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Title: Reductive immobilization of U(VI) in Fe(III) oxide-reducing subsurface sediments: Analysis of coupled microbial-geochemical processes in experimental reactive transport systems

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1. Executive Summary

The purpose of this research was to provide information to DOE on microbiological and geochemical processes underlying the potential use of dissimilatory metal-reducing bacteria (DMRB) to create subsurface redox barriers for immobilization of uranium and other redox-sensitive metal/radionuclide contaminants that were released to the environment in large quantities during Cold War nuclear weapons manufacturing operations. Several fundamental scientific questions were addressed in order to understand and predict how such treatment procedures would function under *in situ* conditions in the subsurface. These questions revolved the coupled microbial-geochemical phenomena which are likely to occur within a redox barrier treatment zone, and on the dynamic interactions between hydrologic flux and biogeochemical process rates.

First, we assembled a robust conceptual understanding and numerical framework for modeling the kinetics of microbial Fe(III) oxide reduction and associated DMRB growth in sediments. Development of this framework is a critical prerequisite for predicting the potential effectiveness of DMRB-promoted subsurface bioremediation, since Fe(III) oxides are expected to be the primary source of electron-accepting capacity for growth and maintenance of DMRB in subsurface environments.

We also defined in detail the kinetics of microbial (enzymatic) versus abiotic, ferrous iron-promoted reduction of U(VI) in the presence and absence of synthetic and natural Fe(III) oxide materials. The results of these studies suggest that (i) the efficiency of dissolved U(VI) scavenging may be influenced by the kinetics of enzymatic U(VI) reduction in systems with relative short fluid residence times; (ii) association of U(VI) with diverse surface sites in natural soils and sediments has the potential to limit the rate and extent of microbial U(VI) reduction, and in turn modulate the effectiveness of *in situ* U(VI) bioremediation; and (iii) abiotic, ferrous iron (Fe(II)) driven U(VI) reduction is likely to be less efficient in natural soils and sediments than would be inferred from studies with synthetic Fe(III) oxides. A key implication of these findings is that production of Fe(II)-enriched sediments during one-time (or periodic) stimulation of DMRB activity is not likely to permit efficient long-term abiotic conversion of U(VI) to U(IV) in biogenic redox barriers designed to prevent far-field subsurface U(VI) migration. Instead our results suggest that ongoing DMRB activity will be required to achieve maximal U(VI) reduction efficiency, and emphasize the need for detailed understanding of patterns of DMRB growth, colonization, and maintenance in physically and chemically heterogeneous subsurface environments in order to predict the effectiveness of subsurface U(VI) bioremediation operations.

A final “capstone” aspect of experimental work on the project was to examine the potential for sustained coupled Fe(III) oxide and U(VI) reduction in experimental flow-through reactor systems (i.e. sediment columns and “semicontinuous culture” systems) that are conceptually analogous to hydrologically-open subsurface environments. The results conclusively demonstrated the potential for sustained removal of U(VI) from solution via DMRB activity in excess of the U(VI) sorption capacity of the natural mineral assemblages as determined in abiotic controls. In addition, the abundance of sorbed U(VI) (a potential long-term source of U(VI) to the aqueous phase) was much lower in the biotic vs. abiotic systems. The latter results agree with other project findings which demonstrated the capacity for *G. sulfurreducens* to reduce sorbed U(VI).

Throughout the project we have developed and refined a variety of reaction-based models of coupled Fe(III) oxide/U(VI) reduction, including a generalized model which accounts for the population dynamics of various respiratory microbial functional groups. These models have been employed in numerical simulations of both batch bench- and field-scale systems. Our progress on this front gives us confidence that such models can be successfully applied to field conditions that required large reaction networks and physical heterogeneity.

Other project accomplishments included careful examination of thermodynamic and kinetic aspects of U(VI) adsorption onto Fe(III) oxide surfaces in the presence of competing ligands such as carbonate and phosphate, and theoretical assessment of the influence of solid-to-solution ratio the reactive transport of U(VI) and dissolved inorganic carbon in hypothetical groundwater aquifer materials.

2. Research Goals and Accomplishments

Although the fundamental microbiological and geochemical processes underlying the potential use of dissimilatory metal-reducing bacteria (DMRB) to create subsurface redox barriers for immobilization of uranium and other redox-sensitive metal/radionuclide contaminants are well-understood (Lovley et al., 1991; Gorby and Lovley, 1992; Lovley and Phillips, 1992; Lovley, 1995; Fredrickson et al., 2000; Wielinga et al., 2000; Wielinga et al., 2001), at the time this project was funded several fundamental scientific questions still needed to be addressed in order to understand and predict how such treatment procedures would function under *in situ* conditions in the subsurface. These questions revolved the coupled microbial-geochemical processes which are likely to occur within a redox barrier treatment zone, and on the dynamic interactions between hydrologic flux and biogeochemical process rates. Below we provide a brief summary of our results, organized in relation to the major research topics addressed in the project.

A. Kinetic and thermodynamic controls on microbial reduction of Fe(III) oxide minerals

A central theme of our ongoing EMSP-funded research (including our original 96-10 award number 55164) has been to evaluate the geochemical and microbiological controls on enzymatic reduction of Fe(III) oxides by DMRB. Such information is critical for predicting the potential effectiveness of DMRB-promoted subsurface bioremediation, since Fe(III) oxides are expected to be the primary source of electron-accepting capacity for growth and maintenance of DMRB in subsurface environments. We have conducted studies with a variety of synthetic Fe(III) oxide phases and DMRB, which collectively indicate that surface area-normalized rates of electron transfer to Fe(III) oxides are comparable (in the presence of excess electron donor) across a wide range of oxide crystal structure and surface area (Roden, 2003a, b, 2005a). These results suggest a rate model in which enzymatic electron transfer is directly dependent on the abundance of reducible oxide surface sites, whose abundance is modulated by the accumulation of surface-associated (adsorbed and/or surface-precipitated) biogenic Fe(II) (Roden and Urrutia, 2002). Studies of the influence of DMRB cell density on rates of oxide reduction demonstrate a hyperbolic relationship between total cell density and surface-area normalized reduction rate (Roden, 2003a, 2005a). The collective results of these studies, together with independent data on FeRB growth yield (with soluble ferric citrate), provided information required for simulation of oxide reduction kinetics in nonsteady-state systems in which DMRB cell density varies over time. Finally, previous and ongoing studies of Fe(II) sorption to residual Fe(III) oxide and other mineral surfaces during enzymatic reduction have permitted development of a reaction-based framework for depicting the influence of surface-bound Fe(II) accumulation on long-term oxide reduction kinetics (Roden, 2004). The developed framework accurately reproduces the results of batch and column studies of synthetic and natural Fe(III) oxide reduction (Roden and Sedo, 2003), and has been used to assess the impact of field-scale physical/chemical heterogeneity on spatial and temporal patterns of bacterial Fe(III) oxide reduction (Roden, 2003c).

B. Microbial reducibility of U(VI) sorbed to Fe(III) oxide and other solid-phase surfaces

A major focus of our research was to examine the extent to which U(VI) associated with Fe(III) oxide and other soil/sediment mineral surfaces was subject to enzymatic reduction by DMRB. This is an important consideration, because although dissolved U(VI) in groundwater is the major environmental health threat associated with subsurface U(VI) contamination, much of the U(VI) in the subsurface is associated with solid (mineral) surfaces. This solid-associated U(VI) represents a potential long-term source for release of dissolved U(VI) to groundwaters. If solid-associated U(VI) can be rapidly and efficiently converted to an immobile U(IV) phase (i.e. $\text{UO}_2(\text{s})$), then stimulation of DMRB activity in source zones may provide an effective means for preventing long-term subsurface contaminant migration.

In addition, the efficacy of in situ biogenic redox barriers for prevention of far-field U(VI) migration in relatively dispersed plumes would be enhanced if the U(VI) that entered and underwent surface complexation in such zones was subject to rapid and complete microbial reduction. Experiments to address this question were conducted with the well-known DMRB *Geobacter sulfurreducens* (Caccavo et al., 1994), which is the focus of major DOE Genomics:GTL-funded research (Methe, 2003). Our results (Jeon et al., 2004) showed that the rate and extent of reduction of U(VI) associated with surfaces of synthetic Fe(III) oxides (hydrous ferric oxide, goethite, and hematite) was comparable to that observed during reduction of aqueous U(VI). In contrast, microbial reduction of U(VI) sorbed to several different natural Fe(III) oxide-containing solids was slower and less extensive compared to synthetic Fe(III) oxide systems. Interestingly, addition of the electron shuttling agent anthraquinone-2,6-disulfonate (Lovley et al., 1996) enhanced the rate and extent of both Fe(III) and U(VI) reduction. These findings suggest that AQDS facilitated electron transfer from *G. sulfurreducens* to U(VI) associated with surface sites at which direct enzymatic reduction was kinetically and/or thermodynamically limited. Together these results demonstrate that association of U(VI) with diverse surface sites in natural soils and sediments has the potential to limit the rate and extent of microbial U(VI) reduction, and in turn modulate the effectiveness of in situ U(VI) bioremediation. We are currently engaged (through funding from DOE's NABIR program) in detailed studies of the speciation of solid-associated U(VI) in natural sediments, which are required to understand and predict the susceptibility of solid-associated U(VI) to enzymatic reduction.

C. Kinetic limitations to the efficiency of dissolved U(VI) scavenging in subsurface sediments

Experiments on the kinetics of dissolved U(VI) reduction by *G. sulfurreducens* were conducted in parallel with the studies of solid-associated U(VI) reduction discussed above. The results showed that this organism is capable of reducing dissolved U(VI) from starting concentrations of a few thousand $\mu\text{g L}^{-1}$ to values below the EPA drinking water MCL of $30 \mu\text{g L}^{-1}$ (Jeon et al., 2004). However, the half-saturation constant for U(VI) reduction by *G. sulfurreducens* (Roden and Scheibe, 2005), like other DMRB (Truex et al., 1997; Liu et al., 2002; Burgos et al., 2005), is on the order of $10,000 \mu\text{g L}^{-1}$. These results suggest that efficiency of dissolved U(VI) scavenging may be significantly influenced by the kinetics of enzymatic U(VI) reduction in systems with relative short fluid residence times.

D. Relative kinetics of enzymatic U(VI) reduction vs. abiotic reduction of U(VI) by surface-bound biogenic Fe(II)

Another key aspect of our research was to evaluate the relative kinetics of enzymatic U(VI) reduction vs. abiotic reduction of U(VI) by surface-associated biogenic Fe(II), i.e. Fe(II) generated during reduction of Fe(III) oxides by DMRB. If sorbed U(VI) can be reduced to an immobile U(IV) phase via abiotic reaction with Fe(II), then stimulation of Fe(II) production by DMRB activity in source zones may provide a means for creating long-term biogenic redox barriers for prevention of far-field U(VI) migration. We found (Jeon et al., 2005) that U(VI) was rapidly and extensively ($\geq 80\%$) reduced abiotically by Fe(II) in the presence of synthetic Fe(III) oxides and highly Fe(III) oxide-enriched (18-35 wt% Fe) Atlantic coastal plain sediments. In contrast, long-term (20-60 d) U(VI) reduction was less than 30% in suspensions of six other natural solids with relatively low Fe(III) oxide content (1-5 wt% Fe). Fe(II) sorption site density was several-fold lower on these natural solids compared to the synthetic Fe(III) oxides, which may explain the poor U(VI) reduction in the natural solid-containing systems. Addition of the reduced form of the electron shuttling compound anthrahydroquinone-2,6-disulfonate (AH₂DS) to the natural solid suspensions enhanced the rate and extent of U(VI) reduction, suggesting that AH₂DS reduced U(VI) at surface sites where reaction of U(VI) with sorbed Fe(II) was limited. Our results demonstrate that abiotic, Fe(II)-driven U(VI) reduction is likely to be less efficient in natural soils and sediments than would be inferred from studies with synthetic Fe(III) oxides. A key implication of these findings is that production of Fe(II)-enriched sediments during one-time (or periodic) stimulation of

DMRB activity is not likely to permit efficient long-term abiotic conversion of U(VI) to U(IV) in biogenic redox barriers designed to prevent far-field subsurface U(VI) migration. Instead our results suggest that ongoing DMRB activity will be required to achieve maximal U(VI) reduction efficiency, and emphasize the need for detailed understanding of patterns of DMRB growth, colonization, and maintenance in physically and chemically heterogeneous subsurface environments in order to predict the effectiveness of subsurface U(VI) bioremediation operations.

E. Sustained coupled Fe(III) oxide/U(VI) reduction in flow-through reactor systems

A final “capstone” aspect of experimental work on the project was to examine the potential for sustained coupled Fe(III) oxide and U(VI) reduction in experimental flow-through reactor systems (i.e. sediment columns and “semicontinuous culture” systems) that are conceptually analogous to hydrologically-open subsurface environments. These experiments were conducted with natural subsurface sediment from the former DOE research site in Oyster, VA (Chapatwala et al., 1996; Palumbo et al., 1996; Zhang et al., 1997; Dong et al., 1999; Fuller et al., 2001; Johnson et al., 2001b; Johnson et al., 2001a; Dong et al., 2002b; Dong et al., 2002a; Wildung et al., 2004) that was a central focus of our work on solid-associated U(VI) bioreduction. The semicontinuous culture reactor (SCR) approach represents a middle ground between closed system batch cultures and column reactor systems involving continuous advective aqueous phase flux. In a SCR experiment, 10-30% of the aqueous phase of the reactor is carefully removed (so as to not disturb the layer of settled materials on the bottom of the reactor) every 3-4 days using a sterile syringe and needle (cf. Roden and Urrutia (1999)). An equal volume of fresh aqueous phase medium is then added to the reactor, after which the sediment is resuspended by vigorous shaking prior to withdrawal of bulk sediment suspension samples. The volume of aqueous phase replacement is decreased incrementally over time in order to maintain a constant solid:solution ratio in the reactor. This procedure can conveniently produce mean aqueous phase residence times of ca. 10 d, which is likely to approach reality for field-scale bioremediation systems. A significant advantage of the SCR approach is that samples of solid-phase materials (containing residual and newly formed mineral phases and DMRB biomass) can be easily obtained on a periodic basis for chemical, microbiological, and mineralogical analysis – in contrast to column reactors, from which solid-phase samples can only be obtained through destructive sampling at the end of the experiment.

The results of the SCR experiments (Roden, 2005b) conclusively demonstrated the potential for sustained removal of U(VI) from solution via DMRB activity in excess of the U(VI) sorption capacity of the natural mineral assemblages as determined in abiotic controls. In addition, the abundance of sorbed U(VI) (a potential long-term source of U(VI) to the aqueous phase) was much lower in the biotic vs. abiotic systems. The latter results agree with other project findings which demonstrated the capacity for *G. sulfurreducens* to reduce sorbed U(VI) (Jeon et al., 2004).

In addition to the SCR experiments, a long-term (ca. 6 month) column reactor experiment on coupled Fe(III) oxide/U(VI) reduction was conducted with *G. sulfurreducens*, once again using natural subsurface sediment (< 2 mm fraction) from the Oyster site in Virginia. The hydrological residence time of the reactors was ca. 2 d, significantly shorter than for the SCRs but not unrealistic with respect to field applications. As in the case of the SCR experiment, the results demonstrated the potential for sustained removal of U(VI) from solution via DMRB activity in excess of the U(VI) sorption capacity of the natural mineral assemblages (Roden, 2005b).

F. Biogeochemical modeling

Throughout this project we have developed and refined a variety of reaction-based models of coupled Fe(III) oxide/U(VI) reduction and associated biogeochemical phenomena, which have been employed in numerical simulations of U(VI) bioreduction in bench-scale (Roden and Sedo, 2003) and field-scale (Roden, 2003c; Scheibe et al., 2005) systems. Our progress on this front gives us confidence that these models can be successfully applied to field conditions that required large reaction networks and physical

heterogeneity. We also developed a generalized microbial population/energetics-based model of Terminal Electron Accepting Processes and other biogeochemical reactions in a hypothetical Representative Elementary Volume of Uranium-contaminated subsurface sediment, which is referred to by the acronym TEAPREVU (Roden et al., 2005). The model was developed to simulate the results of a batch slurry experiment with sediment from Area 2 at the NABIR Field Research Center at Oak Ridge National Laboratory, with the idea that the developed framework will eventually be incorporated into a field-scale reactive transport simulation of in situ biostimulation at Area 2. The model is capable of simulating time-dependent population dynamics of different functional microbial groups in relation to the abundance of various oxidized and reduced species and mineral phases, which in turn are a function of the input of external electron acceptors/donors and other aqueous species. Yilin Fang at PNNL has recently implemented this model into the DOE-supported reactive transport code HYDROGEOCHEM (Fang et al., 2005).

G. Other research accomplishments

As part of our work on the susceptibility of solid-associated U(VI) to enzymatic and abiotic, Fe(II)-driven reduction, a series of experiments examining thermodynamic and kinetic aspects of U(VI) adsorption onto Fe(III) oxide surfaces was conducted. Such information is crucial for modeling the behavior of U(VI) in subsurface environments, because geochemical conditions, particularly pH and the presence or absence of complexing ligands, have profound and sometimes unexpected impacts on U(VI) surface complexation. Among the inorganic ligands, the effects of dissolved inorganic carbon have been studied extensively. Phosphate is a much stronger ligand, which has been shown to control the subsurface mobility of U(VI) at sites that are used as natural analogies of nuclear waste repositories. However, there have been few studies on the effects of phosphate on U(VI) adsorption.

In one study (Cheng et al., 2004), we examined U(VI) adsorption on goethite-coated sand (to mimic natural Fe-coated subsurface materials) as a function of pH in batch systems closed to the atmosphere, in the presence and absence of added phosphate. At low pH, adsorption of U(VI) increases in the presence of phosphate. The phosphate is strongly bound by the goethite surface in the low pH range and the increased uptake of U(VI) is attributed to the formation of ternary surface complexes involving both UO_2^{2+} and PO_4^{3-} . In the high pH range, the adsorption of U(VI) decreases in the presence of phosphate at low solid/solution ratio as a result of competition for surface site between UO_2^{2+} and PO_4^{3-} , and the formation of soluble uranium species. A surface complexation model that incorporates the interactions involving UO_2^{2+} and PO_4^{3-} successfully predicted U(VI) adsorption in the presence of phosphate under a range of conditions.

A related study (Cheng et al., 2005) examined U(VI) adsorption and transport in the presence and absence of phosphate in both batch and column experiments with goethite-coated sand to examine the applicability of batch experiments to porous media transport. Batch kinetics experiments revealed that the presence of phosphate increased both the rate and extent of U(VI) adsorption. U(VI) adsorption experiments at different solid to solution ratios (SSR) indicated that U(VI) adsorption isotherms were independent of SSR in the absence of phosphate, whereas U(VI) adsorption isotherms changed with SSR in the presence of phosphate. Column experiments showed that the presence of phosphate, either as a co-solute with U(VI) in the influent or pre-adsorbed to the goethite-coated sand, increased U(VI) retardation, consistent with the results of batch experiments. We also demonstrated that U(VI) adsorption was rate-limited in the column experiments, which indicates that extrapolation of batch measured adsorption characteristics of U(VI) to field conditions should be done with caution.

Finally, a theoretical study considered the potential influence of solid-to-solution ratio the reactive transport of U(VI) and dissolved inorganic carbon in hypothetical groundwater aquifers (Phillippi et al., 2005). This study was motivated by the fact that predictions of contaminant migration at a site typically involve the measurement of a distribution coefficient (K_D) in a batch system, which is used to describe the interactions between the contaminant and the subsurface. However, such batch experiments are often conducted under conditions significantly different than those encountered in the field, in particular a

much lower solid-to-solution ratio. The assumption implicit in this approach is that adsorption isotherm (e.g., K_D) is independent of the solid-to-solution ratio. A series of calculations showed that under certain conditions, the solid-to-solution ratio can theoretically have a significant impact on U(VI) adsorption. In particular, combining strongly-interacting solutes (U(VI) and carbonate) and adsorbates (Fe(III) oxides) which have individual single-component adsorption isotherms that are independent of the solid-to-solution ratio results in a multi-component system where adsorption isotherms become dependent upon the solid-to-solution ratio. The solid-to-solution ratio is therefore critical when extrapolating the results of batch experiments, generally conducted at low solid-to-solution ratio, to column experiments and then to the field. These results have implications to modeling, scaling, and predicting the reactive transport of U(VI) and other strongly interacting solutes (e.g., metals and dissolved organic carbon) in subsurface environments.

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3. Research Products

A. Referred Publications

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- Cheng, T., M.O. Barnett, E.E. Roden, and J. Zhuang. 2004. The effects of phosphate on uranium(VI) adsorption to goethite-coated sand. *Environ. Sci. Technol.* 38: 3059-6065.*
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B. Submitted Manuscripts

Roden, E. E. 2005. Geochemical and microbiological controls on dissimilatory iron reduction. *C.R. Geosci.* Submitted for publication.

Cheng, T., M. O. Barnett, and E. E. Roden. 2005. Reactive transport of uranyl in a goethite-coated sand column: the effects of phosphate. *Environ. Sci. Technol.* Submitted for publication.

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C. Manuscripts in Preparation

Roden, E.E. Sustained microbial reduction of Fe(III) and U(VI) in experimental flow-through sediment reactors.

D. Unpublished Reports

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<http://bama.ua.edu/~eroden/Publications/Reports&OtherDocuments.htm>.

E. Presentations at National/International Scientific Conferences

Roden, E.E. Geochemical and microbiological controls on dissimilatory iron reduction. French Academy of Sciences, Colloquium on the Biogeochemistry of the cycle of iron; green rusts and fougérite (Biogéochimie du cycle du fer - Rouilles Vertes et fougérite), Paris, December 2004 (Invited).

Roden, E.E. Analysis of Fe^{III} oxide reactivity toward long-term bacterial vs. chemical reduction. 11th International Symposium on Water-Rock Interaction, Saratoga Springs, NY, June 2004 (Invited).

Roden, E.E. and B.H. Jeon. Biological versus chemical reduction of U(VI) at the solid-water interface. American Society for Microbiology General Meeting, New Orleans, LA, May 2004.

Roden, E.E. Thermodynamic versus surface area control of microbial Fe(III) oxide reduction kinetics. American Geophysical Union Annual Fall Meeting, San Francisco, CA, December 2003 (Invited).*

Roden, E.E. and E. Sedo. Framework for numerical simulation of bacterial Fe(III) oxide reduction in circumneutral soil and sedimentary environments. American Geophysical Union Fall Meeting, San Francisco, CA, December 2003.*

Roden, E.E. Geochemical and microbiological controls on dissimilatory iron reduction. International Workshop on Biogeochemical Processes Involving Iron Minerals in Natural Waters, Monte Verita (Ascona), Switzerland, November 2003 (Invited).

B.H. Jeon and E.E. Roden. Reductive immobilization of U(VI) at the oxide-water interface. American Chemical Society National Meeting, New Orleans, LA, March 2003.

Roden, E.E. and T.D. Scheibe. Multiple pore region model of uranium(VI) reductive immobilization in structured subsurface media. American Geophysical Union Fall Meeting, San Francisco, CA, December 2002 (Invited).

Barnett, M.O., E.E. Roden, P.M. Jardine, S.C. Brooks. Biogeochemical interactions of U and Fe(III) oxides in subsurface environments: modeling and experimental results. American Chemical Society National Meeting, Washington, DC, August 2001.*

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<http://bama.ua.edu/~eroden/EMSPUVIFeIIIRedProject/EMSPUVIFeIIIRedProjectIndex.htm>

F. Workshop Presentations

Roden, E.E. U(VI) reduction at the solid-water interface. U.S. Department of Energy, Natural and Enhanced Bioremediation Annual PI Meeting, Warrenton, VA, March 2004.

Roden, E.E. Surface chemical and thermodynamic controls on bacterial metal reduction in subsurface environments. U.S. Federal Interagency Workshop on Conceptual Model Development for Subsurface

Reactive Transport Modeling of Inorganic Contaminants, Radionuclides, and Nutrients, April 2004, Albuquerque, NM April 2004.†

Roden, E.E. Coupled microbial Fe(III) oxide reduction and uranium(VI) reduction in subsurface sediments. U.S. Department of Energy, Natural and Enhanced Bioremediation Field Research Center Workshop, Oak Ridge, TN, September 2003.*

Roden, E.E. Microbial Fe(III) oxide reduction: an obvious choice for mesoscale experiments and numerical modeling. U.S. Department of Energy, Idaho National Engineering and Environmental Laboratory Workshop on Mesoscale Subsurface Science Research, Albuquerque, NM, August 2003.*
Roden, E.E. Reactive transport modeling of microbial-geochemical interactions in the subsurface: coupled Fe(III) oxide/uranium(VI) reduction. U.S. Department of Energy, Basic Energy Sciences Workshop on Integrating Numerical Models of Reactive Flow and Transport into Fundamental Geoscience Research, Carmel Valley, CA, June 2003.*

Roden, E.E. and M.O. Barnett. Reductive immobilization of U(VI) in Fe(III) oxide-reducing subsurface sediments. Poster at joint SCFA-DCFA meeting, March 2002.

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<http://www.iscmem.org/Proceedings.htm>

* PowerPoint presentations or PDFs available at:
<http://bama.ua.edu/~eroden/EMSPUVIFeIIIRedProject/EMSPUVIFeIIIRedProjectPublications.htm>

G. Graduate Theses

McIndoe, M.J. 2003. Uranium(VI) adsorption to a heterogeneous iron containing subsurface soil: The effects of solid-solution ratio and carbonate. M.S. Thesis, Auburn University.

Phillippi, J.M. 2004. Characterizing uranium adsorption and transport in the presence of carbonate. M.S. Thesis, Auburn University.

Romero, M. 2004. The effects of phosphate on uranium adsorption onto goethite-coated sands: application of a surface complexation model. M.S. Thesis, Auburn University.