

## An Introduction to FRx

FRx, Inc.  
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In a broad sense, FRX develops and **installs** innovative methods for controlling and monitoring physical and chemical conditions in subsurface formations, with particular emphasis on environmental processes related to the remediation of contaminated soil, bedrock, and groundwater. The techniques have broad applications in the increasingly demanding market for effective remediation processes. In particular, we introduced and validated the innovative technique of **hydraulic fracturing**, which greatly accelerates remediation of contaminated sites, and are leaders in providing these capabilities as a service to environmental consultants and site owners.

### The Technology

FRX utilizes hydraulic fracturing and related methods to access sub-surface **source zones** (hot spots) or intercept contaminant **plumes** in soil or bedrock for the purpose of **destroying** or **removing** the contaminants. The fracturing methods are in reality a delivery system that allows placement of modest quantities of beneficial solids at chosen in situ locations. The injected materials can be tailored strategically to effect or enhance various physical or chemical processes that result in remediation of the soil. For example, **sand-filled fractures improve in situ fluid** flow in low permeability media by altering the flux field, thereby **promoting recovery processes**, such as NAPL extraction or SVE, as well as remediation processes that depend upon **delivery of reagents** into targeted soils, such as ISCO or bio-stimulation. Alternatively, fracturing techniques can be used to **place reactive solids** into subsurface soil and rock. Examples of these materials include solid potassium **permanganate** or **iron** for chemical destruction of chlorinated solvents, activated carbon for adsorption of contaminants, inoculated porous solids to initiate bioremediation, **oxygen releasing** or **hydrogen releasing** compounds for chemical or biological enhancement, and electrically conductive materials as electrodes. Because we are providing a delivery technique, the examples mentioned must not be considered exhaustive, and materials yet to be invented may also be usable.

Likewise, the list of contaminants that can be targeted is unrestricted. **Contaminants** that may be treated include **petroleum hydrocarbons** such as gasoline, diesel, jet fuel and motor oils and chlorinated solvents such as trichloroethylene (**TCE**) and perchloroethylene (**PCE**), as well as inorganic contaminants such as hexavalent chromium, copper, nitrates, arsenic and selenium and even radionuclides such as uranium and strontium.

Hydraulic fracturing is applicable to a wide variety of site conditions and contaminants. It can be applied at **depths of 5 to 150** feet or greater in either **saturated or unsaturated** soils. Fractures can be **created around and under most structures**. The technology appears viable for all but the smallest jobs. In general hydraulic fracturing has a strong cost advantage compared to other available remediation methods.

## **The Company**

Lawrence Murdoch and William Slack founded FRX in 1994. The two principals synergistically interact to meet the challenges of managing FRX. Presently, Larry Murdoch performs as president and research director while Bill Slack serves as vice president with responsibilities for operations and finance. The company operations are based in Cincinnati, Ohio. Operations are based near Greenville, South Carolina, under the supervision of Douglas Knight.

Larry Murdoch is a nationally recognized authority on delivery and recovery of fluids from soils. He developed his expertise by leading technology development and demonstration programs with a hands-on, personal involvement in the mud and grime of field testing. He conceived and led the US EPA hydraulic fracturing research program during the 1980's and early 1990's. He has a Ph.D. in Geology, a M.S. in Environmental Science and a M.S. in Geology from the University of Cincinnati and a B.S. in Geology from Pennsylvania State University. Dr. Murdoch is registered as a Professional Geologist in Indiana. Presently he holds an appointment as Professor of Geology at Clemson University.

Bill Slack joined the hydraulic fracturing research team in 1990 after 12 years of service in petroleum production industry as an engineer and technical manager of hydraulic fracturing applications and porous media research. He has a Ph.D. and an M.S. in Chemical Engineering from Carnegie Mellon University and a B.S. in Chemical Engineering from Cornell University. He is registered as a Professional Engineer in Ohio and Kentucky. He presently oversees day-to-day operations of the company.

Doug Knight serves as manager of field operations. He selects and hires support labor and services and oversees the logistics of projects. He has recently been taking an increased role in business development. Doug has nearly fifteen years experience with environmental field work. He holds a B. S. in Geology from Clemson University.

In summary, FRX is uniquely positioned to function as a service provider for soil remediation technologies. It will continue to build upon its base of research and innovation by maintaining its links to the research community. This advantage will build upon its strong track record, extensive trade secrets, and strategic partnerships while utilizing its growing collection of specialty equipment in offering the highest caliber services in an expanding market niche.

## **Additional Statements of Qualification**

The following pages present greater detail about FRx.

- Partial Customer List
- Partial Project List
- Bibliography
- Vitae of Principals and Key Personnel
- Corporate Information and Vendor References



Our hydraulic fracturing equipment, on site, Albany, New York.

**Our product: Hydraulic fractures** filled with beneficial materials for clean-up of contaminated soil, bedrock and groundwater. These three hydraulic fractures were created for demonstration purposes by a US EPA research project in 1989

Most of our work occurs at mundane industrial facilities, brown field development sites, or the occasional retail dry cleaner or gas station. But, most memorably, these three unusual locations needed our expertise.



Launch Complex 34, site of the tragic Apollo 1 mission.



The P-Reactor, Savannah River Site. In 1956 the neutrino was discovered in the course of making weapons-grade uranium.



Aerodrome Kluczewo,  
Northwestern Poland.

- Once the largest Soviet fighter base outside of Mother Russia.
- Soviet SS-20 Base
- Test facility for the Nazi ME262 jet fighter
- *Now utterly abandoned!*

## Customer List

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The following persons have consented to our mention of their name to create this partial list of customers:

### **Acuity Environmental Solutions**

7965 East 106th Street, Suite 128  
Fishers, IN 46038  
Steve Irvin

### **Arcadis**

30 Patewood Drive, Suite 155  
Greenville, SC 29610  
Elizabeth Rhine

### **Arcadis**

1114 Benfield Boulevard, Suite A  
Millersville, MD 21108  
Carol Mowder

### **Burns & McDonnell**

425 South Woods Mill Road, Suite 300  
Chesterfield, Missouri 63017  
Tom Zychinski  
John Hessemann

### **CH2M Hill**

1034 South Brentwood Blvd., Suite 2300  
St. Louis, MO 63117  
Anne Nea

### **CH2M Hill**

72 Victoria Street South  
Suite 300  
Kitchener, ON N2G 4Y9  
Canada  
Chris Peace

### **EnviroGroup Limited**

7009 S. Potomac Street, Suite 300  
Centennial, CO 80112  
Ted Kuehster

### **Environmental Consulting, Inc**

500 East Washington Street  
Suite 375  
Norristown, PA 19401  
Rich Warner  
Sam Kucia

### **Fishbeck Thompson Carr & Hyber**

1515 Arboretum Drive SE  
Grand Rapids, MI 49546  
Jerry Lisiecki

### **ERM**

Princeton Crossroads  
250 Phillips Blvd  
Ewing, NJ 08618  
Richard Brown

### **ERM**

7272 E. Indian School Road, Suite 100  
Scottsdale, Arizona 85251  
Anthony Griego

### **AL Neyer, Inc**

302 West 3rd Street, Suite 800  
Cincinnati, OH 45212  
Chris Dabrozsi

### **Rogers & Callcott Engineers Inc**

P.O. Box 5655  
Greenville, SC 29606  
George Maalauf

### **SAIC**

151 Lafayette Drive  
Oak Ridge, TN 37831  
Steve Conner

### **Toxicological & Environmental Associates**

10636 Linkwood Ct  
Baton Rouge LA 70810  
Russ Copeland

### **URS**

8181 East Tufts Avenue  
Denver, CO 80237  
Belinda Butler-Veytia

## State and Federal Contacts

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Paul Blood  
Maine Dept. Environmental Protection  
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## Selected FRx Fracturing Experience

FRx, Inc.  
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The following is a partial list of projects performed in the past few years. Since inception in 1994, FRx has completed over 200 projects.

Iron Project	Large Project	Federal Project	Deep Project	Client, Location, Date & Contact	Project Description and Assessment	Publication
●	●			<ul style="list-style-type: none"> <li>* CH2M Hill Canada</li> <li>* Sarnia, Ontario</li> <li>* August 2010</li> <li>* Ms. Leanne Austrins Kitchener, Ontario</li> </ul>	Creation of 99 hydraulic fractures filled with 212000 lb of granular zero valent iron in combination with vegetable oil substrate solutions to promote biodegradation of solvents. Also created fractures with 14 fractures with 2500 gal of emulsified zero valent iron.	Manuscript drafted
		●		<ul style="list-style-type: none"> <li>* URS Group, LBNL, AFCEE</li> <li>* FE Warren AFB</li> <li>* June 2010</li> <li>* Ms. Belinda Butler Veytia, Denver</li> </ul>	Creation of two sand-filled hydraulic fractures and collection of performance data as part of a demonstration and validation of methods to assess in situ distribution of remediation materials injected by diverse methods.	Manuscript prepared
●	●			<ul style="list-style-type: none"> <li>* SAIC</li> <li>* p-Area, SRS</li> <li>* April 2010</li> <li>* Mr. Steve Conner Oak Ridge</li> </ul>	Twenty five hydraulic fractures were created with 42,000 lb of sand from fourteen PVC casings that had been installed previously. The large diameter PVC casing permitted subsequent construction of 4-inch diameter wells that are being used in SVE and oxidant delivery.	Report under review

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Iron Project	Large Project	Federal Project	Deep Project	Client, Location, Date & Contact	Project Description and Assessment	Publication
●		●		<ul style="list-style-type: none"> <li>* Acuity Environmental Solutions</li> <li>* Ft Benj. Harrison</li> <li>* August 2010</li> <li>* Mr. Steven Irvin Fischers, IN</li> </ul>	This project demonstrated the creation of iron filled fractures, some using jet-fracturing techniques, to support treatment design for a plume emanating from the facility landfill.	Report under review
		●	●	<ul style="list-style-type: none"> <li>* Eichleberger, TetraTek, &amp; US EPA</li> <li>* Hazleton, PA</li> <li>* October 2090</li> <li>* Mr. Bruce Rundell, US EPA, Philadelphia</li> </ul>	Hydraulic fracturing equipment was used to mix and deliver a slurry of potassium permanganate suspended in water. Target formations were weathered and fractured bedrock systems. This was the first application of granular potassium permanganate in bedrock.	Rundell, B., B. Khona, B. White, N. Teamerson, and B Dynkin (2010.) "Enhanced Potassium Permanganate Slurry Injection in Fractured Bedrock Utilizing Hydraulic Fracturing." 7th International Conf. On Remediation of Chlorinated and Recalcitrant Compounds, Session D089., Monterey, CA.
		●	●	<ul style="list-style-type: none"> <li>* ERM West</li> <li>* Cheyenne, WY</li> <li>* May 2009</li> <li>* Mr. Anthony Griego Phoenix</li> </ul>	Various remediation materials were used to create hydraulic fractures in soil contaminated with chlorinated solvents. One object of the project was to compare reductive versus oxidative feasibility, so some fractures were created with EHC and others with persulfate.	
●				<ul style="list-style-type: none"> <li>* Toxicological and Environmental Associates</li> <li>* Sarnia, ON</li> <li>* July 2008</li> <li>* Mr. Russ Copeland Baton Rouge</li> </ul>	Sand-filled hydraulic fractures were created to promote groundwater flow and root growth of willow trees that were planted as part of this phyto-remediation project.	Copeland, R., Campbell, W., Slack, W. W., E. G. Gatliff, C. Creber (2009.) "Enabling Phytoremediation of Chlorinated Solvents in Tight Soils by Use of Hydraulic Fracturing" 10th International Symposium on In Situ and On-Site Bioremediation, Baltimore, MD.

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Iron Project	Large Project	Federal Project	Deep Project	Client, Location, Date & Contact	Project Description and Assessment	Publication
●	●			<ul style="list-style-type: none"> <li>* CH2M Hill Canada</li> <li>* Sarnia, ON</li> <li>* November 2008</li> <li>* Mr. Chris Peace Kitchener, Ontario</li> </ul>	Creation of hydraulic fractures filled with granular zero valent iron in combination with organic substrate solutions to promote biodegradation of solvents. Also created fractures with emulsified zero valent iron. Some of the fractures were dyed with rhodamine to permit better identification in subsequent cores and exploratory trenches.	<p>Austrins, L. M. and C. Peace (2010) "Integrated Approach to the Remediation of Chlorinated Organic Compounds in Low Permeability Soils – A Field Study." The Remediation Technologies Symposium (RemTec), October 22, 2010. Banff Springs, Alberta.</p> <p>Peace, C. and L. M. Austrins (2010) "Evaluation of the Propagation of Secondary Fractures from Hydraulic Fracture and Injection to Create a Treatment Zone in Low Permeability Fractured Clay Soils." The Remediation Technologies Symposium (RemTec), October 22, 2010. Banff Springs, Alberta.</p>
●		●		<ul style="list-style-type: none"> <li>* Burns &amp; McDonnell Engineering</li> <li>* Katy, KS</li> <li>* November 2007</li> <li>* Mr. John Hesemann St Louis</li> </ul>	Jet fracturing techniques were used to deliver reductive agents into non-cohesive soils that otherwise would not support conventional hydraulic fracturing	Confidential, private site.
			●	<ul style="list-style-type: none"> <li>* Washington Savannah River Co</li> <li>* M-Area, SRS</li> <li>* August 2008</li> <li>* Mr. Brian Riha Savannah River Site</li> </ul>	Sand-filled hydraulic fractures were created to support SVE actions.	Riha, B. D., K. L. Dixon, et al. 2005. Evaluation of Enhanced VOC Removal with Soil Fracturing in the SRS Upland Unit. Savannah River National Laboratory. Aiken, SC. WSRC-TR-2005-00415

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Iron Project	Large Project	Federal Project	Deep Project	Client, Location, Date & Contact	Project Description and Assessment	Publication
●	●	●	<ul style="list-style-type: none"> <li>* URS Group</li> <li>* FE Warren AFB</li> <li>* December 2006</li> <li>* Ms. Belinda Butler Veytia, Denver</li> </ul>	<p>Creation of 734 fractures using ___ lb of sand and ___ lb of HRC for subsequent bioremediation by injected cultures.</p>	<p>Butler-Veytia, B., N. Cochran, B. Powers, S. Hrabovsky, and J. Wright. (2008) "Full-Scale Implementation: Bioremediation Using Hydraulic Fracturing for HRC® Emplacement and KB-1TM Injection." 6th International Conf. On Remediation of Chlorinated and Recalcitrant Compounds, Session E027., Monterey, CA.</p> <p>Butler-Veytia, B., N. Cochran, B. Powers, S. Hrabovsky, and J. Wright. (2008) "Pilot Test Update: Bioremediation Using Hydraulic Fracturing for HRC® Emplacement and KB-1™ Injection." 6th International Conf. On Remediation of Chlorinated and Recalcitrant Compounds, Session E041., Monterey, CA.</p>	
●	●	●	<ul style="list-style-type: none"> <li>* URS Group</li> <li>* FE Warren AFB</li> <li>* August 2006</li> <li>* Ms. Belinda Butler Veytia, Denver</li> </ul>	<p>Creation of ___ fractures with ___ lb of solid potassium permanganate granules for the purpose of establishing passive in situ ISCO conditions.</p>	<p>Butler-Veytia, B., R. Coringrato, B. Powers, S. Hrabovsky, and J. Wright. (2008) "Full-Scale Implementation: ISCO Using Hydraulic Fracturing for Potassium Permanganate Emplacement." 6th International Conf. On Remediation of Chlorinated and Recalcitrant Compounds, Session E031., Monterey, CA.</p>	
●			<ul style="list-style-type: none"> <li>* ARM Group / GeoCleanse Intrnl.</li> <li>* Richmond, VA</li> <li>* June 2005</li> <li>* Dr. Dan Bryant GeoCleanse, NJ</li> </ul>	<p>Twenty iron-filled fractures were created with 30,000 lb of iron across a 2 acre site at depths between 15 and 27 feet. The distributed iron established sufficient reducing conditions to drive remediation to closure.</p>	<p>Duchene, M., B. Slack and D. Bryant (2006) "Placement of Zero-Valent Iron by Hydraulic Fracturing." Fifth International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, California. pages C-20. Battelle Press, Columbus, OH</p>	

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Iron Project	Large Project	Federal Project	Deep Project	Client, Location, Date & Contact	Project Description and Assessment	Publication
●				<ul style="list-style-type: none"> <li>* Burns &amp; McDonnell Engineering</li> <li>* Dallas, TX</li> <li>* July 2005</li> <li>* Mr. John Hesemann St Louis</li> </ul>	<p>Six iron-filled fractures were created to intercept drainage before discharging into the Trinity River. The combined treatment schemes at the facility have won closure of the site.</p>	<p>Duchene, M., B. Slack and D. Bryant (2006) "Placement of Zero-Valent Iron by Hydraulic Fracturing." Fifth International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, California. pages C-20. Battelle Press, Columbus, OH</p> <p>Moline, J., C. Mathenia, and M. Dingsens. (2009) "Cleaning Up Groundwater in Place." Pollution Engineering. P24. November 2009.</p>
●	●			<ul style="list-style-type: none"> <li>* US EPA, Lasagna Program</li> <li>* Rickenbacker ANGB, Columbus, OH</li> <li>* July - December 1996</li> <li>* Dr. Wendy Davis-Hoover, EPA, Cincinnati</li> </ul>	<p>Iron filled hydraulic fractures were created as treatment units within the groundwater mobilization fields that were induced by electrokinetics in this research and development project. This may have been the first use of iron as a hydraulic fracturing proppant.</p>	<p>Davis-Hoover, W. J., M. C. Kemper, P. R. Cluxton, S. Al-Abed, M. H. Roulier, L. T. Bryndzia, W. W. Slack, L. C. Murdoch and S. Al-Abed (1998) "In situ horizontal lasagna treatment of TCE in soil using bioremediation and zero-valent iron dechlorination compared to natural attenuation: a preliminary report." International Conf. On Remediation of Chlorinated and Recalcitrant Compounds, Session D.6., Monterey, CA.</p>

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Iron Project	Large Project	Federal Project	Deep Project	Client, Location, Date & Contact	Project Description and Assessment	Publication
●	●	*	*	<p>US DOE, Oak Ridge National Lab, Martin Marietta Energy Systems</p> <p>Portsmouth Uranium Enrichment Plant, Piketon, Ohio</p> <p>July - September, 1996 and July - September, 1997</p> <p>Dr. Bob Siegrist, Colorado School of Mines</p>	<p>A TCE plume is available for demonstrations and tests of innovative and enhanced technologies in low permeability media. Target soil is a ~20 ft thick surficial clay unit. The current year project will test four technologies, all of which will utilize hydraulic fractures as enhancements. Steam and hot air will be injected into sand filled fractures while adjacent fractures are connected to conventional SVE or pump and treat systems. Extensive temperature measurements will permit estimates of efficiency of the processes. Two in situ chemical processes will be tested at other locations at the site. Fractures will be created with iron and with encapsulated permanganate to test iron catalyzed reduction of chlorinated hydrocarbons and to test destructive oxidation of contaminants.</p>	<p>Siegrist, R. L., K. S. Lowe, L. C. Murdoch, T. L. Case, D. A. Pickering and T. C. Houk (1998) "Horizontal Treatment Barriers of Fracture Emplaced Iron and Permanganate Particles." in NATO/CCMS Pilot Study: Evaluation of Demonstrated and Emerging Technologies for the Treatment of Contaminated Land and Groundwater (Phase III) Special Session: Treatment Walls and Permeable Reactive Barriers, Pages 77-83. USEPA, Washington, DC.</p> <p>Siegrist, R. L., K. S. Lowe, L. C. Murdoch, W. W. Slack and T. C. Houk (1998) X-231A demonstration of in situ remediation of DNAPL compounds in low permeability media by soil fracturing with thermally enhanced mass recovery and reactive barrier destruction. ORNL/TM-13534. Oak Ridge National Laboratory, Oak Ridge, TN.</p> <p>Siegrist, R. L., K. S. Lowe, L. C. Murdoch and A. M. Struse (2000) "In situ chemical treatment using hydraulic fracturing to emplace Fe metal and KMnO4 reactive solids." EPA/625/R-99/012 (85-92.)</p>
●	●	*	*	<p>Square D Corp, ERM Bordentown, NJ</p> <p>2001</p> <p>Dr. Richard Brown, ERM, Ewing</p>	<p>Ancient metal plating activities polluted deep soils as well as a thick column of overlying industrial fill. An innovative hydraulic fracturing injection technology (jet fracturing – thru fixed casings) was used to deliver reactive solids that stabilized the heavy metal contaminants in the soil.</p>	<p>Robinson, D., R. A. Brown, C. Christiansen, R. Patel and W. W. Slack (2002) "In Situ Treatment of Copper Contamination using Direct Injection of Lime Slurries." The Second International Conference on Oxidation and Reduction Technologies for In Situ Treatment of Soil and Groundwater, Toronto, Ontario.</p>

## A Bibliography of Hydraulic Fracturing for Soil and Groundwater Remediation



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Albertz, J., L. C. Murdoch, R. M. McCandless and A. Bodocsi (1987) "An algorithm for determining the stability of soil slopes assuming translational failure." 5th National Conference on Microcomputers in Engineering, Orlando, Florida. ASCE

Andrews, S. D., W. R. Mahaffey, V. Barlock and T. Santangelo-Dreiling (2002) "Methane-Enhanced In Situ Biological Degradation Of Chlorinated Hydrocarbons - A Case Study." 3rd Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey. vol: 2B:55 Battelle Press

Arnason, J. G., M. Harkness, and B. Butler-Veytia. (2010) "A Magnetic Susceptibility Method for Evaluating Distribution of Zero-Valent Iron in the Subsurface" 7th International Conf. On Remediation of Chlorinated and Recalcitrant Compounds, Session D071., Monterey, CA.

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Bradner, G. C. and L. C. Murdoch (2001) "Effects of Shallow Induced Fractures on the Performance of." AGU Fall Meeting, San Francisco. vol: 82:47 pages Fall Meeting Supplement, Abstract H52D-09.AGU

Bradner, G. C. (2002) "Effects of Shallow Induced Fractures on the Performance of Soil Vapor Extraction Wells." 10th Annual Hydrogeology Symposium, Clemson SC. pages 1-2. Dept. Geo. Sci., Clemson University

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Slack, W. W. and T. A. Harp (2003) "Long-term Use of Hydraulic Fractures for Delivery of Substrate Solutions." 7th International Symposium on In Situ and On-Site Bioremediation, Session C.7., Orlando, FL.

Slack, W. W. (2003) "Use of Induced Fractures as Enhancements to Soil and Groundwater Remediation Systems." 11th Annual Hydrogeology Symposium, Clemson, SC. pages 27. Dept. Geo. Sci., Clemson University

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Slack, W. W. (2005) "Quantitative Description of Surface Deformation over Typical Horizontal Fractures." 13th Annual David S. Snipes / Clemson Hydrogeology Symposium, pages 40-41. Clemson University, Dept. Geological Sciences

Slack, W. W., K. E. Klint, B. Nilsson, Y. Benoit, F. Haeseler, T. Brøker, T. Kesala and C. Tsakiroglou (2005) "Stimulating Biological Activity Within Fractured Soil At Klucewo, Poland." Eighth International In Situ and On-Site Bioremediation Symposium , Baltimore, Maryland. Battelle

Slack, W. W. and L. C. Murdoch (2006) "Creation of Hydraulic Fractures in Bedrock to Support Remediation Processes." 14th Annual David Strange Snipes / Clemson Hydrogeology Symposium, Clemson, South Carolina. pages 25 - 26. Clemson University, Dept Geological Sciences

Slack, W. W., B. Nilsson, C. Tsakiroglou and F. Haeseler (2006) "Remediation Enhancement by Steam Injection and Steam Heating with Hydraulic Fractures." Fifth International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, California. pages F-30. Battelle Press, Columbus, OH

Slack, W. W., L. C. Murdoch, S. W. Kirschner and B. B. Beegle (2007.) "An Analysis of Bedrock Fracturing to Distribute Vegetable Oil Emulsion in a Metamorphic Rock Formation." Ninth International In Situ and On-Site Bioremediation Symposium, Baltimore, Maryland. pages H-85. Battelle Press, Columbus, OH

Slack, W. W. (2010) "Quantitative Assessment of the Distribution of Injected Material during Hydraulic Fracturing" 7th International Conf. On Remediation of Chlorinated and Recalcitrant Compounds, Session D110., Monterey, CA.

Souders, A. K., L. C. Murdoch and S. E. Kelly (2000) "An In Situ Method for Determining the Hydraulic Conductivity of a Stream or Lake Bed." AGU Fall Meeting, San Francisco. vol: 81:48 pages Fall Meeting Supplement, Abstract H72B-39. AGU

Spence, R. C., A. Bodocsi and L. C. Murdoch (1990) "State of stress and hydraulic fracturing potential in soil/bentonite cutoff walls." 21st Ohio River Valley Soils Seminar, Cincinnati.

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Strong, M., C. Sprinkle, D. Ewing, D. Owens, B. Ventura, L. Smith and J. J. Liskowitz (2004) "Comparison Of Pneumatic And Hydraulic Fracturing For Emplacement Of Treatment Materials In Low-Permeability Formations." 4th International Conf. On Remediation of Chlorinated and Recalcitrant Compounds, Monterey CA. pages 5B-07. Battelle Press

Uber, J. G. (1990) "Combining Groundwater Simulation and Optimization Models." National Conference on Water Resources Planning and Mangement, ASCE

Uber, J. G. and L. C. Murdoch (1991) "Monte Carlo optimization of interceptor trench network for contaminated groundwater remediation." American Geophysical Union Conference,

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Vesper, S. J., W. J. Davis-Hoover, M. H. Roulier, L. C. Murdoch, L. M. Vane and J. G. Hermann (1995) "Advances in TCE Degrading Thermophilic, Mesophilic and Alkaline Resistant Organisms." 21st RREL Research Symposium, Cincinnati. vol: 600/F94/046 pages 325-328. USEPA

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organic compounds, especially in low permeability geology." American Association of Petroleum Geologists (AAPG) Annual Meeting, Denver, CO.

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Whiting, T., W. W. Slack and L. C. Murdoch (1998) "Dual-phase extraction with hydraulic fractures at a superfund site." International Conf. On Remediation of Chlorinated and Recalcitrant Compounds, Session B.1., Monterey, CA.

Wolf, A. J. and L. C. Murdoch (1993) "A Field Test of the Effect of Sand Filled Hydraulic Fractures on Air Flow in Silty Clay Till." 7th NGWA National Outdoor Action Conference, Las Vegas, NV.

Wolf, A. J. (1995) The Effects of Creating Sand-Filled Hydraulic Fractures on Soil Vapor Extraction. a Thesis Submitted to the Department of Civil and Environmental Engineering, University of Cincinnati, Cincinnati, OH

Workman, R. and L. C. Murdoch (2003) "Including the Effects of Wellbore Hydraulics in Analysis of the Performance of Horizontal Wells." 11th Annual Hydrogeology Symposium, Clemson, SC. pages 33. Dept. Geo. Sci., Clemson University

Wu, R. and L. N. Germanovich (2003) "Hydraulic Fracture Branching and Segmentation." 11th Annual Hydrogeology Symposium, Clemson, SC. pages 34. Dept. Geo. Sci., Clemson University

Yang, X-M. and P. M. Davis (1986) "Deformation Due To A Rectangular Tension Crack in an Elastic Half-Space." *Bulletin Seismological Society of America* 76:3 (86-881.)

# LAWRENCE C. MURDOCH

CLEMSON, SOUTH CAROLINA  
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## WORK EXPERIENCE

---

- **3/94 – Present: FRx, Inc.**

*President, Clemson*

Principal and founder of the company, which commercially provides new and recently developed technology, especially in remediation of contaminated soil. In addition, serves as Chief Technology Officer and Director of Research.

- **2/97 – Present: Clemson University**

*Professor, Department of Geosciences*

*Associate Professor, Department of Geosciences*

*Assistant Professor, Department of Geosciences*

Dr. Murdoch's teaching and research interests are in hydrogeology. He teaches an introductory course in applied hydrogeology, and advanced courses in the hydrogeology of U.S. aquifers and fractured rock hydrology. He also teaches a course in methods for analyzing geological processes, and he organizes the hydro field camp. Dr. Murdoch's recent research activities have included projects in environmental remediation, aquifer characterization, interaction between ground water and surface water, and effects of changing land use. He developed techniques for creating and applying hydraulic fractures for environmental applications, and more recently he has been developing hydromechanical techniques for characterizing rock aquifers. Many of his projects involve innovative field or laboratory techniques with modeling coupled processes of flow, transport, and deformation.

- **8/86 – 12/96: University of Cincinnati**

*Director of Research, Center for Geoenvironmental Science and Technology*

*Associate Research Professor, Department of Civil and Environmental Engineering*

*Geohydrology Group Leader, Center for GeoEnvironmental Science and Technology*

*Research Associate*

Conceived the idea of using hydraulic fracturing as a soil remediation tool. Designed and executed experiments to prove the concept, identified potential applications, built equipment to perform the methods, and demonstrated technology at multiple contaminated sites. Directed the efforts of up to 40 people in support of US EPA contracts to the University to operate the Center Hill Laboratory. Published several articles and papers documenting the results.

## EDUCATION

---

- Ph.D., Geology, University of Cincinnati
- M.S., Environmental Science, University of Cincinnati
- M.S., Geology, University of Cincinnati
- B.S., Geology, Penn State University

## PROFESIONAL QUALIFICATIONS

---

- Professional Geologist, Indiana, No. 1421

## CERTIFICATIONS

---

- Hazardous Waste Site Worker (40 hr HAZWPR)
- US DOE Radiological Worker I & II

## AFFILIATIONS

---

- National Groundwater Association
- Affiliate Member, Society Petroleum Engineers
- Member, National Water Well Association
- Member, American Geophysical Union
- Member, Association of Engineering Geologists
- Affiliate Member, Society of Civil Engineers
- Member, Professional Geologists of Indiana

## HONORS / AWARDS

---

- Board of Trustees Award for Faculty Excellence, 2008
- Visiting Scientist, Geological Survey of Denmark, Copenhagen, Spring 2005
- Board of Trustees Award for Faculty Excellence, 2003
- Board of Trustees Award for Faculty Excellence, 2001
- NSF CAREER Award, 1999
- Board of Trustees Award for Faculty Excellence, 1999

## COURSES TAUGHT

---

- Geol 850, Site Assessment and Remediation
- Geol 408/608, Applied Hydrogeology
- Geol 415/615, Method of Analysing Geological Processes
- Geol 816, Aquifer Systems
- Geol 475/675, Hydrogeology Field Camp
- Geol 818, Hydrology and Mechanics of Fractured Media S'00,S'02

## SELECTED PUBLICATIONS / PRESENTATIONS

---

- Murdoch, L.C. and others. Remediation of organic chemicals in the vadose zone, in Vadose Zone, Science and Technology Solutions. Chapter 7. pp 948-1247. R.Falta and B. Looney eds. Battelle Press, 2000.
- Murdoch, L.C., D. Wilson, K. Savage, W. Slack, and J. Uber. Alternative Methods for Fluid Delivery and Recovery. USEPA/625/R-94/003, 1995.
- Murdoch, L.C. Hydraulic and impulse fracturing for low permeability soils, Chapter in Petroleum Contaminated Low Permeability Soil, American Petroleum Institute Publication 4631, 1995.

- Beljin, M. and L.C. Murdoch. Analytical solutions to the performance of interceptor trenches and drains, 1995. International Ground Water Modeling Center, Golden, CO.
- Murdoch, L.C. and W.W. Slack. Forms of hydraulic fractures in shallow, fine-grained formations. *Journal of Geoenvironmental and Geotechnical Engineering*. v. 128, no. 6, p. 479-487
- Murdoch, L.C. Mechanical analysis of an idealized hydraulic fracture at shallow depths. *Journal of Geoenvironmental and Geotechnical Engineering*. v. 128, no. 6, p. 488-495.
- Roulier, Mike, Mark Kemper, Souhail Al-Abed, Larry Murdoch, and Wendy Davis-Hoover. Feasibility of electrokinetic soil remediation in horizontal Lasagna cells, *Journal of Hazardous Materials*, B77, 161-176. 2000.
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- Uber, J.G. and L.C. Murdoch. Evaluation of hopscotch method for transient groundwater flow. *J. Hydraul. Eng., ASCE*, v. 126, n. 8, August 2000, p. 615-626.
- Murdoch, L.C., W.W. Slack, W. Harrar, B. Nilsson, and R. Siegrist. Sidewall sensors for monitoring fractured clay till. *Journal of Nordic Hydrology*, 30, no. 4/5, 1999.
- Chen, J-L, Al-Abed, Bryndzia, and Murdoch, L.C. Effects of cation transport and partitioning during a field test of electroosmosis. *Water Resources Research*, v. 35, no. 2, pg. 3841-3851, Dec. 1999.
- Siegrist R.L., K. S. Lowe, L.C. Murdoch, T.L. Case, and D. A. Pickering. In situ oxidization by fracture emplaced reactive solids. *Jour of Environ. Eng.*, v. 125, n. 5, 429-440. 1999.
- Chen, J-L. and Murdoch, L.C. In-situ electroosmosis between horizontal electrodes: a field test. *J. Geotech. And Geoenviron. Eng.*, v. 125, no. 12, 1090-1100. 1999.
- Murdoch, L.C. and J-L. Chen. Effects of conductive fractures during in situ electroosmosis: *Journal of Hazardous Materials*, 55, 239-262, 1997.
- Chen, J-L. and Murdoch, L.C. In-situ electroosmosis between horizontal electrodes: a field test. *J. Geotech. And Geoenviron. Eng.*, v. 125, no. 12, 1090-1100. 1999.
- Murdoch, L.C. Forms of hydraulic fractures created during a field test in fine-grained glacial drift, *Quarterly Journal of Engineering Geology*, 28, 23-35, 1995.
- Murdoch, L.C. and J. Franco. Analysis of constant head wells using instantaneous source functions, *Water Resources Research* v. 30, (1) 117-124, 1994.
- Murdoch, L.C. Transient analysis of an interceptor trench, *Water Resources Research*, 30(11), 3023-3032, 1994.
- Vesper, S. L.C. Murdoch, S. Hayes, and W. Davis-Hoover. Slow-release oxygen sources for bio-remediation in soils. *Journal Hazardous Materials*, 36, 265-274, 1994.
- Murdoch, L.C. Hydraulic fracturing of soil during laboratory experiments: methods and observations, *Geotechnique*, 43(2), 255-265, 1993.
- Murdoch, L.C. Hydraulic fracturing of soil during laboratory experiments: propagation, *Geotechnique*, 43(2), 266-276, 1993.
- Murdoch, L.C. Hydraulic fracturing of soil during laboratory experiments: theoretical analysis, *Geotechnique*, 43(2), 277-287, 1993.

# WILLIAM W. SLACK

CINCINNATI, OHIO  
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## WORK EXPERIENCE

---

- **3/94 – Present: FRx, Inc.**

*Vice President, Cincinnati*

Principal and founder of the company, which commercially provides new and recently developed technology, especially in remediation of contaminated soil. Responsible for execution of all operations of the company, including administrative oversight, sales, marketing, engineering, and field activities.

- **8/90 – 9/97: University of Cincinnati**

*Geochemical Group Leader, Center for GeoEnvironmental Science and Technology*

Managed a multi-disciplinary group of 9 scientists and engineers doing research of methods for in situ remediation of contaminated soils. Personally listed as principal investigator for research sponsored by the US EPA as well as for research and technical services for corporate clients. As adjunct faculty provided consultation to students and sat upon advisory committees for graduate students in environmental engineering and geology. Also compiled and taught a course on Solidification and Stabilization processes for contaminated soil.

- **88 – 90: Chevron USA**

*Engineering Manager, Midland, Texas*

Supervised twelve engineers and held responsibility for engineering analysis and project design for 37 oil fields, which produced, in aggregate, 22000 bbl oil per day from 3700 wells. Prepared budgets, coordinated efforts with other corporate elements, and negotiated with partners, vendors, and customers.

- **Chevron USA**

*Senior Project Engineer, Houston*

Conducted and directed studies of petroleum reservoirs. Designed and evaluated enhanced oil recovery projects for oil fields along the Gulf coast and in West Texas.

- **Gulf Research and Development Company**

*Research Engineer, Pittsburgh*

Planned, justified, conducted and documented fundamental investigations of multiphase flow through porous media utilizing bench top experiments and numerical models.

## EDUCATION

---

- Ph.D., Chemical Engineering, Carnegie Mellon University
- M.S., Chemical Engineering, Carnegie Mellon University
- B.S., Chemical Engineering, Cornell University

## PROFESIONAL QUALIFICATIONS

---

- Professional Engineer, Ohio, No. E-56519
- Professional Engineer, Kentucky, No. 21337

## CERTIFICATIONS

---

- Hazardous Waste Site Worker (40 hr HAZWPR)
- Hazardous Waste Site Supervisor
- Current 8 Hr Refresher
- OSHA Lockout/Tagout training
- OSHA Respiratory Protection training
- OSHA Hearing Conservation training
- WHIMS for Managers and Supervisors
- Basic Safety Training from Sarnia-Lambton IEC
- US DOE Radiological Worker I & II
- Heavy Equipment Operator Certification
- 10,000 PSI Water Jet Operator Certification
- Hydraulic Fracturing Equipment Operator Certification

## AFFILIATIONS

---

- National Groundwater Association
- American Institute of Chemical Engineers
- Society of Petroleum Engineers

## SELECTED PUBLICATIONS / PRESENTATIONS

---

- Murdoch, L.C., D. Wilson, K. Savage, W. Slack, and J. Uber. Alternative Methods for Fluid Delivery and Recovery. USEPA/625/R-94/003, 1995.
- Seigrist, R. L., K.S. Lowe, L.C. Murdoch, W.W. Slack, T.C. Houk. X-231A demonstration of in situ remediation of DNAPL compounds in low permeability media by soil fracturing with thermally enhanced mass recovery and reactive barrier destruction. DOE document ORNL/TM-13534, March 1998.
- Whiting, T., W. Slack, L.C. Murdoch. Dual-phase extraction with hydraulic fractures at a superfund site. International Conf. On Remediation of Chlorinated and Recalcitrant Compounds, Monterey, CA, May 1998.
- Murdoch, L.C., W. Slack, R. Siegrist, S. Vesper, T. Meiggs, Hydraulic fracturing advances. Civil Engineering, May 1997, 10A-12A.
- Murdoch, L.C., M. Kemper, and W.W. Slack. Applications of hydraulic fractures during in situ remediation. 1st Hawaiian National Remediation Technology Conference, Honolulu, HI, Sept. 1994.
- Murdoch, L.C., W. Slack, R. Siegrist, S. Vesper, T. Meiggs , Advanced hydraulic fracturing methods to create in situ reactive barriers. Proceedings of the International Containment Technology

Conference and Exhibition, Feb. 9-12, 1997, St. Petersburg, FL

- S.C. Hunt, T.O. Meiggs, L.C. Murdoch, W.W. Slack. Method and system for bioremediation of contaminated soil using inoculated support spheres. Patent 5,733,067 issued 31 March 1998.
- Murdoch, L.C., W.W. Slack, W. Harrar, B. Nilsson, and R. Siegrist. Sidewall sensors for monitoring fractured clay till. *Journal of Nordic Hydrology*.
- Murdoch, L.C., W.W. Slack, W. Harrar, R. Siegrist, and T. Whiting. Sidewall sensors for measuring in situ properties. *Remediation of Chlorinated and Recalcitrant Compounds Conference Proceedings*, Monterey, CA, May 18-21, 1998.
- Murdoch, L.C., W.W. Slack, W. Harrar, B. Nilsson, and R. Siegrist. Sidewall sensors for monitoring fractured clay till. *Proceedings of the Mass Transport in Fractured Aquifers and Aquitards Conference*. Copenhagen, DK. May 14-16, 1998.
- Murdoch, L.C., W.W. Slack, W. Harrar, R. Siegrist, and T. Whiting. Arrays of sidewall sensors to monitor subsurface conditions. *4th International Symposium on Environmental Geotechnology*, Boston, Mass. Aug. 9-13, 1998.
- William W. Slack, Lawrence C. Murdoch, Rex Hodges, and Dave Butler, "Recovering Free Product from Clay Using Hydraulic Fractures" *Second Conference on Remediation of Chlorinated and Recalcitrant Compounds*, Monterey, 2000.
- William W. Slack and Lawrence C. Murdoch, "Hydraulic Fractures to Improve In Situ Remediation" *Second Conference on Remediation of Chlorinated and Recalcitrant Compounds*, Monterey, 2000.
- Murdoch, L.C. J.R. Richardson, and W.W. Slack. Hydraulic fractures in fine-grain materials. *Southeastern Geol. Soc. Amer*, abstracts, March 2000.
- Agee, C., L.C. Murdoch, S. Brame, W.W. Slack. Effects of hydraulic fractures on well performance in saprolite *Southeastern Geol. Soc. Amer*, abstracts, March 2000.
- Davis-Hoover, Wendy J., L. Taras Bryndzia, Michael H. Roulier, Lawrence C. Murdoch, Mark C. Kemper, Phillip R. Cluxton, Souhail Al-Abed, William W. Slack, Stephen J. Vesper, "In Situ Bioremediation Utilizing Horizontal Lasagna", *Fifth International Symposium for In Situ and On-Site Bioremediation*, San Diego, CA, April 1999.
- Davis-Hoover, Wendy J., Michael H. Roulier, L. Taras Bryndzia, Lawrence C. Murdoch, Mark C. Kemper, Phillip R. Cluxton, Souhail Al-Abed, William W. Slack, Stephen J. Vesper, "Horizontal Lasagna to Bioremediate Trichloroethylene In Situ", *Midwest Focus Groundwater Conference*, National Groundwater Association, Chicago, October 1999.

# DOUGLAS E. KNIGHT

GREENVILLE, SOUTH CAROLINA  
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## WORK EXPERIENCE

---

- **5/00 – Present: FRx, Inc.**

*Operations Manager, Clemson*

Directs project planning, resource acquisition (including personnel and equipment,) field implementation, and reporting and analysis of multiple projects. Also instrumental in corporate business development.

*Project Manager, Clemson, SC*

Responsible for the logistics, execution and management of environmental hydraulic fracturing projects. Present summaries of work at national conferences.

- **3/99 – 6/01: Clayton Group Services, Inc.**

*Manager, Atlanta Regional Office*

Responsible for the management of multiple environmental projects, including: multiple, state owned, petroleum release site investigations, corrective action plan reports, and remediation projects for Georgia Environmental Facilities Authority (GEFA). Multiple UST projects including corrective action plans, site investigations, tank closures and installations, and remedial system design and O&M.

- **11/97 – 3/99: Environmental Corporation of America (ECA)**

*Project Manager, Alpharetta, Georgia*

Responsible for the management of multiple environmental projects including: Multiple site petroleum release investigations and preparation of corrective action plans for major oil companies in Georgia and Alabama. Phase I, Phase II, and Geotechnical Investigations in several states, including Georgia, Alabama, Colorado, Kansas, Utah, Florida, Washington, and Maryland.

- **11/97 – 3/99: Environmental Construction and Equipment Company (ECEC)**

*Project Manager, Alpharetta, Georgia*

Project Manager for the operation of a mobile thermal oxidizer used for the treatment of offgas from the vacuum extraction of subsurface petroleum hydrocarbons. Project Manager for the design, installation, and operation of a mobile air stripping system for an emergency response diesel release on behalf of a petroleum pipeline company. Duties also involved communications with local, state, and federal regulatory agencies. Technician for the design, installation, maintenance, and monitoring of an air sparging groundwater treatment system for a PCE plume.

- **6/97 – 11/97: United Consulting Group, Ltd.**

*Field Technician, Atlanta, GA*

Geotechnical investigation and construction materials testing and observation for materials used in commercial, multi-story buildings, including steel, concrete, and earth materials.

## EDUCATION

---

- B.S., Environmental Geology, Clemson University

## CERTIFICATIONS

---

- OSHA 30 Construction Safety
- Hazardous Waste Site Worker (40 hr HAZWPR)
- Current 8 Hr Refresher
- OSHA Lockout/Tagout training
- OSHA Respiratory Protection training
- OSHA Hearing Conservation training
- WHIMS for Managers and Supervisors
- Basic Safety Training from Sarnia-Lambdon IEC
- US DOE Radiological Worker I & II
- Heavy Equipment Operator Certification
- 10,000 PSI Water Jet Operator Certification
- Hydraulic Fracturing Equipment Operator Certification
- Environmental Monitoring Well Design and Construction

## OTHER EXPERIENCE

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- Subcontractor procurement/negotiations, client management, supervision and training of field personnel, budget planning, report preparation, and interaction with regulatory agencies.
- Hydrogeologic experience includes the installation of soil borings and monitoring wells, the collection of soil, groundwater and surface water samples, soil classification, aquifer testing, separate-phase hydrocarbon recovery, soil gas surveys, and site surveying. Drilling techniques include hollow stem auger, air rotary, air hammer, mud rotary drill rigs, direct push, CPT technology, and subsurface fracturing technology.

## AFFILIATIONS

---

- National Groundwater Association

## PUBLICATIONS / PRESENTATIONS

---

- Doug Knight and Bill Slack. "Comparison of Techniques for Creation of Iron-Filled Hydraulic Fractures." Seventh International Conference Remediation of Chlorinated and Recalcitrant Compounds, Session D7, Improved Delivery Methods: Injection and Soil-Mixing. Monterey, California; May 24-27, 2010.
- Doug Knight, Jim Richardson, Todd Herrington, Belinda Butler-Veytia. "Delivering HRC with Hydraulic Fracturing." Ninth International In Situ and On-Site Bioremediation Symposium (Baltimore, Maryland; May 7-10, 2007).
- Doug Knight and Graham Bradner. "Delivering HRC Primer™ via Hydraulic Fracturing." Eighth International In Situ and On-Site Bioremediation Symposium (Baltimore, Maryland; June 6-9, 2005)
- Knight, D. E. and W. W. Slack "Delivering Various Reduction and Oxidation Chemicals Via Hydraulic Fracturing." The Third International Conference on Oxidation and Reduction Technologies for In Situ Treatment of Soil and Groundwater, San Diego, CA. , San Diego, California. 2004.

## Corporate Information

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**Incorporated March 17, 1994 as a Pennsylvania Corporation**

**FIT: 23 2759953**

**Dun & Bradstreet: 00-846-5866**

### Principals:

Lawrence C. Murdoch, Ph.D., P.G., President, age 53, 117 Folger Street, Clemson, South Carolina.

William W. Slack, Ph.D., P.E., Vice President, age 60, 11582 Kemper Woods Drive, Cincinnati, Ohio.

### Bank Reference

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### General Legal Counsel

Charles C. Ashdown, Esq.  
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### Accounting Reference

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### Counsel for Intellectual Property

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(513) 421 7269

### Insurance

**Agent:** James Goodwillie, Kernan Insurance Agency, 9932 Brewster Lane, Powell, OH, 43065 Phone: (614) 764-0121. Fax (614) 764-0310.

Commercial General Liability Including Contractors Pollution & Hired and Non-Owned Auto	Limits Available Upon Request
Products/Completed Operations Aggregate	" "
Personal & Advertising Injury	" "
Each Occurrence	" "
Fire Damage Legal Liability and Fire	" "
Medical Expense, any one person	" "
Employers' Liability Insurance	" "
Commercial Inland Marine – Equipment	" "
Vehicle Liability	" "
Uninsured Motorist	" "
Underinsured Motorist	" "
Vehicle Comprehensive	" "
Vehicle Collision	" "
Workers Compensation, Interstate	" "

Ohio Workers Compensation

Policy No. 1149421

## Injury and Illness Information

FRx, Inc.  
P.O. Box 498292  
Cincinnati, OH  
45249-8292



(513) 469 6040 fax (513) 469 6041  
www.frx-inc.com

FRx has not had more than nine employees for several years. During those times, it did not maintain OSHA 300, or the preceding OSHA 200, forms as allowed by law. The following information, which would be used in the OSHA forms, is provided here.

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Year:	2010
Maximum number of Employees:	5
Average Number of Employees:	4.3
Hours Worked:	8191
Recorded Injuries:	0
Recorded Illnesses:	0

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Year:	2009
Maximum number of Employees:	4
Average Number of Employees:	3.5
Hours Worked:	6823.3
Recorded Injuries:	0
Recorded Illnesses:	0

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Year:	2008
Maximum number of Employees:	4
Average Number of Employees:	3.17
Hours Worked:	6123.0
Recorded Injuries:	0
Recorded Illnesses:	0

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