WYOMING DOE/EPSCoR

Grant # DE-FC02-91ER75680

FINAL REPORT

DECEMBER 2003

DISCLAIMER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

Section 1
EXECUTIVE SUMMARY

In the period from 1996 to 2003, the University of Wyoming received funding for a Department of Energy EPSCoR (DOE/EPSCoR) implementation award. This occurred in three two-year grants plus a no-cost extension. Prior to the beginning of these awards, Wyoming developed a strategy to enhance the State's ability to compete for energy-related R&D funds. That strategy involved pursuing three important goals:

- Establish Wyoming as the nation's leader in research associated with fossil fuel utilization and associated environmental technologies.
- Make Wyoming coal, oil and natural gas more available and more competitive sources of energy while enhancing the utilization of Wyoming's renewable energy resources, including wind and solar generation.
- Develop capabilities in Wyoming to support energy-related industry in environmental monitoring, assessment, mitigation and remediation as well as in renewable energy and its impact on the nation's electric power infrastructure.

While these goals emphasize the needs of Wyoming in energy-related research, they clearly coincide with those of the nation and specifically with the USDOE. These were the goals associated with our original DOE/EPSCoR award. Wyoming's governmental leaders, research institutions and industries are committed to them and continue to make the investment needed to be successful. As an important part of Wyoming's pursuit of these goals, the DOE/EPSCoR program adopted several objectives that have contributed to realizing our goals. These included:

1. Enhance research capabilities at the University of Wyoming (UW) and the Western Research Institute (WRI) in energy-related areas of science, engineering and mathematics.
2. Strengthen linkages between UW and the energy industry.
3. Increase the number, quality, and diversity of personnel with expertise in basic energy sciences, especially engineers and scientists building careers in Wyoming.
4. Improve linkages with federal research laboratories.
5. Raise awareness in Wyoming of the importance of energy-related research and education.

With the support of DOE/EPSCoR, we have made significant progress in each of these objectives. A concise summary of progress is provided in the DOE/EPSCoR Goals and Objectives section beginning on page 1-2 of this report. The progress associated with individual projects is detailed in the research cluster sections of this report.

In summary, the extensive planning done to prepare for the DOE/EPSCoR program and the successes in the seven years of its implementation have resulted in a substantial improvement in the research competitiveness of Wyoming scientists and engineers in each of the DOE/EPSCoR research clusters. In addition, the human resource development activities produced many graduates who benefited from energy-related research activities and have entered the workforce. This section concludes with a brief overview of how the DOE/EPSCoR award has changed research competitiveness in Wyoming. The remainder of the Final Report has sections on Human Resources and each of the Research Clusters. An important note is that the PI for the Fossil Fuel Cluster, Dr. Pradeep Agarwal, achieved many important research goals and provided outstanding leadership to that cluster before his untimely death at an early age.

Overview of Wyoming DOE/EPSCoR Achievements

Detailed descriptions of the research achievements are found in the sections associated with the three research clusters: Fossil Energy, Electrical Energy Efficiency, and Environmental Remediation. This overview provides a higher level summary of how the DOE/EPSCoR program has contributed to achieving the overall objectives of the University and the State with respect to improving research capability. In this regard, it is particularly important to note that this funding has improved the interaction among faculty from various disciplines in ways that would not have otherwise occurred. The focus on energy-related research has certainly facilitated new collaborations. The fluidized bed research associated with coal beneficiation is also applied in environmental remediation. Power electronics research done in the Electrical Energy Cluster is being used in a project on electrokinetic remediation in the Environmental Cluster. Exciting new research involving plasma mediated reactions involves investigators from the Fossil Energy and Electrical clusters. The integration of research activities is also occurring as a natural consequence of the interaction among DOE/EPSCoR scientists and engineers. As examples of how this is occurring, we note that individual faculty members in the departments of Electrical Engineering and Civil Engineering now have frequent interaction and improved understanding of their respective areas of expertise. This kind of interaction occurs across clusters as well, where some faculty are active participants in both the Electrical Energy group and the Environmental Group. The preparation for the site visits made a particularly significant impact on all of the participants, since this provided a forum for all of the project personnel to present their research efforts and progress reports while also providing interaction with researchers from DOE laboratories. DOE/EPSCoR has become synonymous in Wyoming with focused research projects emphasizing energy-related natural resources and the environment.

Making the overall activity self-sustaining beyond the period of USDOE support is clearly tied to the primary goal of EPSCoR, i.e., on making Wyoming more nationally competitive in the research areas supported by DOE/EPSCoR. We are particularly encouraged by the progress in this area. Nearly all of the project principal investigators have been successful in obtaining non-EPSCoR support. The Fossil Energy Cluster has succeeded in obtaining many new contracts and grants directly related to DOE/EPSCoR research. Similarly, the Electrical Energy Cluster has obtained ten new grants directly related to EPSCoR funding and additional proposals are currently pending. One of these projects, funded by NSF and EPRI, "Restructuring Power Engineering Education to Meet New Challenges" is of particular importance since it integrates to research activities and undergraduate education. Finally, the Environmental Cluster has seven new contracts funded, including one that is funded by private industry, and all are directly related to the DOE/EPSCoR research. In addition, many other research proposals not directly related to the DOE/EPSCoR research have been funded, showing the effect of this project on the research success of the faculty involved.

DOE/EPSCoR Goals and Objectives

It is clear that the entire state of Wyoming continues its commitment to the goals and objectives of the DOE/EPSCoR program. This section gives a brief summary of progress in achieving the goals of Wyoming DOE/EPSCoR:

1. Research capabilities in energy-related areas of science, engineering and mathematics have increased significantly at UW. New facilities are available, such as fluidized bed

reactors, a large PV array and an energy efficiency motor testing laboratory. Faculty expertise in Chemistry, Chemical Engineering, Electrical Engineering, Mechanical Engineering, Civil Engineering, and environmental remediation areas has been enhanced. Dozens of graduate and undergraduate students were involved in energy-related research projects because of the EPSCoR funding.

2. New linkages exist between UW and Wyoming's energy industry, specifically with FMC and other coal producers who are now involved in cooperative research projects. Also, several Wyoming oil producers have become partners in energy and environmental projects.
3. Faculty members are now involved in energy-related research who had not been involved in such projects in the past. We have been successful in recruiting many women to participate in the DOE/EPSCoR projects both as undergraduates and as high school students, and many of these are now in the science and engineering workforce.
4. Formal articulation agreements are in place with some UW Community Colleges and we are continuing this effort with others.
5. DOE/EPSCoR has provided the impetus for new contacts and projects in cooperation with Los Alamos National Laboratory, Sandia National Laboratory, Idaho National Engineering and Environmental Laboratory, Pacific Northwest National Laboratory and Argonne National Laboratory. UW faculty have spent summer or sabbatical leave at DOE laboratories.
6. The level of awareness of DOE/EPSCoR and the importance of energy research has clearly been raised in Wyoming. The Wyoming high schools are involved in the Earth System Sciences education project, Wyoming legislators have participated in EPSCoR meetings, the Governor and the President of UW publicly advocate support for DOE/EPSCoR and its research projects.

TABLE OF MAJOR IMPACTS

	Fossil Fuel	Electrical Energy	Environmental Remediation	Human Resources	Totals
Proposals, direct	12	7	9	4	32
Publications	38	20	44	2	104
HS				62 *	62
Undergraduates				286 *	286
Graduate Students	14	15	15	18	62
Female/Minority	5	6	9	118	138
Faculty	5	9	12	4	30

*** The high school and the undergraduate students were spread across the three research clusters.**

Summary. It is evident that the research conducted in the DOE/EPSCoR project is directly related to the goals of the State of Wyoming and UW. This is no accident, as the decision makers of these institutions were principal participants in the DOE/EPSCoR planning process that led to the selection of the individual research projects and clusters. Specifically, research in fossil fuel utilization, electrical energy efficiency, and environmental technologies

directly support UW's goal to become a leading institution in environmental and natural resources research and development. Such research is also directly related to Wyoming's largest industries and supports the economic diversification strategy adopted by State government. These research areas are also directly related to USDOE's programmatic interests, because Wyoming's primary industries are all energy-related. These projects align with the focus of such USDOE programs as Clean Coal Technology and Energy Efficiency and Renewable Energy, among others. The research accomplished has made a major difference in the capabilities of young faculty members in chemistry, chemical & petroleum engineering, electrical engineering, civil engineering and mathematics to compete for research funding.

Finally, and perhaps most importantly, all of the research and human resource development projects were systemic in nature with real potential for becoming self-sustaining. They concentrated on building permanent structure, such as faculty expertise, research equipment, the SEM Minority Center, and the School of Environment and Natural Resources. It was the intent of the DOE/EPSCoR project to permanently change the way Wyoming does business in energy-related research, in human development for science and engineering careers, and in the relationships between Wyoming industry, State Government and UW. While there is still much to be done, the DOE/EPSCoR implementation award has certainly been successful in accomplishing that change and in enhancing UW's research competitiveness associated with coal utilization, electrical energy efficiency, and environmental remediation. Final reports for the human resources component and each of the research clusters are provided in the following sections, along with a summary of the many patents, in process or already granted, that are associated with the Wyoming DOE/EPSCoR project.

Section 2
HUMAN RESOURCE DEVELOPMENT

Cluster PI: name, address, phone, fax, email
Sally Steadman
Box 3295 College of Engineering
University of Wyoming
Laramie, WY 82071
307-766-6105, 307-766-4444, Steadman@uwyo.edu

Other Personnel
High School
62
Undergraduates
286
Graduate Students
18
Female/Minority
118

Abstract:
The HRD cluster addresses three objectives: knowledge transfer from the Research Clusters to the citizens and industries in Wyoming; recruitment activities to expand the number of science, engineering, and mathematics personnel involved in energy-related research; and K-12 enrichment activities to heighten awareness of energy issues. These activities have been implemented:

- Research Internship Program for undergraduate students
- Earth System Science Internet Project for K-12 teachers
- Research Apprentice Program for high school students

Research and human resource development activities are carefully integrated. Each project enhances graduate student and junior faculty competence while involving undergraduates and high school students and teachers in research. The participation of the junior faculty in the supervision and execution of the research projects has greatly increased their ability to compete for and manage research funding at a national level. Students and teachers participate directly in the research projects, collecting and analyzing data; and the researchers are active participants in the K-12 Earth System Science Internet Project, contributing to the education of science teachers and the development of instructional materials.

Cluster Accomplishments

1) High School students Andy Coughlin and Bess Eakin, who participated in the Research Apprentice Program for High School Students, were selected as regional finalists in the Siemens Westinghouse Science and Technology Competition. Their project was one of 48 research projects selected to advance to the national competition. Their project was also chosen as the top team project at the Wyoming Science Fair, qualifying them to compete at the International Science Fair.

The students' coal combustion project was directed by Dr. Pradeep Agarwal, PI for the Fossil Energy Cluster. Coughlin and Eakin combusted char in a fluidized bed to gather information about harmful gases (particularly N2O and NOx) emitted during the combustion of char particles. The main goal of the research was to reduce or eliminate these harmful gases during combustion. Parameters such as oxygen concentration and temperature were varied in each experiment to optimize the results.

2) The Earth System Science Internet Project Web Site (http://smtc.uwyo.edu/essip/) was named an Innovator of the Month site by the Eisenhower National Clearinghouse. The site includes an introduction to coal for K-6 students and was developed in conjunction with Dr. Sadrul Ula, PI for the Electrical Energy Cluster.

RESEARCH INTERNSHIP PROGRAM FOR UNDERGRADUATE STUDENTS

Cluster faculty selected undergraduate students to participate in the research projects during the academic year as well as during the summer. Typically, four students worked in each cluster area and often participated in the research for multiple semesters/summers. The students were integral members of the research team, preparing project reports on their individual research projects and assisting with the supervision of the high school students during the summer. The students presented their work at the University's Research Day, an annual showcase of over 100 undergraduate research projects each spring. Student abstracts were published for the Symposium. Students also presented their work at regional and national conferences, including the National Conference for Undergraduate Research (NCUR).

Summer research fellows were required to complete a seminar series/symposium on research topics such as: ethics, scientific communication (both written and presentations), graduate school admissions, fellowship preparation, and entrepreneurial opportunities.

EARTH SYSTEM SCIENCE INTERNET PROJECT FOR K-12 TEACHERS

Two web sites were developed with DOE EPSCoR assistance. Funding provided for web developers to add features related to the research clusters, thus encouraging teachers to include these energy-related topics in their curriculum. The Earth Systems Science Internet Project, ESSIP, web site (**http://smtc.uwyo.edu/essip**) includes activities for students and teachers to investigate the earth as a system and explore connections between the geosphere, biosphere, hydrosphere and the atmosphere. PI Sadrul Ula worked with ESSIP, incorporating materials on the efficient use of electrical energy and an introduction to solar energy. The second site (**http://smtc.uwyo.edu/coal**) presents information about Wyoming Coal for ages 5 to 50. Visitors learn about the process that makes coal, how it is mined and how coal powers the world and helps create everyday products. PI Pradeep Agarwal provided expertise to the developers on coal utilization. The web site includes a virtual tour of a coal mine and resources for teachers to use in the classroom to expose students to coal and its relevance to Wyoming. These web sites have been very helpful for teachers in Wyoming and other locations, increasing the coverage of important energy topics in public schools.

Forty-nine master students in science education were awarded scholarships through DOE EPSCoR funding. Eighteen of these students have graduated, 13 have completed the coursework for the degree and are working on their Plan B project, and 18 will complete their 3-summer course sequence next year. Most of the graduate students for this program are from Wyoming: Buffalo, Burlington, Cheyenne, Casper, Chugwater, Dayton, Douglas, Ethete, Gillette, Hulett, Laramie, Lovell, Midwest, Rawlins, Rock Springs, Sheridan, Thermopolis, and Wheatland. Students from other states include: Colorado (2), Hawaii (1), Montana (1), Nevada (1), and Washington (1).

MSNS Description

The MS in Natural Science is a 3-summer sequence which teachers can enter in any summer and join the rotation from that point. The courses are taught through collaboration with the Colleges of Agriculture, A & S, Education, and Engineering. The program is designed primarily for elementary, middle school and general science teachers who are interested in deepening their understanding of science and the teaching of science. Courses are designed around the unifying concepts and processes in science and the view of science as inquiry. Specific content themes, instructional strategies and topics rotate on a three summer sequence among interdisciplinary problems drawn from the more traditional disciplines of physical science, earth science and life science. The three summer sequence fulfills 24 of 30 credit hours required toward completion of the MSNS degree.

Physical Science (Summer 1)

3hr Physical Science in Global Context (Physics and Astronomy, A & S)
2hr Mathematics and Statistics in Science Teaching (Statisitics, A & S)
2hr Strategies in Integrated Science Teaching (Education)
1hr Energy Policies & Impacts (Electrical Engineering; Engineering)

Earth Science (Summer 2)

3hr Earth Science in Global Context (Geology, A & S; Atmospheric Sciences, Engineering)
2hr Astronomy for Teachers (Physics and Astronomy, A & S)
2hr Natural Science Assessment in Context (Education)
1hr Instructional Technology (Education)

Life Science (Summer 3)

3hr Life Science in Global Context (Zoology, A & S; Botany, A & S; Molecular Biology, Agriculture)
1hr Insects for Teachers (Natural Resources, Agriculture)
1hr Global Population & Environment (Sociology, A & S)
1hr Cell Bio/ Videomicroscopy (Zoology, A & S)
2hr Science, Technology & Society (varied topics, varied instructors)

Example Quotes from MSNS Students

"I think one of the greatest assets of the program is that the content we learned is applicable to the classroom and beneficial to students." Greg Bell – jr. high teacher

"The SMTC offers a challenging science curriculum that helped me understand the 'story' that science tells about the world around us. The interconnectedness of the ideas enables me to then

pass 'the story' along to my students. The students and staff are great people to work with." Mary Lovelace -- elementary teacher

"This program is exactly what I was looking for in a Masters program. It addresses concepts and material that are useable in any science classroom at any level. Quality instruction and the format were perfect for my needs. I will and have enthusiastically recommended this program to all of my fellow science educators. Thanks for the wonderful professional opportunity!" Ron Powell – high school teacher

"The MSNS program has been one of the most valuable learning experiences of my life. Thank you for giving me this wonderful opportunity to be part of a great program." -- Kathy Watson – high school teacher

Graduates' Plan B Project Titles

Britton, L.	The Results of Multiple Activities using the Conceptual Change Model to Eliminate Students' Science Misconceptions about Air
Catchpole, S.	Technology Integration to Enhance Learning in Earth Science
Crips, P.	Do Student Created Science Experiments Make Science More Meaningful and Enjoyable?
Kimble, P.	Working with Tutors to Develop Formative Assessment Tools for Mathematics Drop-in Problems in an Interdisciplinary, Problem-based Setting: A Pilot
Watson, K.	The Effects of Project WYO.BEST Training on Teachers and Students
Catchpole, R.	Modified Just-in-Time Teaching Design
Daniels, D.	The Comparison of Expository Approach and a Guided Discovery Approach for Teaching Multiplication of Fractions in a Middle School Classroom
Mcilvain, M.	Effective Practices in Outdoor Science Education
Ommen, L.	Examining the Effectiveness of Constructivist-based Teaching Strategies with Special Education Students
Brolyer, C.	Investigating HyperStudio as a Tool to Design an Electronic Portfolio Entry
Gaines, M.	Including Field Activities in Middle School Science
Hurst, T.	A Handbook for School Required Immunization
Johnson, A.	Pronghorn Antelope Fawn Survival and Habitat Use in Northeast Wyoming: A Teacher/Student/Scientist Cooperative Study
Juday, J.	Identification of Plant Life on the Munroe Trail and Integration into the Elementary Curriculum
Dillon, N.	The Use of Field Trips to Teach Life Science in the Primary Classroom
Knapp, G.	Relativity for the Secondary Classroom
Miyamoto, K.	Students' Spatial Abilities and the Use of Models in Teaching Phases of the Moon
Peaco, J.	Promoting Science Literacy in the Life Sciences

Awards/Recognition of MSNS Students

- Consultant for the National Weather Service (NWS) and Educational Consultant for U.S. Dept of Commerce's Space Environment Labs in Boulder, CO -- Paul Crips
- Wyoming Science Teachers Association President 2000-01 – Patti Kimble

- National Presidential Award for Excellence in the Teaching of Science and Mathematics - Patti Kimble, Kathy Watson
- Disney American Teacher Award - Paul Crips
- Milken National Educator Award - Paul Crips
- US West Teacher of the Year - Paul Crips
- Distinguished Educator 1997 by WY School Board and WY DOE - Paul Crips
- Governor's Youth Initiative for Wildlife and Natural Resources Conservation - Cheryl Williams
- MetLife Fellow - Donna Daniels

Grants

- Toyota Tapestry Grant - Larry Hodgson (2000)
- US West Connecting Teachers with Technology top grant recipient - Paul Crips
- Space Telescope Science Institute - Paul Crips
- Christa McAuliffe Fellowship Teacher for Wyoming - Paul Crips

Publications

- January 2000 issue of Science and Children (v. 37, n. 4, pgs. 18-21) "Sowing the Seeds of the Standards" - Nancy Dillon
- Past Editor for the Wyoming Science Teacher's Association newsletter - Betty Yedinak

Course/Workshop Facilitation

- GIS/Remote Sensing - Ron Powell
- GLOBE - Greg Bell, Sharon Catchpole
- CRM - Lori Britton, Brant Jungct
- Field Science Activity Facilitator at Casper College - Carolyn Jacobs
- BOCES technology trainer with SCSD #1 - Greg Lundvall

RESEARCH APPRENTICE PROGRAM FOR HIGH SCHOOL STUDENTS

Each summer, approximately 12 high school students were selected for a six-week internship with cluster faculty to conduct research related to their projects. The program was advertised nationally and drew students from Wyoming, as well as New Jersey, Maryland, Texas, Colorado, xxx. The students lived in university housing, were introduced to teaming, and participated in seminars on research related topics such as scientific writing, ethics, and participation in science fairs. University personal met with the students to discuss admissions procedures, scholarships, honors programs, and study abroad opportunities.

The students were integral members of the cluster research teams. They met periodically with the team, discussing their research progress. Each student prepared a written report of their summer activities and presented their research results at a Symposium at the end of the internship. The students also participated in Site Visits, conducted by USDOE personnel.

Section 3
FOSSIL FUEL RESEARCH CLUSTER

Cluster PI: name, address, phone, fax, email
Pradeep K. Agarwal
University of Wyoming
Dept. of Chemical & Petroleum Eng.
P.O. Box 3295
Laramie, WY 82071-3295

Phone: 307-766-4259
Fax: 307-766-6777
E-mail: pagarwal@uwyo.edu

Other Personnel

Undergraduates
28
Graduate Students
14
Female/Minority
5

Abstract

- The first project – upgrading of wet coal – is based on the utilization of CO_2 as (a) a coolant; (b) fluidization medium to promote outstanding heat and mass transfer, and most importantly, (c) as an inert compound that occupies lattice sites in the coal and effectively blocks re-adsorption of moisture. A multi-stage fluidized bed reactor system is being developed for implementation of the process concept.
- In the second project, the role of oxygen (and other oxidants) in the curing step in enhancing the strength of form-coke briquettes is being investigated.
- In the third project, new $DeNO_x$ catalysts and scrubbers based on a novel metallophthalocyanine encapsulated in zeolites are being developed and tested. For example, Co(PC) is readily constructed in the large pores of zeolite A by treating Co exchanged zeolite A with phthalonitrile. These thermally robust dispersed complexes rapidly and reversibly absorb NO in sub ppm gas streams and are proposed as final stage $DeNO_x$ treatments of flue gases.
- The Roddick research component of this cluster has been developing new homogeneous and heterogeneous electrophilic transition metal complexes utilizing perfluorinated ligand arrays.

Cluster Accomplishments

- Consideration of $DeNO_x$ scrubbing strategies in flue gases led Dr Bohle to propose that the unusual termolecular rate law for the oxygenation of NO might have a biological role as well. This led to the establishment and funding (NIH) of a Center of Biomedical Research Excellence in 2000. The intellectual wellspring is from this DOE grant, and the center is funded for 5 years at $6.9 million, the largest grant ever awarded to the University of Wyoming.

- Dr Roddick developed platinum hydrogenation catalysts which function under superacidic conditions. Possible applications include aromatic hydrogenation and hydrocarbon reforming

- Dr Agarwal developed a process for the manufacture of form-coke briquettes. This is under consideration for deployment in the industry.

- The coal-drying rig is now in operation. Dr Dellenback is pursuing more detailed testing of the product, and further development of the apparatus to maximize energy efficiency.

Special Awards And Honors

Identify the award: Henry and Camille Dreyfus Teacher-Scholar Award (1996)
Recipient name and email: Scott Bohle, bohle@uwyo.edu
Issued by: (journal, organization, etc.) Dreyfus Foundation
Description of award (2-3 sentences):
This annual award is given to 15 promising young chemists nation-wide. This is the first time this award has been given to a University of Wyoming Chemist.

Provisional Patents

- Dust suppression in coal transport
- System for Recovery of Sulfur and Hydrogen from Sour Gas
- Apparatus and Method for Production of Methanethiol
- Reforming of methane
- Novel deNO_x device
- Stranded Wind Energy Extraction Process – SWEEP

Research Grants: USA

Research Topic	**Grant (US$)**
FMC Form Coke Process – Binder Preparation in FMC Coking Plant (FMC, Kemmerer, 1995-2002)	$105,000
Utilization of Western Coal (as Cluster Director and Principal Investigator, 1995-99) Projects: • *NO_x and trace metal emissions from FBC* • *Thermal imaging analysis of fluidized beds* • *Coal grinding* • *Spontaneous combustion of coal stock piles*	
National Science Foundation	$897,438
University and State of Wyoming	$1,009,587
Industrial support (in-kind & cash contributions from	

Electricity Trust of South Australia, MTCI, ThermoChem, FMC, ARCO, Kerr-McGee, Encoal, Wyoming Analytical Lab) $800,000

Strength of Form Coke Briquettes (FMC, Kemmerer 1997-98) $7,000

Fossil Energy (as Cluster Director, 1995-2002)
Projects:
Upgrading of Coal (as Principal Investigator, 1995-2002);
Department of Energy $274,439
University and State of Wyoming $123,047

Critical Role of Air in the Manufacture of Formed Coke Briquettes from Low-Rank Western Coals (as Principal Investigator, 1997-2002)
Department of Energy $199,538
University and State of Wyoming $69,900

The Role of Moisture and Carbon Monoxide in the Destruction of Nitrous Oxide in a Pulsed Corona Plasma Reactor (as Principal Investigator with Dr. Temi Linjewile, 1998-2000)
National Science Foundation $220,000
University of Wyoming $40,000

Sweetening of Sour Gas (KCS Mountain Resources, 1999) $25,000

Low-Temperature Oxidation and Tar Yield (FMC, Kemmerer; P&M Coal Mining Company, 1999) $7,000

Laser-induced Fluorescence Diagnostic Studies of Reactive Species in a Pulsed Corona Reactor (as Principal Investigator with Dr. Temi Linjewile, 2000-present)
National Science Foundation $412,963
University of Wyoming $45,000

Investigations of a Pulsed Corona Reactor System towards Remedial of Diesel Engine Exhaust (2001-present)
Department of Defense $210,000
University of Wyoming $26,000

Pulsed Corona Discharge Reactor Systems for Recovery of Hydrogen and Sulfur from Streams Containing Hydrogen Sulfide
Industry (applied for) to UW $840,730
Related R&D expenses incurred by industrial partner $1,000,000

Spontaneous Combustion (Arch Coal, 2001-present) $20,000

Publications
Refereed Journal Papers

1. Linjewile, T.M. and Agarwal, P.K., 1995, *The product CO/CO_2 ratio from the combustion of petroleum coke spheres in fluidized bed combustion*, Fuel, 74, 5-11.

2. Linjewile, T.M. and Agarwal, P.K., 1995, *The influence of product CO/CO_2 ratio on the ignition and temperature history of petroleum coke particles in incipiently gas-fluidized beds*, Fuel, 74, 12-16.

3. Linjewile, T.M., Gururajan, V.S. and Agarwal, P.K., 1995, *CO/CO_2 product ratio from the combustion of petroleum coke spheres in an incipiently fluidized bed*, Chem Engng Sci, 50, 1881-1888.

4. Krishnaswamy, S., Bhat, S., Gunn, R.D. and Agarwal, P.K., 1996, *Low-temperature oxidation of coal 1. A single-particle reaction-diffusion model*, Fuel, 75, 333-343.

5. Krishnaswamy, S., Gunn, R.D. and Agarwal, P.K., 1996, *Low-temperature oxidation of coal 2. An experimental and modeling investigation using a fixed-bed isothermal reactor*, Fuel, 75, 344-352.

6. Krishnaswamy, S., Agarwal, P.K. and Gunn, R.D., 1996, *Low-temperature oxidation of coal 3. Modeling spontaneous combustion in coal stockpiles*, Fuel, 75 (12), 353-362.

7. Sane, S., Haynes, Jr., H.W., and Agarwal, P.K., 1996, *Gas-mixing in bubbling fluidized beds,* Chem Eng Sci, 51 (7), 1133-1147.

8. Sriramulu, S., Sane, S., Agarwal, P.K., and Matthews, T.P., 1996, *Mathematical modeling of fluidized bed combustion 1. Combustion of carbon in bubbling beds,* Fuel, 75 (12), 1351-1362.

9. Bhat, S. and Agarwal, P.K., 1996, *The effect of moisture condensation on the spontaneous combustibility of coal,* Fuel, 75 (13) 1523-1532.

10. Biggs, M.J. and Agarwal, P.K., 1997, *CO/CO_2 product ratio for a porous char particle within an incipiently fluidized bed: a numerical study,* Chem Eng Sci, 52 (6) 941-952.

11. Hull, A.S., Lanthier, J.L., and Agarwal, P.K., 1997, *The role of the diffusion of oxygen in the ignition of a coal stockpile in confined storage,* Fuel, 76 (10) 975-983.

12. Hull, A.S., Lanthier, J.L., Chen, Z., and Agarwal, P.K., 1997, *The role of the diffusion of oxygen and radiation on the spontaneous combustibility of a coal pile in confined storage,* Combustion and Flame, 110 (4), 479-493.

13. Lim, K.S., Khakhar, D.V. Chen, Z. and Agarwal, P.K., 1997, *Raining of particles from an emulsion-gas interface in a fluidized bed,* Chemical Engineering Communications, 161, 205-229.

14. Srinivasan, R., Sriramulu, S., Kulasekaran, S. and Agarwal, P.K., 1998, *Mathematical modeling of fluidized bed combustion 2. Combustion of gases,* Fuel, 77 (9/10), 1033-1049.

15. Hull, A.S., and Agarwal, P.K., 1998, *Estimation of kinetic rate parameters for coal combustion from measurements of the ignition temperature,* Fuel, 77 (9/10), 1051-1058.

16. Kulasekaran, S., Linjewile, T.M., Agarwal, P.K. & Biggs, M.J., 1998, *Combustion of a porous char particle in an incipiently fluidized bed,* Fuel, 77 (14) 1549-1560.

17. Kulasekaran, S., Linjewile, T.M. and Agarwal, P.K., 1999, *Mathematical modeling of fluidized bed combustion 3. Simultaneous combustion of char and combustible gases,* Fuel, 78, 403-417.

18. Hull, A.S., Chen, Z., Fritz, J.W. and Agarwal, P.K., 1999, *Influence of horizontal tube banks on the behavior of bubbling fluidized beds 1. Bubble hydrodynamics,* Powder Technology, 103, 230-242.

19. Chen, Z., Yang, T., Wu, W. and Agarwal, P.K., 1999, *Continuous drying and dehydration of sodium carbonate monohydrate in a fluidized bed,* Powder Technology, 103, 274-285.

20. Hull, A.S., Chen, Z. and Agarwal, P.K., 2000 *Influence of horizontal tube banks on the behavior of bubbling fluidized beds 2. Mixing of solids,* Powder Technology, 111(3), 192-199.

21. Hartman, G., Wu, W., Chen, Z. and Agarwal, P.K., *Heat transfer behavior of an isolated bubble in an incipiently fluidized bed,* submitted Can J Chem Engng, 2000.

22. Chen, Z., Wu, W. and Agarwal, P.K., 2000, *Steam drying of coal 1. Modeling the behavior of a single particle,* Fuel, 79(8), 961-974.

23. Chen, Z., Agarwal, P.K. and Agnew, J.B., 2001, *Steam drying of coal 2. Modeling the operation of a fluidized-bed drying unit,* Fuel, 80(2), 209-223.

24. Chen, Z., Lin, M., Kelly, B., Ignowski, J., Linjewile, T.M. and Agarwal, P.K., 2001, *Mathematical modeling of fluidized bed combustion 4. N_2O and NO_x emissions from the combustion of char,* Fuel, 80, 1259-1272.

25. Paul, S.A., Hull, A.S., Plancher, H. and Agarwal, P.K., 2000, *Use of asphalts for formcoke briquettes,* Fuel Processing Technology, in press.

26. Wu, W., Gerhart, A.L., Chen, Z., Dellenback, P.A., and Agarwal, P.K., 2001, *A device for measuring solids flow rate in circulating fluidized bed,* Powder Technology, 120, 151-158.

27. Plancher, H., Agarwal, P. K. and Severns, R., 2001, *Improving form coke briquette strength,* Fuel Processing Technology, in press.

28. Hu, X., Nicholas, J., Zhang, J., Linjewile, T. M., de Filippis, P. and Agarwal, P.K., 2001, *The destruction of N_2O in a pulsed corona discharge reactor*, Fuel, 81, 1259-1268.

29. Agarwal, P.K., Biggs, M.J., Mark, Hu, X., Linjewile, T.M., Nicholas, J. and Zhang, J., *A novel NO_x destruction device based on pulsed corona discharge*, submitted Fuel, 2001.

30. Wu, W. and Agarwal, P.K., *Heat transfer to an isolated bubble rising in a high-temperature incipiently fluidized bed*, submitted Can J Chem Engng, 2001.

31. Hu, X., Zhang, J., Muknahallipatna, S., Hamann, J., Biggs, M. J., Agarwal, P.K., *Transformations and Destruction of Nitrogen Oxides – NO, NO_2 and N_2O – in a Pulsed Corona Discharge Reactor*, submitted Fuel, 2002.

Publications And Funding
Dean Roddick

1. Shannon White, Eric W. Kalberer, Byron L. Bennett, and Dean M. Roddick, "Synthesis, Structure, and Characterization of a Bridging Ethylidene (Perfluoroalkyl)phosphine Platinum Complex", *Organometallics*, 2001; *20*, 5731-5737.
2. B. L. Bennett, J. M. Hoerter, J. F. Houlis, and D. M. Roddick, "Metal-Alkyl Bond Protonolysis Studies of (dfepe)Pt(Me)X Complexes in Acidic Media", *Organometallics* 2000, *19*, 615-621.
3. J. M. Hoerter, R.C. Schnabel, and D. M. Roddick, "The Fate of a Bimetallic Ethylene Dimerization Catalyst: Synthesis and Structure of $(dfepe)_2Ir_2(H)(\square\text{-}H)(\square\text{-}\square^1,\square^3\text{-}C_4H_6)$", *Organometallics* 1999, *18*, 5717-5720.
4. S. White, B. L. Bennett, and D. M. Roddick, "Organometallics in Acidic Media: Catalytic Dimerization of Ethylene by (Perfluoroalkyl)phosphine Complexes of Platinum and Palladium in Trifluoroacetic Acid", *Organometallics* 1999, *18*, 2536-2542.
5. James F. Houlis and Dean M. Roddick, "Organometallics in Superacidic Media: Generation of Highly Electrophilic (Fluoroalkyl)phosphine Pt(II) Cationic Complexes", *J. Am. Chem. Soc.* 1998, *120*, 11020-11021.
6. Allyn C. Ontko, James F. Houlis, R. Chris Schnabel, Dean M. Roddick, Tina P. Fong, Alan J. Lough, and Robert H. Morris, "Protonation and H_2 Heterolysis Reactions of Electrophilic $(\square^5\text{-}C_5R_5)Ru(dfepe)(X)$ (R = H, Me; X = H, OTf) Complexes", *Organometallics*, 1998, *17*, 5467-5476.
7. R. Gregory Peters, Shannon White, and Dean M. Roddick, "Activation of Aromatic C-H Bonds by (dmpe)Pt(Me)X (X = O_2CCF_3, OTf) Systems", *Organometallics* 1998, *17*, 4493-4499.

Funding Stemming From Doe-EPSCoR Support:

2001 – 2004, NATIONAL SCIENCE FOUNDATION: "Organometallics in Superacidic Media" $380,000.

1997-2000, NATIONAL SCIENCE FOUNDATION: "Organometallic Transformations in Acid and Superacid Media", $293,500.

Section 4
ELECTRICAL ENERGY EFFICIENCY RESEARCH CLUSTER

Cluster PI: name, address, phone, fax, email
Sadrul Ula, Electrical & Computer Engineering, College of Engineering, P.O. Box 3295, Laramie, WY 82071-3295, phone (307) 766-6268, fax (307) 766-2248, email: ulas@uwyo.edu

Abstract:
The focus of this cluster is to address three topics in the area of efficient electrical energy utilization. The first two projects examine technologies associated with efficient electric motors: advanced techniques for optimal energy control of electric motors, and evaluation of electromagnetic radiation effects of energy efficient motor control methods. The final project examines issues involving the evaluation of the power system interface of photovoltaic technologies. There are three common threads between these topics: (1) each is concerned with efficiency improvement, (2) each contains elements leading to a better understanding of the adverse effects resulting from some efficiency improvement methodologies, and (3) each is carefully selected so that the expertise and facilities currently available are maximally leveraged during the EPSCoR funding period to produce highly competitive and self-sustaining research programs.

Other Personnel

Undergraduates
4
Graduate Students
14
Female/Minority
6

Cluster Accomplishments
1) An empirical study of EMI in the range of frequency from 20Hz to 2GHz of a power inverter has been completed. All sources of EMI from the variable speed power inverter have been identified, levels of the electromagnetic field measured, and appropriate shielding and grounding have been proposed. Results of this study are of great importance for designers of electronic equipment which needs to be used in the proximity of variable speed power drives, for example medical equipment in hospitals with modern air conditioning systems or cellular phones.

2) We have acquired a new 10Gsample/s digital storage oscilloscope through a grant from Tektronix. This new equipment allows us to make measurements in the time domain which are useful in developing communications system models for the RF noise radiating from Adjustable Speed Drives (ASDs).

Special Awards And Honors

Identify the award: Graduate Teaching & Research Award
Recipient name and email: Dr. John E. McInroy, mcinroy@uwyo.edu
Issued by: (journal, organization, etc.) College of Engineering
Description of award (2-3 sentences): The Graduate Teaching & Research award is granted each year to just one faculty member in the College of Engineering to recognize excellence in research including graduate education.

PROJECT 1 DESCRIPTION: EFFICIENT AND PRECISE FEEDBACK CONTROL OF LARGE MOTORS

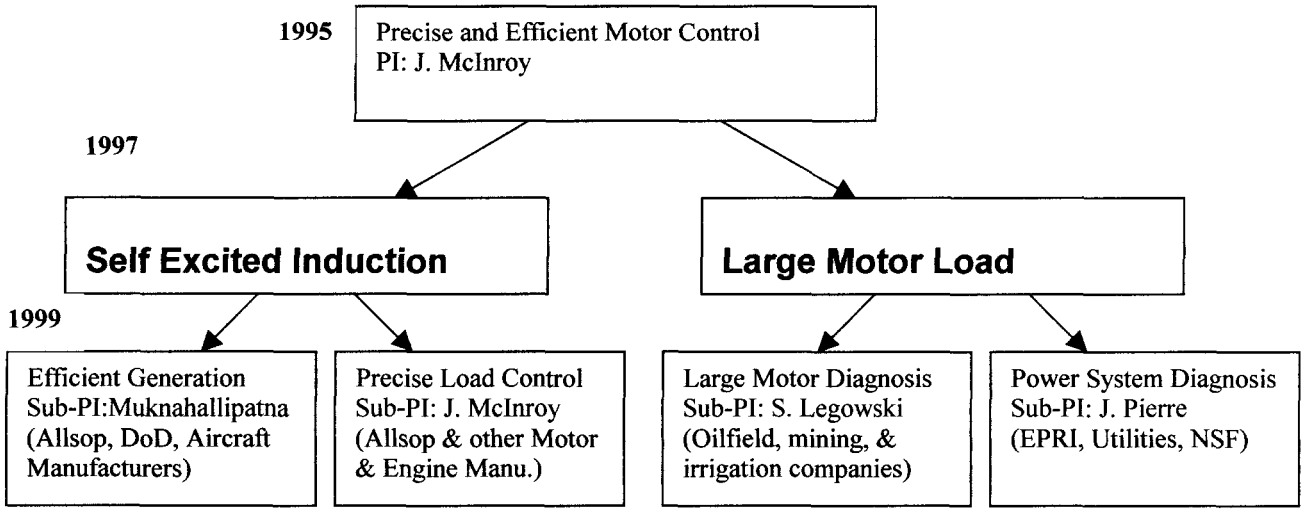
Principal Investigator: John McInroy.
Co-Principal Investigators: Stanislaw Legowski, Suresh Muknahallipatna, John Pierre,and Sadrul Ula. All University of Wyoming.

Executive Summary—Precise and Efficient Motor Control

The DOE/EPSCoR project "Precise and Efficient Motor Control" has made contributions to a diverse array of problems arising in electromechanical systems. Until recently, almost all motors could only be operated at a single speed. Due to recent advances in power electronics and computers, it is now possible to easily and inexpensively control large motors and generators so they perform practically any desired trajectory. This opens a vast number of new applications and methods for using motors and generators. To help advance this technology, the University of Wyoming (UW) has established, with significant help from DOE EPSCoR, a laboratory facility that is capable of controlling motors and generators in a very general fashion, so that many concepts can be quickly tested. Both rotary and *linear* motors and generators have been studied and implemented. This unique, custom made equipment has been used to maximize UW's potential for future research by tackling several related, but distinct research areas. One of these areas involves loading motors for testing purposes. In order to study the dynamical properties, it is important to provide, under laboratory conditions, exactly the same kinds of loads that the motors/generators would experience for a wide variety of applications. New methods for emulating large, time-varying power loads at low cost have been developed. Another research area involves using the available motor control computer and electronics to monitor the entire drivepower system. Electrical input power has been demonstrated to be an effective signal for diagnosing degradations in motor drivepower systems. The methods have been applied to oilfield pumpjacks. A third research area monitors the electrical power grid to help ensure its operation. New methods for estimating power system electromechanical modes from ambient data have been developed, including autoregressive, autoregressive moving average, and adaptive techniques. Finally, new methods for controlling generators so they can respond to changing loads have been developed. Self-excited induction generators have been demonstrated to be a practical method for implementing medium sized (approx. 7.5kW) generators. Advantages include lighter weight and lower cost.

Final Report—Precise And Efficient Control Of Large Motors

During the first two years of DOE/EPSCoR support, our project focused on a single topic, "Precise and Efficient Control of Large Motors." By leveraging the gains made during that initial support, the project responded to technological advances and our new abilities by having two new "child" projects during the first renewal period. Because our infrastructure and expertise again increased, four highly related "grandchild" projects (or sub-projects) were studied during the final renewal. This was only feasible because these sub-projects rely heavily on the infrastructure and expertise resulting from prior DOE EPSCoR funding, so depth can be obtained in several projects with little additional resources. This progression highlights the progress and growth made, and how the research infrastructure has been enhanced through the DOE/EPSCoR program--we are now capable of meaningful contributions in a number of fields related to the original project. The figure below illustrates the progression, sub-projects, sub-Principal Investigators, and interested entities.



The original, 1995 DOE/EPSCoR supported project, "Efficient and Precise Control of Large Induction Motors," achieved goals along both theoretical and experimental fronts. On the experimental front, a highly flexible, precision motor controller has been designed, and constructed. The unit consists of several key components. To actually power the motors, a 7.5 HP inverter has been custom designed. The inverter is specifically designed to that it can easily be adapted to a variety of control schemes. In this manner, many control ideas can be tested without changing the hardware. To accomplish this task, the inverter is operated by a PC based computer. Custom software has been developed to drive the inverter. Again, in the spirit of keeping things highly flexible, the software has been developed in the "C" language so that changes can easily be made. To facilitate development of very precise control algorithms, two features have been built into this system. First, the motor currents are sampled during each control cycle. This allows the motor current to be directly controlled, and current control has been accomplished. Second, precise position sensors which measure the motor's position to within 1/40,000th of a revolution are installed. A much larger, 60 HP custom motor control unit has also been designed and built. Its operation has been compared to a commercial unit produced by Asea Boveri Brown (ABB).

On the theoretical front, advances have been made which improve both the efficiency and the precision with which induction motors can be operated. When an induction motor is subjected to a cyclic loading profile, its operation can become inefficient because the mix of currents (i_d and i_q currents [1]) which minimizes power loss constantly changes. Control algorithms which find the exact mix of currents to minimize the power loss have been found. The figure plots the results. By changing i_d to match the load, the energy required to perform identical tasks is reduced by 25 % to 50 %. These results have been developed using high fidelity computer models of the induction motors

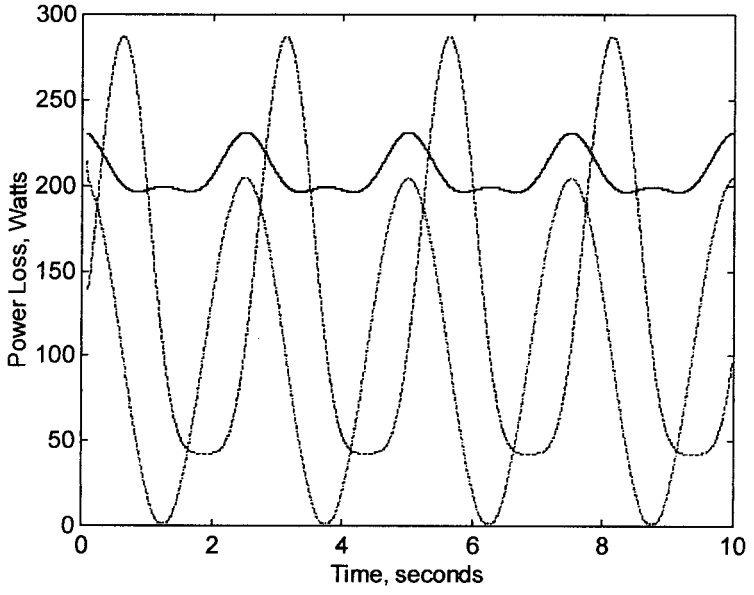


Figure 1: Resistive power lost when using the same motor but different control algorithms to perform a task. By varying i_d, the least energy is lost (dash-dot line). The energy lost increases by 25 % if i_d is kept constant , but is selected to minimize loss (dotted line). The losses again increase (by 50 %) if the motor is operated with constant voltage from the supply grid (solid line).

After the first two years, the project divided into two sub-projects: 1) Detection and Correction of Motor Drivepower System Degradations, which was allocated approximately 2/3 of the budget, and 2) Development of a Self-Excited Induction Generator for Remote Applications, (1/3 of budget).

The first sub-project is aimed at improving the operational efficiency of motor driven systems, termed drivepower systems. As time passes, all drivepower systems degrade: bearings wear, lubrication erodes, insulation breaks down, pipes clog. An induction motor supplied by the grid, which is the most common motor configuration, masks the symptoms. As a consequence, catastrophic failure often occurs. This can close assembly lines, waste energy, cause excessive wear, etc. Consequently, the primary goal is to detect and correct for degradations so that general drivepower systems are optimized by using the motor as a sensor to monitor motor driven systems at low cost. Oak Ridge National Laboratory (ORNL) has actively worked in this area for

the last ten years with a great deal of success. In fact, one of the ORNL project originators (Howard Haynes) received the Nova award from Lockheed Martin for his contributions. The ORNL group has applied their technique to a vast array of applications: motor operated valves, rotational imbalance, compressor surging and cavitation, motor insulation breakdown, motor broken rotor bars, air conditioners, pumps, friction generated wear, automotive alternators, ammunition conveyors, and aircraft generators. However, ORNL has not applied their technique to the heavy industries present in Wyoming: oilfield pumpjacks, coal mining, trona mining, rock quarries, and irrigation pumping. Consequently, considerable potential exists for modifying the ORNL (and other) load diagnosis techniques and transferring them to applications pertinent to Wyoming and the surrounding area. Towards this end, degradations in oilfield pumpjacks have been studied under DOE EPSCoR sponsorship.

Common degradations of oilfield pumpjacks have been identified (valve wear, rod breakage, drying well). Based on these degradations, an analytical model of pumpjack

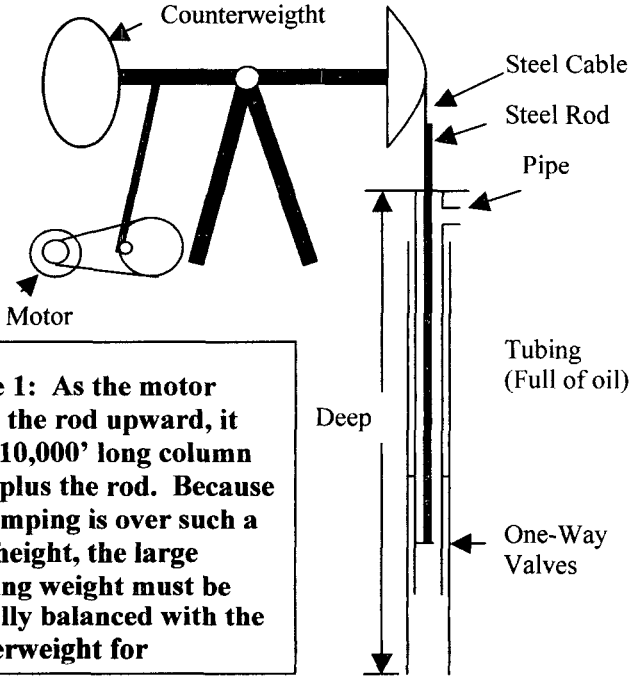


Figure 1: As the motor moves the rod upward, it lifts a 10,000' long column of oil plus the rod. Because the pumping is over such a great height, the large resulting weight must be carefully balanced with the counterweight for

dynamics has been developed which includes the degradations, along with the dynamic effects due to the electrical, mechanical, and fluid system interactions. Because shallow and deep well dynamics differ significantly, separate models are available to treat each case. These models have been used to create computer simulations of valve failures, so that a greater understanding of their effect, reflected back to the motor, can be achieved. Both the traveling valve and the standing valve are located at the bottom of the well. Consequently, they operate in a harsh environment, where sand is often mixed with the fluid, so they degrade rapidly, resulting in extremely poor pumping efficiency and wastage of energy. Moreover, their replacement is very labor intensive—it requires removal of the entire 10,000' rod. For these reasons, timely detection and correction of these valve degradations is especially important. Figure 2 illustrates some of the results when the pumpjack is operating under three conditions: normal operation, a broken traveling valve, and a broken standing valve. Either of the broken valves results in an obvious and easily detectable shift in the input power. Since electrical power is inexpensive to measure, simple methods of monitoring the power signal can

be used to detect these failures. These results have been published in the IEEE Transactions on Industry Applications [2].

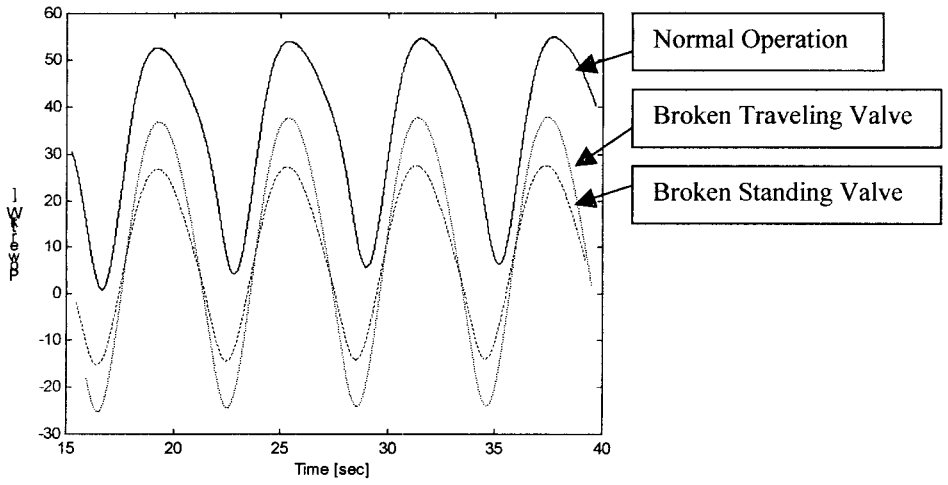


Figure 2: The pumpjack's electrical input power differs significantly when the valves are worn.

In addition to computer simulation, actual pumpjack loads have been measured in the field, and novel methods for re-creating those loads in highly instrumented and controlled laboratory conditions have been developed. Hardware simulation (or emulation) is important because:

1. Laboratory measurements are much more comprehensive than field measurements (torque, velocity, 3 phase power from the grid and inverter are available), so detailed analysis is possible, and
2. Several effects that are difficult to include in computer simulations are present (magnetic saturation, resistive heating, electrical noise, etc.).

Figure 3 illustrates the experimental system and the results obtained when physically emulating an actual, deep well pumpjack. Other than an immaterial shift in starting time, the load on the laboratory motor is nearly identical to the load measured on the motor in the field. Because of the large power flows and sudden changes, laboratory re-creation of this load required new technology. Consequently, new methods for emulating large, time-varying, rotary power loads at low cost were developed and published [2].

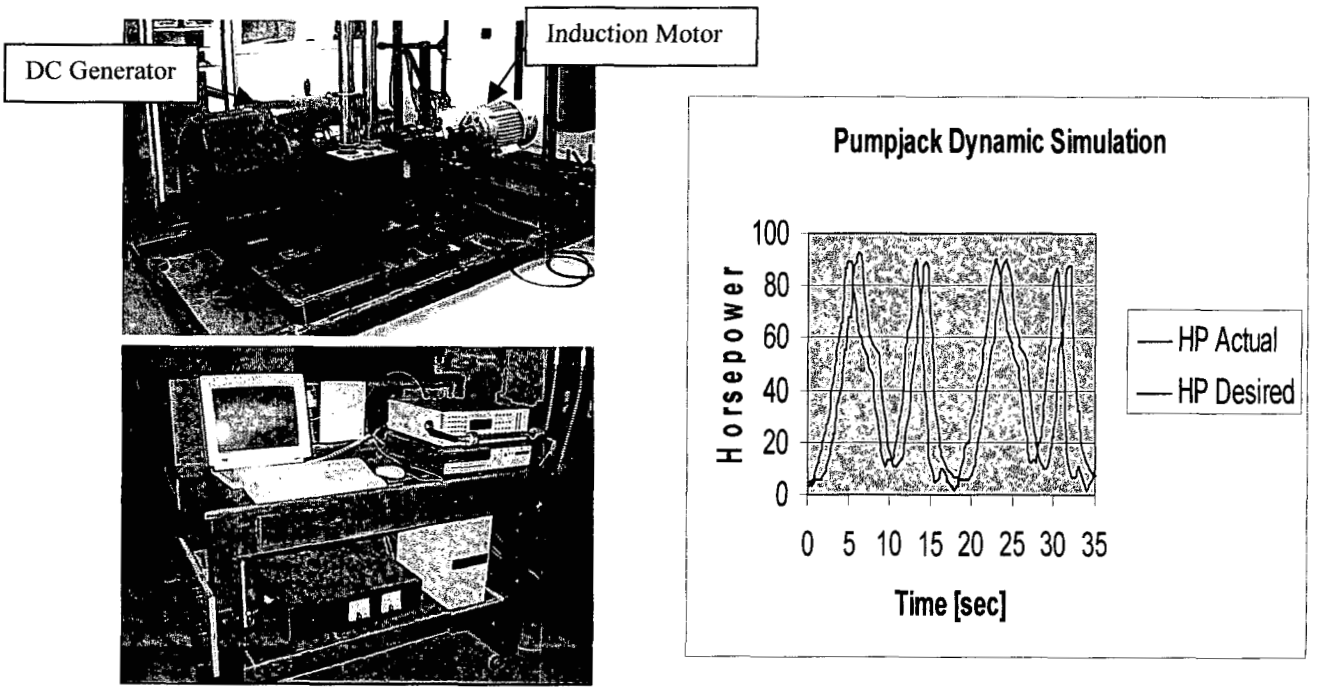


Figure 3: The photographs display the DC generator driven by an induction motor, along with the inverter, computer, and power instruments used to control the generator's field. The plot shows the experimentally obtained load profile when tracking a desired oilfield pumpjack power.

The DOE/EPSCoR supported project, "A Self Excited Induction Generator (SEIG) for Wind Turbines," has also achieved its goals. On the experimental front, two types of self-excited induction generators each capable of producing 7.5 kW of power have been designed, constructed, debugged, and are now operational. The first unit consists of a squirrel cage induction motor with capacitors which are switched manually to maintain the terminal voltage constant with varying load conditions (Figure 4).

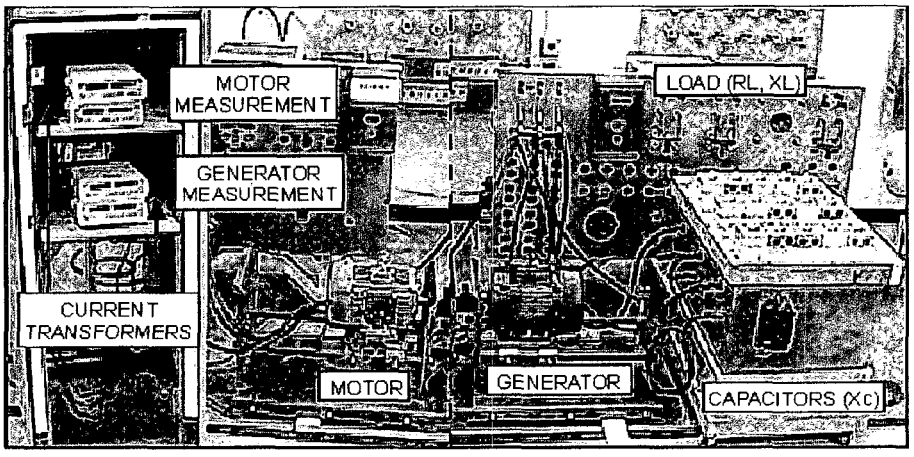


Figure 4 Rotary Squirrel Cage Self Excited Induction Generator Test Setup.

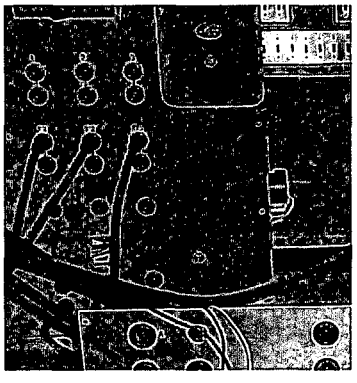
The second unit consists of a wound rotor induction motor and capacitors. In the second unit, a transformed stator voltage is injected into the rotor of the induction motor to maintain a constant output frequency. The scheme of injecting voltage into the rotor to maintain a constant output frequency is simple, effective, and unique.

On the theoretical front, advances have been made in predetermining the amount of capacitance required for varying load and speed conditions. There are a number of methods available to predetermine the amount of capacitance. A total of six different methods have been studied and compared. A Matlab based simulation program has been developed to predetermine the amount of capacitance using any of the six methods. The simulation program can also be used for comparison with experimental results.

For the second unit, using the Matlab based Simulink program, simulations were completed initially to determine the amount of power injection and the control scheme required. At this moment, we are in the process of developing an automated system.

The third phase of the DOE/EPSCoR project supported the development of self excited linear induction generators for use in Aircrafts and linear propulsion systems. Linear Induction Generators are more efficient with linear prime movers since there is a significant loss of energy when linear motion is converted into rotary motion.

Theoretical work with respect to the computation of capacitance required for excitation of a linear induction generator has been completed. Initial prototype development has been completed and tested using two "Polynoid Three Phase Linear motors" as shown in Figure 5.



In Figure 5, two linear motors (LM) are coupled together and the LM to the left is excited by a capacitance connected to the terminals to act as a self excited linear induction generator. The LM on the right is controlled by a linear motion controller which is capable of producing an oscillatory motion. The initial results have demonstrated that linear induction motors can be self excited to produce efficiently electrical energy from a linear source. Since, the Polynoid motors have low power ratings due to

their constructional features; we are now experimenting with linear sliding motors which have higher power ratings used in transportation systems. The initial prototype of this setup is shown in Figure 6.

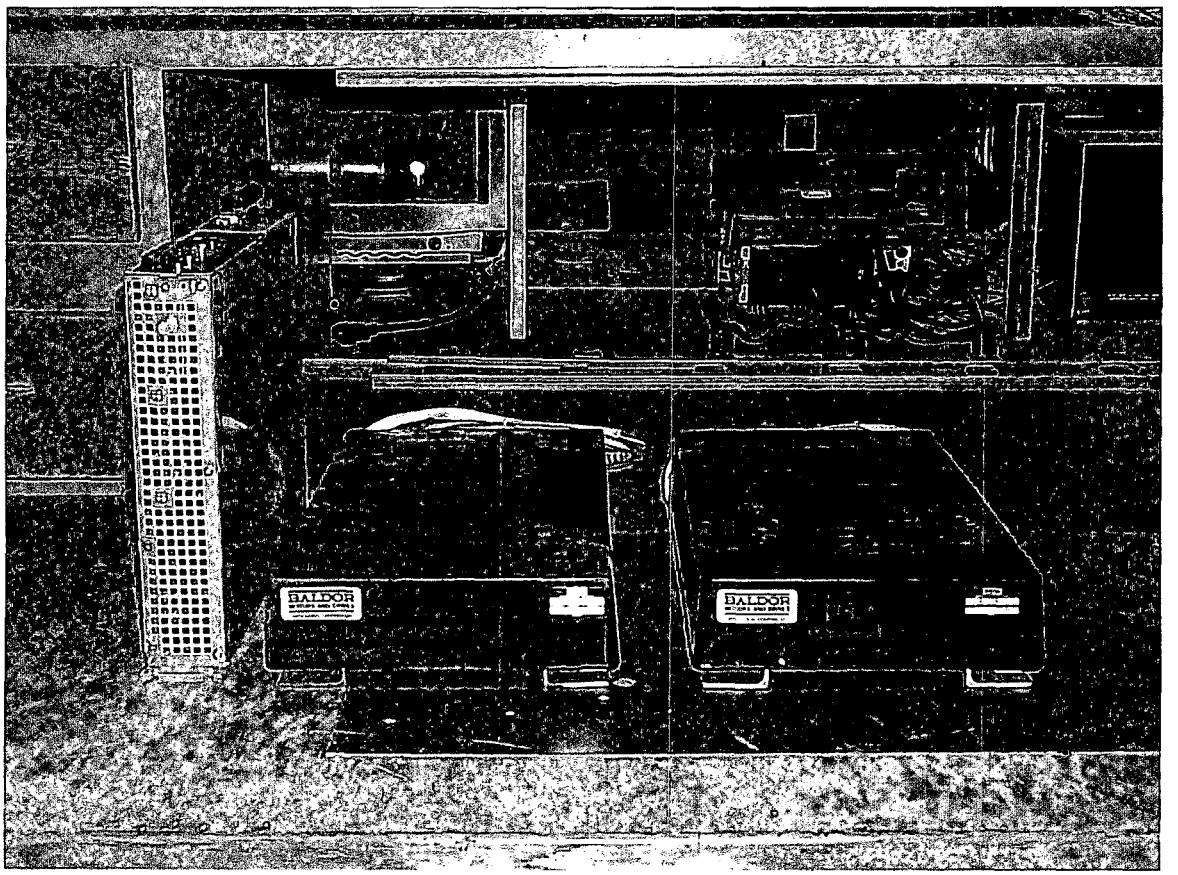


Figure 6 Linear Sliding Motors along with Controller

One Masters student completed the thesis in this area, while a second Masters student is working on developing Linear Self Excited Induction Generator.

The subproject titled Power System Diagnosis made a number of advances in the estimation of power system electromechanical modes from measured power system ambient data. This research was collaborative with Bonneville Power Administration (BPA) and Battelle Pacific Northwest National Laboratories (PNNL). Numerous trips were made to BPA and PNNL to facilitate the collaboration. BPA and PNNL provided actual power system data from the Western US grid and expertise in power systems. Numerous data sets were utilized including data from the August 10, 1996 power outage in the Western United States and Canada. Other data sets were used from points throughout the western grid.

The research focus was on estimating from ambient data the electromechanical modes of oscillation, which pose a potential stability problem. This concept of monitoring the stability of the system in real-time has received significant interest from the power system community because of the major blackout on August 10, 1996. The advancements made included the following. Estimation of the electromechanical mode frequency and damping ratios from

ambient data using AR (autoregressive) and ARMA (autoregressive moving average) modeling. Initial results in the use of adaptive filter techniques for estimating the modes. Preliminary results were also achieved on estimating confidence intervals on the mode frequencies and damping rations using bootstrap techniques. These approaches have been applied to both actual power system data and to simulation data. The simulations included a 19 machine test bed model and a 16^{th} order linear model based on measured data from the western grid.

The project has also resulted in a number of other proposals (3) and papers (7). One Ph.D. student completed his dissertation in this area, while a second Ph.D. student is nearing completion. A third Ph.D. student is starting his research on a related topic.

1] M. Bodson and J. Chiasson and R. Novotnak. 1994 (August). High--Performance Induction Motor Control Via _Input--Output Linearization. *Control Systems Magazine*, pages 25-33.

[2] J.E. McInroy and S.F. Legowski, "Using Power Measurements to Diagnose Degradations in Motor Drivepower Systems: A Case Study of Oilfield Pump Jacks," *IEEE Transactions on Industry Applications*, Vol. 37, No. 6, November/December 2001, pp. 1-8.

[3] J.E. McInroy, S.F. Legowski, C.M. Morris, S. Muknahallipatna, and V. Bershinsky, "Emulating Large, Time Varying Rotary Power Loads at Low Cost", *1999 IEEE International Conference on Control Applications*, pp. 796-801, Kohala Coast, HI, August 1999

[4] J.E. McInroy and S.F. Legowski, "Diagnosis of Motor Drivepower System Degradations with Electrical Input Power," The IEEE Symposium on Diagnostics in Electrical Machines and Power Electronics Devices, Spain, September, 1999.

Nuggets—Precise And Efficient Motor Control

- New methods for emulating large, time-varying power loads at low cost have been developed.
- Electrical input power has been demonstrated to be an effective signal for diagnosing degradations in motor drivepower systems. The methods have been applied to oilfield pumpjacks
- New methods for estimating power system electromechanical modes from ambient data have been developed, including autoregressive, autoregressive moving average, and adaptive techniques.
- Self-excited induction generators have been demonstrated to be a practical method for implementing medium sized (approx. 7.5kW) generators. Advantages include lighter weight and lower cost.

Students

Ph.D. Students – Richard Wies (now an assistant professor at the University of Alaska – Fairbanks), Mike Anderson, Jian Sun, Ning Zhou
M.S. Students—Dan Simon, Brian Miglia, Michael Morris, Sonny Chan, Miranda Hoff, Matthew Burkhart

Undergraduate Students—Ben Coble, High School Students—Nicholas Schabron, Sara Grochowski, Teresa Guardia, Joe Wakeman-Linn, Alex Perry

Publications

Wies, R.W., J.W. Pierre, and D.J. Trudnowski, "Use of ARMA Block Processing for Estimating Stationary Low-Frequency Electromechanical Modes of Power Systems," *IEEE Transactions on Power Systems*, (in press).

Anderson, M. and J.Pierre, "Reduced Order Autoregressive Moving Average (ARMA) Modeling from High Order Autoregressive (AR) Models," *Proceedings International Signal Processing Conference (ISPC),* March 2003.

Anderson, M.G., J.W. Pierre, R.W. Wies, "Confidence Interval Estimates for the Frequency and Damping Ratio of Electromechanical Modes using Ambient Data," *Proceedings of North American Power Symposium (NAPS),* October 2002.

Wies, R.W. and J.W. Pierre, "Use of Least-Mean Squares (LMS) Adaptive Filtering Technique for Estimating Low-Frequency Electromechanical Modes of Power Systems," *Proc. of the American Controls Conference*, May, 2002.

Wies, R.W., J.W. Pierre and D.J. Trudnowski, "Use of ARMA Block Processing for Estimating Stationary Low Frequency Electromechanical Modes," *Proceedings of North American Power Symposium (NAPS),* October 1998.

Chowdhury B.H., R.F. Kubichek, J.E. McInroy, S. Legowski, J.W. Pierre, and S. Ula, "A Multi-Disciplinary Research Initiative In Electric Energy Utilization," *Proceedings of North American Power Symposium (NAPS),* October 1998.

Wies, R.W. and J.W. Pierre, "Use of LMS Adaptive Filtering Technique for Tracking Simulated Low-Frequency Electromechanical Modes of Power Systems," *Proceedings of North American Power Symposium (NAPS)*, October 1997.

J.E. McInroy and S.F. Legowski, "Using Power Measurements to Diagnose Degradations in Motor Drivepower Systems: A Case Study of Oilfield Pump Jacks," *IEEE Transactions on Industry Applications*, Vol. 37, No. 6, November/December 2001, pp. 1-8.

J.E. McInroy, S.F. Legowski, C.M. Morris, S. Muknahallipatna, and V. Bershinsky, "Emulating Large, Time Varying Rotary Power Loads at Low Cost", *1999 IEEE International Conference on Control Applications*, pp. 796-801, Kohala Coast, HI, August 1999

J.E. McInroy and S.F. Legowski, "Diagnosis of Motor Drivepower System Degradations with Electrical Input Power," The IEEE Symposium on Diagnostics in Electrical Machines and Power Electronics Devices, Spain, September, 1999.

Proposals

Advanced Techniques for Power System Identification from Measured Data; $587,535; DOE, pending

Power System Identification Using Injected Probing Signals; $57,487; BPA (Bonneville Power Association); pending

Mode Estimation and Monitoring; $32,780; BPA (Bonneville Power Association); November 1999 – July 2000

PI: J. McInroy, "High Precision, High Frequency, Fault Tolerant Manipulation of Multiple Payloads Aboard a Moving Bus," with F. Jafari, submitted to the Missile Defense Agency's DEPSCoR program, September 2001. requested: $339,323. funded.

PI: J. McInroy, "Forming New Linkages Between UW, JPL, and MSFC Hexapod Vibration Isolation Programs," with J.W. Pierre and F. Jafari, submitted to NASA EPSCoR, March 2000, requested: $66,371. funded.

PI: J. McInroy, "Fault Tolerant High Precision Pointing, Vibration Isolation, and Vibration Absorption Using Flexured Parallel Kinematic Machines," with J.C. Hamann and A.W. Peck, submitted to the Ballistic Missiles Defense Organization's DEPSCoR program, September 1999. requested: $340,674. received: $340,674.

PI: J. McInroy, "Space Based, Long Distance Laser Pointing and Tracking," with J.C. Hamann, S. Yoakum-Stover and T.S. Luk, submitted to the Ballistic Missiles Defense Organization's DEPSCoR program, June 1997. requested: $340,611. received: $340,611.

PROJECT 2 DESCRIPTION: MEASUREMENT AND ASSESSMENT OF POWER SYSTEM RADIO FREQUENCY INTERFERENCE EFFECTS

Principal Investigators: Robert Kubichek and John Pierre
Co-Principal Investigators: Stanislow Legowski and Sadrul Ula. All University of Wyoming

Goals

- Study radio frequency interference (RFI) produced by new power-efficient variable speed drives (VSD's).
- Understand sources of VSD interference and suggest solutions.
- Determine impact of increasing uses of VSD on nearby communications systems.

Technical Accomplishments

- Spectrum survey of Electromagnetic interference (EMI) for wide range of VSD's on the UW campus and around the state. We found significant emissions in over half of the devices tested.
- Room-to-room and floor-to-floor RFI distribution within buildings were measured. VSD-produced EMI was detectable across two floors of a building.

- In-depth analysis of RFI spectrum for selected VSD produced new information about this problem. Effects of cabling and shielding were analyzed, and solutions identified.
- Computer modeling of VSD RFI effects on selected nearby communication systems shows significant impairment of nearby radio devices such as cell phones and other equipment operating at frequencies up to 1 GHz.
- Analyzed accuracy of spectrum estimation techniques used in modern signal analysis equipment, and found important deviations in estimated power levels for some commonly used approaches.

Students

- Project has supported 6 undergraduate, 3 masters, and 1 PhD student

Laboratory Development

- Computer-controlled HP 8595EM Spectrum analyzer
- Four calibrated antennas for wide frequency coverage
- Specialized equipment for both radiated and conducted emissions
- Tektronix TDS 7104 high-speed signal analyzer. *Obtained by proposal to Tektronix*

Publications and Presentations

- 10 publications/presentations at EMC conferences.
- 3 masters thesis's (one in progress)
- 1 PhD thesis (in progress)

FINAL REPORT

Executive Summary

This research has shown that modern high-efficiency inverters and controllers generate Radio Frequency Interference at unexpectedly high frequencies, from below 100 MHz and ranging up to microwave frequencies. This may eventually pose serious compatibility problems as the growing need for higher energy efficiency results in more devices being used. The goal of this research is to measure and understand these threats so that future RFI-related problems caused by improved efficiency designs can be minimized. The work has resulted in the following accomplishments: We have established an EMC testing facility that can be used for pre-compliance tests of both conducted and radiated emissions over a wide frequency range. We have conducted an extensive study of relevant literature and electromagnetic compliance (EMC) standards. We have performed a spectrum survey of selected power inverters and adjustable-speed drives (ASDs) located on the UW campus and around Wyoming, revealing strong RFI emissions at frequencies above 100 MHz in over half of the tested devices.

A web database has been developed, making accessible much of the data to other researchers throughout the world. Detailed experiments studied EMI for a single power inverter in the frequency range from 20Hz to 2 GHz. All sources of EMI from the variable speed power inverter were identified, levels of the electromagnetic field measured, and appropriate shielding and grounding solutions were proposed. In another study, we investigated how ASD RFI energy is distributed in a typical building between rooms and across floors in order to understand potential impact on nearby electronic systems. Finally, we have applied computer modeling techniques to estimate EMI effects on nearby communication systems such as digital radios and cell phones.

One objective of the project is to support the progression toward better energy efficiency by identifying and addressing potential EMC issues before major problems surface. The impact of this project at UW will extend well beyond the duration of EPSCoR funding and open up new opportunities for related research. For example, using the experience and lab equipment from the EPSCoR project we have recently been investigating EMC produced in low-power plasma conversion of hazardous waste materials. This effort may result not only in better energy efficiency, but also in improved methods to process toxic waste.

Project goals

Radiated and conducted radio frequency interference (RFI) from power inverters and controllers are usually assumed to lie at frequencies well below 1 MHz. However, research conducted during the first part of this project has shown that modern high-efficiency designs generate RFI at unexpectedly high frequencies, from below 100 MHz and ranging up to microwave frequencies. This may eventually pose serious compatibility problems as the growing need for higher energy efficiency results in more and more of these devices coming on line. For example, electric vehicles (EVs) that rely on highly efficient motor controller designs are expected to be used in increasing numbers. Although it is likely that EV manufacturers will ensure that individual vehicle emissions are not excessive, deployment of many EVs could raise the overall noise floor, and increase the risk to communication services and other electronics. As another example, efficient variable-speed drives (VSDs) used by air handling units and elevators in office buildings and hospitals raise new concerns about susceptibility of nearby computers and medical instruments.

The goal of this research is to measure and understand these threats in order to minimize future RFI-related problems caused by improved efficiency designs. Accordingly, project work has focused on the following areas: (1) Establish an EMC testing lab facility. (2) Survey EMI of operational VSD's located in the UW motor testing lab, in buildings around the UW campus, and in various locations around the State. (3) Conduct detailed investigation of a single VSD to establish sources of emissions and effects of cabling and shielding. (4) Understand spatial extent of VSD radio emissions within a typical building. (5) Study impacts of EMI on nearby communications equipment. (6) Evaluate accuracy of spectrum estimation techniques used in modern signal analysis equipment.

Lab Development

We established an EMC testing facility consisting of a HP 8595 EM spectrum analyzer, pre-amplifier, line isolation stabilization network (LISN), stepping preselector, and four different calibrated antennas. The system is fully computer controlled using Pentagram EMTest software, and can be used for pre-compliance tests of both conducted emissions from 9 kHz to 30 MHz, and radiated emissions from 9 kHz to 6 GHz. The software includes a complete database of current national and international EMC standards for checking measured emissions against allowed levels in each frequency band. An important recent addition to the lab is a Tektronix TDS 7104 high-speed digital phosphor sampling oscilloscope. This was obtained through a grant from Tektronix.

VSD EMI Survey

We have conducted an extensive and on-going survey of relevant literature, as well as a review of national and international electromagnetic compatibility (EMC) standards. This review has provided basic insight into standard measurement techniques and allowable interference levels in each frequency band. We surveyed the EMI spectra from nearly twenty power inverters and variable-speed drives located on campus and around the state of Wyoming. The investigation revealed strong RFI emission at frequencies above 100 MHz in over half of the tested devices. In some test cases the effectiveness of the manufacturer's RF shielding was studied, revealing a reduction in RF emissions in only certain cases. In addition to far field measurements, the survey also included some near-field probe level measurements. A web database has been developed, making accessible much of the data to other researchers throughout the world.

The results of the study are significant in several ways. Although early results indicated potential problems might exist, the magnitude and scope of the problem was unknown. An extensive literature search reveals that the problem has received minimal attention in research literature, and is not well known to industry. The RFI measurement data is alarming considering the wide variety of radio services that could be affected, including digital mobile radio, radio navigation signals, commercial broadcast TV and FM radio, cellular telephone, and paging services. It may be concluded that some manufacturers are putting little effort into EMC design practices, perhaps because such high-frequency emissions were not anticipated. It should be noted that this component of the project benefited from collaboration with colleagues at the Institute for Telecommunication Sciences, NTIA, U.S. Dept. of Commerce. In addition, students and faculty participated in several HP/Agilent seminars on electromagnetic compatibility.

Within-Building EMI Distribution

ASD interference levels depend on distance from the drive, cable lengths, room configuration, and many others factors. In order to better understand the effects of EMI on victim receivers, a series of tests were conducted to measure ASD noise strength as the receiver is moved further away from the drive. In these tests, the receiver antenna is moved at intervals away from the source, as well as placed on floors above the noise source. Furthermore, to gain a first-order understanding of possible effects on communication devices, we used zero-span analysis of the interference signal. This technique examines signal power within a particular frequency band over time, and works by locking the spectrum analyzer on one frequency and measuring the time-varying power passed through a specified band-pass filter. Since this setup resembles the front end of a typical communication receiver, the zero-span output provides information about signal characteristics and signal-to-noise ratios present in the receiver

Most of the spectra examined exhibit two main characteristics that are common in all the tests performed. The first of these is that EMI statistics appear stationary at all the frequencies tested. This result showed that the power level at each frequency remained constant in time. Cumulative distribution plots demonstrated the impulsive non-gaussian nature of the EMI at most of the frequencies tested.

Significant interference was detected up to two floors above the ASD. It was also seen that EMI levels within a room are greatly affected by destructive and constructive interference, which may result in high levels of EMI at unexpectedly large distances from the ASD. Hallways, for example, appear to act as a wave-guide that preserves signal strength at long range. On higher floors, the noise floor drops off to near ambient, but the peaks are still much stronger than the surrounding noise floor. This phenomenon has potential to cause EMI problems in sensitive electronic and communication systems several floors above or below an ASD.

Focused VSD Measurements

This study focused on understanding the details of EMI emissions from a single commercially available adjustable speed drive attached to a 45 kW 3-phase induction motor. Six EMI sources were identified over a range of 30 Hz to 1 GHz using close proximity antennas (sniffing probes). These include: (1) power grid 60 Hz signal, (2) desired ASD output frequency signal, (3) random pulse-width modulation noise with its 40 kHz folding frequency, (4) switching power supply 2.0 MHz signal, (5) 72.5 kHz clock signal of the control system, and (6) intermodulation products. In addition, we evaluated effectiveness of shielding on both the connection from ASD to the motor as well as on the ASD itself. Tests show that cable shielding and specially designed ASD shielding are both required to mitigate RFI at frequencies over 200 MHz. Unfortunately, current practice is often to use unshielded systems.

Analysis of Spectrum Estimation techniques

Analysis of EMI in this project relied on two different types of equipment. The HP 8595EM is a traditional spectrum analyzer, while the Tektronix TDS 7104 digital phosphor oscilloscopes is a high-speed digital sampling scope capable of rates up to 10 GSa/Sec. While the spectrum analyzer measures only spectral power, the Tektronix records the actual waveform including both magnitude and phase information from which spectral power measurements are derived. As accurate power spectral density information is critical to this project, it is important to understand differences in recorded data between the two devices. We extended this study to look at general power spectral estimation algorithms implemented on related test and measurement equipment.

Although numerous advanced signal-processing methods are available for spectral estimation, many modern test and measurement equipment typically provide only non-parametric Fast-Fourier Transform (FFT)-based approaches. One such approach averages the FFT magnitudes rather than averaging the squared magnitudes as is done in the well-known Welch periodogram. Another approach takes the geometric mean rather than the arithmetic mean. Since these simple but non-conventional methods are common in industry, an understanding of their performance is important. Our analysis found mean and variance statistics for these estimators for finite data length, and showed that both estimators are biased spectral estimators. Furthermore, their MSE's are larger than that of the well known Welch periodogram.

Impact on Communication Systems

This study seeks to understand the effects of VSD EMI on nearby communications equipment such as cell phones, digital mobile radios, paging and geolocation services, and commercial radio and television signals. Since digital transmission techniques are becoming ubiquitous, we

concentrate on typical digital modulation schemes. These are most effectively studied using computer simulations that make it possible to easily change transmission parameters such as modulation type, error correction modes, signal-to-noise ratio, and channel conditions such as fading or non fading environments. As an example, simulations were conducted using actual noise measured from the VSD to show how it might affect digital radio bit-error rate (BER) as a function of user-to-transmitter and user-to-VSD distances. The BER determines transmission quality of the system. These tests show unacceptable BER values occur when the user is within about 3 meters of the VSD for most reasonable user-to-transmitter distances. This "interference radius" increases further when the VSD and user are both indoors, as the walls attenuate the desired signal without affecting VSD noise levels. Thus, for example, indoor cell phone performance would decrease significantly, especially in cases where multiple VSD's are used in elevators or HVAC systems.

Specific Accomplishments

Students

Graduate Students

Past: Dennis Barp (M.S., 2002) and Matt Wisnewski (M.S., 2000)
Current: Hongkang Liang (Ph.D) and Yan Teng (M.S.)

Undergraduate Student Involvement

Chris Larson (2000-2001)
Tyler Chubb (1998-1999). Tyler interned at PNNL as result of DOE experience.
Scott Stiedley (1998-1999)
Tony Larson (1998)
Clayton Fronk (1997)
Janice Koch (1996). Janice interned at PNNL as result of DOE experience.

Publications

Arntzen E., R.F. Kubichek, J.W. Pierre, and S. Ula, "Initial Findings on Electromagnetic Emissions above 30 MHz from Power Inverters and Variable Speed Motor Controllers," *Proc. IEEE International Symposium on EMC*, August 1997.

Barp, D.P. and S.F. Legowski, "Measurements of Spectral Distribution of EMI Emissions from Adjustable Speed Drives of Induction MotorsProceedings of the 2002 IEEE International Symposium on Industrial Electronics, IEEE-ISIE 2002, L'Aquila, Italy, July 8-11 2002, ISBN 0-7803-7300, pp. 1392-1397.

Chowdhury B.H., R.F. Kubichek, J.E. McInroy, S. Legowski, J.W. Pierre, and S. Ula, "A Multi-Disciplinary Research Initiative In Electric Energy Utilization," *Proceedings of North American Power Symposium (NAPS),* October 1998.

Kubichek R., J. Pierre, M. Straub, E. Arntzen, and S. Steidley, "Electromagnetic Interference Generated By Adjustable Speed Drives Between 30 and 900 MHz," *Proceedings of North American Power Symposium (NAPS),* October 1998.

Legowski, S.F. and D.P. Barp, "Experimental Study of Spectral Distribution of EMI Emissions of Modern Adjustable Speed Drives," accepted in IEEE EMC Zurich 2003, Feb. 2003.

Legowski, S.F. and D. P. Barp, "EMI Emissions of Adjustable Speed Drives of Induction Motors," Proceedings of the Scientific Symposium to Commemorate 50th Anniversary of

the Electronics, Telecommunication, and Computer Science Depaertment at the Technical University of Gdansk, Poland, 2002, pp. 141-160.

Liang, H.K., R.F. Kubichek, and J.W. Pierre, "Asymptotic Statistics for Spectral Estimator Used in Test and Measurement Equipment," *IEEE Trans. on Test and Measurement*, (submitted).

Liang, H.K., R.F. Kubichek, and J.W. Pierre, "Asymptotic Statistics for Geometric Mean Spectral Estimator Used in Test and Measurement Equipment," *Proceedings* International Signal Processing Conference (ISPC), March 2003.

Liang, H.K., J.W. Pierre, and R.F. Kubichek, "Asymptotic Statistics for an Uncommon Averaged Magnitude Spectral Estimator Used in Test and Measurement Equipment," *IEEE 1 DSP Workshop*, October 2002.

Pierre, J.W. and R.F. Kubichek, "Spectrum Analysis: Analyzing a Signal Spectrum," Application Note, 16 pages, Tektronix, Inc., 2002.

Wisniewski, M., R. Kubichek, and J. Pierre, "EMI Emissions up to 1 GHz from Adjustable Speed Drives," *Proc. of IECON*, pp. 113-118, November 2001.

Related Successful Proposals

1. Time Domain RF Measurements; $39,035; Tektronix; 2000-2001
2. UW Integrated Design Laboratory; $10,500; Rockwell; 2001

Publications Directly Related to DOE Funding

Arntzen E., R.F. Kubichek, J.W. Pierre, and S. Ula, "Initial Findings on Electromagnetic Emissions above 30 MHz from Power Inverters and Variable Speed Motor Controllers," *Proc. IEEE International Symposium on EMC*, August 1997.

Barp, D.P. and S.F. Legowski, "Measurements of Spectral Distribution of EMI Emissions from Adjustable Speed Drives of Induction MotorsProceedings of the 2002 IEEE International Symposium on Industrial Electronics, IEEE-ISIE 2002, L'Aquila, Italy, July 8-11 2002, ISBN 0-7803-7300, pp. 1392-1397.

Chowdhury B.H., R.F. Kubichek, J.E. McInroy, S. Legowski, J.W. Pierre, and S. Ula, "A Multi-Disciplinary Research Initiative In Electric Energy Utilization," *Proceedings of North American Power Symposium (NAPS),* October 1998.

Kubichek R., J. Pierre, M. Straub, E. Arntzen, and S. Steidley, "Electromagnetic Interference Generated By Adjustable Speed Drives Between 30 and 900 MHz," *Proceedings of North American Power Symposium (NAPS),* October 1998.

Legowski, S.F. and D.P. Barp, "Experimental Study of Spectral Distribution of EMI Emissions of Modern Adjustable Speed Drives," accepted in IEEE EMC Zurich 2003, Feb. 2003.

Legowski, S.F. and D. P. Barp, "EMI Emissions of Adjustable Speed Drives of Induction Motors," Proceedings of the Scientific Symposium to Commemorate 50th Anniversary of the Electronics, Telecommunication, and Computer Science Department at the Technical University of Gdansk, Poland, 2002, pp. 141-160.

Liang, H.K., R.F. Kubichek, and J.W. Pierre, "Asymptotic Statistics for Spectral Estimator Used in Test and Measurement Equipment," *IEEE Trans. on Test and Measurement*, (submitted).

Liang, H.K., R.F. Kubichek, and J.W. Pierre, "Asymptotic Statistics for Geometric Mean Spectral Estimator Used in Test and Measurement Equipment," *Proceedings* International Signal Processing Conference (ISPC), March 2003.

Liang, H.K., J.W. Pierre, and R.F. Kubichek, "Asymptotic Statistics for an Uncommon Averaged Magnitude Spectral Estimator Used in Test and Measurement Equipment," *IEEE 1 DSP Workshop*, October 2002.

Wisniewski, M., R. Kubichek, and J. Pierre, "EMI Emissions up to 1 GHz from Adjustable Speed Drives," *Proc. of IECON*, pp. 113-118, November 2001.

Publications Indirectly Related to DOE Funding

Pierre, J.W. and R.F. Kubichek, "Spectrum Analysis: Analyzing a Signal Spectrum," Application Note, 16 pages, Tektronix, Inc., 2002.

Related Successful Proposals

1. Time Domain RF Measurements; $39,035; Tektronix; 2000-2001
2. UW Integrated Design Laboratory; $10,500; Rockwell; 2001

PROJECT 3 DESCRIPTION: SYSTEM CHARACTERIZATION AND CONDITIONING FOR ENHANCING THE VALUE OF PHOTOVOLTAIC ENERGY SOURCES IN POWER DISTRIBUTION SYSTEMS

Principal Investigator: Sadrul Ula
Co-Principal Investigators: Jerry J. Cupal, Jerry C. Hamann, Stanislaw Legowski, Suresh Muknahallipatna. All University of Wyoming.

Accomplishments

Design and testing of two novel maximum power point tracking circuits for photovoltaic applications has concluded, with a second phase of implementation underway.

System monitoring of the campus-based 5+10+35 kW photovoltaic installation is continuing, with final installation of the 35 kW custom instrumentation nearly completed.

Project expertise has been utilized in obtaining a Wyoming Phase 0 SBIR grant to participate in the development of a NASA Phase I SBIR proposal with Chinook Engineering of Sheridan, Wyoming. Distributed instrumentation integration via internet-based communication is the technical thrust of the proposal, with the immediate target being air-quality monitors in the mineral-rich Powder River basin of north-central Wyoming.

Section 5
ENVIRONMENTAL REMEDIATION AND WASTE REDUCTION RESEARCH CLUSTER

Cluster PI: name, address, phone, fax, email
David Bell, Dept. of Chemical and Petroleum Engineering, (307) 766-5769, fax: (307) 766-6777, email: davebell@uwyo.edu

Abstract:
The five cluster projects are devoted to developing technology to mitigate known environmental problems.

Genetics of the Microbial Dechlorination of the Environmental Pollutant, Pentachlorophenol, explores the genetic engineering that allows microbes to degrade a common wood preservative.

Rhizosphere Microorganisms and Phytorediation, explores the interaction of soil microbes and plants when plants are used to remove toxic heavy metals from soils

Processes for Remediation of Hydrocarbon Sources of Groundwater Contamination, is developing a new process that uses a surfactant and an electric field to remove gasoline from soils.

Hydrocarbon Emissions from Natural Gas Drying, explores the vapor/liquid equilibria of methane/aromatic hydrocarbon/glycol/water systems to better model emissions from natural gas dehydration plants.

Supercritical Fluid Atomization of Ultra-High Viscosity Materials, is characterizing a commercial spray-painting process that replaces most of the paint thinner with supercritical carbon dioxide.

Other Personnel

Undergraduates
8
Graduate Students
14
Female/Minority
9
High School Students
6

Cluster Accomplishments

- We have successfully incorporated two important research methodologies into our program; molecular (RNA and DNA) analysis of soilmicrobial communities and Geographic Information Systems (GIS) mapping of soil contaminants and microbial distributions in soil. These new methods provide us with powerful tools to monitor microbial communities and contaminants in soils as well as the relationships between the two. We have also established a collaborative research project with Phytokinetics, Inc. (a private phytoremediation firm) of Logan, UT, had a sizable grant funded by BP-Amoco Corporation to conduct phytoremediation research at one of their facilities, and had one of our undergraduate students complete a summer internship at Brookhaven National Laboratory sponsored by DOE/EPSCoR.

- Layered Double Hydroxides and Their Derivatives As Adsorbents for Inorganic and Organic Pollutants - Layered double hydroxides (LDHs) are antitype 2/1 clay minerals that can be used as adsorbents for the removal of environmental pollutants from contaminated ecosystems. Our studies have evaluated different LDHs and their derivatives that were synthesized in our lab in order to determine their ability to adsorb inorganic and organic pollutants, such as inorganic oxyanions, pesticides, and various organic solvents. Results indicated selenium, arsenic and dicamba could be adsorbed on LDHs, with the adsorption capacities and release being strongly affected by competing anions in solutions. Calcination at 450°C increased LDH anion exchange capacities, with calcined-LDH having a higher adsorption capacity than uncalcined-LDH. Anionic surfactants could be intercalated into LDHs via ion-exchange, *in-situ* synthesis, and rehydration processes. Organic surfactant modified organo-LDHs were also found to be effective adsorbents for the removal of nonionic organic pollutants, such as 1,2,4-trichlorobenzene, 1,1,1-trichloroethane, TCE and PCE, from aqueous solutions.

- Tests were performed on the shear strength of the soil with electrokinetics and surfactants using a special soil direct shear testing device in which water, surfactant and electrical flow could be controlled. Previous findings indicated that the surfactant tended to decrease the strength of the soil. New tests showed that while surfactants decreased the soil strength, current increased the strength of the soil, essentially in proportion to the voltage gradient. In most cases, the surfactant decreased the strength of the soil and electrical field by approximately 50 percent. Evidence was also found that the strength would increase to some degree when the surfactant was flushed out of the soil. The surfactant tended to decrease the volume of the soil, such that the surfactant and voltage combined may be said to produce a characteristic volume.

- In addition, a field test plot for surfactant enhanced electrokinetic remediation has been selected with the cooperation of the Wyoming Department of Environmental Quality and the land owner of a gasoline contaminated site. A subcontract has been developed with the DEQ to install the wells, electrodes and monitoring devices and testing should begin by early June.

Special Awards And Honors

J.E. Warren Distinguished Professor of Energy and the Environment

George F. Vance, gfv@uwyo.edu
University of Wyoming

The University of Wyoming (UW) J.E. Warren Distinguished Professorship of Energy and the Environment recognizes a UW faculty members who excels in research activities associated with energy- and/or environment-related disciplines. The J.E. Warren Distinguished Professor retains the title for the duration of his/her career at UW and receives an annual $7,000 supplement for three years.

PROJECT 1A. GENETICS OF MICROBIAL DECHLORINATION OF THE ENVIRONMENTAL POLLUTANT, PENTACHLOROPHEOL

PI: M. M. Stayton, Molecular Biology, (307) 766-4025, fax: (307) 766-5098, email: stayton@uwyo.edu.

Abstract

Pentachlorophenol (PCP) is a persistent and hazardous waste that contaminates wood treatment sites in the US and abroad. The current method of disposal, high temperature incineration, is expensive and not widely available. A variety of soil microbes have been identified that mineralize PCP. The aerobic, gram-negative soil bacterium, *Sphingomonas chlorophenolica*, is the best-studied example. In this case, three genes required for PCP mineralization (*pcpA*, *pcpB* and *pcpC*) have been cloned and shown to encode the first three enzymes in the degradative pathway. Many genetic tools are not available for use in *Sphingomonas*. As a result, the regulation of expression of these genes has not been studied. Among other things, this deficiency limits our ability to predict *in situ* conditions favorable for efficient PCP degradation.

Because of these limitations with studies of *Sphingomonas*, we have established a system for dissection of PCP dechlorination in non-K12 strains of the genetic model system, *Escherichia coli*. We have demonstrated that PCP is completely dechlorinated by this organism and we have established a color screen for use in detecting mutants that have lost PCP dechlorination capability. Our short-term objectives are to (a) systematically identify all genetic loci required for PCP dechlorination and (b) to map these loci and clone the genes. We will then be in a position to dissect the regulatory circuits that control expression of the dechlorination pathway. To achieve these objectives, we have carried out a chemical mutagenesis of *E. coli*. We used our color screen to identify a set of mutant strains that cannot dechlorinate PCP or that show reduced rates of dechlorination. We have constructed a wild-type *E. coli* genomic library. We can now transform the library into each mutant strain and screen for complementation of the mutant phenotype as a means to clone the gene. In a parallel approach, we have also initiated a transposon mutagenesis of *E. coli*. This technology provides a second method to identify the *pcp* genes and will also permit us to construct transcriptional and translational fusions between *pcp* gene promoters and screenable marker genes. Such gene fusions can be used as convenient tools to measure the rate of PCP gene expression and to analyze its controlling factors.

Our most significant achievement has been the establishment of a system which will permit the dissection of mechanisms that control expression of PCP dechlorination and which permits a systematic identification of all genes required in the process. Ultimately, this information can be used to survey contaminated sites more systematically for bugs capable of PCP dechlorination. We will also be better able to predict the *in situ* conditions that are optimal for PCP bioremediation. The availability of the cloned PCP genes and an understanding of the factors that control their expression will permit us to construct bacterial strains that are more efficient at PCP dechlorination.

PROJECT 1B. RHIZOSPHERE MICOORGANISMS AND PHYTOREMEDIATION

P.I's: S. E. Williams, (307) 766-2683, email: sewms@uwyo.edu; and P. D. Stahl, (307) 766-2179, email: unclem@uwyo.edu, both of the Department of Renewable Resources, University of Wyoming

I. Research Achievements

1. Peter D. Stahl's group at the University of Wyoming began conducting research on phytoremediation of contaminated soils with DOE-EPSCoR funding in 1996. Last year, Stahl put together a multidisciplinary research team of scientists from UW that was funded by the BP Oil Corporation to investigate the feasibility of using phytoremediation to clean up a refinery site heavily contaminated with petroleum products. The team is conducting laboratory, greenhouse and field studies to evaluate use of this economical and environmentally friendly technology to remove any health hazards from the site and eventually return it to a safe and productive land use.

2. We have successfully incorporated two important research methodologies into our program; molecular (RNA and DNA) analysis of soil microbial communities and Geographic Information Systems (GIS) mapping of soil contaminants and microbial distributions in soil. These new methods provide us with powerful tools to monitor microbial communities and contaminants in soils as well as the relationships between the two.

3. Using a number of both classic (physiological and biochemical) and new molecular-based methods, our work has demonstrated that communities of microorganisms most closely associated with plant roots in contaminated soils are very different than those communities in uncontaminated soils. Rhizosphere microbial communities in the disturbed soils we examined were comprised of different species of organisms, produced less biomass and were generally much less active than those in undisturbed soils.

Final Report

With the widespread production, transport, and use of organic chemicals in our modern world, contamination of soil and other constituents of the environment with these materials is a common problem. Organic pollutants entering soil, usually through accidental spillage from leaky storage tanks or broken pipelines, include petroleum products, industrial solvents, pesticides and munitions. Most often, engineering approaches are employed to remediate contaminated soils. A number of physical, chemical, and thermal methods have been developed and are commonly used to remove or stabilize organic contaminants in soil. Costs of these techniques, however, can be quite high. Biotic remediation techniques such as bioremediation and phytoremediation, while not used as extensively, are generally much lower in cost. The most effective and economical method of remediation for any particular site is dependent on the chemical characteristics of the contaminant and properties of the contaminated soil. As more research, field trials and real remediation projects are being conducted, however, phytoremediation is gaining further acceptance as an efficient and inexpensive option for cleanup of soils polluted with organic contaminants.

Strategies to remediate organic pollutants in soil include both *in situ* and *ex situ* approaches. *In situ* options include volatilization, solidification, vitrification, encapsulation, bioremediation and phytoremediation. *Ex situ* options include soil washing, leaching, thermal desorption, and incineration in addition to the six listed for the *in situ* approach. Volatilization, thermal desorption, soil washing and leaching remove contaminants from soil while solidification, vitrification and encapsulation are methods to stabilize contaminants in soil. *Ex situ* processes have some disadvantages in that contaminated soils must be removed from their original location and transported at least a short distance. This handling results in additional costs. Also, organic contaminants removed by washing, leaching, or volatilization must be disposed, adding more cost.

Phytoremediation can be defined as "the use of green plants and their associated microbiota, soil amendments, and agronomic techniques to remove, contain, or render harmless environmental contaminants" (Cunningham et al., 1996). As the definition implies, phytoremediation includes methods which either extract or stabilize contaminants in soil. Advantages of phytoremediation over nonbiotic methods of remediation are costs, aesthetics and the fact that the growth and health of plants, the agents of remediation, unlike microorganisms, can easily be monitored.

Microorganisms play a critical role in the removal of organic contaminants from a site in that they can transform or degrade many compounds that may not be affected by plant growth (Alexander, 1994). Abundant evidence exists demonstrating the effectiveness of plant-microbe based remediation of soil contaminated with organic pollutants (Curl and Truelove, 1986; Burken and Schnoor, 1996; Ferro et. al., 1994, Schnoor et al., 1995). Plants have the ability to directly uptake some organic compounds from soil and produce enzymes which degrade others. Microbes have tremendous degradative capacity and can decompose a huge variety of organic compounds (Alexander, 1994). Plants and their roots can create a soil environment rich in microbial activity that can change the availability of organic contaminants or enhance the degradation of certain organic contaminants such as petroleum hydrocarbons (Anderson and Coats, 1995). Additionally, it appears that specific compounds in plant root exudates act as metabolites for the preferential growth and long-term survival of selective microorganisms with inherent capabilities for degrading organic contaminants (Angle, 1995; Alvey and Crowley, 1996).

Bioremediation of petroleum hydrocarbons in soil (e.g. fuel leaks, crude oil spills, production waste products) by microbial activity has been effective, but often biodegradation rates for more recalcitrant and potentially toxic compounds, such as polycyclic aromatic hydrocarbons (PAHs), are rapid at first and then decline rapidly (Banks et al., 2000). Biodegradation of these pollutants is often limited by their low solubility and strong adsorption to soil particles. Plants can significantly aid in remediation of soil contaminated with petroleum hydrocarbons by increasing their solubility and decreasing their sorption; thereby making the contaminants more available for microbial degradation. Plants roots also support a large and diverse community of microbes, many of which can degrade petroleum hydrocarbons. Establishment of vegetation on petroleum contaminated sites is an economic, potentially effective, low maintenance strategy for stabilization and remediation (Fiorenza et al., 2000).

Successful remediation of contaminated sites requires completion of a number of steps in order to realize the ultimate goal of a clean site. The first of these steps include site characterization, bioassessment and bioavailability studies, and laboratory testing of remediation techniques (King et al., 1992). Site characterization involves describing location and concentration of contaminants in soil and corresponding groundwater, analysis of important soil

properties, determination of possible movement of contaminants through soil, and for sites where phytoremediation will be employed, description of vegetation, if present. Bioassessment studies involve examination of soil microbial community characteristics, including tests for specific hydrocarbon contaminant degraders. For sites in which phytoremediation is being considered, testing contaminated soil for ability to support plant growth is essential and should include examination of possible soil amendments. Bioavailability studies should determine existing availabilty of contaminants for plant/microbial degradation or plant uptake. Laboratory testing of remediation techniques involve bench scale studies to determine if remediation strategies are effective, at least under controlled conditions (Cole, 1994). For use of plant-microbe based remediation of petroleum contaminated soil, laboratory testing should include studies of degradation of specific contaminants in soil with and without plant roots as well as testing potential phytoremediation plant species for germination and growth in contaminated soil (Banks et al., 2000).

A grid system was used to establish soil sampling locations on the 65 acre Tank farm site. We collected approximately 3 soil samples per acre on the site using a geographical placement system to precisely locate sampling locations. Soil samples were also collected directly adjacent to but outside the site for comparative and database purposes. Approximate 250 soil samples werecollected to allow a detailed assessment of the site. Sampling effort emphasized soils on most heavily contaminated areas as indicated by 1980 aerial photography/contaminant analyses and by current vegetation patterns. In addition, we collected groundwater samples and had them analyzed for complete water quality parameters including petroleum hydrocarbons.

In addition to site characterization, data from soil analyses will be used to determine if, what and where soil amendments may be needed before non-vegetated areas are reseeded (e.g. liming, dilution with clean soil, etc.).

Existing vegetation on the site was assessed in terms of ground cover, biomass production and species composition at individual sampling points on established transects. Soil cover was determined using Daubenmire plots (20 x 50 cm). Ground cover classes will include basal area of plants, bare soil, and sludge. Plant community composition was determined non-destructively by plant basal area. Aboveground standing plant biomass will be determined by species using double sampling methods, estimation and limited harvests to minimize destructive sampling. Belowground plant biomass (root biomass) will also be determined from soil cores taken at sampling points.

Soil cores were collected at individual sampling points along established transects for determination of contaminant concentrations. Soil samples were analyzed for Total Petroleum Hydrocarbons (TPHs), and BTEX compounds. Contaminant analyses will be conducted by an EPA certified lab.

For initial site characterization as well as to determine efficacy of phytoremediation, it wass necessary to determine if there is movement of contaminants from the Tank Farm site. To detect subsurface movement of contaminants, field lysimeter plots (2 x 2 m) will be marked along established transects. Lysimeters will be installed in duplicate on each plot, at two depths to sample water percolating from the plant root zone. One set of lysimeters will be installed near the root-zone and the other will be installed below the root-zone to collect the percolating water. These lysimeters consists basically of a plastic tray approximately 15 by 25 (5 cm high) filled with pre-washed sand. The tray drains into a plastic bottle, which is vented only to the lysimeter tray, so exchange of gas during sample collection is not a problem. Collection bottles will be sampled by syringe to avoid any contact with the atmosphere. Lysimeters are installed by digging a pit next to the experimental plot, tunneling laterally under the point of lysimeter

placement, and pressing the lysimeter upwards against undisturbed soil. The lateral shaft and the pit (with the exception of a pipe to give access to the collection bottle) will be backfilled.

Soil water samples from lysimeters were collected periodically throughout the study. Approximately, 50 ml of solutions was removed from each lysimeter with a air-tight syringe containing a 0.45-□m Millipore filter. Each sample was divided into two subsamples. One subsample was acidified with H_2SO_4 to a pH of 2; these solutions will be measured for Ca, Mg, Na, K, Al, Fe, Cu, Mn, Pb, Zn, As, Se, and Mo. Unacidified subsample will be measure for pH, Eh, EC, NO_3^-, SO_4^{2-}, PO_4^{3-}, Cl^-, F^-, DOC, and dissolved petroleum hydrocarbons (PHCs). PHC analysis will be conducted by an EPA-certified laboratory.

A Geographic Information System (GIS) is a collection of computer hardware and software designed to capture, store, manipulate, analyze, and display spatial and non-spatial information. GIS incorporates the elements of computer cartography, relational databases, and spatial modeling into one system, fully integrating spatial and tabular data. It is this element that makes GIS a powerful analysis tool rather than just a cartographic tool. The power of relational databases and the utility of spatial data models allow the GIS user to make complex spatial analyses. GIS is quickly becoming a critical component in the management of environmental resources. Some recent applications of GIS are on the topics of site assessment (Richards, et. al., 1996; Xue, et. al., 1996), environmental modeling (Loveland and Ohlen, 1993; Frysinger, et. al., 1996), and monitoring of environmental remediation sites (Duguay and Walker, 1996).

The GIS-related portion of the project involved development of a spatially-referenced site characterization database for the study area. This includes the vertical integration of digital geospatial layers incorporating vegetation, soils, and soil contamination levels at a resolution appropriate to the scale of the BP-Amoco remediation site. Data sources will include existing digital and non-digital information, as well as GPS-mapped point and transect data collected during sampling activities. Additional layers will include a digital terrain model and a digital aerial photograph reference layer.

In the initial stages of the project, the most efficient sampling scheme for spatial data collection must be determined. When sampling, an appropriate sampling method and density will be used in order for the locational samples to be coincident with the soil, vegetation and contaminant samples. This method will minimize cost and maximize the efficiency of field sampling because several types of spatial and attribute information will be collected at the same location. To collect locational information, Global Positioning System (GPS) technology will be used. Data will be collected using a Trimble ProXRS field GPS unit. With differential correction, Differential GPS (DGPS) can yield submeter accuracy. These GPS locations can then be stored in a GIS and tied to existing and potential tabular data to complete the geospatial database.

Once data collection is finished, GIS will be used for several things: to store, query, and analyze spatial data in order to support the decision-making process; and to generate detailed maps of the study area. The dynamic and flexible nature of GIS make it an effective tool for managing and storing baseline monitoring data as well as a useful device for subsequent tracking and mapping of treatment effects and remediation efforts.

Finally, by using advanced spatial technologies, SDVC will deliver a long-term tool for tracking remediation at the BP-Amoco site. To follow the progress of the remediation efforts, new data can be collected at previously sampled locations. These data can then be quickly and easily compared to the existing baseline data for simple and complex spatial analyses.

Literature Cited

Alexander, M. 1994. Biodegradation and bioremediation. Academic Press, San Diego.

Alvey, S. and D.E. Crowley. 1996. Survival and activity of an atrazine-mineralizing bacterial consortium in rhizosphere soil. Environmental Science and Technology 30:1596-1603.

Anderson, T.A. and J.R. Coats. 1995. An overview of microbial degradation in the rhizosphere and its implications for bioremediation. p. 135-144. In: Bioremediation: Science and Applications (H.D. Skipper and R.F. Turco, Eds.). Soil Sci. Soc. Am. Spec. Publ. 43., Madison, WI.

Angle, S. 1995. Rhizosphere facilitated catabolism of organics. p. 44-45. In: Abstracts of the 14th annual symposium on current topics in plant biochemistry, physiology and molecular biology: Will plants have a role in bioremediation?, Columbia, MO. Apr, 1995. Interdisciplinary Plant Group, Univ. of Missouri, Columbia.

Banks, M.K., R.S. Govindaraju, A.P. Schwab, and P. Kulakow. 2000. Field demonstration. p. 3-10. In: Phytoremediation of hydrocarbon-contaminated soil (S. Fiorenza, C.L. Oubre and C.H. Ward, Eds.). Lewis Publishers, Boca Raton, FL.

Bedessem, M., R. Semer, E. White and D. Scharre. 2000. "Microbial Enumeration as a Tool for Bioremediation Monitoring," 32nd Mid-Atlantic Industrial and Hazardous Waste Conference Proceedings, Technomic Publishing Co., Inc, pp. 62-71.

Burken, J.G. and J.L. Schnoor. 1996. Uptake and metabolism of atrazine and the role of root exudates. Journal of Environmental Engineering 122:958-963.

Cole, G.M. 1994. Assessment and remediation of petroleum contaminated sites. Lewis Publishers, Boca Raton, FL.

Cunningham, S.D. and C.R. Lee. 1995. Phytoremediation: plant-based remediation of contaminated soils and sediments. p.145-156. In: Bioremediation: Science and Applications (H.D. Skipper and R.F. Turco, Eds.). Soil Science Society of America Special Publication 43., Madison, WI.

Cunningham, S.D. and W.R. Berti. 1993. The remediation of contaminated soils with green plants: an overview. In vitro cellular and developmental biology-plant 29:207-212.

Curl, E.A. and B. Truelove. 1986. The Rhizosphere. Springer-Verlag, Berlin.

Ferro, A.M., R.C. Sims, abd B. Bugbee. 1994. Hycrest crested wheatgrass accelerates the degradation of pentachlorophenol in soil. Journal of Environmental Quality 23:272-279.

Fiorenza, S., C.L. Oubre, and C.H. Ward. 2000. Phytoremediation of hydrocarbon-contaminated soil. Lewis Publishers, Boca Raton, FL.

Horwath, W.R. and Paul, E.A. 1994. Microbial Biomass. In: Weaver RW, Angle S, Bottomley P, Bezdicek D, Smith S, Tabatabai A, Wollum A (eds) Methods of Soil Analysis, Part 2: Microbiological and Biochemical Properties. Soil Science Society of America, Madison, WI.

King, R.B., G.M. Long, and J.K. Sheldon. 1992. Practical Environmental Bioremediation. Lewis Publishers, Boca Raton, FL.

Raskin, I., P.B. Kumar, S. Dushenkow, and D.E. Salt. 1994 Bioconcentration of heavy metals by plants. Curr. Opin. Biotechnol. 5:285-290.

Rice, E.L. and B. Hemmingsen. 1997. "Enumeration of Hydrocarbon-Degrading Bacteria" in *Bioremediation Protocols*, Humana Press, pp. 99-109.

Salt, D.E., M. Blaylock, P.B. Kumar, V. Dushenkov, B.D. Ensley, I. Chet, and I. Raskin. 1995. Phytoremediation: a novel strategy for the removal of toxic metals from the environment using plants. Biotechnology 13:468-474.

Schnoor, J.L., L.A. Licht, S.C. McCutcheon, N.L. Wolfe, and L.H. Carreira. 1995. Phytoremediation of organic and nutrient contaminants. Environ. Sci. Technol. 29:318-323.

Tate, K.R., Ross, D.J., Felthan, C.W. 1988. A direct extraction method to estimate soil microbial biomass C: effects of some experimental variables and some different calibration procedures. Soil. Biol. Biochem. 20: 329-355.

U. S. Environmental Protection Agency. 1994. *How to Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites*, EPA 510-B94-003, X:1-38.

Wenzel, W.W., D.C. Adriano, D. Salt, and R. Smith. Phytoremediation: a plant-microbe based remediation system. Pp. 457-508. In: Bioremediation of Contaminated Soils (D.Cadriano, J.M. Bollag, W.T. Frankenberger, and R.C. Sims, Eds.). Agronomy Monograph no. 37. Soil Sci. Soc. Am., Madison, WI.

Wrenn, B. A. and A. D. Venosa. 1996. "Selective Enumeration of Aromatic and Aliphatic Hydrocarbon Degrading Bacteria by a Most-Probable Number Procedure," *Can. J. Microbiol.* 42:252-258.

Specific Accomplishments

Publications

Mummey, Daniel L., Peter D. Stahl, and Jeffrey S. Buyer. 2002. Soil microbiological and physicochemical properties 20 years after surface mine reclamation: comparative spatial analysis of reclaimed and undisturbed ecosystems. Soil Biology and Biochemistry 34:1717-1725.

Mummey, Daniel L., Peter D. Stahl, and Jeffrey S. Buyer. 2002. Microbial biomarkers as an indicator of ecosystem recovery following surface mine reclamation. Applied Soil Ecology 21:251-259.

Stahl, P.D., B.L. Perryman, S. Sharmasarkar, and L.C. Munn. 2002. Stockpiling vs. exposure to traffic: Best management of topsoil on in-situ uranium wellfields. Restoration Ecology 10:129-137.

Frost, S. M., P.D. Stahl and S.E. Williams. 2001. Long term reestablishment of arbuscular mycorrhizal fungi in a drastically disturbed semi-arid surface mine soil. Arid Land Research and Management 15:3-12.

Wanek, P.L., G.F. Vance, and P.D. Stahl. 1999. Selenium uptake by plants: Effects of soil steaming, root addition, and selenium augmentation. Communications in Soil Science and Plant Analysis 30: 265-278.

Proposals Submitted

Phytoremediation of Petroleum Contaminated Soil on the BP Amoco Tank Farm. P.D. Stahl, K.J. Reddy, J.D. Rodgers, D.W. Johnson, M.E. Bedessem, J.H. Johnson, J.D. Hamerlinck, and B.L. Perryman. Submitted to BP Amoco Corp. for $425,695. 2000.

Controls of carbon sequestration on northern Rocky Mountain rangelands. J.M. Welker, G.F. Vance, and P.D. Stahl. Submitted to USDA-NRI, $180,000. 2000.

Influence of Reclamation Management Practices on Carbon Accumulation and Soil Fertility on Coal Mine Lands in Wyoming. P.D. Stahl, G.F. Vance, L.J. Ingram, S.V. Huzurbazar, and C.J. Bilbrough. Submitted to the Abandoned Coal Mine Land Research Program. $222,885. 2001.

Structure and Function of Microbial Communities in Mine-Impacted and Pristine Environments: A Comparative Study. E. McClain, P.D. Stahl, C.S. Chandler, P.S. Colberg. Submitted to USDA Tribal Colleges Research Grants Program, USDA, $150,000. 2002.

Proposals Funded

Phytoremediation of Petroleum Contaminated Soil on the BP Amoco Tank Farm. P.D. Stahl, K.J. Reddy, J.D. Rodgers, D.W. Johnson, M.E. Bedessem, J.H. Johnson, J.D. Hamerlinck, and B.L. Perryman. Funded by BP Amoco Corp. $425,695. 2000-2003.

Controls of carbon sequestration on northern Rocky Mountain rangelands. J.M. Welker, G.F. Vance, and P.D. Stahl. Funded by USDA-NRI, $180,000. 2001-2003.

Influence of Reclamation Management Practices on Carbon Accumulation and Soil Fertility on Coal Mine Lands in Wyoming. P.D. Stahl, G.F. Vance, L.J. Ingram, S.V. Huzurbazar, and C.J. Bilbrough. Funded by the Abandoned Coal Mine Land Research Program. $222,885. 2002-2005.

Structure and Function of Microbial Communities in Mine-Impacted and Pristine Environments: A Comparative Study. E. McClain, P.D. Stahl, C.S. Chandler, P.S. Colberg. Funded by USDA Tribal Colleges Research Grants Program, USDA, $150,000. 2002-2004.

PROJECT 1C. PROCESSES FOR REMEDIATION OF HYDROCARBON SOURCES OF GROUNDWATER CONTAMINATION

P.I.'s: David H. Foster, Thomas V. Edgar, Civil Engineering; George F. Vance, Plant, Soil and Insect Sciences; M.P. Sharma, Petroleum Engineering; and Sadrul Ula, Electrical Engineering; all of the University of Wyoming

Articles Directly Related

Aaron G. Murray, Thomas V. Edgar, Marjorie E. Bedessem, and Travis W. Halleman, Surfactant Enhanced Electrokinetic Remediation and Soil Shear Strength and Consolidation Effects, in preparation.

Wright, M.D., T.V. Edgar, D.H. Foster, S.K. Bhattacharya, G.F. Vance and M.R. Junna. 2000. An integrated approach to remediation of petroleum contaminated soils: Surfactant enhanced electrokinetics. Treatment of Organic Contaminated Soils Symposium, AIChE Conference Proceedings. 8 pp.

Sharmasarkar, S., W.F. Jaynes and G.F. Vance. 1999. BTEX sorption by montmorillonite organo-clays. Water, Air, and Soil Pollution, 119:252-273

Jaynes, W.F. and G.F. Vance. 1999. Sorption of benzene, toluene, ethylbenzene and xylenes (BTEX) compounds by hectorite clays exchanged with aromatic organic cations. Clays and Clay Minerals 47:358-365.

Zhao, H. and G.F. Vance. 1998. Sorption of BTEX (benzene, toluene, ethylbenzene and xylenes) by soils in the presence of surf*actants*. Agronomy Abstracts, 90:203.

Bhattacharya, Sujan K.; Foster, David H.; Reddy, J.Mohan, 1996, Surfactant enhanced electrokinetic remediation of gasoline contaminated soils. ASCE Specialty Conference, Proceedings, Non-Aqueous Phase Liquids (NAPLs) in Subsurface Environment: Assessment and Remediation, Washington D.C., p 311-322.

Articles Indirectly Related

Jaynes, W.F. and G.F. Vance. 1995. Effect of organo-clay type and properties on the sorption of aromatic gasoline constituents and other compounds from water. Agronomy Abstracts 87:348.

Patents and Intellectual Property

None

Contracts Directly Related

TriHydro Corp/Wyoming Department of Environmental Quality, $39,800. Innovative Technology Demonstration Project: Surfactant Enhanced Electrokinetic Remediation. 2001-2003. M.E. Bedessem, T.V. Edgar and G.F. Vance.

Presentations

Pickering, R., 2003. A Field Study of Surfactant Enhanced Electro-Kinetic Hydrocarbon Remediation. UW Graduate Research Symposium, Laramie, WY.

ZHAO, H. and G.F. VANCE*. 1998. *Sorption of BTEX (Benzene, toluene, ethylbenzene, and xylenes) by soils in the presence of surfactants*. Soil Science Society of American National Meetings, Baltimore, Maryland.

Vance, G.F., S. Sharmasarkar and W.F. Jaynes. 1998. *Sorption of BETX compounds by smectite clays exchanged with a variety of novel organic cations*. American Association for the Advancement of Science/Western Society of Soil Science Meetings, Logan, Utah.

Jaynes, W.F. and G.F. Vance. 1995. Sorption of aromatic gasoline constituents from water by organo-clays. Interdisciplinary Perspectives in Groundwater Research, Laramie, WY.

Jaynes, W.F. and G.F. Vance. 1995. Effect of organo-clay type and properties on the sorption of aromatic gasoline constituents and other compounds from water. Soil Science Society of America National Meeting, St. Louis, MO.

Publications: George F. Vance

Directly Connected to DOE Research

Boyd, S.A., C.T. Johnston, G.F. Vance, J-W Park, T. Pinnavaia and G. Bailey (Organizing Committee). 2000. Bouyoucous Conference Proceedings on Environmental Chemistry at the Clay-Water Interface. Proceedings, Michigan State University, East Lansing, Michigan, 35 pp.

Jaynes, W.F. and G.F. Vance. 1999. Sorption of benzene, toluene, ethylbenzene and xylenes (BTEX) compounds by hectorite clays exchanged with aromatic organic cations. Clays and Clay Minerals 47:358-365.

Pierzynski, G.M., G.F. Vance and A.L. Page (Committee Co-Chairs). 1998. Peer Review of "Draft Risk Assessment for Cement Kiln Dust Used as an Agricultural Soil Amendment". EPA Reference DW12938494-01-0. 22 pp.

Qi, J., Y.W. You,, G.F. Vance, J. Zhuang and Y. Jin. 2002. Removal of bacteriophages from aqueous systems by an anionic clay., University of Iowa, Ames, IA.

Sharmasarkar, S., W.F. Jaynes and G.F. Vance. 2000. BTEX sorption by montmorillonite organo-clays: TMPA, ADAM, HDTMA. Water, Air, and Soil Pollution 119:252-273.

Sharmasarkar, S. and G.F. Vance. 2002. Selenite-selenate sorption in a surface coal mine environment. Advances in Environmental Research 7(1):89-97.

Sharmasarkar, S. and G.F. Vance. 2002. Soil and plant selenium at a reclaimed uranium mine. Journal of Environmental Quality 31:1516-1521.

Vance, G.F. and H. Zhao. 1998. Selectivity and molecular sieving effects of organic compounds by an intercalate of beta-cyclodextrin and layered double hydroxide. American Association for the Advancement of Science/Western Society of Soil Science Proceedings 17:41.

Vance, G.F., W.F. Jaynes and S. Sharmasarkar. 1998. Sorption of BETX compounds by smectite clays exchanged with a variety of novel organic cations. Clay Minerals Society Abstracts 35:51.

Vance, G.F. 1998. Low-molecular-mass organic acids in environmental samples. Agronomy Abstracts 90:204 (Invited)

Vance, G.F. 1999. Review of the Risk Management Criteria for Metals at BLM Sites Technical Note 390 revised December 1996, TRC Mariah Consulting. 3 pp.

Vance, G.F. 2000. Organic chemical indicators of soil quality. Agronomy Abstracts 92:407. (Invited)

Vance, G.F. and G.M. Pierzynski. 2001. Chapter 1 "Bioavailability and Fate of Trace Elements in Residual-Amended Soil Studies" In: I.K. Iskandar and M.B. Kirkham (eds.) Trace Elements in

Soils: Bioavailability, Flux, and Transfer. CRC Publishers Inc., Boca Raton, FL. pp. 1-17 (Invited)

Wright, M.D., T.V. Edgar, D.H. Foster, S.K. Bhattacharya, G.F. Vance and M.R. Junna. 2000. An integrated approach to remediation of petroleum contaminated soils: Surfactant enhanced electrokinetics. Treatment of Organic Contaminated Soils Symposium, AIChE Conference Proceedings. 8 pp.

You, Y.W., G.F. Vance and H.T. Zhao. 2000. Removal of Dicamba (3,6 dichloro-2-methoxy benzoic acid) from aqueous solution by layered double hydroxides (LDHs). Agronomy Abstracts 92:23

You, Y.W., G.F. Vance and H. Zhao. 2001. Selenium adsorption on Mg-Al and Zn-Al Layered Double Hydroxides. Applied Clay Science 20:13-25.

You, Y.W., H. Zhao and G.F. Vance. 2001. Removal of arsenite from aqueous solutions by anionic clays. Environmental Technology 22: 1447-1457.

You, Y.W., H. Zhao and G.F. Vance. 2002. Adsorption of dicamba (3,6 dichloro-2-methoxy benzoic acid) in aqueous solution by calcined-layered double hydroxides. Applied Clay Science 21(5/6):217-226.

You, Y.W., H. Zhao and G.F. Vance. 2002. Hybrid organic-inorganic derivatives of layered double hydroxides and dodecylbenzenesulfonate: Preparation and adsorption characteristics. Journal of Material Chemistry 12:907-912.

You, Y.W., H. Zhao and G.F. Vance. 2002. Surfactant-enhanced adsorption of organic compounds by layered double hydroxides. Colloids and Surfaces: Physicochemical and Engineering Aspects 205:161-172.

You, Y.W. and G.F. Vance. 2002. Sodium-Zinc exchange selectivity on Wyoming montmorillonite in different background anion solutions. Pedosphere 12:289-299.

You, Y.W., H. Zhao and G.F. Vance. 2002. Surfactant-enhanced adsorption of organic compounds by layered double hydroxides. Clay Minerals Society Abstracts 39:181.

You, Y.W., G.F. Vance, D. Sparks, J. Zhuang and Y. Jin. 2003. Sorption of MS2 Bacteriophage to Layered Double Hydroxides: Effects of Reaction Time, pH, and Competing Anions. Journal of Environmental Quality (In press)

Zhao, H. and G.F. Vance. 1998. Molecular inclusion properties of hydrophobic organic compounds by a modified β-cyclodextrin intercalated within a layered double hydroxide. Journal of Inclusion Phenomena and Molecular Recognition in Chemistry 316:305-317.

Zhao, H. and G.F. Vance. 1998. Selectivity and molecular sieving effects of organic compounds by a β-cyclodextrin-pillared layered double hydroxide. Clays and Clay Minerals 46:712-718.

Zhao, H. and G.F. Vance. 1998. Sorption of trichloroethylene by organo-clays in the presence of humic substances. Water Research 32:3710-3716.

Zhao, H. and G.F. Vance. 1998. Sorption of organic compounds by the intercalates of beta-cyclodextrin and layered double hydroxide. Clay Minerals Society Abstracts 35:50.

Zhao, H., K.L. Nagy, J.S. Waples and G.F. Vance. 2000. Surfactant-templated mesoporous silicate materials as sorbents for organic pollutants in water. Environmental Science and Technology 34:4822-4827.

Zhao, H., Y.W. You, and G.F. Vance. 2002. Hybrid organic-inorganic derivatives of LDHs and dodecylbenzenesulfonate: Preparation and adsorption characteristics. Agronomy Abstracts CD-ROM

Indirectly Connected to the DOE EPSCoR Funding

Cassel-Sharmasarkar, F., S. Sharmasarkar, R. Zhang, G.F. Vance and S. Miller. 1999. Micro-spatial variability of soil nitrate following nitrogen fertilization and drip irrigation. Water, Air and Soil Pollution 116:605-619.

Cassel-Sharmasarkar, F., S. Sharmasarkar, R. Zhang, G.F. Vance. S.D. Miller and J.M. Reddy. 2000. Modeling nitrate movement in sugarbeet soils under flood and drip irrigation. International Commission of Irrigation and Drainage Journal 49:43-54.

Cassel-Sharmasarkar, F., S. Sharmasarkar, S.D. Miller, L.J. Held, G.F. Vance and R. Zhang. 2000. Assessment of microirrigation practices for sugarbeet production. Journal of Sustainable Agriculture 17:17-32.

Cassel-Sharmasarkar, F., S. Sharmasarkar, S.D. Miller, G.F. Vance and R. Zhang. 2001. Assessment of drip and flood irrigation on water and fertilizer use efficiencies for sugarbeets. Agricultural Water Management 46(3):241-251.

Christensen, B.M., G.F. Vance, L.C. Munn and J.A. Young. 2003. Applications of land evaluation/site assessment (LESA) and a geographic information system (GIS) in East Park County, Wyoming. Soil and Water Conservation Journal 58(2):105-112.

David, M.B., G.F. Vance and J.S. Kahl. 1999. Chapter 7 "Chemistry of Dissolved Organic Carbon at Bear Brook Watershed, Maine: Stream Water Response to (NH4)2SO4 Additions" In: S.A. Norton and I.J. Fernandez (eds.) The Bear Brook Watershed in Maine: A Paired Watershed Experiment - The First Decade (1987-1997). Kluwer Academic Publishers, Norwell, MA. pp. 149-163.

David, M.B., G.F. Vance and J.S. Kahl. 2000. Chemistry of dissolved organic carbon at Bear Brook Watershed, Maine: Stream water response to (NH4)2SO4 additions. Environmental Monitoring and Assessment 55:149-163.

Edinger, K.D., G.E. Schuman and G.F. Vance. 1999. Evaluation of reclaimed abandoned bentonite mine lands. In: S.A. Bengson and D.M. Bland (eds.) Mining and Reclamation for the Next Millennium. American Society for Surface Mining and Reclamation, Lexington, KY. Vol 1:273-286.

Ganjegunte, G.K., G. F. Vance, L. A. King. 2003. Effects of saline-sodic water irrigation/land disposal on soil properties. Agronomy Abstracts CD-ROM

Ganjegunte, G.K., G. F. Vance, P. D. Stahl and G. E. Schuman. 2003. Carbon sequestration under different grazing regimes. Agronomy Abstracts CD-ROM

Johnson, C.D. and G.F. Vance. 1998. Accumulation of trace elements in plants and soils: Effects of long-term sludge amendments. Agricultural Experiment Station Bulletin B-1062. University of Wyoming, Laramie, WY. 10 pp.

King, L.A., G.F. Vance and G.K. Ganjegunte. 2003. Soil and vegetation impacts from land application of saline-sodic waters. Agronomy Abstracts CD-ROM

King, L.A., G.F. Vance and G.K. Ganjegunte. 2003. Vegetation community responses to saline-sodic waters. Agronomy Abstracts CD-ROM

Krzyszowska, A.J., R.D. Allen, G.F. Vance, R. Zhang and D.E. Legg. 1999. A field lysimeter study to evaluate herbicide transport in a Wyoming irrigated pasture. Communication in Soil Science and Plant Analysis 30:245-263.

Meyer, J and G.F. Vance. 2002. Evaluation of Effects of Soils by Produced Water from Coalbed Methane Operations, Powder River basin, Wyoming and Montana. Eye on Environment: Federal Lands Issue. U.S. DOE National Energy Technology Laboratory. Winter Issue p 6-7.

Miller, B., C.P. Skinner and G.F. Vance. 1999. Environmental selenium relationships: II. Revegetation, remediation and reclamation of seleniferous areas at Fort Carson, Colorado. Proceedings of the Association of American Geographers Meeting. Honolulu HI 95:412.

Pierzynski, G.M., J.T. Sims and G.F. Vance. 2000. Soils and Environmental Quality, 2nd edition. CRC Publishers Inc., Boca Raton, FL. 459 pp.

Pierzynski, G.M., J.T. Sims and G.F. Vance. 2003. Soils and Environmental Quality, 3rd edition. CRC Publishers Inc., Boca Raton, FL. (In progress)

Povirk, K.L., J.M. Welker and G.F. Vance. 2001. Chapter 8 "Carbon Sequestration and Grazing in Cold-Region Environments: Tundra and Mountain Meadow Ecosystems" In: R.F. Follett, J.M. Kimble and R. Lal (eds.) Carbon Sequestration Potential of U.S. Grazing Lands. Ann Arbor Press, Chelsea, MI. pp. 189-228 (Invited)

Schladweiler, B.K., C.P. Skinner and G.F. Vance. 1999. Environmental selenium relationships: III. Selenium concentration in wetland and riparian receptors at Fort Carson, Colorado. Proceedings of the Association of American Geographers Meeting. Honolulu, HI 95:532.

Schladweiler, B.K., G.F. Vance and R. Haroian. 2003. Evaluation of topsoil depth effects on various plant parameters within reclaimed areas in northeastern Wyoming. In: R. Barnhisel (ed.) American Society of Mining and Reclamation and the 9th Billings Land Reclamation Symposium Proceedings, Lexington, KY. CD-ROM pp. 1086-1098.

Schuman, G.E., G.F. Vance and K.D. Edinger. 2001. Long-term effectiveness of bentonite mine spoil amendment in aiding revegetation. In: Land Restoration Success and Sustainability. Society for Range Management 54:114 (Invited)

Sharmasarkar, S., G.F. Vance and F. Cassel-Sharmasarkar. 1998. Analysis and speciation of selenium ions in coal mine environments. International Journal of Geosciences: Environmental Geology 34:31-38.

Skinner, C.P., B.K. Schladweiler and G.F. Vance. 1999. Environmental selenium relationships: I. Using GIS to highlight potentially seleniferous areas at Fort Carson, Colorado. Proceedings of the Association of American Geographers Meeting. Honolulu, HI 95:555.

Skinner, C.P. and G.F. Vance. 1999. Effectiveness of wetland-riparian vegetation in remediation of a disturbed seleniferous environment. 16th National American Society for Surface Mining and Reclamation Proceedings. Lexington, KY. Vol 2:736.

Skinner, C.P. and G.F. Vance. 2001. Soil-geology selenium relationships in disturbed and native ecosystems. In: R. Barnhisel and B. Buchanan (eds.) Land Reclamation - A Different Approach. American Society for Surface Mining and Reclamation, Lexington, KY. Issue 18:300-316.

Skinner, C.P. and G.F. Vance. 2002. Plant-soil selenium in disturbed and native ecosystems. In: R. Barnhisel (ed.) Reclamation with a Purpose. American Society of Mining and Reclamation, Lexington, KY. Issue 19:141-162.

Skousen, J.G. and G.F. Vance. 2003. "Surface Water Pollution from Mining Activities" In: B.A. Stewart and T. Howell (eds.) Encyclopedia of Water Science. Marcel Dekker, Inc. New York, NY (Invited)

Vance, G.F., R.B. See and K.J. Reddy. 1998. Chapter 15 "Selenite Sorption by Coal-Mine Backfill Materials in the Presence of Organic Solutes" In: W.T. Frankenberger, Jr. and R.A. Endberg (eds.) Environmental Chemistry of Selenium. Marcel Dekker, Inc., New York, NY. pp. 259-280 (Invited)

Vance, G.F. and F.J. Sikora. 1998. Selectivity and solubility analysis using ion selective potentiometry: A soil chemistry experiment. Journal of Science Education and Technology. Chemical Engineering Education Publisher. Vol 26(2):119-124.

Vance, G.F. 1998. "An Introduction to Environmental Chemistry", Book Review. Journal of Environmental Quality. 27:466-467.

Vance, G.F., C.P. Skinner, and B.K. Schladweiler. 1998. Evaluation of Environment Selenium Relationships at Fort Carson, Colorado. U.S. Army, Fort Carson DECAM Final Report, Colorado Springs, Colorado. 105 pp.

Vance, G.F. and G.M. Pierzynski. 1999. Bioavailability, Fluxes and Transfer of Trace Elements in Soils and Soil Components Special Symposium: Bioavailability and fate of trace elements in long-term, residual-amended soil studies. 5th International Conference on the Biogeochemistry of Trace Elements. Vienna, Austria, pp. 116-117. (Invited)

Vance, G.F. and L.K. Spackman. 1999. Is it topsoil or overburden? Case study of a small mine in Wyoming. In: S.A. Bengson and D.M. Bland (eds.) Mining and Reclamation for the Next Millennium. American Society for Surface Mining and Reclamation, Lexington, KY. Vol 1:209-224.

Vance, G.F. 2000. Problems associated with selenium leaching from waste shale. In: W.L. Daniels and S.G. Richardson (eds.) A New Era for Land Reclamation. American Society for Surface Mining and Reclamation, Lexington, KY. Vol 17:71-82.

Vance, G.F. and L.K. Spackman. 2000. The topsoil dilemma. In: Striving for Restoration, Fostering Technology and Policy for Reestablishing Ecological Function. Reclamation Research Unit Publication. Montana State University, pp. 135-141.

Vance, G.F. and K.L. Panter. 2001. Backyard composting: Simple small-scale methods. Agricultural Experiment Station Research Publication B-974R. University of Wyoming, Laramie, WY. 8 pp.

Vance, G.F. 2002. "Acidic Deposition" In: Rattan Lal (ed.) Encyclopedia of Soil Science. Marcel Dekker, Inc. New York, NY 6 pp. (Invited)

Vance, G.F. 2002. Undergraduate minor and graduate certificate programs in Reclamation and Restoration Ecology. In: R. Barnhisel (ed.) Reclamation with a Purpose. American Society of Mining and Reclamation, Lexington, KY. Issue 19:1173-1182.

Vance, G.F. 2002. Soil carbon database for Wyoming. Soil Carbon Accounting Systems: I. Carbon Accounting and Monitoring Systems Symposium. Agronomy Abstracts CD-ROM

Vance, G.F. and J.G. Skousen. 2003. "Groundwater Pollution from Mining Activities" In: B.A. Stewart and T. Howell (eds.) Encyclopedia of Water Science. Marcel Dekker, Inc. New York, NY (Invited)

Vance, G.F. and W.B. Stevens. 2003. Soil Characteristics & Planning for Soil Disturbance. p. 1-22. In Sharing Solutions for Successful Plantings in the Northern Great Plains Proceedings, Sheridan, WY. 21-23 May. Lake DeSmet Conservation District, Buffalo, WY pp. 12-33.

Vance, G.F. 2003. Course woody debris and soil organic matter in rocky mountain coniferous forests. Abstracts of the 4th Annual Symposium on Natural Organic Matter in Soils and Water, University of Iowa, Ames, IA.

Vance, G.F. 2003. Influence of coarse woody debris on soil organic substances in a lodgepole pine forest Abstracts of the 4th Annual Symposium on Natural Organic Matter in Soils and Water, University of Iowa, Ames, IA.

Vance, G.F. 2003. Using GIS to Predict Military Areas with Seleniferous Soils and Plants., University of Iowa, Ames, IA. Agronomy Abstracts CD-ROM

Young, J.A., B.M. Christensen, M.S. Schaad, M. Herdendorf, G.F. Vance and L.C. Munn. 1998. Using a geographic information system to identify areas for alternative crops in the bighorn basin, northwestern Wyoming. Proceedings of New Crops and New Uses: Biodiversity and Agricultural Sustainability Meeting. Phoenix, AZ p.51.

Young, J.A., B.M. Christensen, M.S. Schaad, M. Herdendorf, G.F. Vance, and L.C. Munn. 1999. "A Geographic Information System to Identify Areas for Alternative Crops in Northwestern Wyoming" In: J. Janick (ed.) Perspectives on New Crops and New Uses. ASHS Press, Alexandria, VA. pp. 175-180 (Invited)

Young, J.A., B.M. Christensen, M.S. Schaad, G.F. Vance, L.C. Munn and M. Herdendorf. 1999. Using GIS for alternative crop production in northeastern Wyoming, USA. Proceedings of the Association of American Geographers Meeting. Honolulu, HI 95:669.

Young, J.A., G.F. Vance, L.C. Munn, B.M. Christensen and M.S. Schaad. 2000. A Geographic Information System (GIS) for identification of potential alternative crops utilizing soil and climatic variables in the Bighorn Basin, Wyoming. American Journal of Alternative Agriculture 15:160-170.

Young, J.A., B.M. Christensen, M. Schaad, G.F. Vance and L.C. Munn. 2000. Geographic information system identifies alternative crop opportunities for Bighorn Basin producers. Reflections 10:27-30 (received 1st place award for best article)

Young, J.A., G.F. Vance and R. Zhang. 2000. Climatic patterns in the Bighorn Basin, Wyoming. Agricultural Experiment Station Bulletin B-1089. University of Wyoming, Laramie, WY. 11 pp.

Young, J.A., G.F. Vance, L.C. Munn, B.M. Christensen and M.S. Schaad. 2001. Identification of potential alternative crops using a geographic information system in the Bighorn Basin, Wyoming. Agricultural Experiment Station Bulletin B-1109. University of Wyoming, Laramie, WY. 19 pp.

Wanek, P.L., G.F. Vance and P.D. Stahl. 1999. Selenium uptake by plants: Effects of soil steaming, root addition, and selenium augmentation. Communications in Soil Science and Plant Analysis 30:265-278.

Zhang, R., A.J. Krzyszowska-Waitkus, G.F. Vance and J. Qi. 1999. Pesticide transport in field soils. Agronomy Abstracts 91:179.

Zhang, R., A.J. Krzyszowska-Waitkus, G.F. Vance and J. Qi. 2000. Pesticide transport in field soils. Advances in Environmental Research 4:59-68.

PROJECT 2A. REDUCTION OF EMISSIONS FROM DEHYDRATION OF NATURAL GAS

– P.I.'s: B. F. Towler, Petroleum Engineering; and D.A. Bell, Chemical Engineering both of the University of Wyoming

Abstract

Glycol-based natural gas dehydration plants can be major sources of air pollutants. This is because the glycol dessicant, in addition to it's affinity for water, also absorbs aromatic hydrocarbons from the natural gas. These hydrocarbons may be released to the atmosphere when the glycol is dried.

The lack of reliable thermodynamic models has impeded the regulation, design, and operation of dehydration plants to minimize emissions. In this research, we found that the UNIFAC equation of state predictions are a close match to binary mixture data available from the literature. Our attempts to add to this data were unsuccessful because we did not find a reliable means to transfer fluid samples from our apparatus to the gas chromatograph used to analyze the samples. Alternative glycol regenerators (dryers) were modeled. With the alternative designs, air emissions can be largely eliminated, but a contaminated water stream would require further processing.

Background

Natural gas, as it leaves the well, typically contains substantial quantities of water vapor that must be removed before the gas enters the pipeline. Consequently, gas dehydration is a very common surface treatment process. Glycol absorption is the most widely-used natural gas dehydration technique. As shown in Figure 1, the wet natural

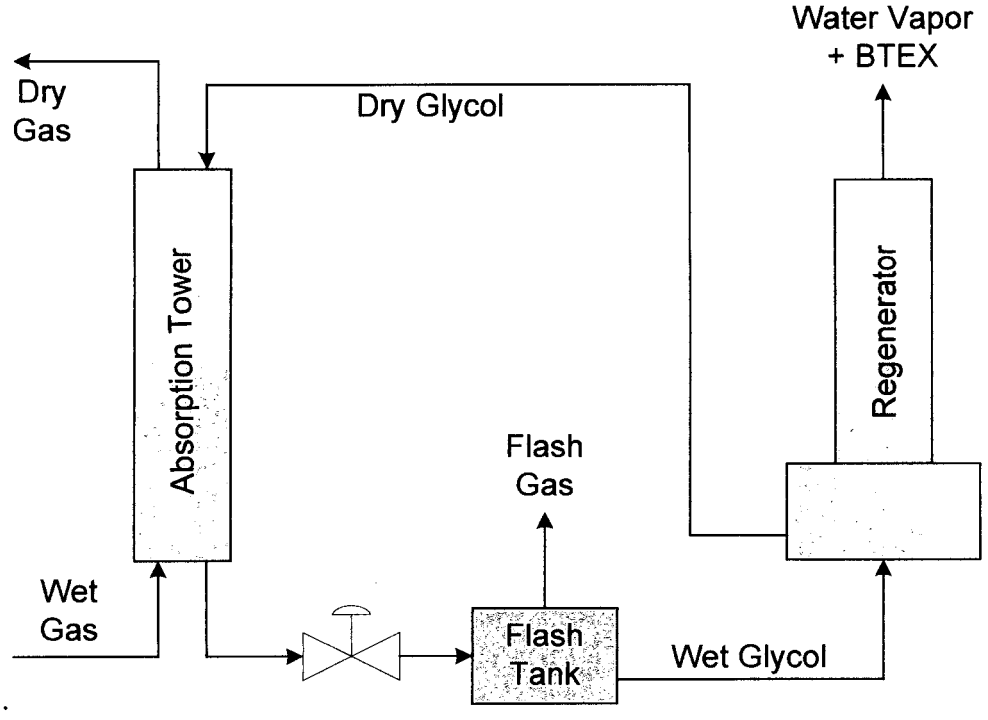


Figure 1. Typical glycol-based natural gas dehydration plant.

gas is contacted with glycol in absorption tower. Triethylene glycol (TEG) is the most widely-used absorbent, but other ethylene glycol oligimers, especially monoethylene glycol (MEG) are also used. The absorption tower typically operates at about 2 to 7 MPa and 15 to 40 °C. The wet glycol leaves the tower, and the pressure is dropped to near-atmospheric levels. Dissolved hydrocarbon gas vaporizes as the pressure is reduced, generating flash gas. The wet glycol is then sent to the regenerator, where it is heated to boil off water. The dry glycol is then returned to the absorption tower. Unfortunately, the glycol has an affinity for aromatic hydrocarbons in the natural gas, collectively know as BTEX (benzene, toluene, ethylbenzene, and xylenes). These are present in the natural gas at low, but significant, concentrations. The dissolved BTEX compounds are vaporized in the regenerator, and, traditionally, the BTEX vapor is vented to the atmosphere along with the water vapor. In many U.S. natural gas dehydration plants, the quantity of BTEX emissions is sufficiently high that they are regulated as major sources under the 1990 Clean Air Act Amendments.

After this research began, many natural gas producers added condensers to their regenerators. The gas leaving the regenerator is condensed, yielding a water-rich liquid and a hydrocarbon-rich liquid. The water-rich liquid is contaminated with dissolved hydrocarbons. In warm climates, refrigeration is needed because cooling water temperatures are too high to adequately condense the regenerator vapor.

Thermodynamic models needed to predict the quantity of BTEX emissions from these plants are poorly developed, and this lack of information hampers regulatory and process design efforts. The development of improved thermodynamic for this process was the major goal of this research.

Experimental Approach

Preliminary experiments were conducted, prior to DOE funding of this project, using an existing vapor-liquid equilibria (VLE) measurement system. The heart of this system was a vapor-liquid contacting vessel, which was made from a commercial high pressure sight glass. To ensure uniform fluid composition and adequate vapor-liquid contact, two circulation loops (one for gas and one for liquid) continually removed fluid from the cell, pumped it past the sampling points, and returned the fluid to the contacting vessel. The contacting vessel and the circulation loops were mounted in a large oven to ensure uniform experimental temperatures.

Sampling valves, designed for gas chromatograph (GC) use, were mounted on the fluid circulation lines inside the oven. These valves could be used to divert a small portion of the recirculating gas or liquid into a flowing stream of helium, which was sent to a gas chromatograph outside of the oven.

During the early experimental phase, this system often leaked. Consequently, the system was rebuilt. The original system used general-purpose fittings, and most of these were replaced by high-pressure fittings. Leakage was much less common after the system was rebuilt.

The GC used in this research was an HP 5790A, purchased in 1983. This GC was equipped with a free fatty acid column that interacts with the glycols. The effluent from this column is initially directed to a second column (Altech Haysep Q) that interacts with the aromatics. The second column effluent passes through a themal conductivity detector (TCD) and a flame ionization detector (FID). After the water, methane, and aromatics leave the first column, and before the glycol leaves the first column, the first column effluent is re-directed though a second FID by a valve between the columns. The analytical technique was refined and calibrated. Since the components analyzed ranged from methane, a low molecular weight,

nonpolar gas, to TEG, a high molecular weight, polar, high-boiling point liquid, the ability of this system to accurately separate and measure calibration mixtures was fairly remarkable. A computer-based data acquisition and control system was built to initiate, record, and analyze the GC measurements.

The key problem with this experimental system was the sampling system used to transfer fluids from the recirculation lines to the gas chromatograph. To obtain accurate data, the composition of the fluid injected into the GC needed to be the same as the composition of the fluid withdrawn at the experimental pressure and temperature. Three general approaches to this problem were attempted. The first approach, the sample transfer line, was the approach used in the original system. We also tried using removable sample bombs installed on the recirculation lines. The third basic approach was a high pressure syringe system. Many variations on each sampling approach were attempted, and all of them failed to deliver accurate fluid samples to the gas chromatograph. After a great deal of time and frustration, we decided that a radically different experimental approach was required, and we had neither the time nor the funds available to investigate such an approach.

System Modeling

Computer-based modeling efforts were initiated, in earnest, after the experimental efforts ended. UNIFAC equation of state[3,4] predictions were compared to experimental vapor-liquid equilibria data, found in the literature[5], for the binary mixtures listed in Table 1. The UNIFAC predictions closely matched the experimental data for all mixtures except for the toluene-diethylene glycol data. The close match between the UNIFAC predictions and the data for the benzene/diethylene glycol mixtures and the diethylene glycol/o-xylene mixtures were especially encouraging, because glycol/aromatic hydrocarbon interactions are responsible for the BTEX emissions from natural gas dehydration plants.

After demonstrating that UNIFAC can be used to model the vapor-liquid data for these components, alternative designs for the regenerator were modeled using this equation of state. The absorbent chosen for this modeling effort was MEG, rather than TEG, because MEG has a lower affinity for BTEX compounds. A potential problem is MEG emissions, since MEG has a lower boiling point than TEG (197 versus 285 °C). Several regenerator configurations and conditions were modeled. Table 2 shows the results for a rectifying column with 6 stages and a partial condenser. The condenser was set at 90 °F (32 °C) based on the assumption that cooling water could be used to attain this temperature. The overhead vapor stream is fairly small, and contains a little less than one-third of the feed BTEX. This stream has very little water, so it could be burned to help fuel the rectifier. Just over two-thirds of the BTEX, and a significant fraction of the ethylene glycol, is contained in the liquid condensate. Further processing.

Table 1. **Experimental data sets used to test the accuracy of the UNIFAC equation of state.**

Component 1	Component 2	Temperature, °C	Pressure, Torr
Benzene	Ethylbenzene	81-135	760
Benzene	p-Xylene	84-129	760
Benzene	m-Xylene	25	29.5-88.8
Benzene	Toluene	81-109	760
Benzene	Toluene	120	1,132-1,868

Benzene	Diethylene Glycol	75	100-636
Benzene	Diethylene Glycol	80-113	760
Toluene	Ethylbenzene	25	14-27
Toluene	p-Xylene	90	207-356
Toluene	Diethylene Glycol	50	56-84
Toluene	Diethylene Glycol	80-113	760
Diethylene Glycol	o-Xylene	150	170-577
Diethylene Glycol	o-Xylene	130	274-632
Diethylene Glycol	Water	149-216	752
Diethylene Glycol	Water	102-159	760

of this stream would be required to recover the ethylene glycol and to produce a water stream that could be discharged.

Conclusions

The UNIFAC equation of state closely matched experimental data for binary mixtures of compounds found in glycol-based natural gas dehydrators. Our attempts to add to the experimental data available in the literature were unsuccessful because we could not find a reliable technique to transfer fluid samples from our vapor-liquid equilibria apparatus to the gas chromatograph used to analyze the samples. Alternative glycol regenerator designs were modeled. We found that BTEX air pollutants could be avoided, but the alternative designs yield a contaminated aqueous liquid that would require further processing.

References

1. Gregg K. Sullivan; "Hydrocarbon Emissions from Natural Gas Dehydrators: Development of a Vapor-Liquid Equilibria Measurement Apparatus," M.S. Thesis in Chemical Engineering, University of Wyoming (2000).

2. John V. Brown; "Mathematical Modeling of the Phase Behavior of a Natural Gas Dehydrator," M.S. Thesis in Chemical Engineering, University of Wyoming (2002).

3. A. Frendenslund; R.L. Jones; J.M. Prausnitz; "Group-Contribution Estimation of Activity Coefficients in Non-ideal Liquid Mixtures," AIChE Journal, vol. 6, pp. 1086-1099 (1975).

4. A. Frendenslund, J. Gmehling, P. Rasmussen; Vapor-Liquid Equilibria Using UNIFAC, Elsevier, Amsterdam (1977).

5. J. Gmehling; U. Onken; Vapor-Liquid Equilibrium Data Collection, Deutsche Gessellschaft für Chemisches Apparatewesen (DECHEMA).

Table 2. **Simulation results for a six stage rectifying column, operating at standard atmospheric pressure, with a partial condenser and a 0.25 reflux ratio. In this simulation, the reboiler and the condenser are each counted as one of the six stages.**

		Vapor Overhead	
Component	Feed, kg/hr	kg/hr	wt. % of feed component
methane	0.00404	0.00275	68.01
benzene	0.124	0.0349	28.11
toluene	0.125	0.0409	32.72
ethylbenzene	0.0135	0.00395	29.27
o-xylene	0.130	0.0400	30.76
water	20.0	0.00247	0.01
ethylene glycol	79.6	3×10^{-6}	0
TOTAL	100	0.15	0.15
Temp., °F (°C)	100 (38)	90 (32)	

	Liquid Condensate		Bottoms	
Component	kg/hr	wt. % of feed	kg/hr	wt. % of feed
methane	0.0129	31.92	3×10^{-5}	0.07
benzene	0.0876	70.62	0.00158	1.27
toluene	0.0829	66.27	0.00126	1.00
ethylbenzene	0.0094	69.69	0.00014	1.04
o-xylene	0.0400	68.31	0.00120	0.93
water	16.5	82.74	3.45	17.24
ethylene glycol	6.03	7.58	73.6	92.42
TOTAL	22.9	22.9	77.0	77.0
Temp., °F (°C)	90 (32)		316 (158)	

PROJECT 2B. SUPERCRITICAL FLUID ATOMIZATION (SCFA) OF ULTRA-HIGH VISCOSITY MATERIALS

PI's: M. P. Sharma, Petroleum Engineering; W. R. Lindberg and P. A. Dellenback, Mechanical Engineering, all of the University of Wyoming
Collaborators: K. Nielsen, Union Carbide Corporation; D. Edgar, Argonne National Laboratory; M. Donohue, Johns Hopkins University

Outside Collaborating Organizations

Union Carbide/Dow Chemical (Contact Person: Dr. Ken Nielsen, Senior Research Scientist)

Summary

The atomization of ultra-high viscosity (UHV) materials is a critical component in many industrial processes (spray coating, spray drying, heavy oil/waste combustion). Unfortunately, present atomization technologies are limited to viscosities of less than approximately 500 cP.

Consequently, the current approach to atomizing these materials is to thin with solvents, whose emissions are severely restricted, or to heat the fluid stream. At best, this approach results in significant hazardous emissions as well as significant energy usage to heat the materials and control emissions. More significantly, new materials that offer significant process advances are not used since they can not be atomized with present atomization technologies that rely on hydrodynamic instability mechanisms. In contrast, Supercritical Fluid (SCF) Atomization using carbon dioxide offers the potential to atomize UHV materials with minimal environmental impact and at low cost (see Figure 1).

The goals of the project were to (a) establish the rheological bounds for SCF atomization, (b) to investigate the effects of pressure and temperature on CO_2 solubility in a range of polymers (UCON polymers supplied by Union Carbide/Dow Chemical) and (c) to determine and correlate the phase behavior of these polymers and the supercritical CO_2 for characterizing the operating parameters (pressure, temperature, and supercritical CO_2 loading) for the best sprayability of the polymers, (d) investigate the choking flow behavior of the mixture of supercritical CO_2 and polymers, and (e) investigate the effect of different nozzle geometry and designs on the spray quality.

In addition to the DOE/EPSCoR support, considerable technical, financial, equipment and materials assistance was provided by the Union Carbide/Dow Chemical Corporation in assembling and building a state-of-the art experimental facility. Equipment purchased through DOE/EPSCoR support has enabled us to carry out the objectives of this research on improving the understanding and applications of Supercritical Carbon Dioxide technology. The facility has now enabled us to competitively carry out a research project partially funded by Dow Chemical to study the "Mechanisms of Making Micronized Powders using Decompressive Spray Drying".

The research effort successfully addressed all of the project goals, with more limited success for goal (c). The chosen working fluids proved to be difficult to work with, due to the fluid's unanticipated high affinity for CO_2. In addition, the development of high-speed, high-magnification spray imaging techniques have revealed many details of the atomization process which have only been speculated upon prior to this work.

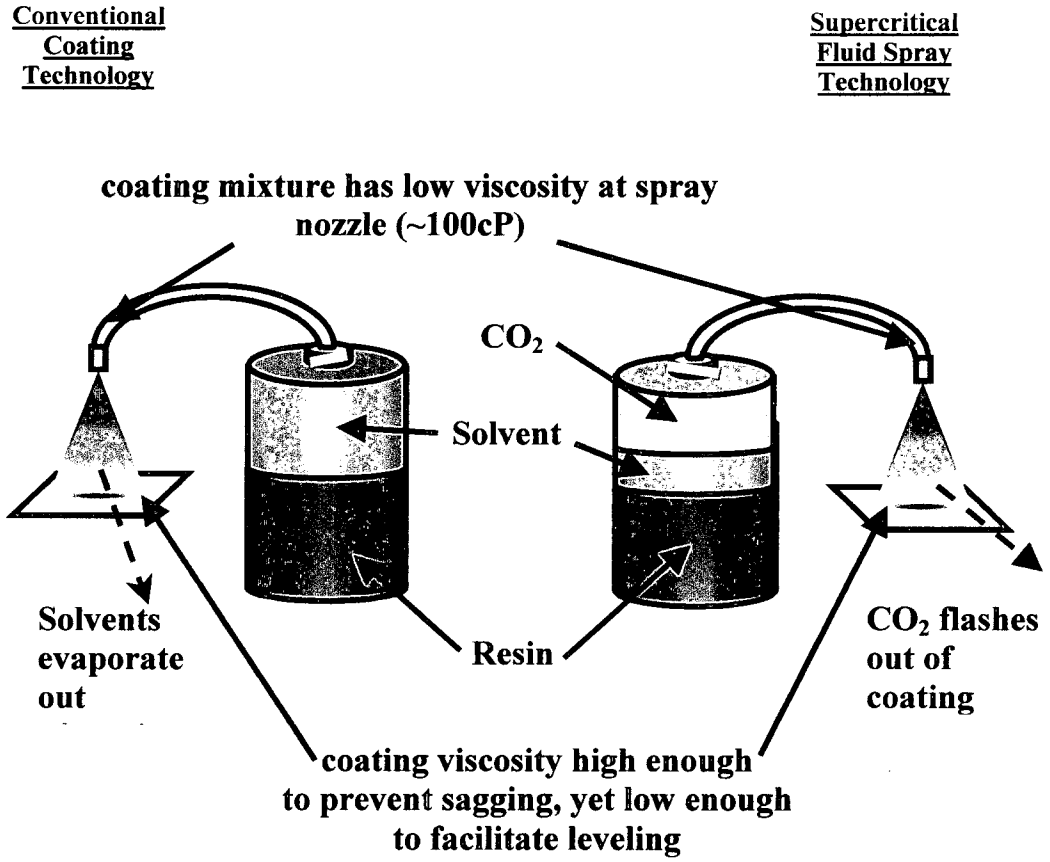


Figure 1 – Comparison of the supercritical spray process to conventional spray techniques.

Background and Problem Description

The present approach of reducing the viscosity of high and ultra high viscosity materials with solvent addition or heating to a level that may be atomized with conventional atomization technologies is not only VOC generating and energy intensive, but more importantly, it has severely limited the scope of materials considered for industrial processes. For example, paint formulators have consistently rejected high molecular weight systems which exhibit superior physical or chemical properties but which are too viscous (or visco-elastic) to apply properly at economical solids loadings. There is clearly a need for atomization technologies that are not limited by hydrodynamic instability considerations and applicable to high viscosity materials. In addition to reducing the adverse solvent (VOC) emissions and energy impact of current processes, these technologies could facilitate the use of new materials which would provide step-wise as opposed to incremental process advances.

Supercritical fluid (SCF) atomization, is presumed to depend on nucleation as opposed to hydrodynamic instability mechanisms for atomization. The basic approach to SCF atomization is to mix the material to be atomized with a driver fluid at or near its critical point and then to pass

the mixture through a nozzle. While passing through the nozzle, the mixture is subjected to a rapid decompression (on the order of microseconds). This serves to separate the mixture and diluent on a very fine scale (on the order of microns or less) which leads to fine atomization. This mechanism is in sharp contrast to the hydrodynamic instability mechanisms of conventional atomization. Consequently, one would expect the atomization quality to be controlled by solubility and nucleation rate considerations as opposed to viscous considerations (Refs.1,2,3). Because of a distinct mechanism involved in atomization, this process has been termed the "Decompressive Spray" method.

In selecting a driver fluid, careful consideration must be given to its solubility in the material to be atomized, its critical temperature and pressure, its cost and its environmental impact. Ideally, driver fluid solubility should be sufficiently high to facilitate fine atomization, the critical temperature and pressure should be low enough so that standard components may be used, the cost should be low and the environmental impact low. For many materials, carbon dioxide fulfills these criteria. Union Carbide (prior to its merger with Dow Chemical) commercialized the supercritical fluid spray process for the application of coating materials. In spite of the initial success of the SCF atomization coating processes, there continues to be a need for systematic studies of the basic mechanisms to help explain and control the spray dynamics (Refs. 1,2,3) and thus design appropriate fluid and spray systems for quality coatings with reduced environmental impact. Dow Chemical has been continuing its efforts to understand fundamentals of this process to further improve this technology and scope.

Description of Experimental Approach

The basic experimental approach used in this research was a combination of several experimental techniques to investigate the phenomena and identify the mechanisms. The approach was built upon using (a) a phase-behavior (PVT) cell specially designed and built for studying super-critical conditions of carbon dioxide in mixture with polymers of our concern (a "Phaser III" unit), (b) a supercritical fluid spray batch system (c) a continuous spraying equipment fitted with temperature and pressure controls for creating supercritical conditions (a "PT-II" unit), (d) a spray-gun fitted to accommodate various sizes and designs of spray nozzles, (e) high speed photographic techniques, (f) optical spray diagnostic methods for measuring the size of atomized droplets in the spray. The fluids that were used in the study were supplied by Union Carbide/Dow Chemical. These materials, with a trade name of UCON fluids, were polyalkalyne glycol monomer materials with a wide range of viscosities.

Different classes of UCON fluids were blended to yield viscosity in the range of 100 to 10,000 cP. The phase behavior of these polymers and polymer mixtures with supercritical CO2 was studied using the Phaser III equipment to delineate their phase transition boundaries. These polymer mixtures were sprayed with supercritical CO_2 using the batch supercriticall fluid spray system. The atomization quality (drop size distribution) of the resulting sprays was evaluated with Fraunhofer diffraction light scattering methods (using Malvern System). Parametric variations in carbon dioxide loading, mixture pressure and mixture temperature were measured. The parameter bounds were determined by practical hardware considaations as well as solubility considerations. The internal and external nozzle flows were examined via high-speed photography (10 nanosecond pulse widths). These images provided considerable information on the mechanisms that limit atomization performance at specific carbon dioxide loadings, inlet pressures and inlet temperatures.

Results and Discussions

- Prior to spray studies using UCON fluids, an extensive series of experiments were performed using acryloid polymer coatings (automotive clear-coat). Nozzle length was identified as the most important parameter in obtaining sprays with small droplets and wide spray spans. Smaller L/D ratios were found to give better spray quality (narrow droplet size distribution). V-grooved exit produces better spray quality compared to axisymmetric nozzles. Reduction in operating pressure, temperature and carbon dioxide loading led to formation of sprays with narrower angles and spray spans (Ref. 7).

- A series of experimental tests were made on the detection and measurement of the choking behavior of SCF spray nozzles. Data indicates that choking behavior is dominated by the supercritical CO_2 conditions and not by the particular coating that is being sprayed (Ref. 8). More detailed examination and modeling of this important phenomenon is still in progress.

- Data on rheological bounds of SCF spray: A very complete study of the viscous and phase behavior of CO_2/polymer systems using selected fluid polymer series has been completed (Ref. 9).

- Development of external R/D partnerships: (a) A series of research and development collaborations with private industry have evolved, principally with Dow Chemical. However, collaborative studies which center on the use of environmentally friendly agricultural spray additives have also been ongoing. For example, the initial testing emphasis has been on use of guar gum as an adjuvant additive. (b) proposals to the Department of Defense (Navy and Air Force) to study the potential of supercritical CO_2 in extracting oily contaminants from bilge-water, chrome(0) plating and field coatings with minimal overspray (Ref. 10). The cooperative ventures of these high-risk, high-gain proposals have been with Argonne National Laboratory and Federal Energy Technology Center scientists.

Conclusions

Some of the prominent conclusions of the study can be summarized as follows:

- The study conducted on "Physical Properties of Polyalkalene Glycol Fluids (UCON Fluids) with Supercritical Carbon Dioxide" using the Phaser-III system: (a) laid the ground work for understanding the phase behavior and solubility characteristics for creating Decompressive atomization, and (b) provided the quantitative boundaries for the "window of operating variables" for the sprayability of such polymers/coatings .

- Spray studies have shown that a dramatic decrease in drop size results when conditions of a Decompressive spray is achieved; and consequently a very significant increase in spray quality is achieved (low SMD's).

- It was found that the atomization mechanism of Decompressive Sprays is quite different than the usual "viscous-surface tension" mechanisms. A detailed characterization and understanding of the mechanism was achieved by using high-speed photographic techniques.

- Nucleation kinetics and solubility kinetics of the polymer/CO_2 system were found to play a very dominant role in the sprayability of high viscosity fluids (beyond the steady phase equilibrium boundaries). They seem to be even more important and controlling than viscosity effects in Decompressive Atomization mechanism.

- The studies on viscosity reduction of the polymers showed a decrease in the viscosity as the CO_2 concentration is increased. However, a point of diminishing returns was reached (the viscosity is reduced by nearly an order of magnitude as the CO_2 concentration is increased from zero to 30 wt%.)

- The decompressive spray, including good spray quality, typically occurs when spraying at conditions near the phase boundary measured by the phaser test cell. Decompressive spray can occur either above or below the phase boundaries and mapping of each spray condition is necessary.

Future Goals and Objectives

The Coatings and Applications Laboratory is currently involved in a joint study with Dow Chemical on the spray drying of fine particles, using SCF technology. The work being done at the University is a continuation of the imaging work that was developed under the DOE/EPSCoR effort, where an understanding of the atomization process is critical to proper modeling of spray drying techniques. Much of the work continues to have a proprietary component, where archival publication will lag the research by a longer period of time than is typical.

A current goal is to accelerate the publication of previous SCF atomization work (including the DOE/EPSCoR research effort) in the archival literature and at conferences, such as ILASS (Institute for Liquid Atomization and Spray Systems).

In the course of the research program, significant progress has been made in the development of theoretical models for the SCF spray process (choking behavior, compressible supersonic nozzle flows and solubility kinetics). The principal investigators plan on further developing these models as they represent very useful tools in the design and application of this technology.

The National Science Foundation has in place two programs that are very appropriate for this research and the resulting industrial interaction: GOALI (Grant Opportunities for Academic Liaison with Industry) and the NSF/EPA Partnership for Environmental Research: Technology for a Sustainable Environment. We are currently in discussions with Dow Chemical to explore possible joint programs for GOALI/TSE. A major advantage to this approach is the added flexibility the University would have to pursue longer-term, high-risk/high-gain research, while at the same time utilizing our Dow associates and Dow's technology and expertise.

While the experimental imaging capability of the Laboratory is vastly improved, future capabilities that will be necessary include a second, sequentially pulsed laser (for particle

tracking in time) and a high-speed digital camera (capable of buffering sequential, high-resolution images). Such systems are being written into research proposals (by the Coatings and Applications Laboratory and also by the UW Aeronautical Laboratory (UWAL) and UW Active Aero Center, whose technical interests are aligned with the scientific nature of the high-speed, two-phase fluid flow systems that comprise SCF spray systems.

References

(1) Lefebvre, A.H., Atomization and Sprays. Hemisphere Publishing, New York, 1989.

(2) Nielsen, K.A., C.W. Glancy, K.L. Hoy and K.M. Perry, "A New Atomization Mechanism for Airless Spraying: The Supercritical Fluid Spray Process", Proceedings of the Fifth International Conference on Liquid Atomization and Spraying Systems, MD, July 1991, NIST Special Publication 813, pp. 367-374.

(3) Senser, D.W., J.D. Colwell and K.A. Nielsen, " A Comparison between the Structure of Supercritical Fluid and Conventional Air Paint Sprays", Proceedings of the Seventh Annual ILASS-Americas Conference on Liquid Atomization and Spray Systems, Bellevue, WA, May 31-June 3, 1994, pp. 35-39.

(4) Lee, Y. M. and R.A. Berry, "Quasi-One-Dimensional Analysis of the Two-Phase Flow in a De Laval Spray Coating Nozzle and Exit Plume", Proceedings of the 1993 National Thermal Spray Conference, Anaheim, CA., June 7-11, 1993.

(5) Sharma, M.P. and C.T. Crowe, " A Numerical Model for Gas-Particle Flow Through an Orifice", International J. of Mathematical Modeling, Vol. 9, No. 9, pp. 691-700, September 1987.

(6) Miller, R.L., D.M. Jain, and M.P. Sharma, "Modeling Venturi Scrubber Performance for Particulate Collection and Pressure Drop", Chemical Engineering Communications, May 1990.

(7) Sridhar, M. V., "Atomization Characteristics of Supercritical Fluid Sprays", M.S. Thesis, May 1996, Mechanical Engineering Department, University of Wyoming.

(8) Kaushik, Ravi, "Choking Behavior of Supercritical Fluid Spray Nozzles", M.S. Thesis, 1999, Mechanical Engineering Department, University of Wyoming.

(9) Sizemore, Sarah, "Physical Properties of Polyalkylene Glycol Fluids with Application to Supercritical Fluid Sprays", M.S. Thesis, December 1998, Environmental Engineering Program, University of Wyoming.

(10) Sharma, M.P., W.R. Lindberg, and R.W. Peters, "An Innovative Technique for Separating/Extracting Hydrocarbon Contaminants from Shipboard Bilgewater Using Supercritical CO2 Treatment", Proposal submitted to Department of Defense, Arlington. VA, July 1998.

Schroeder, Karl and W.R. Lindberg "Chrome Plating by Thermal Decomposition of Chromium Complexes", (a joint proposal with DOE/FETC and U of Wyoming) . Submitted to SERDP program, 1998.

Lindberg, W.R., M.P. Sharma, "Field Spray Coating Methods for Aircraft: the Trade-offs Between Surface Quality and Particle Size", Submitted to SERDP Program, 1998.

(11) Crowe C.T., M. Sommerfeld, and Y. Tsuji, "Multiphase Flows with Droplets and Particles", CRC Press, 1998.

APPENDIX
Other Information in Nuggets and Bullets Format

Main Achievements:

- Identification that the solubility kinetics of the polymer/CO_2 system plays a dominant role in the sprayability of high viscosity fluids; it portends to be even more important than viscosity effects.
- Development of high-speed spray imaging techniques for investigating and identifying the mechanisms of atomization.
- Important progress in the clarification of the details of the atomization mechanism for SCF (Supercritical Fluid) spray formation.

Added Research Capabilities:_ during the performance of this project following research capabilities and facilities were added and/or enhanced in our laboratories:

- Our High-speed photography facility has been enhanced by adding (a) Ultra CFR Pulsed YAG Laser System that has capability of flash durations to 7 nanoseconds, and (b) high speed cameras/film.

- The lease of the Phase III and PT-II System with the Malvern Laser System to the University by Union Carbide/Dow Chemical has added to our capability of working with Supercritical Fluid phase behavior and Spray behavior research.

- These facilities have given us capability to work on the investigations of understanding the process of "Micronized Powder Making"

Disseminations:

"Physical Properties of Polyalkalyne Glycol Fluids with Application to Supercritical Fluid Sprays" by S.E. Sizemore, W.R. Lindberg, M.P. Sharma, , and Matt Hittle. Presented (by Matt Hittle) at AIChE 1999 Annual Meeting Session-01F02-Replacement Solvents, Dallas, October 31- November 5, 1999.

"Sprayability Investigation of High Viscosity Coating Materials Using Supercritical Carbon Dioxide", by Matt Hittle, M.P. Sharma, and W.R. Lindberg. Presented at AIChE Spring 2000 meeting, Session-96- Practical Topics in Polymer Production and Applications, Atlanta, March 5-9, 2000.

Patent Disclosure: "Variable Pattern Supercritical Fluid Nozzle" August, 1999: John Carter, W.R. Lindberg and K.A. Nielsen (filed through Union Carbide Corporation).

Proposals:

Funded Projects:

- "An Experimental Study of the Flow through Supercritical Fluid Nozzles and Corresponding Spray Characteristics" (W.R. Lindberg) Union Carbide Corporation, $70,000 (funding initiated in 1997).

- "Micronized Powders By Decompressive Spray Drying" (co-PI with Dr. W.R. Lindberg), Dow Chemical Corporation, $40,000 (funded for 1-year, 2002-2003)

- "Use of Guar Gum as a Biological Amendment" with RANTC, Sheridan, WY, USDept. of Agriculture, UW share: $15,000 (funded, 2000).

- "Improved Natural Gas Storage Well Remediation", A collaborative (industry, national laboratory, university) proposal to the Federal Energy Technology Center (FETC). J.C. Furness (Furness-Newburge, Inc., KY), R.W. Peters (Argonne National Lab, IL), M.P. Sharma (University of Wyoming), J.R. Wilson (Nicor Gas Co., IL); $800,000 (2 years), May 13, 1999. (Funded,2000-02)

Proposal submitted (but not funded):

- "An Innovative Technique For Extracting and Separating Hydrocarbon Contaminants from Bilge and Wastewater Using Supercritical CO_2 Treatment", M.P. Sharma, W.R. Lindberg, and R.W. Peters (Argonne National Lab), submitted to U.S. Department of Defense, Office of Naval Research, Arlington, VA., ($345,000/ 3 years), August 1998.

- "Chrome Plating by Thermal Decomposition of Chromium Complexes", W.R. Lindberg and Karl Schroeder, DOE/FETC. Submitted to SERDP program, 1998.

- "Enhanced Supercritical CO_2 Process for Extraction/Separation of Hydrocarbons from Wastewater", M.P. Sharma, W.R. Lindberg, R.W. Peters (Argonne National Lab.), submitted to National Science Foundation/Wyoming EPSCoR, ($453,000/ 3 years), January 1999.

- "Sweetwater Pit Reclamation Project Phase I: Evaluation of Alternative Options", PIs: K.J. Reddy, J.P. Turner, Q.D. Skinner, M.P. Sharma, R.W. Peters (Argonne National Lab.),, and B.L. Perryman; submitted to Kennecott Uranium Company, ($1,150,000/ 2 years), March 1999.

- "Development of an In-Situ Combination Process Using Enhanced Electrokinetics and Surfactant treatment for Remediation of Heavy Metals and Radionuclides contaminated Vadose Zone", R.W. Peters (Argonne National Lab) and M.P. Sharma, A joint proposal submitted to the Subsurface Contaminant Focus Area of the US Department of Energy, $86,700 (UW portion for 2 years). This solicitation was only open to national laboratories (universities can participate as sub-contractor); submitted through the Argonne National Lab, Junel, 1999.

- "Remediation of Trichloroethylene (TCE) and Other Chlorinated Organics from Contaminated groundwater Using Sonication and Vapor Stripping", M.P. Sharma and R.W. Peters (Argonne National Lab); A pre-proposal submitted to Wyoming EPSCoR Program Office for the US Department of Defense, $446,000 (3 years); July 20,1999.

- "Advanced Technologies for Stripper Gas Well Enhancements", A collaborative (industry, national laboratory, and university) proposal; J. R. Wilson (Nicor Technologies, IL), M.W. Fugate (Nicor Gas Co.), J.C. Furness (Furness-Newburge, Inc., KY), R.W. Peters (Argonne National Lab, IL), M.P. Sharma (University of Wyoming); $780,000 (2 years), July 20, 1999.

- "Remediation of Trichloroethylene (TCE) and Other Chlorinated Organics from Contaminated Groundwater Using Sonication and Vapor Stripping", M.P. Sharma and R.W. Peters (Argonne National Lab); A Proposal submitted to US Department of Defense (EPSCoR Program) Office, $446,000 (3 years); August 30,1999. (not funded)

- "Advance anode materials for electro-osmotic-pulse technology to control water intrusion in porous structures": S. Sarangpani (PI, Innovative Chemical and Environmental Technology, Inc, Norwood, MA), M.P. Sharma (Co-PI), August 2000, DOE/SBIR, $33,200 (UW portion).

PROJECT 2C. MASS TRANSFER STUDIES FOR BASE HYDROLYSIS OF EXPLOSIVES - *D. A. Bell, Chemical Engineering*

Collaborator: R. L. Flesner, Los Alamos National Laboratory

Base hydrolysis is an environmentally-benign method for the disposal of high explosives. The traditional disposal technique is open burn/open detonation. Concern about the release of toxic explosive compounds to the environment and the unconfined, uncontrolled nature of open burn/open detonation has prompted the search for confined, environmentally-benign alternatives. The explosives of interest in this project are HMX (1,3,5,7-tetraaza-1,3,5,6-tetranirocyclooctane) and the HMX-based, plastic-bonded formulations used in DOE weapons systems.

In base hydrolysis, solid explosives are mixed with an aqueous base, such as sodium hydroxide, sodium carbonate, or ammonia. The explosive compounds react with the base to form water-soluble, non-explosive compounds, and a small amount of gas. Our research showed that the water-soluble compounds include nitrite, nitrate, formate, and acetate ions, hexamine, and a large number of unidentified organic compounds.

The liquid product of the hydrolysis reaction must be further treated prior to release to the environment. Successful post treatment techniques include supercritical water oxidation and molten salt oxidation. Biodegradation of ammonia hydrolysis fluids has been demonstrated, but biodegradation was not successful when sodium hydroxide was used.

Coupled Kinetic/Mass Transfer Models for Base Hydrolysis

Prior to this project, the rate of reaction for the base hydrolysis of dissolved HMX was known[1]. Since HMX is only very slightly soluble in water, practical hydrolysis reactors operate with a mixture of aqueous base and solid explosive. Initially, the reaction was carried out in

atmospheric pressure reactors, but the reaction time required for complete destruction at temperatures less than the boiling point of water is unreasonably long. Consequently, experiments were initiated to measure reaction rates in pressurized reactors at temperatures above the boiling point of water. Initial results at these higher temperatures suggested that the reaction may be mass transfer limited, that is, limited by the rate of HMX dissolution and convection away from the solid/liquid interface.

We successfully used film theory, normally used to describe gas/liquid reactions, to develop a model for the base hydrolysis of HMX and HMX-based, plastic-bonded explosives (PBX 9404 and PBX 9501). The bases were sodium carbonate[2] and sodium hydroxide[3]. Only a single fitting parameter, related to the surface/volume ratio for the particles, was required to correlate the experimental data. The sodium hydroxide model is being used to guide operations in a pilot scale reactor that was assembled at Los Alamos National Laboratory and installed at the Pantex weapons plant[4].

During the course of this research, Harradine[5] showed that, under a limited set of conditions, the explosive would detonate during hydrolysis. We were able to explain Harradine's results by adding heat of reaction and heat transfer effects to the film theory model. At high reaction rates, the solid/liquid surface can be significantly hotter than the bulk liquid, and if the rate of heat generation is greater than the rate of heat loss to the bulk liquid, the surface temperature can rapidly rise, resulting in a detonation. Based on this model, safe operating conditions were recommended. This work will be the subject of a forthcoming paper.

Funding Sources

This research was carried out at Los Alamos National Laboratory, primarily by Robert Bishop, a University of Wyoming graduate student. Most of the project funding came from DOE/DOD Memorandum of Understanding funds that were awarded to Los Alamos. Funds from DOE/EPSCoR were used for graduate student tuition, faculty summer salary, and travel.

References:

1. Heilmann, H.M.; Senstrom, M.K.; Hesselmannn, R.P.X.; Weismann, U.; Kinetics of the Aqueous Alkaline Homogeneous Hydrolysis of High Explosive 1,3,5,7-Tetraaza-1,3,5,7-Tetranitrocylcooctane (HMX). *Wat. Sci. Tech.* **1994**. *30,* 53-61.

2. Bishop, R.L.; Flesner, R.L.; Dell'Orco, P.C.; Spontarelli, T.; Larson, S.A.; Bell, D.A. Application of Gas-Liquid Film Theory to Base Hydrolysis of HMX Powder and HMX-Based Plastic-Bonded Explosives Using Sodium Carbonate. *Ind. Eng. Chem. Res.* **1998**. *37,* 4551-4559.

3. Bishop, R.L.; Flesner, R.L.; Dell'Orco, P.C.; Spontarelli, T.; Larson, S.A.; Bell, D.A. Application of Gas-Liquid Film Theory to Base Hydrolysis of HMX Powder and HMX-Based Plastic-Bonded Explosives: Treatment with Sodium Hydroxide. To be published, pending revisions, in *Ind. Eng. Chem. Res.*

4. Flesner, R.L.; Brewer, R.; Larson, S.A.; Polston, C.; Le, L.; Muske, K.; Dell'Orco, P.C.; Bishop, R.L.; Archuleta, F.; Uher, K. Pilot-Scale Pressurized Base Hydrolysis of HMX Plastic-Bonded Explosives. Presented at *6th Global Demilitarization Symposium,* May 14, 1998, Coeur d' Alene, Idaho.

5. Harradine, D.; Bishop, R.L.; Flesner, R.L.; Safety Analysis: Reaction Temperature Limits for the Base Hydrolysis of HMX-Based Explosives. Presented at *6th Global Demilitarization Symposium,* May 14, 1998, Coeur d' Alene, Idaho.

WYOMING DOE EPSCoR PATENT INFORMATION

Faculty	Technology #	Date	Serial No.	Status	App Type	Title
Agarwal, Pradeep						
US	00-002	1/25/2000	60/177,829	Expired	Provisional	Dust Suppression System
US	00-002	1/24/2001	09/768,714	Issued	Utility	Dust Suppression System
US	01-001	6/14/2000	60/211,317	Expired	Provisional	Apparatus and Method for the Production of Methanethiol
	01-001	6/13/2001	PCT/US01/18984	Filed	PCT	Apparatus and Method for the Production of Methanethiol
Canada	01-001	6/13/2001	2,412, 057	Filed	Nationalized PCT	Apparatus and Method for the Production of Methanethiol
Japan	01-001	12/13/2002	2002-510434	Filed	Nationalized PCT	Apparatus and Method for the Production of Methanethiol
Republic of Korea	01-001	12/13/2002	2002-7016991	Filed	Nationalized PCT	Apparatus and Method for the Production of Methanethiol
Mexico	01-001	12/13/2002	PA/A/2002/012448	Filed	Nationalized PCT	Apparatus and Method for the Production of Methanethiol
Brazil	01-001	12/13/2002	PIO111690-B	Filed	Nationalized PCT	Apparatus and Method for the Production of Methanethiol
US	01-001	12/12/2002	10/318,392	Filed	Nationalized PCT	Apparatus and Method for the Production of Methanethiol
European	01-001	1/14/2003	1,948,344	Filed	Nationalized PCT	Apparatus and Method for the Production of Methanethiol
Australia	01-001	6/13/2001	2,001,269,805	Filed	Nationalized PCT	Apparatus and Method for the Production of Methanethiol
US	01-007	9/27/2000	60/235,998	Expired	Provisional	Conversion of Methane in Nonthermal,Silent, and Pulsed Corona Discharge Reactors
	01-007	9/26/2003	PCT/US01/30110	Filed	PCT	Conversion of Methane in Nonthermal,Silent, and Pulsed Corona Discharge Reactors
US	01-007	3/21/2002	10/393,843	Filed	Nationalized PCT	Conversion of Methane in Nonthermal,Silent, and Pulsed Corona Discharge Reactors
European	01-007	4/28/2003	1,975,413	Filed	Nationalized PCT	Conversion of Methane in Nonthermal,Silent, and Pulsed Corona

					Discharge Reactors
Japan	01-007	3/25/2003	2002-530200	Filed	Nationalized PCT	Conversion of Methane in Nonthermal,Silent, and Pulsed Corona Discharge Reactors
Korea	01-007	3/25/2003	2003-7004258	Filed	Nationalized PCT	Conversion of Methane in Nonthermal,Silent, and Pulsed Corona Discharge Reactors
Australia	01-007	9/26/2001	PCT/US01/30010	Filed	Nationalized PCT	Conversion of Methane in Nonthermal,Silent, and Pulsed Corona Discharge Reactors
Mexico	01-007	3/27/2003	PA/A/2003/002763	Filed	Nationalized PCT	Conversion of Methane in Nonthermal,Silent, and Pulsed Corona Discharge Reactors
India	01-007	3/26/2003	441/chenp/2003	Issued	Nationalized PCT	Conversion of Methane in Nonthermal,Silent, and Pulsed Corona Discharge Reactors
Canada	01-007	9/26/2001	2,434,410	Filed	Nationalized PCT	Conversion of Methane in Nonthermal,Silent, and Pulsed Corona Discharge Reactors
	01-012	none				A Novel Reactor System for the Reduction of Carbon Dioxide Using the Sabatier Reaction
US	01-018	5/30/2001	60/294,526	Expired	Provisional	Destruction of N20 and NO by a Pulsed Corona Reactor
	01-018	5/29/2002	PCT/US02/16812	Filed	PCT	Destruction of N20 and NO by a Pulsed Corona Reactor
US	01-018	11/25/2003	not available	Filed	Nationalized PCT	Destruction of N20 and NO by a Pulsed Corona Reactor
US	02-020	12/18/2001	60/341/925	Expired	Provisional	A Novel NOx Destruction Device Based on Pulsed Corona Discharge
	02-020	12/17/2002	PCT/UW02/40265	Filed	PCT	A Novel NOx Destruction Device Based on Pulsed Corona Discharge
US	02-027	4/18/2002	60/373,624	Expired	Provisional	Stranded Wind Energy Extraction System
US	02-031	6/4/2002	60/385,520	Expired	Provisional	Novel Membrane for Hydrogen Recovery From Streams Containing Hy
	02-031	6/2/2003	PCT/US03/17353	Filed	PCT	Novel Membrane for Hydrogen Recovery From Streams Containing Hy

Venezuala	02-031	6/2/2003	not available	Filed	Non-PCT filing	Novel Membrane for Hydrogen Recovery From Streams Containing Hy
Gulf Coast Coop	02-031		not available	Filed	Non-PCT filing	Novel Membrane for Hydrogen Recovery From Streams Containing Hy
US	03-003	6/28/2002	60/392,204	Expired	Provisional	A Novel Device for the Measurement of Gas Permeability Through Membranes
	03-003	6/27/2003	PCT/US03/20592	Filed	PCT	A Novel Device for the Measurement of Gas Permeability Through Membranes
US	03-007	9/18/2002	60/411,816	Expired	Provisional	A Novel Process for the Manufacture of Hydrogen Cyanide and Acrylonitrite with Simultaneous Recovery of Hydrogen
	03-007	9/18/2003	PCT/US03/29419	Filed	PCT	A Novel Process for the Manufacture of Hydrogen Cyanide and Acrylonitrite with Simultaneous Recovery of Hydrogen
US	03-013	10/24/2002	60/420,956	Expired	Provisional	A Novel Process for the Production of Ethanol and Methanol with Simultaneous Recovery of Hydrogen
US	99-002	3/24/1999	60/125,962	Expired	Provisional	System for Recovery of Sulfur and Hydrogen from Sour Gas Using Plasma Reactor
	99-002	3/23/2000	PCT/US00/007753	Filed	PCT	System for Recovery of Sulfur and Hydrogen from Sour Gas Using Plasma Reactor
US	99-002	9/21/2001	09/960/659	Filed	Nationalized PCT	System for Recovery of Sulfur and Hydrogen from Sour Gas Using Plasma Reactor
Norway	99-002	9/24/2001	20014615	Filed	Nationalized PCT	System for Recovery of Sulfur and Hydrogen from Sour Gas Using Plasma Reactor
Japan	99-002	9/25/2001	2000-606336	Filed	Nationalized PCT	System for Recovery of Sulfur and Hydrogen from Sour Gas Using Plasma Reactor
Canada	99-002	9/20/2001	2,367,846	Filed	Nationalized PCT	System for Recovery of Sulfur and Hydrogen from Sour Gas Using Plasma Reactor
European	99-002	9/25/2001	916313.8	Filed	Nationalized PCT	System for Recovery of Sulfur and Hydrogen from Sour Gas Using Plasma Reactor

Bohle, Scott

US	00-003	3/14/2000	60/189,186	Expired	Provisional	Zeolite Based Encapsulated Catalysts for Denitroxylating Gas Stream Applications

Dellenback, Paul

US	01-005	8/15/2000	60/225,351	Expired	Provisional	Alternative Cofiguatrion for a Reenerative Gas Turbine Engine Cycle
	01-005	8/14/2003	PCT/US01/41714	Abandoned	PCT	Alternative Cofiguatrion for a Reenerative Gas Turbine Engine Cycle

Lindberg, William

	01-020	none				Off-Set technology Valve (OST Valve)
	02-023	none				High Frequesncy Fluidic Actuator
US	03-005	8/22/2002	60/405,317	Expired	Provisional	Active Parachute Riser
	03-005	8/21/2003	PCT/US03/26180	Filed	PCT	Active Parachute Riser
US	03-010	10/1/2002	60/415,206	Expired	Provisional	Aircraft Lift Control System
US	03-010	9/30/2003	10/674,367	Filed	Utility	Aircraft Lift Control System
US	03-024	5/21/2003	60/472,347	Filed	Provisional	A Dynamic Resonant Surface Fluidic Shear Stress Sensor
US	97-002	9/6/1997	08/925,535	Issued	Utility	Flow, Split, Venturi, Axially-Rotated Valve
US	97-002	7/23/1998	08/121,650	Issued	Utility	Flow, Split, Venturi, Axially-Rotated Valve

McInroy, John

US	03-005	8/22/2002	60/405,317	Expired	Provisional	Active Parachute Riser
	03-005	8/21/2003	PCT/US03/26180	Filed	PCT	Active Parachute Riser
US	03-010	10/1/2002	60/415,206	Expired	Provisional	Aircraft Lift Control System
US	03-010	9/30/2003	10/674,367	Filed	Utility	Aircraft Lift Control System
US	03-011	9/27/2002	60/414,751	Expired	Provisional	Precision Positioning Device
US	03-011	9/26/2003	10/672,954	Filed	Utility	Precision Positioning Device

Muknahalipatna, Suresh					
	01-011	none			Network Management Software
US	03-007	9/18/2002 60/411,816	Expired	Provisional	A Novel Process for the Manufacutre of Hydrogen Cyanide and Acrylonitrite with Simultaneous Recovery of Hydrogen
US	03-007	9/18/2003 PCT/US03/29419	Filed	PCT	A Novel Process for the Manufacutre of Hydrogen Cyanide and Acrylonitrite with Simultaneous Recovery of Hydrogen
US	03-013	10/24/2002 60/420,956	Expired	Provisional	A Novel Process for the Production of Ethanol and Methanol with Simultaneous Recovery of Hydrogen
US	03-003	6/28/2002 60/392,204	Expired	Provisional	A Novel Device for the Measurement of Gas Permeability Through Membranes
	03-003	6/27/2002 PCT/US03/20592	Filed	PCT	A Novel Device for the Measurement of Gas Permeability Through Membranes
	03-025	none			
Pierre, John					
US	00-007	3/15/2000 60/190,226	Expired	Provisional	Multifrequency Vector Calibration System
Reddy, KJ					
US	04-003	9/19/2003 60/504,329	Filed	Provisional	A Novel Method to Remove Arsenite and Arsenate from Water
Towler, Brian					
US	03-006	9/13/2002 60/410,472	Expired	Provisional	Mitigation of Parafin Wax Deposition From Crude Oil By Using Ultrasonic Waves
	03-006	9/12/2003 PCT/US03/28834	Filed	PCT	Mitigation of Parafin Wax Deposition From Crude Oil By Using Ultrasonic Waves
US	03-015	10/10/2002 60/417,712	Expired	Provisional	Improvement of Crude Oil Separators Using Ultrasonic Waves
	03-015	10/9/2003 PCT/US03/32208	Filed	PCT	Improvement of Crude Oil Separators Using Ultrasonic Waves