Award Number: DOE-SBIR DE-FG02-04ER84013

Automated Impedance Tomography for Monitoring Permeable Reactive Barrier Health

Project Summary

The objective of Phase II research is the development of an autonomous, automated electrical geophysical monitoring system which will allow for near real-time assessment of Permeable Reactive Barrier (PRB) health and aging and which will provide this assessment through a web-based interface to site operators, owners and regulatory agencies.

Two rounds of laboratory experiments were carried out during the project period. In column studies with high concentrations of calcium and carbonate/bicarbonate, we observed that the increase of electrical resistivity and decrease of polarization magnitude is significant and is mainly controlled by the precipitation of calcium carbonates.

Surface data over existing PRBs were collected. After the initial round of data collection, this goal was modified to include studies inside the barriers in order to better understand barrier aging processes. These preliminary data were collected during the first and second periods of the project. An autonomous data collection system was designed and installed at the EPA PRB site in East Helena, Montana. In September, 2006, the electrode setups in East Helena were revised and three new vertical electrode arrays were placed in dedicated boreholes and were in direct contact with the PRB material.

In general, the electrical properties of all of the barriers studied follow a pattern. New barriers are fairly resistive with in-situ conductivity only a few times background (outside the barrier) values. Older barriers get increasingly conductive, with failed barriers showing values of over 100 S/m. The induced polarization response is more complicated. Chargeability values increase over time for young barriers, are largest for healthy barriers in the middle of their lifespan, and decrease as the barrier ages. These results suggest that normalized IP appears promising as a measure of barrier age.

This technology can potentially resolve several issues involving PRBs. Because the monitoring systems would operate autonomously and automatically - apart from initial hardware costs and a modest yearly support fee - these systems would require no further attention or investment. It is a cost-effective method for long-term monitoring of barrier performance and aging. It can also provide a tool for placement verification and can allow agencies to better understand whether problems arise from geochemical processes, site hydrology or installation errors.

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**Automated Impedance Tomography for Monitoring
Permeable Reactive Barrier Health**

Multi-Phase Technologies, LLC, Sparks, NV

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Project Goals

The objective of Phase II research is the development of an autonomous, automated electrical geophysical monitoring system which will allow for near real-time assessment of barrier health and aging and which will provide this assessment through a web-based interface to site operators, owners and regulatory agencies. The following tasks were established in order to meet this objective:

1. Experimental validation of the relationship between barrier aging and complex resistivity (CR) response for long term (1 year) controlled laboratory studies.
2. Collection of suites of surface data over existing Permeable Reactive Barriers (PRB).
3. System field testing and validation for an existing PRB.
4. Enhancement of a novel, cost-effective data acquisition strategy.
5. Enhancement of web-based accessible automated geophysical monitoring systems.
6. Integration of 3D/4D imaging software capable of imaging temporal CR signature.
7. Implementation of mapping relationships in imaging software to allow for PRB status validation and development of experimental and theoretical relationships between PRB and geophysical measurements.

Project Accomplishments

Laboratory Studies (Task 1)

The first round of laboratory studies was conducted from February to May 2006. We conducted column experiments to investigate the effect of mineralogy on the electrical signatures resulting from iron corrosion and mineral precipitation in Fe^0 columns. A contrasting time-lapse electrical response was observed between the two columns with calcite and magnetite precipitation, respectively. Solid phase analysis confirmed the formation of corrosion halos and increased mineralogical complexity in the corroded sections of the columns compared to the minimal/non-corroded sections. The contrasting time-lapse signatures were attributed to the differences in the electrical properties of the mineral phases formed within the two columns. While newly precipitated/transformed polarizable and semi-conductive iron oxides (mostly magnetite and green rust) increase the polarization and conductivity of the sulfate column, the decrease of both parameters in the bicarbonate column is attributed to the precipitation of non-polarizable and non-conductive calcite. This experiment shows that precipitate mineralogy is an important factor influencing the electrical properties of permeable reactive barrier (PRB) material and must be considered if electrical geophysical methods are to be developed to monitor PRB barrier corrosion processes in situ.

The second round of the experiment was carried out from January to April 2007 to investigate electrical signatures associated with iron corrosion processes under simulated real barrier installations with complex mineral precipitate profiles including concurrent CaCO_3 and iron oxide precipitation. Solid phase analysis identified CaCO_3 (calcite and aragonite) as a major mineral phase throughout the columns, with magnetite being another major phase close to the influent. Electrical measurements revealed a consistent decrease in conductivity and polarization magnitude of both columns, suggesting that the electrically insulating CaCO_3 dominates the electrical response despite the presence of both electrically conductive iron oxides and CaCO_3 precipitates. SEM/EDX (energy dispersive X-ray spectroscopy) imaging suggests that the electrical properties result from the geometrical arrangement of the mineral phases. The CaCO_3 forms an insulating film on zero valent iron (ZVI)/magnetite surfaces, which we assume restricts redox-driven transfer of electric charge between the pore electrolyte and ZVI particles, as well as across interconnected ZVI particles. This experiment demonstrates the use of electrical methods to evaluate CaCO_3 precipitation that result in reduction of ZVI surface redox properties, and thus can potentially serve as a methods to evaluate the change of ZVI reactivity in terms of its ability to engage in redox reactions.

Field Studies (Task 2)

Under Task 2, preliminary data were collected during the first period of the project at the Kansas City, Denver Federal Center (DFC), Monticello and East Helena PRB sites. During the second period, surveys were redesigned and secondary data were collected at the DFC, Monticello and East Helena sites. Continuity and Pole-Pole data were re-tested at Kansas City. Preliminary data acquisition tests at Helena and Monticello were completed and the results were presented in our semi-annual reports. During the last phase of the

project, final data for all four sites were collected in the fall of 2007; results are presented below and were also presented at the American Geophysical Union (AGU) fall meeting in San Francisco, December 10-14, 2007.

Data Acquisition (Tasks 3 - 4)

Under Tasks 3 and 4, an autonomous data collection system was designed and installed at the EPA PRB site in East Helena, Montana.

In September, 2006, the electrode setups in East Helena were revised. The system was shut down for several days while three new vertical electrode arrays were added. These new arrays were placed in dedicated boreholes and were in direct contact with the PRB material. In addition, the original PVC insulated cables were replaced with polyurethane insulated cables to reduce system noise. For the remainder of the project the site was fully configured with a total of 8 wells.

Web-based monitoring system (Tasks 5 – 7)

A web accessible database in which the data from the field system is automatically parsed was implemented. We created a basic interface allowing for data retrieval from this database. A more rigorous approach was to implement each of the processing steps as web services which can be invoked through a workflow.

This implementation required substantial underlying architecture design, for instance, the selection of an appropriate workflow engine, decisions on applicable standards, and deciding on the protocol on how to pass data between different web services, creation of appropriate user interfaces, slight adaptations of the underlying databases, and installation of appropriate extensions to our web server software.

We completed this implementation, which allowed several tasks to be performed on the field data. They include relatively basic ones such as generation of current, voltage and reciprocity distribution graphs.

Summary of Project Activities

Lab Studies

In the first round of laboratory experiments, we investigated the effects of different fluid chemistry on PRB behavior and associated electrical responses. In the second round of laboratory experiments we observed the electrical response from simulation of actual field PRBs at two sites: the Kansas City barrier and the East Helena barrier. As these sites are also used for our field monitoring efforts, this allowed for a comparison between field and laboratory. Although the columns were designed to run continuously for 100 days (to simulate 10 years of operation of the Kansas City barrier and 3 years of operation for the Helena barrier), after about 80 days into the experiment (86 days for Helena and 80 days for the KC column) the columns were terminated because the column effluent pH reached equal values with the influent, indicating complete loss of iron reactivity. Therefore, the data presented here are 86 days for the Helena column and 80 days for the KC column. An additional column, KC2, was run for 23 days. In order to provide a uniform basis for comparison the data are presented with regard to the volume of solutions used instead of actual days of laboratory experiment or simulated days of field operation. The total volumes of solutions used for the Helena, KC and KC2 columns are about 460 L, 250 L and 17 L, respectively.

Groundwater information, including water constituents and concentration, dissolved oxygen (DO) level, as well as flow rate, was acquired from site experts (Rick Wilkins for Helena and Nic Korte for Kansas City). The flow rate was scaled up in order to simulate a long running time within a short period of experiment time, i.e. the acceleration factor for Kansas City is 36.5 and about 11 for Helena, based on the flow rate (about 3 L/day for the Kansas City column and 5 L/day for the Helena column).

Along with the Kansas City and Helena columns, an additional column which was a duplicate of the Helena column was run in parallel to study the effect of flow rate on geochemical parameters and electrical measurements. Thus, the three columns which were run in parallel are: the Kansas City column (KC), the Helena column (Helena 02) and the flow rate test column (Helena 01).

Electrical measurements

A full waveform, multi-channel instrument was used for electrical measurements. In brief, twelve channels were available for measurements with one designated to a reference resistor and the remaining channels for the column. Current was injected through spiral electrodes placed in the end caps of the column (Figure 1), into a circuit consisting of the column and a precision reference resistor placed in series with the column. Data acquisition was done autonomously and automatically.

Measurements were collected over a frequency range from 0.01 – 1000 Hz. For each measurement, a voltage of 1 Volt at the selected frequency was applied across the injection electrodes located at either end of each column, and the resulting full waveform voltages were measured over both the reference resistor and the measurement channels.

Figure 1. Schematic diagram of the column setup showing column and channel configuration as well as the method of anaerobic control.

Electrical data modeling

Electrical data can be studied at a single frequency (or set of single frequencies) or at the full range of the frequencies as a whole. The advantage of using full range frequency data over single frequency is because the full frequency data can provide information on the global changes of the electrical data as well as avoid erroneous data points that can be easily ignored during single frequency studies. Cole-Cole modeling of the full spectrum of the electrical data is critical in order to acquire meaningful parameters that could be related to the electrochemical properties of the material across the full range of the frequencies.

Solid phase analysis

The columns were transported into an anaerobic chamber to extract samples for solid phase characterization after completion of electrical measurements. One sample was acquired from each channel of each column and split into two sub-samples for scanning electron microscopy (SEM) imaging and X-ray diffractometry (XRD) measurements. Surface and cross sectional SEM imaging was performed to characterize mineralogical changes during corrosion and precipitation processes in each column.

X-ray diffractometry, assisted by SEM/EDX (energy dispersive X-ray spectroscopy) imaging, was used for mineral phase identification. Several grams of each sample were ground with an agate mortar and pestle to acquire fine grains.

Results

Fluid geochemistry

Figure 2 shows the effluent aqueous geochemical data collected from the Helena and KC columns. Note that influent data is plotted at day 0 for comparison with effluent in order to demonstrate aqueous chemical changes across the columns.

Fluid conductivity changes are minimal for both columns. The influent conductivity of the Helena column is 2.62 ± 0.03 mS/cm with effluent conductivity showing a 6% variation. The influent conductivity of the KC column is 1.62 ± 0.02 mS/cm, and the effluent conductivity decreased to 1.54 ± 0.04 mS/cm after passing through the column with a variation of effluent conductivity of about 5% during the experiment. The pH of the Helena column increased from 7.25 ± 0.3 at the influent to 8.2 ± 0.2 at the effluent for the first 220 L of solution followed by a period of gradual decreasing back to 7.4 ± 0.1 for the last 240 L of solution. For the KC column, the pH increased from 6.7 ± 0.3 at the influent to 7.2 ± 0.2 at the effluent for the first 120 L of solution followed by a period of gradual decreasing back to 6.7 ± 0.1 for the last 120 L of solution. The pH increase for the first period of the experiment for both columns indicates the occurrence of anaerobic corrosion. This is supported by visual observation of the generation of H_2 gas. The generated H_2 had to be released by opening the electrode housing ports on a daily basis in order to minimize the influence on conductivity and porosity due to gas accumulation. The H_2 gas generation was gradually reduced to non-detectable levels by the end of the experiment accompanied with the decrease of pH, also providing evidence of the loss of iron reactivity.

Figure 2. Effluent chemistry of Helena and KC columns with influent chemistry plotted at volume 0 for comparison: (a) σ_w ; (b) pH; (c) Eh and (d) Dissolved iron. Note that aqueous chemistry data for KC2 is not plotted for brevity.

The Helena column had an influent Eh of -37 mV and it dropped to between -85 and -90 mV during saturation with the first 220 L of solution. After the first 220 L of solution, the Eh started to gradually increase back to around -42 mV (close to the influent value) at the end of the experiment. For the KC column, the effluent Eh dropped to and stayed constant at -25 to -30 mV compared to about -4 mV at the influent during the first 120 L of solution. After that, the Eh gradually climbed back to about -5 mV, almost the same as the influent Eh at the end of the experiment with a total of about 240 L of solution used for this column. The change of Eh values is in complete agreement with the pH changes, both indicating the loss of iron reactivity.

Effluent dissolved iron concentration of the Helena column started at 2.1 ppm and quickly dropped to about 1.1 ppm after the first day. The dissolved iron level in the Helena column slowly decreased to about 0.7 ppm for the duration of the experiment. For the KC column, a start value of 1.3 ppm was measured and dropped to about 0.2 ppm and stayed constant for the duration of the experiment.

Solid phase analysis

Solid phase analysis with SEM/EDX and XRD identified the major mineral phases of each column, which are: calcite, aragonite and magnetite. All of the columns were similar. XRD results for the Helena column are presented in Figure 3. XRD analysis demonstrated that major magnetite peaks (at $2\theta = 35.45^\circ$) are present predominantly at the first two or three channels (Channel 2, 3 and 4) closest to the influent end, compared with much reduced magnetite peaks at the channels (Channel 5-8) deep into the column. Similar to magnetite, calcite is also a mineral phase present mainly at the first one or two channels of each column as demonstrated from the XRD spectrum (Figure 3).

Figure 3. X-ray diffractograms of samples extracted from Helena column. Ar= aragonite, Cal = calcite, Mag = magnetite, Fe = ZVI, Q = quartz.

Electrical data

Figure 4 compares the changes of σ' and σ'' as a function of frequency for the duration of the experiment on selected days for the interface channels (Channel 2) of the Helena column (Figure 4a, b) and the KC column (Figure 4c, d).

Figure 4 reveals a consistent decrease of both σ' and σ'' at the interface channels of both columns for the duration of the experiment with a much greater rate of change at the beginning stage of the experiment with respect to the later stage. Similar to the interface channels, channels deep into the columns demonstrate the same trend of changes for both σ' and σ'' indicating a uniform response of the whole column to the reaction processes.

Figure 4. Spectral electrical data of (a) σ' and (b) σ'' of Helena column at the interface channel at solution volume usage of 10L (●), 170L (◆), 276L (■), 403L (□), and 493L (◇). (c) σ' and (d) σ'' of KC column at the interface channel at solution volume usage of 6L (●), 70L (◆), 130L (■), 187L (□), and 245L (◇).

The following table (Table 1) demonstrates the percentage of resistivity increase and polarization decrease for all the channels of all three columns.

Parameters	Column	Ch2	Ch3	Ch4	Ch5	Ch6	Ch7
Increase of ρ_0	Helena	169%	175%	177%	174%	205%	210%
	KC	323%	447%	680%	433%	210%	172%
	KC2	44%	206%	113%	100%	170%	72%
Decrease of m_n	Helena	79%	75%	83%	73%	72%	74%
	KC	77%	82%	88%	86%	75%	79%
	KC2	25%	72%	59%	51%	64%	45%

Table 1. Percentage of change of electrical resistivity (ρ_0) and polarization magnitude (m_n) for each channel of all three columns for the duration of the experiment.

This table confirms that the increase of resistivity and decrease of polarization magnitude is present for all the channels of all three columns despite their different magnitudes of change. In comparing the rates of change of electrical signatures, it is clear that the rate of change of electrical data for the KC columns is higher than that of the Helena column. This is attributed to the high concentrations of calcium and carbonate/bicarbonate in simulated KC groundwater as well as the slower flow rates allowing sufficient residual time for mineral precipitation.

Column Study Conclusions

In column studies with high concentrations of calcium and carbonate/bicarbonate, we observed that the increase of electrical resistivity and decrease of polarization magnitude is significant and is mainly controlled by the precipitation of calcium carbonates.

Field Studies

Final data collection at three barrier sites took place in September and October, 2007; (1) a uranium tailing site near Monticello, Utah, (2) the DOE complex at Kansas City, Missouri, and (3) the Denver Federal Center in Denver, Colorado. At the Asarco Smelter site in East Helena, Montana, nearly continuous data were collected by the autonomous monitoring system from June 2006 to November 2007. This data provided a basis for comparison with laboratory studies outlined previously in this report. It also provides us with a picture of the evolution of the barrier, enabling us to examine barrier changes more precisely and determine whether these changes are due to installation issues or are normal barrier aging.

Asarco Smelter

Barrier Aging

The Asarco site, the youngest of the barriers in this study, was installed in May of 2005 as a pilot study to test treatment of an arsenic plume. The barrier was installed from 45 feet (13.7 m) to approximately 20 feet (6.1 m) below ground surface (bgs). It is 100 % zero valent iron (ZVI) and 6 feet (1.8 m) thick. It is oriented perpendicular to groundwater flow. The water table was at approximately 33 feet (10 m) bgs. A map view of the final configuration of arrays used for the autonomous monitoring system is shown in Figure 5.

Figure 5. Map view of the Asarco, East Helena barrier array configuration. Note that ground-water flow is from upgradient (UG) to downgradient (DG)

Ample data have now been collected to allow us to examine the variations within the barrier over time. The most reliable data are those from the arrays placed near the center of the barrier in direct contact with the barrier material; Array NWN (approximately in the center of the barrier) and Array NWS (near the up-gradient edge of the barrier) (Figure 5).

Autonomous data collection continued through October 2007 using single well Wenner arrays and 3-D data across multiple wells. Figure 6a is an ERT cross-section image of borehole NWN taken with .375 meter electrode separations and plotted as the change in resistivity from a 1 Hz background image taken on December 06, 2006 to October 11, 2007. Figure 6b is the corresponding 1 Hz data plotted on a monthly basis from September 22, 2006 to October 14, 2007. These data show that in the upper portion of the borehole, the resistivity values are very low; some are below .5 Ohm m. The lower portion of the barrier remains highly resistive, but these values continue to decrease. Although the changes are small they are perceptible.

Figure 6. Change in apparent resistivity of the East Helena barrier. Figure 6a is an ERT cross-sectional image showing the location of array NWN and is plotted as the change in resistivity from a background image taken on December 06, 2006 to October 11, 2007. Figure 6b is the corresponding data plotted on a monthly basis from September 22, 2006 to October 14, 2007.

Figure 7 shows three-dimensional ERT images of the barrier plotted using the same background data in Figure 6a. The large blue area in the figure indicates the upper portion of the permeable reactive barrier and shows small but continuing changes through October 2007. In the lower portion, the change in resistivity is evident by the decreased size of the red area from one month to the next. There are apparent changes outside the barrier region but these do not show a consistent pattern from month to month.

Figure 7. 3-D ERT views of resistivity as percent change from background data taken at 1 Hz on December 06, 2006. The view is from October, 2007. The large blue area represents the upper portion of the barrier and shows very little change in resistivity. The decrease in size of the red area in the lower portion represents a decrease in resistivity.

Field Studies Conclusions

In-situ resistivity and induced polarization studies have now been completed at six barriers at the four different sites: Monticello, Utah; the Denver Federal Center; Kansas City, Missouri; and East Helena, Montana. As some barriers tend to age dramatically faster than others, for this study we consider low permeability barriers as of greater age, as “old” barriers tend to loose permeability rather than exhaust reactive materials. The old barriers examined tended to have increasingly higher electrical conductivities; for pure

ZVI barriers resistivity is probably a good indicator of age in most cases. One complicating factor is that two of the barriers studied appear to have issues related to installation.

The former Asarco Smelter Site near East Helena, Montana, showed surprisingly rapid evolution over the first year of monitoring with changes in both resistivity and chargeability of tens of percent per month. In general, the electrical properties of all of the barriers studied follow a pattern. New barriers are fairly resistive with in-situ conductivity only a few times background (outside the barrier) values. Older barriers get increasingly conductive, with failed barriers showing values of over 100 S/m. The induced polarization response is more complicated. Chargeability values increase over time for young barriers, are largest for healthy barriers in the middle of their lifespan, and decrease as the barrier ages (Figure 8). These results suggest that normalized IP appears promising as a measure of barrier age.

Figure 8. First IP window chargeability (IP) normalized over .125 Hz value for the East Helena and Monticello PRBs compared to the ZVI column in the laboratory study.

Earlier in the study we hypothesized that perhaps the Helena barrier would eventually behave similarly to other barriers after a longer period of time, giving the aging processes more time to manifest. The upper portion of the barrier appears to be moving to values similar to those at sites such as the Denver Federal Center barrier. However, this is not the case for the lower part of the barrier, as we observe from six additional months of data which show an increase in resistivity. Another hypothesis, that the guar-gum polymer (which is viscous and water soluble) that was placed in the barrier trench during construction would take time to break down, has also proven to be inaccurate for the same reason stated above. A third and more likely explanation for the increase in resistivity could be that the walls of the barrier may have partially collapsed during the ZVI installation. Because of the guar-gum it was impossible to see any depth into the trench and thus there was no available method to test for this during and after the placement of the

ZVI. Core data from both Kansas City and the Denver Federal Center showed significant inclusions of non-ZVI material in the completed barriers indicating that this is a common problem during barrier installation. Furthermore, the values of resistivity and chargeability in the Helena barrier are similar to those in the ZVI/gravel mixture at the Monticello barrier which suggests that the base of the barrier at East Helena is probably a mixture of sediments and ZVI (Figure 9).

Figure 9. Comparison of barrier resistivities. Note the resistivity value of the lower portion of the Helena barrier is similar to the gravel/ZVI mix in the Monticello barrier.

Data Acquisition

An autonomous data collection system was designed and installed at the EPA PRB site in East Helena Montana in June, 2006. In September, 2006, the electrode setups in East Helena were revised and three new vertical electrode arrays were added. These new arrays were placed in dedicated boreholes and were in direct contact with the PRB material. In addition, the original PVC insulated cables were replaced with polyurethane insulated cables to reduce system noise.

For the remainder of the project the site was fully configured with a total of 8 wells and the data acquisition schedule included fully three-dimensional (3-D) data collection, in addition to monitoring of the arrays imbedded in the barrier (see Figure 5 above).

Because many of the data surveys took multiple days - in particular cross-borehole 3-D data at lower frequencies - the use of automated data collection proved to be invaluable for this project.

Web-based Monitoring System

One of the objectives of this project was the development of an autonomous, web accessible data processing package. This processing package would perform the standard tasks associated with ERT data acquisition, inversion and processing.

Earlier in this project we implemented a web accessible database in which the data from the field system is automatically parsed. We created a basic interface allowing for data retrieval from this database. However, a more rigorous approach was to implement each of the processing steps as web services which can be invoked through a workflow. The advantage of such an architecture is that, by encapsulating each of the modular tasks (for instance, enumerating datasets associated with a project, retrieving data from a dataset, processing the data, and graphing the results) in a web service it becomes very easy to build different workflows.

This implementation required a fair amount of underlying architecture design, which was partially done under other projects. For instance, it required the selection of an appropriate workflow engine, decisions on applicable standards, and deciding on the protocol on how to pass data between different web services, creation of appropriate user interfaces, slight adaptation of the underlying databases, and installation of appropriate extensions to our web server software.

We completed this implementation, which allowed several tasks to be performed on the field data. They include relatively basic ones (generation of current, voltage and reciprocity distribution graphs), but extending these tasks to more complex ones is now relatively straightforward.

Products

A paper titled: “Effect of mineralogy on low frequency electrical properties of corroded iron columns: implications for the monitoring of permeable reactive barriers (PRBs)” by Yuxin Wu, Roelof Versteeg, Lee Slater, Douglas LaBrecque, and Roger Sharpe, 2006, has been published in the Geological Society of American Abstracts with Programs, Vol. 38, No. 7, p. 197.

A paper titled: “A comparison of the low frequency electrical signatures of iron oxide versus calcite precipitation in granular zero valent iron columns” by Yuxin Wu, Lee D. Slater, Roelof Versteeg, and Douglas LaBrecque, 2008, has been published in the Journal of Contaminant Hydrology; volume 95 (3-4): 154-167.

A paper titled: “Calcite precipitation dominates the electrical signatures of Fe^0 columns under simulated field conditions” by Yuxin Wu, Roelof Versteeg, Lee Slater, and Douglas LaBrecque, is in preparation for submission to Environmental Science and Technology.

Conference Proceedings

A paper titled: “Low frequency electrical responses from simulated zero valent iron in PRBs with high carbonate concentration” by Yuxin Wu, Roelof Versteeg, Lee Slater, and Douglas LaBrecque was presented at the American Geophysical Union (AGU) fall meeting in San Francisco, California, December 10-14, 2007.

A presentation titled: “Monitoring of zero valent iron permeable reactive barriers, electrical properties and barrier aging” by Douglas LaBrecque, Paula Adkins, Roger Sharpe, Lee Slater and Roelof Versteeg was given at the American Geophysical Union (AGU) fall meeting in San Francisco, California, December 10-14, 2007.

A presentation titled “Geophysical investigations of PRBs” by Douglas LaBrecque, Roger Sharpe, Roelof Versteeg and Lee Slater was given at the RTDF (Remediation Technologies Demonstration Forum), sponsored by the Environmental Protection Agency (EPA) and the Dupont Corporation Remediation Group, Charleston, SC, Oct. 10-11, 2006.

A poster titled “Geophysical investigations of PRBs” by Douglas LaBrecque, Roger Sharpe, Lee Slater and Roelof Versteeg was presented at the American Geophysical Union (AGU) fall meeting in San Francisco, California, December 11-15, 2006.

A paper titled: “Automated acquisition and processing of multichannel complex resistivity data” by Roelof Versteeg, Douglas LaBrecque, Roger Sharpe, Yuxin Wu, Lee Slater, Alex Richardson, and Trevor Rowe was published in the Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), Seattle, Washington, April 2-6, 2006.

A paper titled “Managing a capped acid rock drainage (ARD) repository using semi-autonomous monitoring and modeling” by Roelof Versteeg, Ken Wangerud, Alex Richardson, Trevor Rowe and Gail Heath was presented at the 7th International Conference on Acid Rock Drainage (ICARD) in St. Louis, Missouri, March 26-30, 2006.