Federal Remediation Technologies Roundtable Meeting Summary

November 9, 2010
Arlington, VA

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ACTION ITEMS

- ► Information suitable for the development of new cost and performance case studies of innovative technologies should be sent to Jim Cummings or Marti Otto.

WELCOME/INTRODUCTION

Arnold Layne, Director of the Technology Innovation and Field Services Division (TIFSD) in the U.S. Environmental Protection Agency's (EPA) Office of Superfund Remediation and Technology Innovation (OSRTI), welcomed the attendees to the 41st meeting of the Federal Remediation Technologies Roundtable (FRTR). He thanked the members and presenters responsible for developing the meeting's agenda on the topic of fractured rock characterization and remediation. Noting the retirement from EPA of FRTR icon John Kingscott, formerly Chief of the TIFSD Technology Assessment Branch, he introduced the current Acting Chief, Jim Cummings. Layne reminded the attendees that as a public meeting, the FRTR proceedings would be conducted using a Web conference tool to permit remote participants to watch the presentations live on line.

Following self introductions, the attendees were given the opportunity to announce any events or activities relevant to FRTR interests.

FRTR ANNOUNCEMENTS AND MEETING OBJECTIVES

Agency Announcements (Projects/Initiatives) & FRTR Subgroup Reports

Jim Cummings reported that John Quander (EPA/TIFSD) is working with the University of Massachusetts at Amherst to organize an international conference—Sustainable Remediation 2011: State of the Practice (www.umass.edu/tei/conferences/SustainableRemediation/)—to be held June 1-3, 2011. He reminded participants of the ongoing effort to collaborate in the development of cost and performance case studies of cleanups using innovative technologies to add to the FRTR database and urged them to send any new information to him or Marti Otto (EPA/TIFSD). Additionally, he welcomed hearing about any cleanups where the source zone will be addressed and the site has a small, shallow plume suitable for monitoring at reasonable cost over the next 5-10 years. Data gathered from these sites will inform future discussions of the impact of source reduction on plume longevity.

Carol Dona, U.S. Army Corps of Engineers (USACE), said that the federal partners in the Green and Sustainable Remediation (GSR) Subgroup are working on a framework and metrics to define the effort based on EPA's determination of how green remediation fits within the nine criteria defined under CERCLA. Three frameworks are in development by other organizations: the Interstate Technology Regulatory Council (ITRC), the Sustainable Remediation Forum (SuRF), and ASTM International. The Army currently has five of 12 planned study projects under way to evaluate GSR alternatives and identify options, determine the cost impacts, and document the results. The objective is to determine which GSR alternatives have the greatest impact and when and where implementing each alternative makes it most effective. The Navy recently led a joint proposal to the Environmental Security Technology Certification Program (ESTCP) to compare two publicly available GSR tools for consistency and reliability: the Sustainable Remediation Tool (SRT) developed by the Air Force Center for Engineering and the Environment (AFCEE), and the SiteWise™ Sustainable Environmental Remediation Tool developed jointly by the Navy, USACE, and Battelle. Full lifecycle analysis of both tools will identify improvements that can be made to increase user confidence in the results they provide. Both tools are available on line (www.ert2.org/t2gsrportal/tools.aspx). The second version of SiteWise™ should be issued in March 2011 with several improvements: technology mapping to show the activities involved and a cost package to cost-out alternatives and calculate energy costs.

Beth Moore, U.S. Department of Energy (DOE), said that DOE's Office of Energy Efficiency and Renewable Energy is co-sponsoring with EPA and other organizations the 2011 Brownfields Conference (www.brownfields2011.org), to be held April 3-5 in Philadelphia, PA. A large part of the conference focus is on green remediation topics, including metrics and green jobs.

Dan Powell (EPA/TIFSD) noted that EPA released the final *Superfund Green Remediation Strategy* (www.epa.gov/superfund/greenremediation/) in September. The strategy outlines 40 specific action items aligned with 9 key actions designed to encourage examination of cleanup alternatives that decrease the environmental footprint of remediation. In the coming year, the cross-agency project to update the software tools listed in the FRTR Decision Support Tools matrix (www.frtr.gov/decisionsupport/) for characterization, remediation, and project visualization will incorporate green remediation tools. Several of the new tools will be evaluated and compared at the Grants Chlorinated Solvents Plume site located in Grants, New Mexico, and a report will be prepared. He also mentioned a new program initiative proposed by Kathy Yager that builds upon EPA experience in the optimization of long-term monitoring for groundwater treatment systems to encompass holistic cleanup optimization for remediation sites.

Linda Fiedler (EPA/TIFSD) announced that EPA is compiling resources to develop a new Focus Area on fractured rock for the CLU-IN website, as well as updating the Fractured Bedrock Project Profiles with new material. The new Focus Area will provide overviews and links to a variety of reports and papers on fractured bedrock topics. The project profiles will be expanded to describe about 150 sites where treatment has been selected or implemented. The new resources should be available at the end of December 2010 or in early January 2011.

Paul Beam (DOE) suggested adding landfills to the ballot of potential topics for the spring 2011 FRTR meeting. He is interested in landfills that contain low-level radioactive waste with respect to long-term monitoring, geomembrane lifespan, contaminant transport within the landfill, settling/shifting of landfill content and the effect on the cover system, and interaction of co-disposed contaminants. If there is sufficient interest in this topic, a subgroup could be formed to gather and develop additional information.

Kim Parker Brown, Naval Facilities Engineering Command (NAVFAC), reported that the Navy plans to update its remedy optimization policy with GSR guidance. Efforts are ongoing to develop GSR metrics and capture them in the NORM database, the internal database of contamination problems at Navy installations.

Karla Harre (Naval Facilities Engineering Service Center) greeted the assembly as a new member replacing long-time member Chuck Reeter. She added to Carol Dona's description of the joint Navy/Army/Air Force project to compare SRT and SiteWise™ software by identifying SimaPro® as the lifecycle assessment software to be used in the study. The software tools will be applied to two sites during remedial system evaluation optimizations. A report discussing the ease and appropriateness of each tool, as well as comparing the results and identifying areas for improvement, will be published.

David Carrillo (U.S. Air Force) reported that the Air Force is placing increasing emphasis on performance-based contracting for environmental cleanup.

Mark Schoppet (NASA Remediation Program Manager) said that several meetings have been held by NASA's new green remediation team. The group is still working to identify benchmarks and tools that will help NASA develop GSR guidance.

Meeting Objectives

The meeting had the following overall objectives:

1. Improve communication and common understanding of characterization and remediation issues with fractured bedrock.
2. Share experience and lessons learned in advancing best practices.
3. Outline key issues and develop shared strategies to address them.

Jim Cummings went over the ballot of potential topics for the spring 2011 FRTR meeting and asked that a representative from each member agency present cast a ballot and return it after the lunch break, with the results to be announced at the end of the meeting. He then introduced Allen Shapiro of the U.S. Geological Survey (USGS) as the first presenter and moderator of the initial portion of the technical program.

CHARACTERIZATION OF CONTAMINATION IN FRACTURED MEDIA

Addressing the Complexities of Contamination and Remediation in Fractured Rock Aquifers

Allen Shapiro gave an overview of some of the complexities involved in dealing with contaminants in fractured rock (Attachment A). Fractured rock and carbonate aquifers offer a degree of geologic complexity that far exceeds that of near surface, unconsolidated, porous media aquifers. The complex distribution and connectivity of fractures, joints, conduits, vugs, and other discontinuities in the rock, coupled with the large range in their hydraulic properties, results in highly convoluted flow paths over distances from meters to kilometers. Fractured rock and carbonate aquifers are also characterized by void space associated with the initial formation of the rock. The rock matrix is not significant in characterizing groundwater flow; however, it does play a significant role in the long-term retention of contaminants and the design, implementation, and success of remediation strategies.

Recent advances in understanding physical and chemical processes and characterizing groundwater flow and chemical transport in fractured rock aquifers are leading to defensible site conceptual models that can minimize the number of monitoring locations to achieve long-term monitoring objectives. At the former Naval Air Warfare Center (NAWC), West Trenton, New Jersey (http://nj.usgs.gov/nawc/), the presence of chlorinated solvents in fractured sedimentary bedrock has provided opportunities for studies of subsurface processes and new characterization and monitoring technologies. Innovative methods of monitoring in situ changes in biogeochemical conditions point to further reductions in long-term costs at geologically complex sites of groundwater contamination.

Existing remediation technologies may be insufficient to achieve management objectives in the complex geology of most fractured rock aquifers. Significant quantities of contaminant mass will continue to be present in the groundwater, even after aggressive remediation technologies have been applied. Efforts need to be directed at minimizing costs and streamlining protocols that recognize the long-term stewardship that will be warranted at these geologically complex sites.

Given the prospect of long-term stewardship of fractured bedrock sites, Shapiro made several management recommendations:

- Look for methods of reducing long-term operational monitoring costs,
- Manage the site with a financially prudent approach, and
- Elucidate the basis for implementing any aggressive remediation technology.

In the area of ongoing research, he cited the following needs:

- Methods of making monitoring more cost effective,
- Enhanced characterization that allows installation of fewer monitoring locations to reach project objectives,
- A better understanding of in situ physical, chemical, thermal, and biogeochemical processes that affect contaminant fate and transport,
- Synthesis of lessons learned from different geologic settings at different scales, and
- Development of innovative methods for monitoring in situ processes.

Question: Do you think in situ thermal treatment can reach DNAPL in fractured bedrock?
Response: The technology is promising, but its effectiveness depends on the hydrogeology of the area. A tight area with little water intrusion might be a candidate, but if a lot of fluid is coming in, energy costs will increase. In a tight area, however, DNAPL movement would be small and might not be a problem.

Question: Your example sites are skewed toward rocks in the Midwest. Why are there not more studies in eastern sites?
Response: It is a matter of opportunity. If anyone has glaciated crystalline rock sites in the Northeast for long-term study, please let me know.

Tools for Characterization and Monitoring of Contaminated Fractured Rock

Dan Goode (USGS) acknowledged the work of many colleagues over decades in providing the information he came to share (Attachment B). His presentation highlights a brochure prepared by Linda Fiedler and Claire Tiedeman (USGS) that describes the types of technical assistance available from EPA and USGS in the characterization and remediation of contaminated fractured-rock sites.

He drew attention to a recent 2-volume report, *Fractured Bedrock Field Methods and Analytical Tools* (www.sabcs.chem.uvic.ca/fracturedbedrock.html), written as guidance for contaminated sites practitioners by Tom Doe of Golder Associates Inc. for the British Columbia Ministry of Environment, Canada. A table from this publication provides a list of characterization recommendations, although it omits important tools such as modeling and synthesis. Many of the approaches and methods used at porous rock sites are applicable at fractured rock sites.

An example of a crystalline rock site in a report entitled *Influence of Geologic Setting on Ground-Water Availability in the Lawrenceville Area, Gwinnett County, Georgia* (http://pubs.usgs.gov/sir/2005/5136/) was used to illustrate the importance of mapping the surface geology locally. The large-scale geologic structure is correlated with permeable features in the ground. Cross-sections show that the major water-bearing zones in the crystalline rock are associated with contacts that are mappable at land surface.

In a discussion of the work conducted at the NAWC site in West Trenton, New Jersey, Goode pointed out the cost-effectiveness of aquifer testing at a site where a pump-and-treat system is in place. In a system with seven pumping wells, it is easy to switch a well off and run an aquifer test for as long as desired, thereby gaining additional information through the remediation system. Hydrogeologic characterization at the NAWC was critical to achieving effective bioaugmentation of the rock fractures. The information was used in designing the strategy for injection of bioaugmentation amendments, for determining importance of monitoring at intermediate wells, and for interpreting bioaugmentation results, in which work is ongoing. Investigators used rock coring to evaluate the effectiveness of a thermal conductive heating pilot study at NAWC and found the method had removed nearly 70 percent of the trichloroethene (TCE) from the saturated rock samples. As heating the ground required the installation of three transformers at considerable cost, however, this use of technology likely would not be considered green remediation.

Goode provided the following take-home message: Tools are available for characterization and monitoring in fractured rock sites. Good site conceptual models are critical for selection of methods and synthesis. Continuous characterization of fractured rock sites, even during the remediation phase, is essential to achieve an iterative synthesis of multiple investigations.

Question: How do you use the hydrogeologic information to move to a modeling scenario and to determining whether remediation is feasible?

Response: These data provide a broad range of results. One would be that if bioaugmentation is done throughout the site, how can amendments be introduced to the contaminated areas? If an existing well is contaminated, it may be possible to bioaugment a different well connected in the subsurface to the contaminated one with good assurance that both wells will be affected. Knowledge of the connection allows use of the natural flow system to carry the amendments to where they are needed. Knowledge of the connections also pinpoints the critical monitoring locations. With the proper hydrogeologic framework and with the models, it is possible to have a systematic, transparent way of identifying where to pump and where to monitor.

Demonstration and Validation of the Fracture Rock Passive Flux Meter

Kirk Hatfield (University of Florida) pointed out that complex hydrogeologic conditions such as fractured and karst bedrock settings pose substantial economic and technical challenges to both the characterization and remediation of DNAPL source zones (Attachment C). The objective of his project is to demonstrate and validate the fractured rock passive flux meter (FRPFM) as a new technology for measuring the magnitudes and directions of cumulative water and contaminant fluxes in fractured rock aquifers. The sensor consists of an inflatable core that compresses a reactive fabric against the wall of a borehole and to any water-filled fractures intersected by a borehole. The reactive fabric is designed to intercept and retain target groundwater contaminants (e.g., TCE). In addition, the fabric releases non-toxic tracers, some of which visibly indicate active fracture location, aperture, orientation, and direction of fracture flow along a borehole, while others quantify cumulative groundwater discharge within the fractures.

Demonstration and validation studies are in progress to compare multiple competing technologies, including fractured rock passive flux meters, hydrophysical logging, scanning colloidal borescope, and borehole dilution tests. The technologies are being evaluated based upon their ability to identify flowing fractures, determine flow direction, and quantify both water and contaminant mass flux in flowing fractures. Recently completed laboratory studies test the capabilities of each technology in two separate flow simulators: a planar single-fracture simulator (performed multiple tests for varying duration; fracture aperture = 0.5 mm; specific discharge range 25 to 2,500 cm/day) and a large-scale three-dimensional aquifer box with layered high-contrast flow zones (physical flow domain 2 m length, 0.5 m width, and 1 m height; alternating layers of low-permeability sand separated by high-permeability gravel; specific discharge range 25 to 4,000 cm/day (per layer)).

Demonstration objectives include assessing the performance of the competing technologies under controlled conditions and developing a standard operating procedure for using these technologies to characterize both flow and contaminant flux accurately in fractured rock systems. Field demonstration tests have started at a site in Guelph, Ontario, and also will be performed at the NAWC site in West Trenton, New Jersey.

Question: Once the point measurements have been validated with the instrument, do you plan to integrate any of the existing methods for calculating discharge from the plumes that have been developed in past work for ESTCP?

Response: Yes. A major issue with site risk assessment is the estimation of water and contaminant discharges and their uncertainties. Usually complex stochastic simulations are required to generate these estimates. We plan to submit a paper demonstrating simple techniques for estimating water and contaminant discharges and discharge uncertainties using flux data from multi-well transects. Typical statistical methods can’t be used to make such calculations, because point measurements of flux produce skewed distributions and are spatially correlated. Typical statistical methods assume data follow symmetric distributions and are independent or uncorrelated. However, we present a way in which spatial correlation and skewness are considered and simple statistical tools yield valid estimates of water and contaminant discharge and their uncertainties.

Question: Has the flux meter been used yet at the NAWC test site?

Response: Not yet, but possibly this winter. At this stage we are validating the technology, and it is preferable to test it at sites that are well characterized.

Comment: As previously discussed, one of the key issues here is that when dealing with highly complex sites, as one starts to integrate over areas, one starts to reduce that complexity. The uncertainty of concentration at a given point is huge, but by integrating over an area, that uncertainty can be dramatically reduced.

Fractured Bedrock Characterization and Effective Remedy Selection in Region 4

Ben Bentkowski (EPA Region 4) provided a regional perspective on characterization of fractured bedrock aquifers and how it has aided in effective remedy selection (Attachment D). Generally, Appalachian tectonics caused a large region of fractured igneous and metamorphic aquifers in the central portion of Region 4. This tectonic deformation also caused the Valley and Ridge province to the west of the mountains resulting in fractured sedimentary aquifers. Characterization of these fractures is the key to understanding the hydrogeology of each site. As the characterization of each site needs its own approach formulated from a range of techniques, the general approach is first to understand the groundwater flow system and then the contaminant distribution. This base level of knowledge is necessary for effective remedy selection.

The Region 4 federal facilities with fractured bedrock generally are larger sites with multiple release locations and often large release amounts. Non-federal sites usually are smaller with smaller release amounts. The sites presented were evaluated as to the conceptual site model, type and degree of characterization, and the possible or selected remedy. Details from the following sites—most of them large, complex sites at federal facilities—illustrated the discussion:

- Air Force Plant No. 6, Marietta, Georgia (Fractured Metamorphic Rock)
- Alabama Army Ammunition Plant, Childersburg, Alabama (Fractured Sedimentary Rock)
- Redstone Arsenal, Huntsville, Alabama (Fractured Sedimentary Rock)
- Oak Ridge Reservation, Oak Ridge, Tennessee (Fractured Sedimentary Rock)
- Anniston Army Depot, Anniston, Alabama (Fractured Sedimentary Rock)
- J.P. Stevens Facility, Upstate South Carolina (Fractured Metamorphic Rock)
- Hitachai, Greenville, South Carolina (Fractured Metamorphic Rock)

Preliminary conclusions are presented as to which types of aquifer characterization aided in more effective remedy selection. This work does not include evaluating the more purely karst regions of Kentucky, Tennessee, Florida, and southern Georgia. Also, the evaluation focuses on CERCLA sites rather than RCRA sites, with limited evaluation of state lead sites.

Question: Does in situ thermal treatment actually remediate down to remediation goals? Where does it work, and under what circumstance does it not work?

Response: At the Hitachi site, in situ thermal desorption within the small treatment area met the goal of 60 μg/kg TCE in the vadose zone and saprolite, but not in the bedrock. The areal extent of contaminated groundwater was much larger, and it would have been very expensive to attempt to treat the entire plume.

Question: Did Air Force Plant No. 6 or any of your other large sites apply for a technical impracticability (TI) waiver?

Response: Air Force Plant No. 6 is currently regulated under RCRA, and the plume lies within the facility boundaries, so it has not applied for waiver. That cleanup is managed by the State of Georgia and the Air Force. Anniston Army Depot tried for a front-end TI waiver, but it did not go forward. Region 4 has never granted a TI waiver.

Question: At Air Force Plant No. 6, they were looking for flux reduction. How is it being monitoring?

Response: The people who would know are Lester Williams from the USGS and staff in CH2M Hill's Atlanta office, in addition to the Air Force staff involved.

Autopsy of a Small UST site in Bedrock: Implications for Remedial Effectiveness

Bill Brandon (EPA Region 1) described complications that beset monitoring the remedy for releases from a 5,000-gallon underground storage tank, UST-13 (Attachment E). UST-13 was used for collecting waste oils (mainly spent fuels and chlorinated solvents) at the former Defense Reutilization and Marketing Office, Fort Devens, Massachusetts. The tank was removed in 1992 with a limited amount of contaminated soil, as the tank grave was partially excavated into bedrock. From 1994 to 1997, a remedial investigation, feasibility study, and record of decision were completed for the site. In 1998, the selected remedy implemented monitored natural attenuation (MNA) with long-term monitoring (LTM) to evaluate groundwater cleanup following the source actions.

An extensive cut-and-fill program, including significant bedrock blasting carried out to prepare the site for construction of a large warehouse structure in 2000-2001, destroyed some key monitoring wells and complicated the ongoing evaluation of MNA and source action effectiveness. New monitoring wells were installed post-construction in 2001, and LTM efforts were resumed, but the presence of the new building precluded replacement of many wells to the original locations. Moreover, changes were observed in post-construction groundwater flow patterns, and it was expected that additional work would be needed to verify the adequacy of the monitoring network and to make adjustments to the well network or the remedy.

The presence of shallow bedrock beneath large portions of the site, as well as the setting of the shallow water table locally within the bedrock, further complicate analysis of groundwater cleanup. The former tank grave is located at or near a local groundwater divide, where the grave of the former leaking UST-13 penetrated into the upper bedrock. The release of contaminants has affected bedrock, and it appears likely that some residual source material exists in the bedrock beneath the former tank grave. These matters support the ongoing need for additional evaluation of bedrock.

Persistent lingering contamination in the source area supported additional efforts to address the bedrock contamination more comprehensively. In 2007, EPA performed an analysis of bedrock data collected during the 2000 blasting event. As fresh bedrock exposures were created, EPA conducted geologic mapping and measured the three-dimensional (3-D) orientations of the rock fabric and associated fractures identified in the sheared granite gneiss and meta-sedimentary bedrock. A total of 156 joint orientation measurements were collected (66 stations) and 49 foliation measurements were recorded (49 stations). The data were used to create an updated conceptual site model, particularly with respect to elements of the bedrock fracture network relevant to groundwater flow at site scale. Stereo plots and 2-D mapping of these bedrock structural elements were integrated with updated maps of the bedrock surface morphology. Additionally, lateral hydraulic gradients, vertical hydraulic gradients, and long-term water level trends were reevaluated for the bedrock and overburden groundwater systems, culminating in a series of detailed hydrogeologic cross sections parallel and normal to groundwater gradients in the area centered on former UST-13. The prevalence and consistency of the bedrock foliation strongly suggest that this basic characteristic of the bedrock needs to be factored into any remedial or monitoring scheme. Although joint orientations were much more variable, the most prevalent joint orientations are generally also parallel to the foliation. These foliation-parallel joints may play a significant role in contaminant migration, particularly in the immediate vicinity of UST-13. The analysis suggests that the potential for down-dip migration of contaminants, including residual NAPL, to the west/southwest and lateral migration of dissolved contaminants of concern along strike to the south are possible, yet neither pathway is currently monitored.

To address these findings, new monitoring wells were recommended for the UST-13 source area and in down-gradient directions, but the project team refocused available resources in 2009 to address persistent residual fuel hydrocarbons and chlorobenzene compounds. An in situ chemical oxidation (ISCO) injection effort, aimed at the hotspot area near well 32M-01-18XBR, was conducted in February 2009. About 1,800 gallons of water/sodium persulfate solution with a sodium hydroxide catalyst was injected through 4 new injection wells drilled into or on top of the bedrock in the former UST-13 area. The 4 post-injection monitoring events conducted to date point to significant decreases of many key contaminants of concern in well 32M-01-18XBR, but hydraulic information collected during the injection events suggests considerable uncertainty still exists with respect to the interconnectivity of the fracture system, and by extension, the appropriateness of the current monitoring and injection wells.

Moving forward, evaluation of time-series contaminant trends will need to consider the role of seasonal water-level changes in relation to oscillating contaminant values. If contaminants persist, additional remedial action may be needed, and optimization of remedial systems and associated monitoring likely will need more careful consideration of the bedrock fracture system characteristics.

Question: Did you do any numerical modeling to try to understand how the site has changed?

Response: No, those resources have not been applied because it is essentially considered a "nuisance" site.

Question: Are there any fluctuations due to tidal influence?

Response: No, the site is 40 miles inland.

Question: Is your desire to re-inject under the building reinforced by subsequent data?

Response: It is a logical inference: the hydraulic head data show a pressure gradient in that direction and the geologic data show a slope in that direction.

Question: Was this site labor intensive?

Response: The problem was more a matter of time than money. The 5-year review report for the three UST sites at Ft. Devens shows that they are all still being monitored because residual contamination remains in the top of the rock.

Question: In the design of the persulfate injection, was the decision to inject into the contaminant mass based on knowledge backed up by geochemical information?

Response: Essentially, they came up with a scheme to zap a small hot spot, expecting it to go away.

TREATMENT OF FRACTURED ROCK SITES

In Situ Bioremediation at FracRock Sites

Mary deFlaun (Geosyntec Consultants Inc.) pointed out that retention of bacteria in fractured bedrock can be a challenge for bioaugmentation (Attachment F). The relatively low surface area in the aquifer compared to porous media sites may not retain a high enough density of bacteria for effective remediation. Recirculation can be used to retain bacteria within the area of concern, but the cost and infrastructure associated with this strategy can be prohibitive at some sites. Two case studies illustrate the passive and semi-passive application of bioaugmentation in fractured bedrock. The NAWC site in West Trenton, New Jersey, has high concentrations of TCE indicating the presence of DNAPL in fractured mudstones. Similarly, a site in Tennessee had DNAPL concentrations in both the clay overburden source area as well as further downgradient in a karst aquifer.

Both sites were treated with a combination of emulsified oil substrate and KB-1® bacterial consortium, which contains dechlorinating *Dehalococcoides ethenogenes* (DHC) bacteria. The working hypothesis is that the hydrophobic oil partitions to coat the surface of the fractures and helps to retain the hydrophobic bacteria at the surface of the fractures. Long-term monitoring suggests that the oil/bacteria coating on the fractures prevents further diffusion of TCE into the groundwater from the bedrock by degrading the TCE at the rock/water interface. The combination of a long-term electron donor and a bacterial consortium that uses TCE as an electron acceptor is a remedial approach that does not require an ex situ operating system. Effective concentrations of the KB-1® bacterial consortium are expected to exist (and increase by growth and replication) as long as adequate electron donor and electron acceptor persists. This passive approach requires replenishment of the electron donor only on a periodic basis, but the indications are that this replenishment is needed relatively infrequently, on the order of years.

Question: Did you need to characterize the local microbial community prior to treatment?

Response: No, aside from looking for DHC in the groundwater where chloroethenes are involved. If DHC is present in sufficiently high concentrations, injections of EVO alone will speed up the dechlorination process. If DHC is absent or found only at low concentration, bioaugmentation is indicated.

Question: Has modeling been done to help estimate the optimum number of treatments?

Response: The problem is knowing how much contaminant is in the rock. It is difficult to model around that major uncertainty.

Question: Was the spike in DHC in well 38BR at NAWC (see slide 21) attributed to inoculation with KB-1® or to growth of the indigenous population?

Response: Well 38BR received only EVO, so the spike probably was attributable to down-gradient movement of bacteria over the 3-year period following injection.

Question: Did you examine any other substrates? Why choose emulsified oil over molasses?

Response: Emulsified vegetable oil is available from a number of different vendors, and it is easy to use it to reach the target area because it is completely soluble in water in its emulsified state. The emulsion does not break down for several days, which gives it time to move around. Substrates like molasses are consumed much more rapidly than emulsified oil and require more frequent addition to maintain the effect. Some of the vendors claim emulsified oil will remain effective up to five years, although our experience has indicated effectiveness for one and one-half years to two years. Substrate longevity is dependent on a variety of site-specific factors, such as the types and amounts of contaminants present, the composition of the indigenous microbial population, and the presence of other sinks for organic carbon in the system.

Question: If rebound occurs in three to four years, what is the implication in terms of treatment? Is it the result of back diffusion? Do you have to change the strategy?

Response: Monitoring results indicate when carbon levels decrease and contaminant levels increase, which is a signal to add more substrate. Contaminants can travel from up gradient as well as diffuse from the bedrock. They move out of the rock much more slowly than they move into it, so treatment could continue for a very long time.

Question: Has any mass balance analysis been done with electron donor and the amount of TCE that has been reduced?

Response: Mass balance analysis is done initially to determine how much substrate to add, but for treatment longevity, a greater amount of substrate than indicated is often used. In these two projects, no follow-on mass balance analysis was performed in the years after injection.

Question: Would it be better to wait until rebound occurs to add amendments rather than injecting them on a regular basis?

Response: For the pilot test at NAWC, waiting for rebound was the preferred technical course, but that was not an option due to factors of timing and funding.

Question: What was the concentration of EVO injected? How many gallons per well? Were any problems observed with channeling due to recirculation? Any problems with pH?

Response: The EVO injected was a 2-percent solution. The amount added varied from 100 to several hundred gallons depending upon how long it took for the EVO to show up in the extraction well. After EVO appeared, the inoculant was added. Some channeling likely did occur with the second injection in BRP-1 as no EVO was detected between wells BRP-1 and 41BR. No pH problems occurred.

Question: For future applications of this technology in fractured bedrock, would there be any benefit to looking for substrate with a smaller droplet size, which might allow it to penetrate farther into the formation?

Response: Yes. Some of the products have a smaller droplet size than others and possibly achieve greater penetration.

Successful DNAPL Remediation Using Radio Frequency Heating and Return to Thermal Equilibrium

Alicia Kabir, Environmental Resources Management (ERM), described how radio frequency (RF) heating technology works and how it is applied, and then presented a case study of the technology's implementation at an active manufacturing facility in the New England area (Attachment G). The facility's bedrock was affected by residual 1,1,1-trichloroethane (TCA) DNAPL. Removal of up to 99.9% TCA was observed in the source area after three years of full-scale RF system operation. Active treatment was suspended in November 2006. ERM is now monitoring the bedrock aquifer as it returns to thermal equilibrium and is evaluating potential rebound of the concentrations of volatile organic compounds (VOCs) in groundwater.

This was the first-ever in situ application of RF heating to treat TCA DNAPL in bedrock. The implementation of in situ RF heating increased groundwater temperatures, accelerated DNAPL dissolution, and transformed TCA into its daughter products through abiotic elimination and hydrolysis.

In RF heating, electromagnetic radiation is directed toward a non-conducting material (e.g., bedrock). The advantage of the RF heating process is that the heat is generated from within the material on the molecular level. Thus, RF heating does not necessarily require as detailed an understanding of hydrogeologic conditions as other remedial technologies. RF heating targets a volume of the aquifer, and its effectiveness is largely unrelated to subsurface stratigraphy and homogeneity.

Groundwater temperatures have declined steadily since suspension of system operation. Unlike other remedial technologies that target DNAPL, rebound of VOC concentrations is not expected to occur with RF heating. Because RF heating is not a "contact" technology, no pockets of DNAPL within the treatment zone that have not been affected by the RF system are expected to occur. Additionally, the RF equipment can be decontaminated and reused.

Question: During the feasibility study, did the regulators ask for comparisons with other thermal technologies for this site?

Response: Yes. Sampling indicated that such a large number of coils would be needed for effective electric resistance heating of the rock that it would tremendously energy intensive, expensive, and detrimental to the environment in terms of waste. Thermal conductive heating depends on water to push the energy, and too little water was available in the subsurface for this technology to be feasible.

Question: Has this technology been coupled with passive follow-on technologies, such as MNA or bioremediation?

Response: There are synergies to be obtained. For example, the heat can be used to activate persulfate for in situ oxidation. The temperatures achieved with RF heating can be detrimental to microbial populations; although once the temperature subsides bioremediation might be an option.

Question: What diameter were the boreholes?
Response: The wells used in the case study were 6-inch CPVC wells.

Question: How did you re-use the boreholes as monitoring points?
Response: The wells were installed initially as monitoring points with 15 feet of riser and 50 feet of screen; the rest was open borehole. The RF heating antenna was installed temporarily in the monitoring well.

Question: Did the heat not melt the PVC?
Response: We use CPVC or fiberglass as regular PVC wells will melt. If thermal heating might be used at the site, it will save money to design the monitoring system with that in mind.

Question: Are the heating wells the only ones used to verify treatment performance?
Response: The site had a network of about 50 monitoring wells, 15 in the source area and 30 in the immediate down gradient. The wells down gradient showed a 50-60 percent mass reduction. Several sentinel wells placed at the drinking water source showed no increase in concentrations.

Question: From a thermodynamic standpoint, does heating the water not eventually heat the rock?
Response: The fractures in the rock contain water, and the rock does heat to some extent, but not as much as it would using some of the other thermal technologies. Latent heat remains in the subsurface; when the RF system was turned off at the case study site, the subsurface took 18 months to regain thermal equilibrium.

Question: Are there parameters that are not conducive to RF heating, such as excessive moisture?
Response: The presence of too much water and rapid subsurface flushing can dissipate the heat too quickly. The site must be able to retain the heat to be suitable for RF heating.

Question: Will high concentrations of disseminated sulfides impact RF heating?
Response: No impact is expected as sulfides do not respond to heat. Their presence should not alter the RF heating approach.

Source Removal of VOC Contaminants in Bedrock, Letterkenny Army Depot, Chambersburg, Pennsylvania

Paul Stone (USACE) reported on the use of three separate technologies for three separate operable units in a four-mile continuous section of karst valley at Letterkenny Army Depot (Attachment H). The highly folded and fractured karst bedrock underlying the Industrial Area was the main source of VOCs contaminating the groundwater. Three different in situ technologies were demonstrated successfully at this site: two ISCO pilot studies and one enhanced biological treatment.

Fenton's reagent was applied in the Disposal Area, the first application of hydrogen peroxide in a karst bedrock aquifer. The well-developed epikarst allowed for the even spread/dosing of the Fenton's into the underlying VOC bedrock source. Very high pressures were obtained that could be controlled, directionally, by venting. The pilot study resulted in the first recorded change in Disposal Area groundwater quality. The goal was to test whether this process would reduce the mass of NAPL VOCs beneath a former waste disposal lagoon (the K-1 Area) at the site. The pilot was done to support a focused feasibility study (FFS) of this area.

In the winter of 2001 an ISCO pilot study was completed to determine the feasibility of remediating VOCs in the groundwater at the Lagoon Area (SE OU 11) using pressurized ozone (i.e., O^3, peroxone). The pressurized O^3 increased the concentration of oxidant at the bedrock surface. Despite highly porous bedrock media, the injection zone pressure was maintained, which allowed a larger than normal amount of ozone to be injected for enhanced destruction of VOCs. This pilot study resulted in the first recorded change in Lagoon Area groundwater quality. Active remediation (i.e., oxidant introduction) occurred over a period of about three years. The oxidant distribution system is designed to place the oxidant solution specifically in the portions of the aquifer where groundwater passing through comes in contact with the aquifer matrix. This potential treatment alternative also was evaluated in the FFS

Enhanced biological treatment over a period of years remediated petroleum hydrocarbons and chlorinated solvent constituents in the groundwater in the South East Industrial Area both on and off post. A 6-month pilot indicated that the discharge of VOCs to the springs was nondetectable within 1 month of injection sodium lactate. Biological indicator compounds, particularly methane, also showed marked increases in concentration. In late 2000, the Army implemented the enhanced bioremediation effort at full scale. The program involved the introduction of sodium lactate, with a tracer dye, into a series of injection wells over a 30-day period every 6 to 8 months. Bi-monthly groundwater samples were collected from a series of on-site and off-site locations for analysis of lactate, dye, VOCs, and dissolved gases to track cleanup progress. A ROD selecting enhanced bioremediation as the remedy for the SE OU 10 groundwater was signed in 2006.

Question: Was carbonate quenching a problem at this site?
Response: There is no primary porosity at this site as it is all secondary, very fine grained. A bench study was performed to make sure carbonate quenching would not be an issue.

Question: Typically when applying Fenton's reagent, a certain amount of off-gassing occurs. Was the off-gas captured in this demonstration?
Response: The injectors had pressure gauges and pressure release valves. The system responded so rapidly by slowing down when pressure was vented that it was almost like cooking on a gas stove. Sometimes the system was used to push the CO_2 that formed over the area.

The Application of In Situ Chemical Oxidation (ISCO) in Fractured Bedrock Using Geophysical Aided Design

Susanne Borchert (CH2M HILL) discussed the application of ISCO to several fractured bedrock sites and how the results of geophysical tests and hydraulic tests were used in the application design to overcome the challenges presented by a bedrock matrix (Attachment I). Permanganate is commonly used during ISCO applications for groundwater remediation. Experience gained from most permanganate sites in the United States is from applications in unconsolidated aquifers.

Examples of unique characterization tools for bedrock include hydraulic connectivity tests and effective permeability tests to help predict and optimize distribution of the permanganate. Another example is analysis of the fracture apertures (Paillet ranking method) to determine the percentage of open fractures per linear foot. This analysis not only allows estimation of the quantity and distribution of groundwater in the bedrock matrix, but also helps predict the amount of contact the permanganate oxidant will have with contaminants in the estimated groundwater volume and with the bedrock surface. These factors are important in calculating permanganate dosing during remedial designs.

Open borehole field tests were conducted at several Defense sites prior to permanganate injection. The tests included isolated vertical chlorinated solvent profiling with packers, fluid temperature and resistivity, hydraulic testing for connectivity and permeability, and down-hole geophysical logging. These and other data were used to develop the injection volumes, rates, and pressures; the injection method; the permanganate mass requirements; the permanganate concentrations per linear foot; and the amount of chase water per boring.

Lessons were learned over multiple applications:

1. The characterization tests that prove most useful at any a given site are unpredictable and need multiple lines of evidence to shape the conceptual site model for ISCO design and delivery. The following tools were most useful at their respective sites:
    - Televiewer and hydraulic connectivity tests in Maryland
    - Caliper, televiewer, and heat pulse flow meter in Georgia
    - FLUTe™ liners, caliper, fluid temperature and conductivity in West Virginia
2. To mitigate plume displacement by oxidant solution, use small injection volumes (fraction of estimated pore volume). Do not underestimate the transport distance of a low volume of injectant in fractures/lineaments—monitor potential surfacing.
3. During ISCO injection in an open borehole extending beyond treatment zone, consider placing the packer below the lowest impacted water-bearing fracture. This practice enhances the use of oxidant to destroy contaminants in open fractures.

Question: Is ISCO effective enough for use on fractured bedrock sites? Is it worth it in terms of the amount of chemical required?

Response: Time is also a factor, and ISCO will destroy the contaminants faster than bioremediation. It is a question of priorities. Is it important to destroy a large fraction of the contaminant mass even if complete remediation is not achieved?

Comment: Matrix diffusion analysis is very important for figuring out the mass of contaminant to be treated. At a site in Region 3, the analysis indicated that most of the contaminant mass was in the upper 20 feet of bedrock, with only small lenses occurring below that depth. This information allowed better focus of the treatment process, with far less waste.

Subsurface Characterization, Modeling, Monitoring, and Remediation of Fractured Porous Rocks

Sammantha Magsino (National Academies) gave a quick overview of the history and organization of the National Academy of Sciences and the National Research Council (Attachment J). Within the National Academies, the Committee on Geological and Geotechnical Engineering (COGGE) has the following charges:

- To identify, investigate, and report on questions relating to geological and geotechnical engineering to government, industry, academia, and the public;
- To inform public policy on geological and geotechnical engineering issues;
- To identify new technologies and potential applications; and
- To promote the acquisition and dissemination of knowledge.

Geological and geotechnical characterizing, modeling, and monitoring of the subsurface are integral to safe, economical, and environmentally responsible development, maintenance, operation, remediation, and decommissioning of infrastructure related to energy, water, waste, and transportation. Modeling and monitoring fluid travel paths and velocities through subsurface fractures and pore space are among the most significant engineering challenges associated with these tasks. Monitoring and modeling of subsurface fluid flow and transport are especially important at sites where wastes or hazardous substances are produced, stored, or unintentionally released.

Carlos Santamarina (Georgia Institute of Technology and member of the standing committee (COGGE) presented evidence to illustrate the importance of coupled processes in fractured porous rocks, and examples of potential emergent phenomena, including:

- Flow localization. Spatial variability (linked to the earlier presentation by Allen Shapiro on pore space, pore size, viability, and connectivity) leads to flow localization; this phenomenon is exacerbated in spatially correlated fractured media.
- Fines migration. The coupling between fluid migration and fines migration can lead to clogging; in particular, a clogging ring may form at a characteristic distance from the extraction well, significantly diminishing flow rate and altering the effective stress field.
- Bioremediation. There is increasing recognition of the importance of pore size for bioactivity. For a nominal bacteria size of 1 micron in diameter, larger sediment pores and fracture openings are required to allow for bioactivity. Indeed, bioclogging studies show highest impact in silts and fine sands.
- Reactive fluid transport. Extreme pH conditions promote mineral dissolution. In particular, acid fronts will dissolve grains and fracture walls facilitating fluid transport, which further promotes further dissolution. This positive feedback mechanism can lead to piping. Localized erosion or homogeneous dissolution is determined by the interplay between advection, diffusion and reactivity.

- Hydro-chemo-mechanical coupling. Mineral dissolution can have important mechanical implications. In particular, experimental and numerical results show that there is a pronounced decrease in horizontal stresses during mineral dissolution under zero lateral stress conditions, often reaching the Coulomb failure condition.

These examples show that hydro-chemo-bio-thermo-mechanical processes are inherently coupled in fractured porous rocks (thermo not shown in this brief presentation), and can lead to unanticipated phenomena.

In closing, Sammantha Magsino suggested that an ad hoc committee of the National Research Council could conduct a study to address issues relevant to flow and transport in fractured porous rocks, underlying coupled processes and potential emergent phenomena. Subsurface characterization, modeling, monitoring, and remediation aspects applicable throughout the lifecycle of engineered facilities that have potential to release contaminants would be considered. The committee would plan and hold a workshop to examine the state of art and state of practice in the following areas:

- Subsurface fracture and matrix *characterization*, especially relevant geotechnical and hydrological properties, and the development of conceptual models; detection of fluid and contaminant pathways and travel times;
- *Coupled processes,* governing parameters in various regimes, emergent phenomena and implications;
- *Modeling* of factors that affect change in geotechnical and hydrological properties over time; modeling contaminant transport and remediation to aid decision making during facility design, operation and monitoring, remediation, and decommissioning;
- *Early indicators* (such as change in fracture properties; moisture levels) of system failures resulting in unintentional release of fluids; and
- Potential *mitigation measures* to eliminate or reduce adverse impacts of system failures and related releases.

The committee would issue a final report that will include recommendations with respect to where research and development could improve the current state of art in SCMMR, and where incorporation of scientific and technical advances could enhance the state of practice in SCMMR and inform federal regulations and implementing guidance. A meeting will be scheduled for the near future to refine the statement of task for the study committee and to identify those willing to partner with the Nuclear Regulatory Commission in supporting this activity.

MEETING WRAP-UP/NEXT MEETING AGENDA

Balloting for the next FRTR meeting topic indicated monitoring and characterization as the topic of greatest interest to member agencies. The next meeting will be scheduled in May 2011. Jim Cummings thanked everyone for attending, and the meeting was adjourned.

ATTACHMENTS

A. Addressing the Complexities of Contamination and Remediation in Fractured Rock Aquifers
B. Tools for Characterization and Monitoring of Contaminated Fractured Rock
C. Demonstration and Validation of the Fracture Rock Passive Flux Meter
D. Fractured Bedrock Characterization and Effective Remedy Selection in Region 4
E. Autopsy of a Small UST site in Bedrock: Implications for Remedial Effectiveness
F. In Situ Bioremediation at FracRock Sites
G. Successful DNAPL Remediation Using Radio Frequency Heating and Return to Thermal Equilibrium
H. The Application of In Situ Chemical Oxidation (ISCO) in Fractured Bedrock Using Geophysical Aided Design
I. Source Removal of VOC Contaminants in Bedrock, Letterkenny Army Depot, Chambersburg, Pennsylvania
J. Subsurface Characterization, Modeling, Monitoring, and Remediation of Fractured Porous Rocks