Bioaugmentation for Groundwater Remediation

SERDP and ESTCP Remediation Technology Monograph Series
Series Editor: C. Herb Ward, Rice University

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SERDP and ESTCP have joined to facilitate the development of a series of monographs on remediation technology written by leading experts in each subject area. This volume provides a review of the state-of-the-art on bioaugmentation for groundwater remediation. Previously published volumes include:

- *In Situ* Bioremediation of Perchlorate in Groundwater
- *In Situ* Remediation of Chlorinated Solvent Plumes
- *In Situ* Chemical Oxidation for Groundwater Remediation
- Delivery and Mixing in the Subsurface: Processes and Design Principles for *In Situ* Remediation

Additional volumes planned for publication in the near future include:

- Chlorinated Solvent Source Zone Remediation
- Processes, Assessment and Remediation of Contaminated Sediment

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Preface

In the late 1970s and early 1980s, our nation began to grapple with the legacy of past disposal practices for toxic chemicals. With the passage in 1980 of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), commonly known as Superfund, it became the law of the land to remediate these sites. The U.S. Department of Defense (DoD), the nation's largest industrial organization, also recognized that it too had a legacy of contaminated sites. Historic operations at Army, Navy, Air Force, and Marine Corps facilities, ranges, manufacturing sites, shipyards, and depots had resulted in widespread contamination of soil, groundwater, and sediment. While Superfund began in 1980 to focus on remediation of heavily contaminated sites largely abandoned or neglected by the private sector, the DoD had already initiated its Installation Restoration Program in the mid-1970s. In 1984, the DoD began the Defense Environmental Restoration Program (DERP) for contaminated site assessment and remediation. Two years later, the U.S. Congress codified the DERP and directed the Secretary of Defense to carry out a concurrent program of research, development, and demonstration of innovative remediation technologies.

As chronicled in the 1994 National Research Council (NRC) report, "Ranking Hazardous-Waste Sites for Remedial Action," our early estimates on the cost and suitability of existing technologies for cleaning up contaminated sites were wildly optimistic. Original estimates, in 1980, projected an average Superfund cleanup cost of a mere $3.6 million per site and assumed only around 400 sites would require remediation. The DoD's early estimates of the cost to clean up its contaminated sites were also optimistic. In 1985, the DoD estimated the cleanup of its contaminated sites would cost from $5 billion to $10 billion, assuming 400–800 potential sites. A decade later, after an investment of over $12 billion on environmental restoration, the cost-to-complete estimates had grown to over $20 billion, and the number of sites had increased to over 20,000. By 2007, after spending over $20 billion in the previous decade, the estimated cost to complete the DoD's known liability for traditional cleanup (not including the Munitions Response Program for unexploded ordnance) was still over $13 billion. Why did we underestimate the costs of cleaning up contaminated sites? All of these estimates were made with the tacit assumption that existing, off-the-shelf remedial technology was adequate to accomplish the task, that we had the scientific and engineering knowledge and tools to remediate these sites, and that we knew the full scope of chemicals of concern.

However, it was soon and painfully realized that the technology needed to address the more recalcitrant environmental contamination problems, such as fuels and chlorinated solvents in groundwater and dense nonaqueous phase liquids (DNAPLs) in the subsurface, was seriously lacking. In 1994, in the "Alternatives for Ground Water Cleanup" document, the NRC clearly showed that as a nation we had been conducting a failed 15-year experiment to clean up our nation's groundwater and that the default technology, pump-and-treat, was often ineffective at remediating contaminated aquifers. The answer for the DoD was clear. The DoD needed better technologies to clean up its contaminated sites, and better technologies could only arise through a better scientific and engineering understanding of the subsurface and the associated chemical, physical, and biological processes. Two DoD organizations were given responsibility for initiating new research, development, and demonstrations to obtain the technologies needed for cost-effective remediation of facilities across the DoD: the Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP).

SERDP was established by the Defense Authorization Act of 1991, as a partnership of the DoD, the U.S. Department of Energy, and the U.S. Environmental Protection Agency; its mission is "to address environmental matters of concern to the Department of Defense and the Department of Energy through support of basic and applied research and development of technologies that can enhance the capabilities of the departments to meet their environmental obligations." SERDP was created with a vision of bringing the capabilities and assets of the nation to bear on the environmental challenges faced by the DoD. As such, SERDP is the DoD's environmental research and development program. To address the highest-priority issues confronting the Army, Navy, Air Force, and Marine Corps, SERDP focuses on cross-service requirements and pursues high-risk and high-payoff solutions to the DoD's most intractable environmental problems. SERDP's charter permits investment across the broad spectrum of research and development, from basic research through applied research and exploratory development. SERDP invests with a philosophy that all research, whether basic or applied, when focused on the critical technical issues, can impact environmental operations in the near term.

A DoD partner organization, ESTCP, was established in 1995 as the DoD's environmental technology demonstration and validation program. ESTCP's goal is to identify, demonstrate, and transfer technologies that address the DoD's highest priority environmental requirements. The program promotes innovative, cost-effective environmental technologies through demonstrations at DoD facilities and sites. These technologies provide a large return on investment through improved efficiency, reduced liability, and direct cost savings. The current cost and impact on DoD operations of environmental compliance is significant. Innovative technologies are reducing both the cost of environmental remediation and compliance and the impact of DoD operations on the environment, while enhancing military readiness. ESTCP's strategy is to select laboratory-proven technologies with potential broad DoD application and use DoD facilities as test beds. By supporting rigorous testing and evaluation of innovative environmental technologies, ESTCP provides validated cost and performance information. Through these tests, new technologies gain end-user and regulatory acceptance.

In the 17–21 years since SERDP and ESTCP were formed, much progress has been made in the development of innovative and more cost-effective environmental remediation technology. Since then, recalcitrant environmental contamination problems for which little or no effective technology had been available are now tractable. However, we understand that newly developed technologies will not be broadly used in government or industry unless the consulting engineering community has the knowledge and experience needed to design, cost, market, and apply them.

To help accomplish the needed technology transfer, SERDP and ESTCP have facilitated the development of a series of monographs on remediation technology written by leading experts in each subject area. Each volume will be designed to provide the background in process design and engineering needed by professionals who have advanced training and five or more years of experience. The first volume in this series, *In Situ Bioremediation of Perchlorate in Groundwater*, met a critical need for state-of-the-technology guidance on perchlorate remediation. The second volume, *In Situ Remediation of Chlorinated Solvent Plumes*, addressed the diverse physical, chemical, and biological technologies currently in use to treat what has become one of the most recalcitrant contamination problems in the developed world. The third volume, *In Situ Chemical Oxidation for Groundwater Remediation*, provided comprehensive, up-to-date descriptions of the principles and practices of *in situ* chemical oxidation for groundwater remediation based on a decade of intensive research, development, and demonstration. The fourth volume, *Delivery and Mixing in the Subsurface: Processes and Design Principles for In Situ Remediation,* described the principles of chemical delivery and mixing systems, and their design and implementation for effective *in situ* remediation. Other volumes will follow on such topics as the remediation of DNAPL-chlorinated solvent source zones and remediation of contaminated sediments. Additional volumes will be written as new remediation technologies are developed and proven to be effective.

This volume, *Bioaugmentation for Groundwater Remediation*, provides a review of the past 10–15 years of intensive research, development, and demonstrations that have been at the forefront of developing bioaugmentation into a viable remedial technology. In addition, both a primer on the basic microbial processes involved in bioaugmentation as well as a thorough summary of the methodology for implementing the technology is provided within this volume. It is our intention that this will serve as a valuable resource for environmental remediation professionals who seek to understand, evaluate, and implement bioaugmentation. Topics addressed in this volume include:

- A brief history and overview of bioaugmentation (Chap. 1).
- A detailed review of the discovery of *Dehalococcoides* and the development of reductive dechlorination of chlorinated solvents as a remedial technology (Chap. 2).
- The state-of-the-science for the production and handling of *Dehalococcoides* bioaugmentation cultures (Chap. 3).
- An overview of a decision process for determining whether to implement bioaugmentation with *Dehalococcoides* (Chap. 4).
- Design considerations for implementing bioaugmentation (Chap. 5).
- A summary of microbial monitoring options during bioaugmentation with *Dehalococcoides* (Chap. 6).
- A thorough review of the use of bioaugmentation for treatment of chemicals other than the more common chlorinated solvents (TCE and PCE), including DCE (Chap. 7), aerobic cometabolism of chlorinated solvents (Chap. 8), carbon tetrachloride (Chap. 9), and MTBE (Chap. 10).
- An analysis of cost considerations needed to evaluate whether bioaugmentation should be considered for the treatment of chlorinated aliphatic compounds in groundwater (Chap. 11).
- An assessment of important unknowns and uncertainties that impact the state-of-the-science that underpins bioaugmentation development and implementation. This chapter, written in consultation with a broad range of experts in the remediation field, should help guide the research agenda on bioaugmentation (Chap. 12).

Each chapter in this volume has been thoroughly reviewed for technical content by two or more experts in each subject area covered. The editors and chapter authors have produced a well-written and up-to-date treatise that we hope will prove to be a useful reference for those making decisions on remediation of contaminated sites, for remediation practitioners, and for those involved in development of advanced technology for the *in situ* remediation of contaminated groundwater.

SERDP and ESTCP are committed to the development of new and innovative technologies to reduce the cost of remediation of soil, groundwater, and sediment contamination as a result of past operational and industrial practices. We are also firmly committed to the widest dissemination of these technologies to ensure that our investments continue to yield savings for not only the DoD, but also the nation. In sponsoring this monograph series, we hope to provide the broader remediation community with the most current knowledge and tools available in order to bring these technologies to bear on the remediation of contaminated sites.

Jeffrey A. Marqusee, PhD, Executive Director, SERDP and ESTCP
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About the Editors

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Dr. Stroo is a Principal Technical Advisor with HydroGeoLogic, Inc. He provides technical support on large remediation projects for private- and public-sector clients and has served as a technical advisor to the Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP) for over 10 years.

Dr. Stroo received his BS degrees in Biology and Soil Science from Oregon State University, his MS in Soil Science from West Virginia University, and his PhD in Soil Science (Soil Microbiology) from Cornell University.

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Dr. Stroo has served on several expert review panels for SERDP, other government agencies, and private companies. Recently, he served as co-chair of the SERDP workshops on Remediation of Chlorinated Solvents in Groundwater and Remediation of Dense Nonaqueous Phase Liquid (DNAPL) Source Zones. He is coeditor of the SERDP-facilitated monographs, *In Situ Bioremediation of Perchlorate in Groundwater* and *In Situ Remediation of Chlorinated Solvent Plumes*.

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Dr. Leeson has been the Environmental Restoration Program Manager at SERDP and ESTCP since 2001. She was formerly a Research Leader at Battelle Memorial Institute and worked on the design and implementation of innovative physical/chemical and biological treatment technologies for site remediation and treatment of industrial/hazardous wastewater for 10 years prior to working at SERDP and ESTCP.

Dr. Leeson served as chairperson of the Fourth, Fifth, and Sixth International *In Situ* and On-Site Bioremediation Symposium and was the founding Managing Editor for *Bioremediation Journal* from 1996 to 1999 and the Editor-in-Chief from 1999 to 2001. She has developed and implemented several expert panel workshops on topics ranging from contaminant bioavailability to chlorinated solvent-contaminated groundwaters.

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Dr. Ward holds the Foyt Family Chair of Engineering in the George R. Brown School of Engineering at Rice University. He is also Professor of Civil and Environmental Engineering and Ecology and Evolutionary Biology.

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Protection Agency (USEPA)-sponsored National Center for Ground Water Research and the U.S. Department of Defense (DoD)-sponsored Advanced Applied (Environmental) Technology Development Facility (AATDF).

Dr. Ward has been a member of the USEPA Science Advisory Board and served as Chair of the SERDP Scientific Advisory Board. He is the founding and current Editor-in-Chief of the international scientific journal *Environmental Toxicology and Chemistry*.

Dr. Ward received the Frederick George Pohland Medal for Outstanding Contributions to Bridging Environmental Research, Education, and Practice and the Brown and Caldwell Lifetime Achievement Award for Remediation in 2006, the Water Environment Federation Jack Edward McKee Medal for Achievement in Groundwater Restoration in 2007, and the Society for Industrial Microbiology and Biotechnology Charles Thom Award for bioremediation research in 2011.

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Mr. Cox has helped to pioneer the development of MNA and EISB technologies, including bioaugmentation, for remediation of chlorinated solvents, propulsion energetics (perchlorate, n-nitrosodimethylamine [NDMA]), and explosives (RDX, TNT) in porous media and fractured bedrock. He works with private sector interests and government research programs to develop innovative *in situ* treatment technologies and to demonstrate and validate their use at field-scale for widespread commercial use. As part of his *in situ* remediation research, development, and implementation work, he has authored over 30 professional publications and articles regarding the degradation of hazardous contaminants in subsurface environments and has coauthored multiple guidance documents and educational courses on these subjects.

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Dr. Criddle is a Professor of Civil and Environmental Engineering at Stanford University and Senior Fellow in the Woods Institute for the Environment. He received his BS in Civil and Environmental Engineering and his BA in Spanish from Utah State University in 1982, followed by an MS in Environmental Engineering in 1984. In 1990, he completed his PhD at Stanford University in Civil Engineering (Environmental Engineering and Science). His research focus is environmental biotechnology.

Dr. Criddle began his academic career in 1989 as a faculty member at Michigan State University (MSU). While at MSU, he served as Project Director for the Schoolcraft project, a field-scale test of bioaugmentation that involved faculty from diverse disciplines and institutions, staff scientists, students, consultants and outreach education to members of the public and officials in Michigan. The National Ground Water Association (NGWA) named it one of two Outstanding Remediation Projects for 2002. Since 1998, he has been a member of the Stanford faculty, serving as Associate Chair in 2003 and as Director of a bioremediation field project at the U.S. Department of Energy (DOE) Field Research Center in Oak Ridge, Tennessee (2000–2006). This project entailed a multi-year series of experiments focused on *in situ* sequestration of uranium in groundwater and involved faculty from several universities, DOE scientists, and many students. Dr. Criddle has over 100 peer-refereed publications and is coauthor with award-winning artist Larry Gonick of *The Cartoon Guide to Chemistry* (2006), a widely used supplementary text for high school and freshman chemistry.

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Dr. Edwards is internationally known for her work on anaerobic bioremediation, the application of molecular biology and metagenomics to uncover novel microbial processes, and the transition of laboratory research into commercial practice to develop bioremediation and bioaugmentation strategies for groundwater pollutants. Dr. Edwards and Geosyntec Consultants were recognized with the 2009 National Science and Engineering Research Council of Canada Synergy Award for their long-standing partnership that led to the development of KB-1®, a successful commercial microbial bioaugmentation culture. She has been inducted into the Canadian Academy of Engineering and is a Fellow of the American Association for the Advancement of Science.

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Dr. Koenigsberg was a Founder of Regenesis, where he coinvented or managed the development of the company's major products including ORC®, HRC®, MRC® and Regenox®. Also during his tenure, Regenesis produced one of the first commercial *Dehalococcoides* products (BDI®) and associated deoxyribonucleic acid (DNA) probes (Census℠) through the work of Dr. Frank Löffler at the Georgia Institute of Technology. Upon retiring from Regenesis, Dr. Koenigsberg was a Partner at WSP and a Principal at ENVIRON. In 2010, he received a Lifetime Achievement Award from the Association for Environmental Health & Sciences (AEHS) Foundation. He is a member of several editorial and advisory boards and is an Adjunct Professor at California State University at Fullerton where he also serves on the Dean's Advisory Council.

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Dr. Petrovskis is an Associate/Engineer with Geosyntec Consultants, Inc. in Ann Arbor, Michigan. He received his BS (Honors) in Biochemistry from The University of Wisconsin and his MSE and PhD degrees in Environmental Engineering from The University of Michigan. Dr. Petrovskis began his career as a molecular biologist. His 17 years of environmental consulting experience have focused on development and implementation of innovative technologies for remediation of chlorinated solvents, including bioaugmentation and surfactant-enhanced aquifer remediation. He has served as Principal Investigator (PI) or Co-PI on four Small Business Innovative Research or SERDP/ESTCP projects related to chlorinated solvent bioremediation. He is a member of the ITRC EMD team. He is also a Lecturer in the Department of Civil and Environmental Engineering at The University of Michigan.

Kirsti M. Ritalahti

Dr. Ritalahti is a Research Assistant Professor in the Department of Microbiology at the University of Tennessee, Knoxville. She received her BS degree in Microbiology in 1992 from Oregon State University and her PhD from the Center for Microbial Ecology and Department of Microbiology at MSU in 2000. Her primary research focus is to design and employ molecular tools to detect and quantify relevant target genes from microbes pertinent to bioremediation applications. She is also attempting to harness the horizontal gene transfer mechanisms by which organohalide respiring organisms acquire new capabilities.

A. P. ("Sandy") Robertson

Dr. Robertson is a Senior Research Engineer and Lecturer working in the areas of physical chemical processes for water and wastewater treatment as well as aquatic geochemistry. He received his bachelor's degree from Harvard College in Engineering and Applied Physics. He did his MS and PhD work in Environmental Engineering and Science at Stanford University. Dr. Robertson spent 2 years in Thailand as a Peace Corps volunteer working on village water projects. He has also worked as a consulting engineer in Sacramento, California. At Stanford, his work has included studies related to copper partitioning in soils and groundwaters, photocatalytic oxidation of contaminants, membrane processes and children's exposure to pesticides. He has helped develop and run the Clean Water (research) and Singapore Stanford Partnership (graduate education) programs – joint efforts involving the Stanford Environmental and Water Studies group and Singapore's Nanyang Technological University.

Joseph P. Salanitro

Dr. Salanitro is an Adjunct Research Professor in the Department of Civil and Environmental Engineering at the University of Houston, Texas, where he teaches environmental chemistry, environmental engineering, water quality engineering, and environmental microbiology. He received his PhD in Microbiology from Indiana University in 1968.

Dr. Salanitro was previously employed by Shell for 31 years, where he was involved in the chemical and oil sectors of environmental research and development, including the biodegradability assessment of surfactants, solvents, pesticides, and petrochemical waste effluents; the role of microbes in sour gas formation in oilfield waterfloods; biocorrosion potential; oilfield biocide evaluations; and defining the potential and limits of natural attenuation, biostimulation, and bioaugmentation processes for crude oils, fuels, and fuel oxygenates in soils and groundwater. During the last several years, he has consulted for companies on the biodegradation evaluation of drilling fluids in the seafloor environment and the degradation of petroleum products and chlorinated solvents in bioreactors using immobilized microbial cultures.

Lewis Semprini

Dr. Semprini is a Distinguished Professor of Environmental Engineering at Oregon State University. He received his BS degree in Chemical Engineering from the University of California, Berkeley, and MSE and PhD degrees in Civil and Environmental Engineering from Stanford University. His research involves laboratory, field, and modeling investigations on the aerobic and anaerobic transformations of chlorinated solvents. He has served as a PI or Co-PI on several SERDP/ESTCP projects, including the SERDP project "Development of Effective Aerobic Cometabolic Systems for *In Situ* Transformation of Problematic Chlorinated Solvent Mixtures." He has also authored over 80 peer-reviewed scientific papers and book chapters.

Jim C. Spain

Dr. Spain has been a Professor in Civil and Environmental Engineering at the Georgia Institute of Technology since 2005. He received his PhD in Microbiology from The University of Texas at Austin. Dr. Spain has 30 years of experience studying the mechanisms of biodegradation of organic compounds and the ecology of the bacteria that catalyze the processes. He worked on fate and transport of marine pollutants including pesticides and petroleum for 5 years at the USEPA Marine Environmental Research Laboratory before joining the Air Force Research Laboratory (AFRL) in 1985. As head of Biotechnology Research at AFRL, he directed a program to discover and develop strategies for biodegradation of industrial and military chemicals, including fuels, solvents, and explosives. Research at the Air Force also included the exploration of biocatalysts for transformation and synthesis of materials. He is a former editor of *Applied and Environmental Microbiology* and has published extensively on biodegradation and biotransformation of synthetic organic compounds.

Gerard E. Spinnler

Dr. Spinnler is a Senior Consultant in the Soil and Groundwater Management Group at Shell Global Solutions US Inc., Houston, Texas. He received his PhD in Geology from Arizona State University and is a Professional Geoscientist in Texas. Dr. Spinnler is a remediation expert for Shell's East Region of the United States. He has been active in research on fuel oxygenate remediation, bioaugmentation, biostimulation, oxygen distribution, chemical oxidation, and most recently on the application of isotopic and molecular biological tools.

Robert J. Steffan

Dr. Steffan is Director of Biotechnology Development and Applications at Shaw Environmental, Inc. He received his PhD in Biology from the University of Louisville in 1988, and then received an Alexander von Humboldt Fellowship to perform research at the National Institute for Biotechnology (GBF) in Braunschweig, Germany, from 1988 to 1990. He joined Envirogen, Inc. as a research scientist in 1990, and from 2001 to 2003 served as Envirogen's Vice President of Technology Development. He has served in his current position since the acquisition of Envirogen by Shaw Environmental and Infrastructure, Inc. in March 2003. He has worked for more than 20 years on the development and application of biotechnologies for treating some of the nation's most challenging pollutants, including chlorinated solvents, methyl *tert*-butyl ether (MTBE), and 1,4-dioxane. He has published more than 70 research papers, manuscripts, and book chapters, has earned ten U.S. and international patents, and has served on a wide array of national and international committees and scientific review panels. In addition, he earned a

Juris Doctorate degree from the Temple University School of Law in 1997 and is licensed to practice law in the states of Pennsylvania and New Jersey.

Gregory M. Tatara

Dr. Tatara is the Utility Director for the Marion, Howell, Oceola, and Genoa (MHOG) Sewer and Water Authority located in Howell, Michigan. He received his BS in Biology from Gannon University in 1991. In 1996, he completed his PhD at MSU in Microbiology (Center for Microbial Ecology). His research focus was environmental biotechnology.

Dr. Tatara began his professional career in 1996 as a Project Manager with the Traverse Group in Ann Arbor, Michigan. In 2000, he became the Deputy Drain Commissioner for Livingston County, coordinating the operation and maintenance of the county's numerous sanitary sewer systems and overseeing the installation of remediation and methane gas mitigation systems for the Livingston County Landfill. In 2006, he became the Utility Director for the MHOG Sewer and Water Authority, which serves 20,000 customers in central Livingston County. As Director, Dr. Tatara has upgraded existing microbial wastewater treatment systems and initiated hydraulic modeling of water systems to improve quality and pressure. Dr. Tatara oversees a staff of 22 personnel.

Simon Vainberg

Dr. Vainberg is the Fermentation Manager in the Biotechnology Development and Application Group of Shaw Environmental, Inc. in Lawrenceville, New Jersey. He received his MS and PhD degrees in Chemical Engineering and Industrial Biotechnology from D. Mendeleev University of Chemical Technology of Russia (Moscow). He also received a Certificate of Completion from the Patent Training Academy of the U.S. Patent and Trademark Office (USPTO).

Dr. Vainberg has more than 30 years of experience in industrial microbiology and biotechnology and has been involved in the isolation of microorganisms for bioremediation, development of aerobic and anaerobic fermentation processes, and production of bacterial cultures for a wide variety of environmental projects. He has worked as a Patent Examiner for the USPTO, has coauthored more than 20 scientific articles, and has received four patents in the United States and the former Union of Soviet Socialist Republics (USSR) in the area of bioremediation and applied biotechnology.

Georgina Vidal-Gavilan

Ms. Vidal-Gavilan is Director of Research, Development and Innovation (R&D&I) and Remediation Department at D'ENGINY BIOREM, an engineering bioremediation firm in Barcelona, Spain. She received her BS in Environmental Sciences from the Autonomous University of Barcelona (1996) and MSc in Environmental Engineering from Michigan State University (MSU) (2000). She is an expert in soil and groundwater remediation. Currently, she is completing her PhD at the University of Barcelona, with a focus on the application of isotopic techniques for enhanced attenuation of nitrate-polluted groundwater.

Ms. Vidal-Gavilan began her remediation career at MSU, participating in the Schoolcraft project, in which she developed her Master's Thesis on the bioremediation of carbon tetrachloride in a three-dimensional laboratory-scale reactor. She then returned to Barcelona, where she worked in the private sector, developing characterization and remediation projects for industry and government. At BIOREM, she leads remediation activities with local and international projects that use new applications of bioremediation and natural attenuation technologies for groundwater recovery. She combines research, innovation, consultancy, and field-scale remediation, networking between involved stakeholders with the goal of technology transfer and enhancement, and often participates in research seminars, lectures, and congresses.

Timothy M. Vogel

Dr. Vogel is professor of Microbiology and Environmental Engineering at the University of Lyon. He received his BS degrees in Geology and Oceanography from the University of Washington and his MSE and PhD degrees in Environmental Engineering from Stanford University. He has worked for 30 years on the biodegradation and bioremediation of environmental contaminants and has over 70 scientific publications and 8 patents. He works as a consultant for both environmental consulting firms and various industries, was on the faculties of Michigan State University and the University of Michigan, and was responsible for environmental biotechnology at Rhône-Poulenc for 8 years. He is a partner in the recent environmental biotechnology start-up, ENOVEO.

Helen Vrionis

Dr. Vrionis has expertise in environmental and anaerobic microbiology. She received her BSc degree in Biology from the University of Windsor, Ontario, her MSc in Microbiology and Immunology from Queen's University in Kingston, Ontario, and her PhD (2002) in the Department of Chemical Engineering, Queen's University, Ontario. She has postdoctoral experience from the laboratory of Dr. Derek Lovley in the Department of Microbiology at the University of Massachusetts Amherst, from the Department of Biology at the University of Calgary, and from the Department of Chemical Engineering and Applied Chemistry at the University of Toronto.

Christopher B. Walker

Dr. Walker is an Environmental Engineer with Geosyntec Consultants, Inc., in Seattle, Washington. He received his BS in Environmental Engineering from Northwestern University and his PhD in Environmental Engineering from the University of Washington. Dr. Walker provides operational and strategy consulting for commercial, industrial, and federal clients on remediation and water management issues. His experience includes the evaluation, design, and installation of *in situ* and *ex situ* remedial systems for chlorinated solvents, energetics, heavy metals, and organics, as well as liability valuations and lifecycle assessments of contaminated sites.

Lance B. Warnick

Mr. Warnick is a Principal Engineer with Aspen Engineers in Nampa, Idaho. He received his MS degree in Environmental Engineering from Michigan State University (MSU) and his BS degree in Environmental Engineering from Utah State University. While a student at MSU, he performed bench-scale experiments to help simulate the anticipated geochemical changes associated with the Schoolcraft Bioaugmentation Project in Michigan. As a consultant for the last 14 years, he has worked on many projects, managing and treating contaminated soils and groundwater at decommissioned oil refineries in Oklahoma and Wyoming, rail yards in Nebraska, and wood treatment facilities in Colorado. He has experience in developing and implementing pilot-scale evaluations of biologically enhanced remediation. Much of his current work is centered in Idaho, where he focuses on assisting private land owners and local government entities in developing plans and management systems to help protect land and soil from contamination and help them comply with the state Department of Environmental Quality and USEPA regulations.

Ryan A. Wymore

Mr. Wymore is a Principal Environmental Engineer with CDM Smith in Denver, Colorado, where he serves as a national resource for evaluation, selection, and implementation of remediation strategies. He received his BS in Biological Systems Engineering from the University of Nebraska-Lincoln and his MS in Civil/Environmental Engineering from the University of Idaho. Mr. Wymore has spent the last 14 years specializing in innovative groundwater remediation technologies, particularly bioremediation, natural attenuation, and chemical oxidation. He also serves as the administrator for CDM's Research and Development Program, where he coordinates all of the company's internally and externally funded research. He joined ITRC in 2002, has had membership on six technical teams, and currently serves on the ITRC's Board of Advisors as the industry representative. He is a registered professional engineer in Colorado and Idaho.

Steven H. Zinder

Dr. Zinder is Professor of Microbiology at Cornell University, Ithaca, New York, where he has been on the faculty for over 30 years. He received his BA in Chemistry from Kenyon College and his PhD in Bacteriology from the University of Wisconsin, where he was mentored by the microbial ecologist T. D. Brock and was a Postdoctoral Fellow at the University of California, Los Angeles (UCLA). His research has centered on anaerobic microbes that carry out environmentally important chemical transformations, and over the years he has studied metabolism of organic sulfur compounds, methanogenesis from acetate, nitrogen fixation, and reductive dehalogenation. In the latter arena, his laboratory isolated and characterized *Dehalococcoides ethenogenes* strain 195 and helped analyze its genome sequence. He participated in the writing of the *Treatability Test Protocol for the Reductive Anaerobic Biological In Situ Treatment Technology (RABITT)*.

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