Final Report
DE-FG02-07ER64416

The grant was distributed in three installments for 9 months in March 2007, for 1 year December 2007 and a final installment for 1 year in January 2009. In the first 9 months a PhD student Einar Fridjonsson was employed for 6 months and studied precipitation reactions in porous media [E.O. Fridjonsson *et al*., *Journal of Contaminant Hydrology* **120-121**:79-88. 2010.] and colloid transport in porous media [T.R. Brosten, *et al*., *Journal of Colloid and interface Science* **349**: 384–391. 2010.]. A postdoctoral researcher for 4 months Dr. Jennifer Brown who initiated the 3D magnetic resonance imaging (MRI) pulse sequence design to acquire isotropic high resolution MRI data on structure and velocity for comparison with hydrological models and computer simulation code. A graduate student was not recruited to the project until February 2009 Ms. Sarah J. Vogt. She acquired high resolution $(20\ \mu m)^3$ spatial structural MRI's and $(40\ \mu m)^3$ velocity images which were shared with collaborators at PNNL so they could generate an identical digital porous media and solve hydrological continuum mechanics based fluids code for the velocity field in that porous media for direct comparison to the MRI experimental data. The comparison has been published [X. Yang, *et al*., *Advances in Water Resources* **54**: 228–241. 2013] and demonstrates the accuracy of the code . Ms. Vogt has been highly productive in fulfilling the research goals of the project. She has helped develop and apply multidimensional NMR methods to measure biofilms in model and natural porous media [S.L. Codd, *et al*., *Organic Geochemistry* **42**: 965–971. 2011] and also made direct MR measurements of the bacterial reduction and precipitation of soluble uranyl ion (UO_2^{2+}) to insoluble uraninite ($UO_{2(s)}$) [S.J. Vogt, *et al.*, *Biotechnology and Bioengineering* **109**(4): 877-883. 2012.]. Ms. Vogt completed her Ph.D. in Fall 2012 and is a postdoctoral researcher at University of Western Australia. PI's Codd and Seymour also wrote a review article on NMR of hydrodynamic dispersion and the interplay of structure and transport in porous media [S.L. Codd and J.D. Seymour, *European Physical Journal Applied Physics* **60**: 24204. 2012.]. The research funded by this grant has developed NMR methods for Uranium and biofilm detection, characterized colloid transport in porous media, tested models for flow in porous media and generated data on biofilm induced reactions in porous media, thus advancing the current state of the art in environmental remediation modelling and detection.

Products
Peer Reviewed Journal Publications

E.O. Fridjonsson, J.D. Seymour, L.N. Schultz, R. Gerlach, A.B. Cunningham and S.L. Codd, "NMR measurement of hydrodynamic dispersion in porous media subject to biofilm mediated precipitation reactions", *Journal of Contaminant Hydrology* **120-121**:79-88. 2010.

T.R. Brosten, E.O. Fridjonsson, S.L. Codd, and J.D. Seymour, "Transport of colloidal particles in a porous open cell foam." *Journal of Colloid and interface Science* **349**: 384–391. 2010.

S.L. Codd, S.J. Vogt, J.A. Hornemann, A.J. Phillips, J.E. Maneval, K.R. Romanenko, L.

Hansen, A.B. Cunningham, J.D. Seymour, "NMR Relaxation Measurements of Biofouling in Model and Geological Porous Media." *Organic Geochemistry* **42**: 965–971. 2011.

S.J. Vogt, B.D. Stewart, J.D. Seymour, B.M. Peyton and S.L. Codd, "Detection of biological uranium reduction using magnetic resonance" *Biotechnology and Bioengineering* **109**(4): 877-883. 2012.

S.L. Codd and J.D. Seymour, "Nuclear magnetic resonance measurement of hydrodynamic dispersion in porous media: Preasymptotic dynamics, structure and nonequilibrium statistical mechanics" *European Physical Journal Applied Physics* **60**: 24204. 2012.

S.J. Vogt, A.L. Sanderlin, J.D. Seymour and S.L. Codd, "Permeability of a Growing Biofilm in a Porous Media Fluid Flow Analyzed by Magnetic Resonance Displacement-Relaxation Correlations." *Biotechnology and Bioengineering* **110**(5): 1366-1375. 2013. Article Featured as a *Biotechnology and Bioengineering* Spotlight.

X. Yang, T.D. Scheibe, M.C. Richmond, W.A. Perkins, S.J. Vogt, S.L. Codd, J.D. Seymour, M.I. Mckinley, "Direct Numerical Simulation of Pore-Scale Flow in a Bead Pack: Validation against Magnetic Resonance Imaging Observations." *Advances in Water Resources* **54**: 228–241. 2013

E.O. Fridjonsson, J.D. Seymour and S.L. Codd, "Application of PFG–NMR to Study the Impact of Colloidal Deposition on Hydrodynamic Dispersion in a Porous Medium." *Transport in Porous Media* **103**: 117-130. 2014.

Conference Presentations

J.D. Seymour, S.L. Codd, "Magnetic resonance measurement of scale dependent dynamics in porous media: interplay of structure and transport." Invited Talk H23H-01, American Geophysical Union Fall Meeting, San Francisco, CA, December 15-19, 2008.

E.O. Fridjonsson, S.L. Codd, J.D. Seymour, "Dynamic NMR study of colloidal particle deposition in a model porous media", Poster P15, 10th International Conference on Magnetic Resonance Microscopy, West Yellowstone, USA, Aug. 30 – Sept. 4, 2009.

S.J. Vogt, J.D. Seymour, B.D. Stewart, B.M. Peyton and S.L. Codd, "Detection of Uranium Oxidation and Solubility using NMR", Poster P61, 10th International Conference on Magnetic Resonance Microscopy, West Yellowstone, Montana, USA, August 30-September 4, 2009.

S.J. Vogt, J.A. Hornemann, K.V. Romanenko, S.L. Codd, and J.D. Seymour, "Relaxation Measurements Determine Degree of Biofouling in Porous Media", Poster P4, 10th International Conference on Magnetic Resonance Microscopy, West Yellowstone,

Montana, USA, August 30-September 4, 2009.

T.R. Brosten, E.O. Fridjonsson, J.D. Seymour, R.S. Maier and S.L. Codd, "Experimental and Numerical Study of Hydrodynamic Dispersion and Colloidal Transport in Solid Cellular Foam", Talk 148d, AIChE Annual Meeting, Nashville, Tennessee, USA, November 8-13, 2009.

S.J. Vogt, S.L. Codd, J.D. Seymour, "2-D Relaxation and Diffusion Measurements of Biofouled Porous Media", P-17, 10th Bologna Conference on Magnetic Resonance in Porous Media, Leipzig, Germany, September 12-16, 2010.

S.J. Vogt, H.T. Fabich, A.B. Sanderlin, S.L. Codd, J.D. Seymour,"Colloid Transport and Biofouling in Model Porous Media",11th International Conference on Magnetic Resonance Microscopy, Changping, Beijing, China, August 14-18, 2011.

S.L. Codd, J.D. Seymour, A.B. Sanderlin, S.J. Vogt, "Impact Of Biofouling On Porous Media Transport Dynamics Measured By Magnetic Resonance Displacement Relaxation Correlation." Invited Oral Talk, Interpore, Purdue, USA, May 14-16, 2012.

S.J. Vogt, A.B. Sanderlin, J.D. Seymour, and S.L. Codd, "Displacement-Relaxation Correlations of Biofilm Growth in Porous Media." Oral Talk 12th International Conference on Magnetic Resonance Microscopy Fitzwilliam College, Cambridge, UK, August 25- 29, 2013.