher steam injection rates were needed in some areas. Even a full-scale pumping test, conducted afterwards, failed to predict the measured anisotropy factor. In addition, the pilot experienced some down time due to equipment failures. Fouling of extraction wells occurred due to the buildup of naphthalene wax, and chemical incompatibility with equipment was a problem.

Mary Jane Nearman presented preliminary conclusions. To date, lessons learned at the site include:

- Waste reduction and treatment system design must be robust;
- Contracting mechanism must allow for flexibility in scope;
- QA on selection of materials for chemical incompatibility is required;
- Contingency funding must be available at start up;
- Team should plan for design modifications in the field;
- Need a team to watch the subsurface and digest data daily.

The system will be restarted later in 2003.

**To view the Wyckoff presentation for more information, click here.**

## Questions and Answers

*Question:* When can you declare victory with the steam injection system?

*Answer:* Victory at Wyckoff can be declared when: (1) mobile product is removed to the maximum extent possible; (2) an acceptable residual source term is achieved (surface water protection); and (3) the site meets the State's residential cleanup standards in the top 15 feet.

*Question:* How did you evaluate the portions of the containment walls where the seams were not welded?

*Answer:* We installed three observation channels on the pilot wall and eight on the outer wall to measure water flow outward through the sheet piles.

*Question:* By mobilizing stable DNAPL, don't you increase the risk that contaminants will migrate offsite?

*Answer:* Mobilization occurs at every site where thermal remediation is used. This is an important concern that must be monitored carefully, but mobilization is necessary if DNAPL is to be extracted from soil or ground water. That's why hydraulic control is important. You must also ensure that you don't run out of money while the NAPL is mobile—you must collect and extract what you mobilize.

*Question:* How did you monitor potential migration from the upper aquifer to the lower aquifer?

*Answer:* Five monitoring wells in the deep aquifer were sampled before and during the injection. During system operation, the water moves upward through the aquifer, which is good for hydraulic containment. However, the upward movement of cool water impedes heating near the base of the aquifer. Options to address this problem include electrical resistance heating (metal wells are a problem though), installing more injection wells in the cold spots, and injecting steam below the aquitard.

### **Field Trip to Wyckoff/Eagle Harbor Superfund Site**

Following the introductory presentations, TSP participants took a tour of the Wyckoff Superfund site and the steam injection facility. Staff from Region 10, the U.S. Army Corps of Engineers, and site contractors who were familiar with site operations led participants through six stations at the facility and summarized operations.

#### **Water Treatment Facility**

Cliff Leeper (Operations Management International, Inc.) explained that the wood treating facility operated for almost 100 years before EPA took over the site in 1993. The onsite water treatment facility, part of the pump and treat system, has operated since 1988. System influent, containing 35-45 mg/L total PAHs, enters a new induced air floatation thickener for oil and suspended solids treatment. It then passes through an aqueous equalization tank and activated sludge system, which remove over 99.9% of the PAHs and 98% of the PCP. Before the water is discharged to the sound, it is passed through Multimedia filtration and granular activated carbon units as a final polishing step. A unique feature of the facility is that the brackish water contains an extensive microbial population that aids in reducing pollutant concentrations. In the future, the treatment system will be augmented with a crystallizer or API separator in order to treat spikes of naphthalene.

The discharge water meets the ppb-level discharge limits. The sludges from the system are pressed, drummed, and sent to a hazardous waste incinerator. There are no air monitoring requirements on the aeration system.

#### **Computerized Monitoring**

In the onsite trailer computer room (housed in a trailer), Mike Bailey (USACE) showed data displays of the various monitoring instruments used at the site. There are 631 subsurface monitoring points associated with the steam injection pilot: 464 thermocouples and 67-fiber optic sensing points. In



addition, 16 pressure transducers were installed—one in each of the seven extraction wells and nine not in extraction wells. The transducers installed in the extraction wells work well because they were installed using conventional filter packs. The other nine, which have since been replaced, failed originally because they were installed using techniques from the dam-building industry. A high-temperature grout was used with 40% silica flour that penetrated the transducers.

Above ground monitoring—both automated and manual—includes liquid flow, vapor flow, temperature, and pressure gauges. Total organic carbon of the system influent is also monitored.

One laptop in the computer room is dedicated to fiber optic monitoring. The fiber optic sensors are located along two loops, and the data from each are downloaded once daily. The fiber optic system runs continuously and it takes about 10 minutes to query and download data from one loop. A second computer is used to collect data from the other monitoring instruments. A Microsoft Access database is used to merge all the data.

### Well Field

Gorm Heron (SteamTech) pointed out the vapor cap covering the approximate one-acre area. The 16 injection wells and 7 extraction wells were drilled through the cap. Steam is carried to the injection wells via an insulated pipe from the operations building. The injection is regulated to 15-20 psig per well. A vapor extraction pipe applies a vacuum to each extraction well and transports the vapor back to the building. During the pilot, naphthalene precipitation created problems for the vapor extraction system. Heat from the extracted fluids is removed in a heat exchanger, which in turn pre-heats the feed water to the steam generator.

The aquitard beneath the upper aquifer that is being treated by the steam injection is 15 to 20 feet thick. The aquitard is about 20 feet bgs near the operations building and dips north toward Puget Sound.

### Boiler Building

Rick Smith and Rich Fink (USACE) explained how equipment in the boiler building is used to produce steam for the pilot. Water pumped from a 500-ft deep aquifer is first passed through a water softener, de-aerated to remove oxygen, and chemically treated to resist corrosion of the boiler. The boiler super heats the water, and the steam is injected into the pilot area with the goal of heating the subsurface to 130°C. The steam both mobilizes and volatilizes the DNAPL. The vapors are extracted, and the non-condensable vapors are transported to a heat exchanger before sending them to the thermal oxidizer or incinerating them in the boiler. The liquids are cooled by a liquid heat exchanger and sent to the water treatment system.

### Sheet Pile Wall

Kathy LeProwse (USACE) explained that the sheet piles used to construct the perimeter sheet pile wall are made of interlocking sections of 5/8-inch thick steel made in the United Kingdom. The wall is set five feet into the aquitard. Due to the dip of the aquitard, the depth of the wall range from 45 to 95 feet bgs. The wall cost \$5 million for materials and installation.

## Beach Remediation and Revegetation Area

Mary Jane Nearman (Region 10) explained that approximately \$7 million was spent to cap sediments in the harbor and revegetate the beach. The beach must be maintained in perpetuity by whomever purchases the property, and institutional controls will remain. The Bainbridge Island community is happy that EPA is attempting steam injection to clean up the Wyckoff facility and the beach, and hopes to turn the property into a park, including a Japanese war memorial. The Wyckoff property has been appraised at \$8 million.

### **DNAPL Characterization Overview**

Bernie Kueper, Queen's University

Bernie Kueper emphasized the importance of adequate DNAPL characterization in order to answer key questions about remediating a site:

- Should any mass removal be pursued?
- If so, what technology should be employed? and
- Will a containment system still be required?

Determining whether mass removal is necessary and which technology to use will depend on several factors, such as whether the source includes moving or pooled DNAPLs and how the dissolved plume will be affected by mass removal. The affect of mass removal on the plume could have a positive or negative effect on risk values; therefore, the source zone must be adequately characterized. Dr. Kueper's presentation mainly covered the characterization of DNAPL distribution and DNAPL properties, although he noted that aquifer properties and the effectiveness of any current remediation system must also be characterized.

DNAPL composition can range widely at a site, which can markedly affect its properties and thus, behavior across the site. Raoult's Law is used to calculate the effective solubilities of the DNAPL components from their measured concentrations. The effective solubilities can then be used to evaluate the possible presence of DNAPL and the evolution of the plume with time. Other properties of DNAPL, such as density, viscosity, and interfacial tension, should also be measured to help evaluate DNAPL mobility, whether the DNAPL may be present as pools or residual, and potential pool heights. Another useful property to measure is the wettability of the DNAPL, which determines whether the DNAPL tends to spread or bead up. Capillary pressure has an important effect on DNAPL flow. In order for a DNAPL to flow into a pore space, the capillary pressure must exceed the displacement entry pressure.

The amount of pooled versus residual DNAPL present at a site affects the need for mass removal as well as the technology used. Pooled DNAPL is present to some degree at all DNAPL sites. They are easily mobilized and have a small DNAPL-water surface area available for mass transfer. Thus, removal technologies such as oxidation, enhanced bioremediation, and surfactants may not be optimal for pooled DNAPL. Numerous factors, including interfacial tension, DNAPL density, and hydraulic gradient, influence the formation of pools and pool heights. Less dense DNAPLs such as coal tar and creosote form higher pools. Using concentration data to determine whether or not a pool or residual DNAPL is present will not work—visual observation of cores and wells, identification of site conditions favorable to pool formation, and determining if soil concentrations exceed calculated thresholds are key to an accurate determination. Dr. Kueper noted the equation for a calculated threshold. If concentrations in the soil exceed the calculated threshold, then DNAPL is present in the sample. For a multi-component NAPL, NAPL is considered present if the sum of the mole fractions of

the components is greater than one, and the calculation does not require knowledge of the DNAPL composition.

It is also important to determine the mobility of the DNAPL and the time scales of migration. Fluid density and viscosity strongly influence time scales. Due to its lower density and higher viscosity, a coal tar DNAPL moves more slowly than a solvent DNAPL, but is likely to still be moving at a site. Other factors include the DNAPL-water interfacial tension, the medium permeability, the volume and duration of the release, etc. There are several indicators of mobile DNAPLs including the persistent appearance of sheens or NAPL in receiving water bodies and the unexplained recent appearance of a VOC breakthrough curve in a monitoring well.

Dr. Kueper summarized a field experiment where a few gallons of TCE were poured onto the ground and soil cores were drilled in the spill location. The results illustrated how just a small distance between soil sampling locations could mean the difference in finding or missing the presence of DNAPL. A second example showed how the difference in well screen length and screened interval could impact the concentrations of NAPL detected. Although long-screened wells increase the chance of encountering a pool of DNAPL, dilution could affect the findings if a pump is used to collect the sample. Using a series of diffusion samplers would help avoid this problem.

High solubility compounds are preferentially depleted early from multi-component DNAPLs. As these compounds are depleted, the relative concentrations of others rise, and total VOC concentrations (and mass flux) will decrease with time. This trend in monitoring wells indicates the presence of upstream DNAPL. The effect of flow direction change can affect concentrations of DNAPL compounds. If flow direction change (e.g., due to pumping) does not result in a reduction of concentrations in a well, then DNAPL may be present at that location.

The vertical extent of DNAPL is difficult to determine in fractured rock, and in reality, remedy choices must be made at fractured rock sites without knowing how deep DNAPL has migrated. Capillary pressure builds up quickly with depth in a bedrock structure. The aperture required to stop migration of DNAPL into bedrock decreases sharply with depth for coal tars/creosote and solvents. Once a DNAPL penetrates a fracture, forward diffusion into the rock matrix can occur. The potential for back diffusion from the rock matrix into the ground water has several implications for remediation. Back diffusion takes longer than forward diffusion and can lead to decades of back diffusion and increased remediation times. The potential for back diffusion can be evaluated by measuring field parameters, such as matrix porosity, matrix dry bulk density, and matrix fraction organic carbon, and by estimating fracture spacing and when the matrix was first exposed to contaminants. Fracture spacing can be estimated by drilling both vertical and angled cores and using various downhole video techniques, straddle packer testing, and multiple monitoring intervals. Time scales for back diffusion can be estimated using simple analytical solutions.

In conclusion,

- The lateral extent of a DNAPL source zone can be estimated using converging lines of evidence. The likelihood of pools being present can be estimated.
- The depth of DNAPL in fractured rock cannot, in general be delineated very easily.
- Through careful investigation, the parameters required to make decisions regarding the implementability of mass removal technologies can be assessed, but not necessarily the prediction of benefits.

## **Options for DNAPL Source Area Containment**

John Guswa, GeoTrans, Inc.

John Guswa subdivided containment technologies into three main groups: stabilization/fixation, physical barriers, and hydraulic barriers. The first step in the design selection process for containment is to characterize the hydrogeologic setting and identify where the contaminants are present within it. The next step is to examine the available technologies and pick the most likely to succeed based on criteria such as the required barrier dimensions, type of bottom (e.g., rock or clay), and whether it can be built and operated cost effectively. The selected technology will depend on its compatibility with the chemicals of concern and on its geotechnical needs—more specifically, the nature of the geologic materials along the path of the barrier and the nature and continuity of the materials the barrier will be keyed into.

After choosing the most applicable technology, the containment system can be designed. Barrier design requires a thorough understanding of both where the chemicals of concern are and how they got there, as well as how the barrier is going to alter the groundwater flow system. It is typically necessary to install some form of long-term performance monitoring system to ensure the barrier is performing as designed and that the conceptual model of how the flow system will react is still accurate. Long-term barrier monitoring can be done by evaluating changes in ground-water quality downgradient from the barrier, comparing piezometric head data of wells upgradient and downgradient of the barrier, and/or by placing measuring devices within the barrier wall itself to evaluate physical/chemical changes over time.

For many DNAPLs, stabilization/fixation or solidification will not be appropriate. However, for some DNAPLs under certain site-specific conditions, these containment technologies might be appropriate. Dr. Guswa cited an example of a site in Florida that had shallow soil contamination consisting of LNAPLs and PCB oils. Using large-diameter augers with overlapping holes, the soil was mixed with concrete to produce a large, thick concrete pad.

Physical barriers are generally vertical and are designed to contain or deflect NAPL and/or ground water. They can also be used to reduce the pumping rates needed to contain ground water behind a barrier. Physical barriers can be constructed from a variety of materials, including steel sheet piles with sealable interlocks, HDPE geomembranes, slurries (soil, bentonite, cement), and grout injection.

In the past, steel sheet wall design suffered from leakage at the joints. Technologies have since been developed that reduce or eliminate leakage. The Waterloo Barrier™ is a steel sheet wall that is designed to be sealed after placement. The wall is generally effective to a depth of about 80 feet, except in rocky or very dense soils. Following placement of the sheet pile sections, the joints are cleaned with a water jet and then sealed from the bottom up with a sealant selected based on the contaminant and intended use. Funnel and gate barriers are designed to direct contaminated ground water through a treatment zone. They have the advantage that they are low maintenance and can treat, in-situ, a variety of dissolved-phase contaminants. In an example provided, it cost \$250,000 for a pilot program to treat a few hundreds parts per billion of chlorinated organics with a barrier 12-foot long and 3.5 feet thick. Dr. Guswa said one of the disadvantages of treatment barriers is that they have not been deployed long enough to be able to evaluate their long-term performance. Possible problems also include reduction in permeability due to chemical precipitation and/or biofouling. Underflow is also a potential failure mechanism. Performance monitoring can be designed to address this issue.

The typical slurry wall is constructed by trenching with a backhoe. The trench is initially filled with a bentonite/water mixture to prevent it from collapsing and to provide a filter cake seal along the walls. As the trenching proceeds, the actual slurry mixture is added and allowed to set. Unless the wall is hanging and designed to stop a shallow material like an LNAPL, its bottom must be keyed into a low-permeability aquitard such as a clay or competent rock layer.

Grout walls, which are more expensive than slurry walls, are generally constructed using drill rigs and injection tools in a closely spaced array. The holes are drilled and grouted in a pre-specified pattern with several lines of holes designed to ensure full subsurface coverage.

A final technique for emplacing physical barriers is deep soil mixing. Deep soil mixing barriers consist of overlapping columns created by a series of large-diameter, counter-rotating augers that mix in-situ soil with additives—usually a bentonite or cement grout—which is injected through the augers.

Dr. Guswa also described two types of hydraulic barriers: in-situ recirculation wells and common pump and treat systems. He emphasized the importance of ensuring that the capture zone of the wells encompass the region to be contained and provided a description of the methods for assessing it.

## Questions and Answers

*Question:* With regards to the pilot that cost \$250,000, since the success of the wall is based on chemistry and hydraulics, couldn't much of the pilot be done in the laboratory rather than the in-situ pilot?

*Answer:* Since this was one of the earlier walls that was installed, the installation and testing was very conservative. As more reactive barriers are installed and monitored, there is increased acceptance of them. Consequently, much of the detailed pilot testing is no longer required. In the future, costs may go down further, but you still need performance monitoring of how it works at the site in terms of keying into aquitards and hydraulics.

*Question:* If a regulator sees a proposal for installing a reactive wall without the pilot study should they reject it?

*Answer:* Not necessarily. You can evaluate overall design without a pilot study, but depending upon the site, a pilot may be needed. It is also possible to build the wall in sections or phases and evaluate their performance before constructing the whole wall.

## **Chlorinated Solvent DNAPL Source Area Remediation—East Gate Disposal Yard, Fort Lewis, Washington**

Richard Smith and Kira Lynch, U.S. Army Corps of Engineers, Seattle District

Richard Smith described the operational and site investigation histories of the logistics center at Fort Lewis, a large military installation situated 55 miles south of Seattle, Washington. He also summarized the site conceptual site model and the Phase I and Phase II tools used in the dynamic site characterization of the Fort Lewis Logistics Center source area.

The Logistics Center, currently used for logistics and vehicle maintenance, was originally the location of a motor base in 1942, and then later used as an ordnance depot. Logistics Center wastes (mostly cleaning and degreasing solvents and POLs) were disposed in trenches or burned from 1946-1970. In 1983, EPA confirmed the presence of TCE and DCE originating from the Air Force Base in wells at a housing development north of the facility. Between 1984 and 1986, an additional TCE plume was

found under the logistics center. Site investigation activities showed that the TCE was part of a 13,000-foot-long plume (5  $\mu\text{g/L}$  contour) in the upper Vashon Aquifer and was emanating from beneath the East Gate Disposal Yard (EGDY) located southeast of the Logistics Center.

The Corps completed an RI/FS in 1988, and a ROD was signed in 1990 designating pump and treat the preferred remedy, although not enough information was available to determine if TCE was present in the lower Sea Level Aquifer. In 1992, the Phase I design was completed and installation of the extraction wells began. Between 1994-95, Phase II construction of the treatment and infiltration systems was completed, and a lower aquifer study was undertaken. The pump and treat system began operating in 1995, and the system performance was evaluated in 1998. It was determined that the Sea Level Aquifer was contaminated and the pump and treat system was not containing the entire source area; thus, TCE from the source was able to bypass portions of the pump and treat system and enter the Sea Level Aquifer. In 1999, a Phase I source area investigation was conducted to confirm the presence and general location of DNAPL. In 2000, an engineering evaluation/cost analysis (EE/CA) was completed to evaluate remedial alternatives to accelerate cleanup and reduce costs. The preferred alternative was to: (1) optimize the pump and treat system to capture the plume; (2) remove the source area drummed NAPL; and (3) thermally treat DNAPL hotspots. The following year, a Phase II expanded site assessment was initiated at EGDY. By 2002, an addendum to the original risk assessment was prepared, and a thermal treatment contract awarded for the plume at EGDY.

The conceptual site model for EGDY shows ground-water flow towards the town of Tillicum and the American lake. TCE plumes present in both the Vashon and Sea-Level Aquifers extend into under Tillicum. The ground-water contours for the Sea Level Aquifer are much steeper than in the Vashon. Seven Three Fort Lewis water production wells (used for drinking water and cooling systems) screened in both aquifers have been placed on standby. Geology across the site is characterized by complex stratification of glacial and non-glacial units. Buried channel facies pinch out abruptly.

Site characterization at EGDY involved a dynamic investigation approach, systematic planning, and real-time data collection using qualified field personnel. The site investigation was conducted in two phases due to funding constraints: Phase I in 1998-99 and Phase II in 2001-02. The main Phase I DQO was to determine if DNAPL was present beneath EGDY. Aerial photography and EM-61 were used to identify the locations of disposal trenches. The EM-61 results showed did not locate all the trenches observed in the aerial photos, and the photos did not locate all the contaminated areas found by EM-61. Soil gas sampling was also conducted, but the difference in concentrations between known clean areas and trenches was not significant unless the soil gas sample was collected immediately above NAPL. Exploratory trenches found buried drums and both chlorinated and non-chlorinated NAPL. Contouring of drive point ground-water sampling results showed three major hotspots and concentrations exceeding 10,000  $\mu\text{g/L}$ . Source removal involved excavating over 1,000 drums and 50,000 pounds of TCE DNAPL.

The primary Phase II DQO was to obtain data for the design of the NAPL thermal treatment. SCAPS lithium induced fluorescence was used to locate petroleum, oil, and lubricants (POLs), but was not capable of pushing to the required depth in the dense gravelly soil. Geoprobe's membrane interface probe (MIP) was also used for both the POLs and chlorinated VOCs; the probe worked well despite gravel layers, but did not penetrate as deep as desired. Sonic coring was used to penetrate the very deep gravel and helped locate both continuous and discrete sources of NAPL.

## Questions and Answers

*Question:* Does the plume extend beneath buildings? If so, did you monitor indoor air?

*Answer:* Yes. The potential for indoor air exposures has been modeled, which indicated no significant risk via the indoor air exposure pathway. No indoor air sampling has been performed to date. Indoor air was tested at these buildings, but no problems were found.

*Question:* What was the total amount of TCE in the dissolved plume?

*Answer:* We estimate 13,000 pounds of TCE and 1,000 pounds of DCE.

*Questions:* Is it possible that drilling wells created pathways along which NAPL could migrate downward?

*Answer:* All of the wells were telescoped and grouted to prevent that from happening. Whenever possible, we used techniques that would minimize the potential for contaminant transport. We stopped drilling if we encountered pools of NAPL.

### Kira Lynch, U.S. Army Corps of Engineers, Seattle District

Kira Lynch continued the discussion of Ft. Lewis by detailing the work done to remediate the three major hotspot source areas found during characterization activities. She began by noting that an addendum to the risk assessment had to be prepared since the original risk assessment did not consider the potential for vapor intrusion, exposure to soils in the EGDY, the use of the lower aquifer for drinking water, or ecological impacts to a nearby creek. Unacceptable risk values were calculated for the soil exposure pathway and the use of the lower aquifer for drinking water. Although the lower aquifer is not currently used, some wells may be at future risk and the site is in a sole source aquifer area. Ms. Lynch noted that although risks were acceptable for the indoor airway, this result could be different if houses were built above the plume in the future.

Most of the calculated risk was driven by the presence of TCE. Therefore, the three areas with the highest percentages of NAPL mass were targeted for treatment. The estimated treatment volumes ranged from 20,100 yd<sup>3</sup> at NAPL Area 3 to 52,200 yd<sup>3</sup> at NAPL Area 2. In general the top of the treatment areas was the ground surface; the bottom ranged from about 30-40 feet bgs. Area 2 was divided into three subareas with different bottom depths: a, b, and c. The top of Subarea C was about 10 feet bgs. It was estimated that 50,000 pounds of TCE source was removed during drum excavation, but approximately 140,000 pounds remain in the three areas. The NAPL contained different percentages of TCE in each area due to disposal differences.

Ms. Lynch explained the contracting mechanism for thermal treatment of the source area needed to be very flexible and did not specify whether electrical heating or steam heating would be needed. In the design/build solicitation, the contractor would take responsibility for their own design. The solicitation specified that the treatment would proceed sequentially so that lessons learned could be integrated.

After summarizing the contract performance requirements and the in-situ thermal team, Ms. Lynch indicated that construction of an electrical resistance heating treatment system will begin in July 2003 at Area 1. Electrical shakedown will begin in October, and the treatment period is estimated for November 2003 through April 2004. An array of 106 electrodes wells will be installed in Area 1. Multi-phase extraction wells will extract ground water, DNAPL, and vapor, and the data will be available on the web in real time.

Collaborations with ESTCP and SERDP are planned to evaluate: (1) several alternative dissolved-phase treatment technologies; (2) alternative or supplemental source zone treatment technologies; and (3) evaluate tools to measure mass discharge before and after treatment so that impacts of source treatments and the risks of a residual source can be determined.

Ms. Lynch explained that the primary driver for source area treatment is the reduction of risk; however, a decrease in source longevity, lower O&M costs, a shortened time frame for plume management, an increase in natural attenuation potential, and a reduction in mass discharge to reduce risk to the lower aquifer are also goals. The total costs for thermal remediation are \$15.3 million (about \$160/cy), assuming a 60-day heating period. These costs include hydraulic control, mobilization/demobilization, construction/deconstruction, analytical, and O&M. Costs for hazardous waste disposal, electrical consumption, treatment time, and the savings from lessons learned are yet to be determined.

**To view the Fort Lewis presentation for more details, [click here](#).**

### Questions and Answers

*Question:* Will you monitor the decrease in interfacial tension as the temperature is increased?

*Answer:* Yes, by taking water level measurements in the 20 monitoring wells to show hydraulic control, and by installing deep wells.

*Question:* Do you anticipate problems with heating till and gravel in the subsurface due to differential heating of the units?

*Answer:* No, because we can direct heat better with electrical heating.

*Question:* Will you verify the results of the Johnson-Ettinger model (conducted to assess indoor air risks) by collecting indoor air samples?

*Answer:* Yes, this is under negotiation.

*Question:* Are you aware of the recent lower slope factors used in the model.

*Answer:* Yes, we were aware of the new slope factors during the risk assessment. Our team conducted a sensitivity analysis and the results of the risk assessment were the same in regard to acceptable vs unacceptable risk.

*Question:* Why was electrical heating selected over steam heating?

*Answer:* Both were feasible at the site and would have met requirements, but electrical heating was more economical based on the bids received by the government.

### **In-Situ Flushing Technologies**

Michael Annable, University of Florida

Michael Annable's presentation on in-situ flushing covered both surfactant and cosolvent flushing techniques. Previously, the focus of in-situ flushing remediation was on how much material could be removed; the focus is now shifting toward how the removal of material changes a system's mass flux and the shape and size of the dissolved fraction plume. There are many types of surfactants and cosolvents that provide the ability to control fluid properties like interfacial tension, solubilization capacity, and viscosity. Surfactants increase solubility linearly, whereas cosolvents increase solubility exponentially. The injection fluid for surfactant flushing generally contains less than 5% of a



surfactant, and neutral buoyancy is possible. Using surfactants in combination with isopropanol cosolvent is also common. Injection fluids for cosolvent flushing generally have a high percentage ( $\geq 70\%$ ) of alcohol. As a result, the agent is less dense than water and has rapid dissolution kinetics.

Dr. Annable described two field studies conducted at Hill Air Force Base in the mid-1990s: in-situ flushing with a cosolvent (ethanol) and with a surfactant/cosolvent mixture. The contaminants of concern were aviation fuel hydrocarbons and chlorinated solvents. In the surfactant/cosolvent flood, nine pore volumes were cycled through the test area with mobilization of the contaminants appearing toward the end of the first pore volume and the great majority of the contaminants appearing during the second pore volume. Mobilization tapered off to nearly zero by the fourth pore volume. Mobilization of individual contaminants in the cosolvent flood was spread across more pore volumes as a result of their different solubilities.

At Dover Air Force Base, a cosolvent flushing demonstration was conducted in 1999 in a test cell surrounded by a sheet pile wall. PCE was injected into the subsurface at known points and recovered using an ethanol flushing mixture. The flushing was conducted for 30 days, and the contaminated ethanol was recycled. Approximately 60% of the injected PCE was recovered. A partitioning interwell tracer test (PITT) was conducted before and after the flushing. The PITT predicted 60 liters of PCE were present in the cell when 85 had been injected. After the flushing, the PITT predicted 5 liters remained whereas 25 to 30 liters were not recovered.

In 1998, a cosolvent flushing pilot test was conducted at the Sages Dry Cleaner site in Jacksonville, Florida. DNAPL was present at the site from 8 to 9.5 m bgs with the ground water table at 2 m bgs. CPT cores were collected from an area about 3 m by 7 m to estimate the amount of PCE present and determine where to target the flood. The cores were tested every 2 inches, and the profile that emerged was a series of high-concentration lenses overlying soils with minor permeability contrasts—a distribution that is difficult to accurately characterize. A PITT was also conducted to estimate the amount of PCE present. Three injection wells and six injection wells were subsequently installed. The injection wells were packed off to allow them to inject water on top of the aquifer and inject ethanol into the bottom target zone. The recovered solution was not recycled but was treated onsite with a stripper and micro porous polymer units. 43 L of PCE were recovered, which is a 63% removal based on the PITT, and a 65% removal based on soil core data.

The Sages site has a multilevel ground-water monitoring system in the source zone and the downgradient plume. It took over a year for the source zone wells to show an impact from removal of the source. This time delay will generally occur in all but very fast moving ground water as the system needs to equilibrate and flush. Over four years of collecting data, a significant drop in the concentrations of dissolved PCE (flux reduction of about 47%) has occurred. Dr. Annable described two methods for measuring flux: the Tübingen method where a transect of wells is pumped for a period of time and the contaminant concentrations in the effluent are measured, and the flux meter borehole method where sorbent devices are placed in wells for specified periods of time and then removed and tested for the contaminants of concern. The rate of dissolution of tracers in the sorbents can be used to estimate ground-water velocity.

For source management, the cosolvent flushing has removed the more accessible fraction of the DNAPL, which has resulted in a drop in dissolved contaminant concentrations. The drop in dissolved concentrations should reduce the time/distance needed to meet ground-water quality objectives. The presence of residual alcohol has also changed the area's redox conditions so that the PCE is

undergoing reductive dechlorination. This biodegradation process has resulted in a marked increase in 1,2-*cis*-dichloroethene concentrations.

**To view Dr. Annable's presentation for more details, click here.**

### Questions and Answers

*Question:* What was the cost of the Sages pilot?

*Answer:* The pilot cost around \$400,000 for a 25 x 10 x 10-foot zone.

*Question:* Did you perform any hydraulic conductivity testing at the site before and after flushing?

*Answer:* No, but there were no changes in head before and after flushing.

*Question:* You noted an increase in DCE concentrations, did you recalculate the change in risk?

*Answer:* No.

*Question:* At the Dover site, the pre- and post-flush PITT tests underestimated mass. Do you know why?

*Answer:* There might have been some areas that were not accessible to the tracers.

*Question:* Should enough ethanol be injected so that some remains at the end of a flood to promote biodegradation?

*Answer:* At the end of the flood, there was about 1-5% alcohol left. Three to four years later, there is still some alcohol in the ground. They are considering periodic injections of more alcohol though.

*Question:* Did you detect any vinyl chloride during the pilot?

*Answer:* Vinyl chloride is being generated, but only after three years. However, the concentrations are rising.

*Question:* Should high permeability zones be targeted for remediation?

*Answer:* It might be a good idea, but locating these zones may be challenging.

### **In-Situ Chemical Oxidation: Theoretical and Practical Considerations**

Scott Huling, U.S. EPA, Ground Water and Ecosystems Restoration Division - Ada

Scott Huling provided an overview of Fenton and permanganate chemistry and presented guidelines and recommendations to consider when conducting bench- and pilot-scale treatability studies and full-scale applications of in-situ chemical oxidation—specifically, in-situ Fenton oxidation (ISFO) and in-situ permanganate oxidation (ISPO). ISFO is based on the injection of Fenton's reagent—hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) and  $\text{Fe}^{2+}$ , or  $\text{H}_2\text{O}_2$  alone—into the subsurface, which react to form hydroxyl radicals. The hydroxyl ions ideally break down organic contaminants to  $\text{CO}_2$ ,  $\text{Cl}^-$ , etc. ISPO involves the injection of sodium or potassium permanganate. The permanganate ion ( $\text{MnO}_4^-$ ) reacts with organic contaminants and ideally breaks them down to  $\text{CO}_2$ ,  $\text{Cl}^-$ , etc., plus a manganese oxide precipitate.

Both ISFO and ISPO have potential limitations that were identified and must be considered to understand whether the technology is appropriate and whether site-specific improvements to the technology can be made, if necessary. Because  $\text{Fe}^{2+}$  is often the rate limiting constituent to radical production, vendors may inject ferrous iron to enhance radical production. Additionally, the optimum pH range for ISFO is 3-4, and ground-water pH may require adjustment. Due to the reactive transport

of oxidant reagents, in some instances, some vendors have injected stabilizer reagents to enhance the transport distance of  $\text{H}_2\text{O}_2$  and  $\text{Fe}^{2+}$ . The relatively fast reaction of  $\text{H}_2\text{O}_2$  in the subsurface results in short transport distances and low concentrations. Greater injection rates, shorter distances between injection wells, and pH reductions may be used to enhance the transport distance of  $\text{H}_2\text{O}_2$  in the subsurface.  $\text{MnO}_4^-$  reacts more slowly than  $\text{H}_2\text{O}_2$ , which offers some advantages over ISFO, however, some limitations still exist. For example, potassium permanganate purchased commercially may have trace levels of heavy metals (chromium and arsenic). As a result, lower concentrations of permanganate solutions may be required to avoid exceeding MCLs in ground water, or more expensive remediation grade permanganate may be needed. In addition, ISPO is not as aggressive an oxidant as the hydroxyl radical and is less reactive for certain target compounds, such as TCA, DCA, carbon tetrachloride, chloroform, methylene chloride, benzene, chlorinated benzene, PCBs, and some pesticides. The production of manganese dioxide precipitate can form crusts on DNAPL limiting mass transfer.

Laboratory treatability tests are important for ISFO and ISPO to quantify the extent of oxidation given the potential limitations. If significant contaminant reduction does not occur using reasonable quantities of oxidant reagents, under reasonable environmental conditions, at bench-scale, it is unlikely it will occur at field-scale. Treatability tests also can help identify undesirable reaction byproducts as well as changes in metals mobility (e.g., the oxidation of  $\text{Cr}^{3+}$  to  $\text{Cr}^{6+}$ ). Dr. Huling summarized a list of guidelines for conducting both bench-scale and pilot- and field-scale applications of ISFO and ISPO. He noted how heterogeneities in the subsurface, such as complex stratification and wide ranging hydraulic conductivity values can affect the transport of injected chemicals to contaminated areas. Non-ideal conditions such as these may require multiple injections to improve transport and also to address possible contaminant rebound. It is important to adequately characterize the distribution of target contaminant(s) in order to accurately identify the location(s) where the oxidant should be delivered. Since there is a high probability of contaminant rebound, long-term monitoring and multiple applications of oxidant reagents should be planned and budgeted.

The reaction of  $\text{H}_2\text{O}_2$  is exothermic and significantly elevated temperatures can result, which decreases the viscosity of DNAPL (increasing mobility) and increases volatilization, solubility, and desorption. SVE can be used as a complimentary technology with ISFO to capture and treat the volatiles. The heat and oxygen can improve conditions for aerobic degradation of contaminants; however, the microbial population can also be adversely affected by the addition of peroxide and permanganate, which are both antiseptics. Microbial populations and rates of degradation have been reported to increase following chemical oxidation, but recovery times will vary.

The cost of Fenton's reagent is generally cheaper than permanganate (\$0.26/pound vs. \$1.40-\$4.95/pound), but both offer numerous advantages and disadvantages that must be considered on a site-specific basis. In conclusion, bench-scale testing provides useful information to evaluate how site-specific various parameters may influence the success or failure of the technologies. Preferred monitoring parameters should be measured for proper performance monitoring of field applications. The potential for enhanced mass transport and volatile emissions must be recognized and addressed.

**To view Dr. Huling's presentation for more details, [click here](#).**

## Questions and Answers

*Question:* Would ISPO be useful for immobilizing NAPL (i.e., due to  $\text{MnO}_2(\text{s})$  encrustment) at sites where the location(s) of NAPL in the porous aquifer could not be determined?

*Answer:* When DNAPL is encrusted with manganese dioxide ( $\text{MnO}_2(\text{s})$ ), it is not necessarily sealed off. Therefore, mass transfer may be impeded, but the DNAPL will still dissolve into the water and would not be sufficiently “immobilized.”

*Question:* Is the  $\text{MnO}_2(\text{s})$  encrustment permanent, or will it dissolve?

*Answer:* The long term effects of manganese dioxide encrustment on DNAPL have not been fully investigated and I do not know what geomorphological changes could occur. ISPO is an emerging technology, so there is a lot to learn about these mass transfer conditions.

## **Enhanced Bioremediation for Treatment of Chlorinated Solvent Source Areas—Case Studies and Implications**

Kent Sorenson, North Wind, Inc.

Kent Sorenson summarized recent research that indicates that in-situ bioremediation may be extremely effective for chlorinated solvent source areas. Several studies have shown that in-situ bioremediation enhances mass transfer of contaminants through at least three mechanisms:

- Bioremediation of dissolved contaminants sets up a maximum concentration gradient so that clean water moving past the DNAPL quickly reaches the saturation concentration;
- The solubilities of the solvent and the reductive dechlorination degradation products increase as the dechlorination process continues greatly increasing the maximum aqueous contaminant loading; and
- The electron donor solution can be used to decrease interfacial tension, and appears to increase effective solubilities through a cosolvency effect.

The first two mechanisms have been demonstrated in laboratory batch studies and a column study, which showed a 5- to 6-fold increase in mass removal of chlorinated ethenes with reductive dechlorination as compared to abiotic washout. The third mechanism has been shown to be successful in laboratory studies using sodium lactate as the electron donor. The process, which is being patented, is called “Bioavailability Enhancement Technology™” (BET). Although the process appears to be correlated to interfacial tension, the mechanism hasn’t been defined.

Dr. Sorenson described a field study conducted at the Idaho National Engineering and Environmental Laboratory (INEEL) which showed enhanced mass transfer due to the interaction of concentrated sodium lactate with nonaqueous TCE followed by complete reductive dechlorination. The TCE is within a deep fractured basalt aquifer, which overlies an impermeable silt interbed. The dissolved plume is nearly 2 miles long, and the source area is about 200 feet in diameter. Treatability studies for alternative technologies to pump and treat—including in-situ bioremediation—were conducted. Sodium lactate was injected into the aquifer across a range of frequencies and concentrations. Ultimately, large batches (i.e., 20,000 to 50,000 gal at about 3% by weight) at lower frequencies (i.e., about every 2 months) were found to provide the most efficient degradation. For the first two years, a downgradient extraction well was pumped continuously at 50 gpm to create a hydraulic treatment cell for containment of the source area and to control residence time. Extraction was discontinued once it was determined not to be necessary.

Chemical oxygen demand (COD) was used as a surrogate measure of electron donor distribution. Results indicated the most COD in the deeper part of the aquifer. In reductive dechlorination, redox conditions often limit dechlorination beyond *cis*-DCE. In this case, the onset of methanogenesis corresponded exactly with the dechlorination of *cis*-DCE to vinyl chloride and ethene. Within three months of the lactate injection, there was a significant reduction in of TCE; within 21 months, there

were non-detect levels of TCE in six wells. Investigators also looked at long-term dechlorination. Significant dechlorination to ethene was observed at the injection well, and nearly complete dechlorination to ethene was observed in downgradient wells. In order to show that enhanced mass transfer was occurring rather than physical displacement, tritium concentrations were measured at the wells, and concentrations remained stable with time. Because tritium was also present in the source material, this indicated that chlorinated ethenes were preferentially being removed from the source. Another line of evidence for reductive dechlorination was the decrease in the amount of  $^{13}\text{C}$  in TCE, while the amount in *cis*-DCE and other degradation products increased. It appears fresh TCE with more  $^{12}\text{C}$  was being exposed as the outer, weathered “rind” was degraded. The success of the treatability study led to in-situ bioremediation replacing pump-and-treat as the remedy for the source area in a 2001 ROD amendment.

Chitin (ground shrimp and crab shells) was tested as a long-term amendment for accelerating reductive dechlorination in a variably saturated source area at the Distler Brickyard site in Louisville, Kentucky. TCE concentrations were lower than at INEEL, and pump and treat was not effective at the site due to the low permeability of the fine-grained alluvium (FGA). Reductive dechlorination was occurring in the FGA, but not enough to prevent migration to the coarse-grained alluvium (CGA) below.

Laboratory column studies conducted with chitin prior to the field effort showed that volatile fatty acids from chitin enhanced PCE dissolution after 101 days and supported anaerobic reductive dechlorination. In the field test, delivery of the chitin to the contaminants was enhanced by hydraulic fracturing. The chitin was injected in a sand/slurry mixture creating fracture zones at three intervals below ground surface. Tiltmeter monitoring showed that the fractures did not propagate well in the upper zone in a more sandy unit, but propagated well in the lower two silty clay zones. After nine months, significant concentrations of volatile fatty acids remained, and the chlorinated compounds were reduced to below MCLs at three of five monitoring wells.

In conclusion, Dr. Sorenson emphasized that delivery of the electron donor to the source is a driving factor for effective bioremediation in source zones and summarized factors that affect the ease of delivery. In addition, he noted that the radius of influence of the injection wells is very important in determining the appropriate number of wells needed to reach the source. Two rate constants affect the cleanup timeframe: (1) how quickly the dissolved contaminants are biodegraded; and (2) how quickly the source is dissolved. Increasing the biodegradation rate of the dissolved contaminants by adding an electron donor increases the rate the source is dissolved, thus decreasing cleanup times.

**To view Dr. Sorenson’s presentation for more details, [click here](#).**

## Questions and Answers

*Question:* When will the Phase 2 report for the chitin project be available?

*Answer:* The first year of results will be ready in time to present at the 2004 Battelle conference.

*Question:* Did the tiltmeter results from Distler Brickyard indicate the fractures were horizontal?

*Answer:* No. There was preferential propagation along of fractures along approximately 45° angles. The orientation is affected by site-specific soil conditions. While the chitin distribution is limited to the fractures, the presence of volatile fatty acids, reducing conditions, and enhanced dechlorination in all of the monitoring wells indicates that the effect of the chitin was widespread.

*Question:* Is the source zone at INEEL well-monitored?

*Answer:* There are about thirteen monitoring locations within 250 feet of the original waste injection well. Due to the high costs of drilling monitoring wells (\$100 thousand/well), it is cost prohibitive to drill many more. In addition, the permeability of the aquifer is very high, so the site can be viewed on a larger scale than most sites.

*Question:* What amendment will you use in the planned Fort Lewis bioremediation demonstration?

*Answer:* We are planning on using lactate, but may move to a donor that decreases interfacial tension even more with the hope of increasing the apparent cosolvency effect.

## **Performance Assessment and Forecasting**

Lynn Wood, EPA, National Risk Management Research Laboratory-Cincinnati

Lynn Wood explained that the purpose of his presentation was to give his perspective on DNAPL source remediation performance assessments. The typical DNAPL contaminant area is represented by a small source with a very large dissolved plume. It would make sense to address the small source area in order to impact the plume size. However, Dr. Wood questioned whether the proper assessment and monitoring data are being collected to determine the impacts of remediating the source area.

Traditional source treatment assessment has focused on changes in the source zone with regards to mass removal, dissolved contaminant concentrations, and soil contaminant concentrations.

Dr. Wood suggested that a more encompassing assessment be made. The focus should not be on source mass reduction alone, but on how mass reduction affects the mass flux response, the dissolved plume, and risk. He suggested that aggressive source remediation such as thermal remediation, oxidation, and in-situ flushing may have unintended impacts—positive or negative—on the overall system that should be assessed with source removal. Such impacts may result from biogeochemical changes within the source or plume.

Monitoring programs should be designed to provide data required to assess the relationships between source mass reduction, contaminant mass discharge (source strength) and plume response. Such monitoring data will provide a foundation for developing improved predictive tools. However, it must be recognized that the collection of these data requires a long-term monitoring commitment at most sites.

Plume properties are a function of source strength, the assimilative capacity of the system, and time. If the source is reduced, then the overall strength of the plume likely will be reduced. This reduction may or may not attain the required concentration at a downgradient compliance point. Limited field data suggest that, for some sites, biogeochemical changes as a result of aggressive source remediation may enhance the attenuation capacity and increase the probability of meeting regulatory goals without complete source removal or subsequent implementation of extensive plume remediation efforts.

With support from the Strategic Environmental Research and Development Program (SERDP), NRMRL has just begun a project with the objective of developing a protocol for forecasting and predicting the impact of aggressive DNAPL source remediation. Specifically, investigators are trying to:

- characterize the relationship between DNAPL architecture, mass removal, and contaminant mass flux in laboratory aquifer models;
- assess response to DNAPL mass removal of mass flux and plume behavior at several field sites;

- conduct numerical simulations to describe the relationship between DNAPL removal, mass flux, and subsequent plume response for laboratory and field sites; and
- compile statistics on the relationship between partial DNAPL removal and contaminant flux reduction for several hydrogeologic templates of actual field sites.

Both Lagrangian and deterministic modeling approaches will be used to forecast responses to source remediation. Output from source models will provide input to coupled plume models such as MT3DMS or RT3D. The Laboratory and field tested models will be used in conjunction with Monte Carlo simulations to examine relationships between source mass reduction and contaminant mass flux for several hydrogeologic and source scenarios. As an outcome of this work, they hope to develop a guidance document on predicting relationships between source reduction and mass flux reductions.

**To view Dr. Wood's presentation for more details, [click here](#).**

### **Forecasting Benefits of Flushing Remediation**

Carl Enfield, EPA, National Risk Management Research Laboratory-Cincinnati

Carl Enfield discussed the prototype of the predictive models that the National Risk Management Research Laboratory (NRMRL) is developing. The data requirements for the model include the ability to describe the movement of ground water through the flow field and the distribution of the NAPL in the formation. NRMRL is using a Lagrangian approach to the source distribution part of the model, which allows them to simulate a 3-D environment using 1-D elements. The model assumes that the NAPL phase is stationary. To simplify the modeling effort, the following assumptions are made:

- the NAPL removal does not impact the flow field;
- the NAPL and fluids are in equilibrium; and
- the remedial fluid does not interact with formation solids.

These assumptions are valid on average but are probably not valid locally.

Dr. Enfield explained that researchers have a reasonable idea of how to describe the fluid flow through the aquifer and use various types of data to obtain a number of population distributions of hydraulic conductivity and travel times for input into the model. On the other hand, research is not nearly as advanced regarding how NAPL is distributed in the flow fields—whether it is uniformly distributed, log normally distributed, or just correlated with the flow field, which causes problems with modeling it. They have tried to account for this unknown by dividing their modeling populations into two groups: one where they assume NAPL is present and one where they assume it is not.

There are several ways to obtain the hydraulic data. A conservative tracer study can be conducted, or hydraulic conductivity can be calculated using head data or data from aquifer pumping tests. These data are used to get the geometric mean of the population and its standard deviation. To obtain NAPL distribution data, a retarded tracer test can be conducted, continuous cores in source area can be collected, or the vertical and horizontal dissolved phase concentrations can be profiled.

The model allows the user to vary NAPL distribution scenarios with aquifer heterogeneity scenarios to estimate the effect on the flux that various amounts of mass removal will achieve. This information can then be used to estimate the effect a flushing action may have on plume concentrations and plume geometry to determine if it is worth doing.

Dr. Enfield indicated that he needs beta code testers for the model to give feedback on how to make it more useful to the user. The model is easy to use, has an Excel front end with basic code underneath. It takes 4 to 8 hours to run. Anyone interested in beta testing the model should contact him at [enfield.carl@epa.gov](mailto:enfield.carl@epa.gov).

**To view Dr. Enfield's presentation for more details, click here.**

## Questions and Answers

*Question:* Does the model include biodegradation?

*Answer:* Yes.

## **DNAPL Source-Zone Remediation: What Is the Case for Partial Source Depletion?**

Suresh Rao, Purdue University

Suresh Rao discussed the preliminary conclusions of a 14-member expert panel charged by EPA to study four specific issues concerning DNAPL source remediation: (1) the status of technology development and deployment, (2) performance goals and metrics, (3) costs and benefits, and (4) research needs. Although several DNAPL technologies have demonstrated a 60-90% depletion in DNAPL source mass, EPA and the panel recognized the need for improved understanding of the factors that have limited full-scale applications. One limiting factor may be that achieving MCLs as a cleanup metric for the entire source zone is nearly impossible. This is leading to an apparent paradigm shift in deciding to undertake source removal, including the need to link DNAPL source-zone treatment with an altered dissolved plume response; develop a new conceptual framework for site-specific decision-making involved in site assessment, remediation end-states, and technology integration; and examine regulatory flexibility for establishing intermediate cleanup goals.

The panel recognized that partial mass depletion may result in reduced risk to public health and the environment due to a reduction in DNAPL mobility, source longevity, and source strength. Other potential benefits include the increased attenuation of dissolved plumes, reduced long-term management and project costs, and improved site stewardship. Conversely, the panel recognized that partial mass depletion may pose increased financial risk and incompatibility with follow-on technologies used for site remediation. Partial source depletion also may increase public health and environmental risk posed by expansion of the source zone (due to DNAPL migration), and by short-term increases in contaminant concentrations or discharge (due to residual remedial agents, decreased microbial activity, and increased ground-water flux).

The panel found that a combination of flux-averaged concentrations and source/plume strength measurements can be useful for evaluating risk and remediation performance. Among other findings, the panel concluded that measurements taken at multiple control planes and times can be used to assess source or plume behavior and attenuation. Issues involved in the adoption of new performance metrics for DNAPL source depletion include field-scale validation and regulatory compliance mapping, cost-benefit analysis, long-term institutional controls, unconsolidated versus fractured media, and monitoring needs and technology failure analysis.

Traditional monitoring methods used to measure source strength are limited. New approaches for source measurement (based on flux meters and pump tests) are under development but will require further evaluation concerning reliability and implementation costs. The interagency Strategic Environmental Research and Development Program, DOD's Environmental Security Technology



Development Program, and/or the Air Force Center for Environmental Excellence will conduct field tests at federal facilities such as Dover Air Force Base, Cape Canaveral, and Port Hueneme to further evaluate source strength measurements.

**To view Dr. Rao's presentation for more details, click here.**

## Questions and Answers

*Question:* Is partial source removal sufficient if risk at a site is reduced significantly?

*Answer:* Public perception commonly claims that site cleanup is not complete if contamination remains.

*Question:* Is the panel evaluating different types of DNAPL contaminants?

*Answer:* Yes, the panel is examining scenarios involving various contaminants and chemical break-down products, as well as the different metrics applicable to contaminant types.

## **Western Region—Hazardous Substances Research Center**

Dr. Lewis Semprini, Oregon State University

Dr. Semprini explained that Western Region Hazardous Substances Research Center (WRHSRC) is one of five centers created by EPA to focus on different aspects of environmental problems. WRHSRC serves Regions 9 and 10 and includes researchers from Oregon State and Stanford Universities. The primary focus of WRHSRC is ground-water cleanup and site remediations associated with volatile organic compounds in ground water with an emphasis on chlorinated organics. Their research is aimed at improving in-situ biological and chemical treatment processes.

The WRHSRC supports two major programs—basic research and outreach. The basic research program includes projects investigating anaerobic biological processes, aerobic co-metabolic processes with the potential of biologically treating dilute plumes of chlorinated solvents, abiotic processes (catalytic reduction of chlorinated solvents), and site assessment. The outreach program consists of technical outreach services for communities, technical assistance on brownfields issues, and technology transfer to the private sector.

The first research project Dr. Semprini discussed was the reductive dechlorination of solvents using biological processes. The objective of this research was to develop organisms capable of rapidly degrading high concentrations of PCE and TCE. Researchers obtained cultures from two different sites: Pt. Mugu in Southern California and the Evanite site in Corvallis, Oregon. The Pt. Mugu culture was very aggressive toward high concentrations of TCE, but was not useful for degrading PCE or VC. The Evanite culture was effective in taking the process from PCE to ethene, but not at particularly high concentrations. By mixing the two cultures and controlling their chemical environment over time, the cultures have evolved in a fashion that makes them more effective in degrading higher concentrations of TCE and taking the degradation process to ethene. The project also involved studying the ability of the cultures to degrade specific chlorinated ethenes in the presence of various concentrations of other chlorinated ethenes in order to determine kinetic values for the reactions and model them. The model allows users to predict how a culture will perform given a specific mix of chlorinated solvents and their degradation products.

Another WRHSRC research project is developing methods to employ redox indicators for monitoring environmental redox conditions. The objectives of the project are to employ redox indicators to

spectrometrically monitor redox conditions in aqueous systems; to develop and improve low-cost, light-emitting-diode-based, field spectrometers for long-term field monitoring of redox conditions; and to develop hydrogen gas sensors based on redox indicators and a Pd or Pt catalyst. Redox indicators are electroactive compounds that change color (i.e., absorbance characteristics) when going from an oxidized to a reduced state. Redox indicators are organic compounds that can be very finely tuned to match the redox state being monitored (e.g., iron reduction or sulfate reduction). The gradual color change of the indicator can be directly correlated to the change in redox condition. A potential use for redox indicators, involves embedding them on a small disk, which can be placed in a culture bottle. A laser beam from a light-emitting diode (LED) is directed onto the disk, and the redox condition in the bottle can be measured over time without disturbing its contents or opening the bottle. Another use is to fix the indicators on a probe in a flow-through cell; a laser beam is directed on the probe to give redox conditions over time in a well or water body. The WR-HSRC has found that there is a sharp drop in redox potential in the VC to ethene step of the degradation of TCE.

A third WRHSRC project is the development of a single well, push-pull test to monitor bioaugmentation with dehalogenating cultures. One of the key steps in this test is the use of a fluorinated surrogate to track the dehalogenation process. By using trichlorofluoroethene as a tracer, researchers can measure the rates of dehalogenation of a given substrate because the cultures do not reduce the fluorine. Hence, the tracer can be introduced at a known concentration into an aquifer contaminated with TCE and its degradation products, and the rates at which it degrades can be measured to estimate the reduction potential of the aquifer.

A fourth WRHSRC project is addressing the aerobic cometabolic destruction of chlorinated aliphatic compounds with butane-grown microorganisms. This process oxidizes chlorinated compounds to carbon dioxide and chlorine, taking advantage of microorganisms that grow on specific substrates. In order to grow using both the substrate (e.g., propane, butane) and the chlorinated hydrocarbon, the organisms have to possess a mono-oxygenase enzyme. The process is more complicated than anaerobic reduction and is intended for dilute plumes in situations where aerobic conditions must be maintained in the aquifer. WRHSRC field demonstrated the process with a butane substrate in an aquifer contaminated with 1,1,1-TCA. They injected a butane/oxygen mixture into two wells—one of which was injected with lab-grown microbes and the other with native microbes. During the first season, researchers did not observe a difference in TCA destruction between the lab culture and the native cultures. They had a problem with their butane feed during the first season, and the culture may have died. During the second season, they found that they had identical butane and oxygen utilization by the native and lab microbes. The lab-grown microbes metabolized the TCA while the native microbes did not. Thus, they achieved higher destruction of the 1,1,1-TCA with the lab-grown microbes than they did with the native microbes.

The fifth and final WRHSRC project described is a study of the surface chemistry of palladium catalysis under ground-water treatment conditions. Palladium in the presence of hydrogen is an excellent catalyst for reducing TCE to ethane and chlorine. It can be placed on a small support medium (e.g., alumina, granular activated carbon, or zeolite) at 0.5 to 5% by weight and injected with hydrogen into the subsurface. However, when in the subsurface, the palladium loses its activity over time, and it is not clear what is poisoning it. The WRHSRC is studying different commercially available catalysts to see how they perform both in terms of reduction potential and regeneration.

**To view Dr. Semprini's presentation for more details, [click here](#).**

## Questions and Answers

*Question:* Who funds the WR-HSRC?

*Answer:* The Superfund STAR program with the goal of doing basic research on specific topics. Each HSRC has a website that includes information about their research activities. The WRHSRC receives about \$600,000 from EPA to do basic research and is trying to get demonstration money from DoD, DOE, as well as the private sector.

*Question:* What is the outreach program to disseminate results?

*Answer:* Generally the WRHSRC's results are published in peer-reviewed journals and at the Battelle conferences. They also post research briefs on their website. The WRHSRC is developing an e-mail distribution list for the technical briefs.

*Question:* How do you address palladium problems in reduced sulfite environments?

*Answer:* We are looking at using several different oxidants, like hydrogen peroxide, in situ to regenerate the catalyst. We have had some success with using nitrates.

## Interstate Technology & Regulatory Council

Ana Vargas Arizona Department of Environmental Quality, Mike Smith Vermont Department of Environmental Conservation, and George Hall, ITRC Program Adviser

Ana Vargas opened the Interstate Technology and Regulatory Cooperation (ITRC) presentation with some background information on the ITRC's DNAPL Team. The team was formed in 1999 and currently has about 50 members. To date, the team has produced four documents:

- *Dense Non-Aqueous Phase Liquids (DNAPLs): Review of Emerging Characterization and Remediation Technologies* (June 2000)
- *DNAPL Source Reduction: Facing the Challenge* (April 2002)
- *Technical and Regulatory Guidance for Surfactant/CoSolvent Flushing of DNAPL Source Zones* (April 2003)
- *Characterization Strategies, DNAPLs-4*, April 2003

The DNAPL Team's guiding principles for their work include requiring adequate site characterization, encouraging source mass and free phase removal, no routine TI waivers, and a presumptive ground-water remediation strategy that requires remediation of DNAPL source areas.

The DNAPL Surfactant/Cosolvent Flushing Sub-Team has just released a guidance document (available at <http://www.itrcweb.org> under "guidance documents"). When the ITRC produces a guidance document, they also provide training. Public sessions for the Internet training for surfactant/cosolvent flushing will be offered June 19, 2003, September 9, 2003, and October 23, 2003. Registration for classes opens about six weeks before the scheduled date, and registrants are provided with all the information needed to participate. ITRC's primary Internet-based training course contact is Mary Yelken (402) 325-9615.

Mike Smith continued the presentation by summarizing a document the DNAPL Characterization Sub-Team recently produced. The document addresses characterization strategies for sites contaminated with DNAPL and stresses that these sites should be considered as a whole. It is aimed at an audience that may have some technical background but is not intimately familiar with DNAPL fate and transport dynamics or site characterization techniques. The document begins with a general overview of DNAPL distribution, their behavior in the subsurface, and why characterization is so difficult. The next section provides an overview of the characterization process, followed by a section that suggests the best characterization approach is one that is dynamic. A dynamic approach involves using systematic

planning to develop a conceptual site model that is verified and modified using a flexible work plan and onsite decision-making supported by the real-time field analysis of samples. The document also discusses data collection and evaluation techniques, with an emphasis on the toolbox approach, and regulatory issues.

George Hall provided an overview of what the DNAPLs Team is planning for the future. More guidance documents are planned for 2003-2004 that address remediation performance evaluation and integrated approaches for DNAPL cleanup. One of the team's guiding principles is to remediate residual DNAPL to the point where the rate of natural attenuation exceeds the rate of mass flux from the source area to the dissolved plume. The team is developing a decision tree document that will address how to decide when to transition from an aggressive to a more passive approach in the remediation process using a treatment train approach. This document is due out in 2004.

The DNAPLs Team is also working on a document, *Performance Metrics for DNAPL Source Zone Remediation*. The questions they want to answer include: what is performance?, what can be measured?, how to employ multiple lines of evidence?, and what are the available tools? They anticipate an aggressive schedule and would like to collaborate with the Army Environmental Center and EPA. They anticipate that the document will be ready in 2004.

**To view the ITRC's presentation for more details, [click here](#).**

## Questions and Answers

*Question:* How were source removal and mass flux addressed?

*Answer:* When the DNAPL Team prepared the document, *Facing the Challenges*, they indicated that source removal should be done, when feasible. The results of a poll of the states, consultants, and federal and industry representatives on the team were unanimous that source removal should be done when possible.

*Question:* How are the guiding principles translated in practice at the state level?

*Answer:* The guiding principles are agreed upon by the states. In Arizona, the laws have been changed and require source removal. Vermont also requires source removal.

*Question:* Have you polled the states to find out how they are addressing DNAPL removal?

*Answer:* No, and the DNAPL Team does not know which states are implementing the principles and which are not.

*Question:* Agreement among the members of the team on a document and principles, does not mean that the political leadership of a state will support it, does it?

*Answer:* Our review process asks the state to concur with a document issued by the ITRC. If the state concurs, it does not mean they agree with everything in the document, but that they consider the document useful in decision making and encourage its use.

## **Superfund Basic Research Program: A Program Update**

Larry Reed, National Institute of Environmental Health Sciences

Larry Reed described the Superfund Basic Research Program at the National Institute of Environmental Health Sciences (NIEHS) and how NIEHS is collaborating with EPA and ATSDR in its research. NIEHS was established in 1986 under SARA and was intended to complement EPA and ATSDR. It provides training and outreach services (e.g., to public schools and the Technical

Assistance Grant (TAG) program) and is involved with the Small Business Innovative Research Program. The goal of NIEHS's Superfund Basic Research Program is to use the knowledge acquired in their research as the foundation for practical benefits, such as lower cleanup costs and improvements in human and ecological health risk assessment. Dr. Reed described the research priorities for the multi-disciplinary research program, which include developing new methods and tools for site evaluation, fate and transport, and remediation, and understanding effects of hazardous substances on plants and animals.

The program's university-based grants program is funding research at schools across the country. Results are disseminated via research briefs (which are available on the web at <http://www-apps.niehs.nih.gov/sbrp/index.cfm>), conferences, and publications.

NIEHS sets its research agenda with input from the scientific community, EPA, and ATSDR, as well as states and community groups. They will plan the next 5-year grant cycle this fall. NIEHS, EPA, and ATSDR will co-fund a sharing symposium to plan for leveraging. Claudia (?) noted that NIEHS is interested in input from the TSP forums regarding research needs and cited several projects of potential interest to the forums that the Superfund Basic Research Program is currently funding. These projects involve fate and transport of contaminants in ground water, remediation technology studies, integrated approaches to ground-water studies, and analytical studies. She concluded by mentioning several of the Superfund Basic Research Program's notable achievements, including research by Jennifer Fields, of the Oregon State University, on the microbial transformation of TCE in ground water (see next presentation).

**To view the NIEHS presentation for more details, click here.**

### **Microbial Transformation of TCE in Anaerobic Ground Water**

Jennifer Fields, Oregon State University

Jennifer Fields discussed her research on a single well, push-pull test to determine microbial transformation rates for the reductive dechlorination of TCE in ground water. A method for determining in-situ rates is important because rates can vary significantly across a site, and rates are not adequately predicted by laboratory microcosms or by monitoring the spatial and temporal changes in TCE or its degradation products. In-situ rates are necessary for assessing the potential for intrinsic bioremediation at a site, designing engineered bioremediation systems, and monitoring remediation progress.

The single well, push-pull test involves the injection of a solution containing known concentrations of a tracer and a substrate followed by an extraction phase. Flow is reversed and samples are analyzed to develop breakthrough curves for the tracer, substrate, and product. Trichlorofluoroethene (TCFE) was used as a surrogate for TCE in the tests due to its analogous reductive dechlorination pathways, transformation rates, and transport behavior. Bromine was the tracer.

The results showed that transformation rates varied across the site. Injecting a chemical amendment (fumarate) with the substrate/tracer to serve as an electron donor was shown to stimulate rates.

**To view Ms. Field's presentation for more details, click here.**

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