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University of North Dakota
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www.undeerc.org

April 1, 2016

Ms. Karlene Fine
Executive Director
ATTN: Lignite Research Program
North Dakota Industrial Commission
600 East Boulevard Avenue
State Capitol, 14th Floor
Bismarck, ND 58505-0840

Dear Ms. Fine:

Subject: EERC Proposal No. 2016-0121 Entitled "Managing Aerosol Emissions from CO_2 Capture Systems"

The Energy & Environmental Research Center (EERC) of the University of North Dakota is pleased to submit an original and one copy of the subject proposal. Also enclosed is the $100 application fee. The EERC is committed to completing the project as described in the proposal if the Commission makes the requested grant.

If you have any questions, please contact me by telephone at (701) 777-5177 or by e-mail at sbenson@undeerc.org.

Sincerely,

Bruce Folkedahl for Steve Benson

Steven A. Benson
Associate Vice President for Research

Approved by:

Ed for

Thomas A. Erickson, CEO
Energy & Environmental Research Center

SAB/bjr

Enclosures

Lignite Research, Development and Marketing Program

North Dakota Industrial Commission

Application

Project Title: Managing Aerosol Emissions from CO_2 Capture Systems

Applicant: University of North Dakota Energy & Environmental Research Center

Project Manager: Steven A. Benson

Co-Principal Investigators: Bruce C. Folkedahl and John P. Kay

Date of Application: April 1, 2016

Amount of Request: $300,000

Total Amount of Proposed Project: $600,000

Duration of Project: 10 months

Point of Contact (POC): Steven A. Benson

POC Telephone: (701) 777-5177

POC E-Mail: sbenson@undeerc.org

POC Address: 15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

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ABSTRACT

Objective: The goals of this Energy & Environmental Research Center (EERC) project are to determine the potential impacts of low-rank coal combustion system aerosol formation, abundance, and chemistry in flue gas downstream of particulate and sulfur dioxide control systems; determine their effect on solvent aerosol formation in postcombustion CO_2 capture (PCC) systems; and identify methods to control the formation of aerosols. In order to meet the goals of the project, the following specific objectives have been identified:

- Measure the levels of aerosols in flue gas downstream of electrostatic precipitators (ESPs), wet flue gas desulfurization (FGD) units, and spray dryer fabric filter systems.
- Determine the mechanisms of aerosol formation during low-rank coal combustion and gas cooling.
- Determine the effect of the coal combustion-formed aerosols on PCC system solvent aerosol formation.
- Identify and test measures to control the formation of aerosols through modeling and pilot-scale testing.

Expected Results: The results of this project will lead to a fundamental understanding of the aerosol formation process in electrical generation units (EGUs) firing low-rank coal and the interaction and effect of those combustion aerosols on aerosol formation in PCC systems for the control of CO_2 emissions. This information will be used to develop mitigation techniques and processes that will be verified in a follow-on Phase II demonstration project at larger scale.

Duration: Phase I is a 10-month project.

Total Project Cost: The proposed budget of Phase I is $600,000. We are proposing $300,000 of funding by a consortium of coal companies, utilities, and technology vendors. Sponsorship of the consortium will be at a level of $50,000/participant. The balance of the funding, $300,000, is requested from the North Dakota Industrial Commission's Lignite Research, Development and Marketing Program. The EERC is currently pursuing an additional $300,000 in federal cost share from the U.S. Department of Energy's National Energy Technology Laboratory.

Participants: Electrical utilities, coal companies, technology vendors, and state and government agencies.

PROJECT SUMMARY

Growing concerns over the impact of CO_2 emissions from combustion sources on global climate change have prompted numerous research and development projects aimed at developing cost-effective technologies for CO_2 capture. One of the technologies being demonstrated at pilot and full scale globally is a postcombustion CO_2 capture (PCC) system that employs amine-based solvents. Recent work to evaluate the performance of a PCC system at a full-scale power plant in Germany revealed significant levels of solvent emissions from the PCC (Moser et al., 2014). Not only does this add to operating costs in lost solvent, but it also contributes to pollution control issues. Coal-fired combustion systems exclusive of PCC systems can produce ultrafine aerosols in the form of alkali sulfates (Laumb et al., 2009) and SO_3 (McCollor et al., 2011) that form as a result of the condensation and reaction of flame-volatilized elements during gas cooling. These combustion-generated aerosols not captured by particulate and sulfur dioxide systems enter the solvent CO_2 capture system and generate solvent loss.

The goals of this Energy & Environmental Research Center (EERC) project are to determine the potential impacts of low-rank coal combustion system aerosol formation, abundance, and chemistry in flue gas downstream of particulate and sulfur dioxide control systems; determine their effect on solvent aerosol formation in PCC systems; and identify methods to control the formation of aerosols. In order to meet the goals of the project, the following specific objectives have been identified:

- Measure the levels of aerosols in flue gas downstream of electrostatic precipitators (ESPs), wet flue gas desulfurization (FGD) units, and spray dryer fabric filter systems.
- Determine the mechanisms of aerosol formation during low-rank coal combustion and gas cooling.
- Determine the effect of the coal combustion-formed aerosols on PCC system solvent aerosol formation.
- Identify measures to control the formation of aerosols through modeling.

Project deliverables will include information that can be used by vendors to design downstream equipment and determine capital, operating, and maintenance costs. The information will include:

- Levels of aerosols in flue gas downstream of existing air pollution control devices as a function of fuel properties and combustion system type.
- Operating parameters that will minimize the production of aerosols.
- Impacts of aerosol on solvent loss and emissions.
- Identification of measures to control aerosol formation.

The Energy & Environmental Research Center (EERC) has structured this project in two phases. Phase I will address the objectives and deliverables described above, and Phase II will be pilot-scale testing of potential mitigation techniques and full-scale demonstration of the identified control technologies at a participating power generation facility. The duration of Phase I is anticipated to be 10 months. The proposed budget of Phase I is $600,000. In order to minimize the cost to individual project participants, we propose that this project be funded by a consortium of coal companies and utilities. Sponsorship of the consortium will be at a level of $50,000/participant or $300,000 for Phase I. The balance of funding, $300,000, is being requested from the North Dakota Industrial Commission's (NDIC's) Lignite Research, Development and Marketing Program. The EERC is currently pursuing an additional $300,000 in federal cost share from the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). Should this DOE funding become available for the project, the scope of work will be increased to include potential pilot-scale validation of the modeling efforts.

PROJECT DESCRIPTION

Objectives: The overall goal of this proposed project is to determine the extent of aerosol formation in lignite and subbituminous coal combustion and PCC systems to allow the development of amelioration technologies to mitigate aerosol emissions. This goal will be accomplished through the following project tasks.

Methodology:

***Task 1 Field Measurement of Aerosol Emissions at Full-Scale Lignite and Subbituminous Power Generation Plants*:** Task 1 will consist of quantifying the aerosol levels at various locations in existing power generation facilities. Project sponsor sites will be selected, and field surveys will be conducted to identify aerosol levels and the level of very fine particulate ash in the flue gas stream in select locations. Particle-size distributions will be identified by utilization of scanning mobility particle sampling (SMPS) and multistage cascade impactor (MSCI) particle-sampling techniques. SMPS is a dynamic real-time particle sample size and distribution monitoring technique. MSCIs are used to collect the actual particles, with each stage collecting a given size range. This technique then allows for chemical composition and imaging techniques to be performed on the collected samples. The ultrafine (10 to 50 nm) and fine (50 to 250 nm) submicrometer particulate ash entrained in the gas stream has been correlated with aerosol formation and emission in PCC systems (Moser et al., 2014). Knowing the size and chemical distribution of these very fine ash particles in the flue gas prior to the entrance to the PCC will aid in understanding the fundamental formation route to aerosols and, ultimately, amelioration technologies. This information will be used to provide inputs into the modeling effort in Task 2.

***Task 2 Modeling and Computer Simulation*:** In this task, all of the data collected in Task 1 (field measurements) will be integrated into a modeling effort. The purpose of this modeling effort is to simulate the mechanisms of aerosol formation both from the combustion of lignites and those formed in the PCC systems. Aerosols formed in the combustion of lignites will be modeled as to the behavior of these aerosols as they travel through specific pollution control devices and their interactions and effect on other flue gas constituents, particularly aerosols forming in the PCC systems from the capture solvents and the potential induced amine aerosol formation the combustion-based aerosols may have on the capture solvents. This effort will aid in developing mitigation techniques for methods to reduce or prevent formation and emission. The models will build upon previous EERC modeling work in aerosol formation (Hamel et al., 2003) and work by Dr. Bowman of the University of North Dakota (UND) Chemical Engineering department (Bowman et al., 1997; Bowman and Eskelson, 2009). This modeling effort will utilize an EERC-developed ash formation model ATRAN, originally designed to predict ash transformation from coal in combustion systems, which was updated in previous separately funded projects to include some aerosol species; Chemkin, a commercial chemical thermodynamic and kinetics model; and Fluent, a commercial CFD (computational fluid dynamics) model. The results of the modeling effort will be used to predict both pilot- as well as full-scale emissions of aerosols and to develop methodologies for mitigation of aerosol emissions. A plan will be developed based on discussions with the project sponsors for Phase II work to perform model validation at full scale and to deploy aerosol mitigation techniques in the field. Full-scale model validation and demonstration in Phase II will also include the optimization of an ASPEN model based on the previously mentioned customized modeling work, utilizing power generation system configuration and process conditions of the sponsors.

Task 3 Project Management and Reporting**:** The project management and reporting task includes three main subtasks: 1) Management and Summary Progress Reporting – summary reports will be provided on a quarterly basis. Additionally, regular conference calls and face-to-face meetings with project participants will be conducted to allow for the exchange of information and input on test plans; 2) Presentations and Travel – the management task will provide detailed project presentations at sites to be selected by the project sponsors and the EERC; and 3) Final Report – a detailed final report will be provided discussing all of the project results.

Anticipated Results: It is anticipated that the results of this project testing as described above will lead to a fundamental understanding of the aerosol formation process in electrical generation units (EGUs) firing low-rank coal and the interaction and effect of those combustion aerosols on aerosol formation in PCC systems for the control of CO_2 emissions. This information will be used to develop mitigation techniques and processes that will be verified in a follow-on Phase II demonstration project at larger scale.

Facilities: The EERC has over 54,000 square feet of demonstration facilities. These facilities contain a variety of demonstration venues for a variety of technologies as well as space for construction of new pilot-scale components to fit client needs. Additionally, the EERC has been involved in many projects that are demonstrated off-site but require EERC technical and field sampling expertise. Much of the mechanical design and modeling of equipment and machinery for our demonstration facilities is done on-site in our in-house machine shop. This allows the EERC to demonstrate technologies in a more rapid, cost-effective way.

Resources: The EERC's staff is a multidisciplinary team of approximately 210 highly skilled scientists, engineers, and support personnel representing more than 140 different disciplines, making it one of the world's leading developers of energy and environmental technologies. The personnel and facilities at the EERC combined with the expertise and resources available through partnership in this project with UND's Institute for Energy Studies (IES) and the Chemical Engineering Department will provide for ample resources to complete the project in a timely and effective manner.

Techniques to Be Used, Their Availability and Capability: The techniques to be used and their capabilities are described above in the Statement of Work. Their availability will be prioritized with other projects at the EERC and UND to ensure timely completion of this project.

Environmental and Economic Impacts while Project is under Way: Environmental impacts will be minimal during execution of this project. Sampling at full-scale utilities will not interfere with regular operation of the power generation plants or have any noticeable environmental impacts. Pilot- and lab-scale testing at the EERC will be in a controlled environment with very small amounts of material utilized that will be disposed of according to standard UND Environmental Health and Safety practices once the testing is complete. Economic impacts will also be minimal and will not have appreciable effects on any of the organizations participating, with the exception of regular employment economic effects for those working on the project.

Ultimate Technological and Economic Impacts and Why the Project Is Needed: The ultimate impact of this project will be the demonstration of techniques to allow the operation of PCC systems utilizing amine-style solutions to operate functionally on low-rank coal-fired EGUs. As this technology is by far the most commercially advanced technology for CO_2 capture and subsequent sequestration of the captured gas, this will be critical to the continued operation of the power generation industry in North Dakota. PCC systems will not be able to operate effectively if they are losing their operating solution to the atmosphere through aerosol formation and emission, causing increased annual costs for solvent makeup, emission monitoring, and possible additional subsystems for solvent makeup. This raises the cost of CO_2 capture and negatively impacts any financial gains that may be employed through sale and utilization of the captured CO_2 for enhanced oil recovery (EOR) within the state. If the power industry in North Dakota has to meet the U.S. Environmental Protection Agency (EPA) CPP (Clean Power Plan) regulations without the use of PCC systems utilizing amines, the use of coal for power generation will ultimately be eliminated in North Dakota, and the economic impacts would be significantly negative for the state.

STANDARDS OF SUCCESS

A successful test program will meet all of the deliverables and milestones listed in the statement of work section in a timely manner. Successful demonstration of an understanding of the fundamental processes involved in aerosol formation in PCC systems and development of a plan to mitigate aerosol formation in PCC systems will be a hallmark of success for the project. This fundamental understanding and the development of a mitigation plan will justify moving to Phase II to demonstrate mitigation techniques at a large-scale facility employing a PCC system. The EERC will work closely with technology providers after conclusion of a successful project to work on the detailed design of the demonstration-scale system. The testing performed in this program will enable the EERC to advise the technology providers as well as electrical generation utilities on potential mitigation techniques and to inform them of the fundamentals of aerosol formation. The inputs from the pilot-scale system will be used to design a demonstration-scale system to mitigate aerosol formation in PCC systems.

BACKGROUND/QUALIFICATIONS

Background: CO_2 emission reduction goals for fossil fuel power plants have been identified in EPA's CPP on a state-by-state basis. The CO_2 reduction goal for North Dakota is 45% by 2030. The use of renewables to decrease the emission of CO_2 will not achieve the goal by 2030. Therefore, to reach the EPA-mandated targets, EGUs will require the employment of PCC systems as a means to meet these reduction goals. The most mature technology is the amine-based PCC system, using solvents such as monoethanolamine (MEA). Such technology is still under development for fossil/renewable fuel-fired energy-generating plants, primarily as slipstream or pilot-scale demonstration facilities. Recent experience with laboratory- and pilot-scale slipstream PCC units has raised concerns about the emission of amine solvent from the process. These emissions are not only because of amine volatility, but previous studies indicate that the presence of ultrafine combustion-derived aerosols and fine water droplets can increase amine emissions to as high as grams per Nm^3 levels (Moser et al., 2015; Khakharia et al., 2015).

Aerosol formation can occur as a homogeneous process such as condensation of flame-volatilized species to form fine aerosol particles or as a heterogeneous process in which vapors condense on surfaces of existing particles known as seeds. The process is controlled by the cooling rate, degree of supersaturation of the vapor-phase species, and concentration of existing particulate material present (Lighty et al., 2000). The aerosols produced by homogeneous condensation typically are very fine (<1 μm). Particles in this size range are difficult to collect with an ESP and similarly pass through a wet scrubber. In the downstream PCC process, these aerosols provide nucleation sites for amine-based vapors. These amine-based aerosols are emitted from the PCC system.

The combustion of low-rank coals, biomass, and waste materials is prone to produce alkali sulfate aerosols (Lighty et al., 2000). In previous studies, North Dakota lignite-fired power plants have shown that the presence of aerosols in the flue gas has the potential to impact the performance of CO_2 capture systems. Work conducted by a team of personnel from Microbeam Technologies Inc., the EERC, and the Chemical Engineering Department at UND has shown that the level of aerosols on a number basis is on the order of 10^7 particles per cm^3 in the less than 100-nm range (Laumb et al., 2009) in flue gas that would enter a PCC system. As shown in Figure 1, there is a clear correlation of MEA emissions with the change in inlet aerosol (soot and H_2SO_4) number concentration. Testing conducted by Khakharia et al. (2015) found significant emission of solvent from amine-based capture systems when the number of

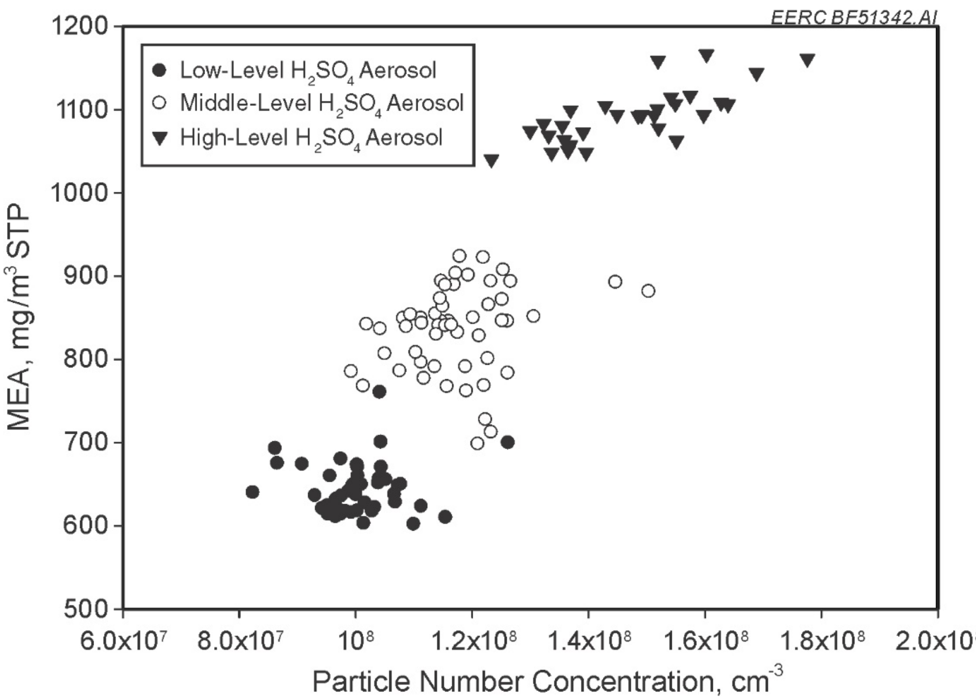


Figure 1. Particle concentration entering amine scrubber and aerosol emission rate.

aerosol particles entering the PCC system was in the range of 10^7–10^8 per cm^3. Therefore, measures to reduce aerosol formation in lignite-fired power plants must be identified.

The EERC has previously worked with methods to reduce the concentration of aerosols in combustion flue gases. The EERC conducted a study to mitigate SO_3 aerosols to reduce pollution and opacity issues through fuel blending and additives (Hamel et al., 2003; McCollor et al., 2011; Hurley and Katrinak, 1992).

Qualifications:

Key Personnel: Dr. Steven A. Benson is the Associate Vice President for Research at the EERC and will serve as project manager. As Associate Vice President for Research, Dr. Benson assists the Vice President for Research in overseeing the activities of a team of scientists and engineers focused on research, development, demonstration, and commercialization of energy and environmental technologies. Dr. Benson has over 25 years of research and development experience related to the development of efficient and clean energy production systems. Prior to his current position, he served as the Director of the IES, Petroleum Engineering Department Chair, and Professor of Chemical Engineering at UND. Before that, he worked at the EERC as a Senior Research Manager and Associate Director for Research.

Dr. Benson's principal areas of interest and expertise include development and management of complex multidisciplinary programs focused on solving environmental and energy problems associated with the development and utilization of fuel resources. These programs include 1) technologies to improve the performance of fuel resource recovery, refining, conversion, and environmental control systems; 2) impact of fuel properties on combustion and gasification systems; 3) carbon dioxide separation and capture technologies, 4) advanced analytical techniques; 5) computer-based models to predict the performance of combustion and gasification systems; 6) technical and economic feasibility of fuel conversion technologies; and 7) state and national environmental policy.

Dr. Bruce C. Folkedahl will serve as a co-principal investigator for the project. Dr. Folkedahl is a Senior Engineer at the EERC in combustion and gasification for electricity generation; research on the fundamental mechanisms of ash deposition and fouling during firing of fuels; process development for the conversion of coal and biomass feedstocks to fuels, chemicals, and value-added products; and corrosion and development of high-temperature materials to withstand aggressive combustion environments. Dr. Folkedahl has been responsible for the development of two novel technologies for water reduction in power generation systems. He received his Ph.D. degree in Materials Science and Engineering from Pennsylvania State University and his B.S. degree in Computer Science from UND.

Mr. John Kay will serve as co-principal investigator on the project with Dr. Folkedahl. Mr. Kay is a Principal Engineer and Emissions and Carbon Capture Group Lead at the EERC, where his responsibilities include the management of CO_2 separation research related to bench-, pilot-, and demonstration-scale equipment for the advancement of the technology. This also includes the development of cleanup systems to remove SO_x, NO_x, particulate, and trace elements to render flue gas clean enough for separation. Mr. Kay's principal areas of interest and expertise include applications of amine solutions for removing CO_2 from gas streams and field testing site management. Mr. Kay received a B.S. degree in Geological Engineering from UND and an Associate degree in Engineering Studies from Minot State University.

Serving as a project advisor for the project will be Dr. Frank Bowman, Associate Professor and Tom Owens Endowed Fellow for the Department of Chemical Engineering at UND. Dr. Bowman received his Ph.D. in Chemical Engineering from the California Institute of Technology and his B.S. in Chemical Engineering from Brigham Young University. Dr. Bowman is a renowned expert in the field of aerosols. Also serving as a project advisor will be Dr. Mike Mann. Dr. Mann is a Chester Fritz Distinguished Professor at the Department of Chemical Engineering and Executive Director of the IES at UND.

Resumes for key personnel can be found in Appendix A.

***EERC*:** The EERC is one of the world's major energy and environmental research organizations. Since its founding in 1949, the EERC has conducted research, testing, and evaluation of fuels, combustion and gasification technologies, emission control technologies, ash use and disposal, analytical methods, groundwater, waste-to-energy systems, and advanced environmental control systems. Today's energy and environmental research needs typically require the expertise of a total-systems team that can focus on technical details while retaining a broad perspective.

The EERC has over 65 years of coal research, with extensive experience on low-rank coals (lignite and subbituminous). The EERC has conducted measurement sampling at over 80 coal-fired units at utilities since 1996. The EERC has developed several new methods for characterization of materials and sampling methodologies over the years, including the Ontario Hydro (OH) and M30B for measuring mercury in flue gas at the ppb level, and routinely is called upon to evaluate measurement errors and biases that can be introduced during measurement and ways to overcome sampling problems. On projects, the EERC goes significantly beyond the requirements of the sampling methods to ensure that lessons learned over the years result in quality, reliable data.

VALUE TO NORTH DAKOTA

In order to secure lignite's future in energy production, novel and innovative technologies are needed to improve efficiency and reduce the CO_2 footprint of the fuel. North Dakota power utilities will be significantly impacted by EPA's CPP and will be required to spend millions of dollars in emission reduction technologies. While CPP is being challenged in court and currently is suspended, at some point in the future, carbon reduction will be implemented on coal-fired power generation plants whether it is CPP or some other regulation. If CPP is allowed to move forward, North Dakota utilities will be mandated to reduce carbon emissions by 45% by the year 2030. The use of renewables to decrease the emission of CO_2 will not achieve the goal by 2030. Therefore, to reach the EPA-mandated targets, EGUs will require the employment of PCC systems as a means to meet these reduction goals. The most mature technology is the amine-based PCC system, using solvents such as MEA.

Such technology is still under development for fossil/renewable fuel-fired energy-generating plants, primarily as slipstream or pilot-scale demonstration facilities. Recent experience with laboratory- and pilot-scale slipstream PCC units has raised concerns about the emission of amine solvent from the process. These emissions are not only because of amine volatility, but previous studies indicate that the presence of ultrafine combustion-derived aerosols and fine water droplets can increase amine emissions to as high as grams per Nm^3 levels. For these technologies to be viable as a PCC system such that North Dakota EGUs can meet current EPA CPP CO_2 reduction goals, the aerosol emissions from PCC systems must be fundamentally understood and mitigation techniques developed. Additionally, the captured CO_2 would be made available to the oil industry for EOR which would provide an economic balance between the cost of reducing emissions and the utilization of the captured CO_2.

Aerosols present a concern with the development of that process in North Dakota and could hamper statewide development of carbon management with the time constraints set forth by EPA. This project is of value to North Dakota as a means to assist the power generation industry in meeting reduced CO_2 emission goals and to preserve this industry and the numerous jobs it provides.

MANAGEMENT

An organizational chart is shown below in Figure 2. Overall project direction will come from an advisory committee formed with members from the industrial partners funding the project, including NDIC. This advisory committee will provide project guidance to Project Manager Dr. Benson. Dr. Folkedahl and Mr. Kay will act as the co-principal investigators, and Dr. Bowman and Dr. Mann will be project advisors. Mr. Kay will be responsible for leading Task 1, and Dr. Folkedahl will lead Task 2 and assist Mr. Kay with Task 1 and Dr. Benson with Task 3. All key personnel will be responsible for interpretation of results and writing reports. Resumes of all key personnel are enclosed in Appendix A.

Once the project is initiated, monthly or as-needed conference calls will be held with project sponsors and team members to review project status. Quarterly reports will be prepared and submitted to project sponsors for review. At 4 and 8 months in the project schedule, meetings will be held to review the status and results of the project and discuss directions for future work.

Several milestones have been identified for the program. Milestones include completion of field measurement, completion of process modeling, and periodic reporting. The timing of the milestones is indicated on the time line shown in the next section.

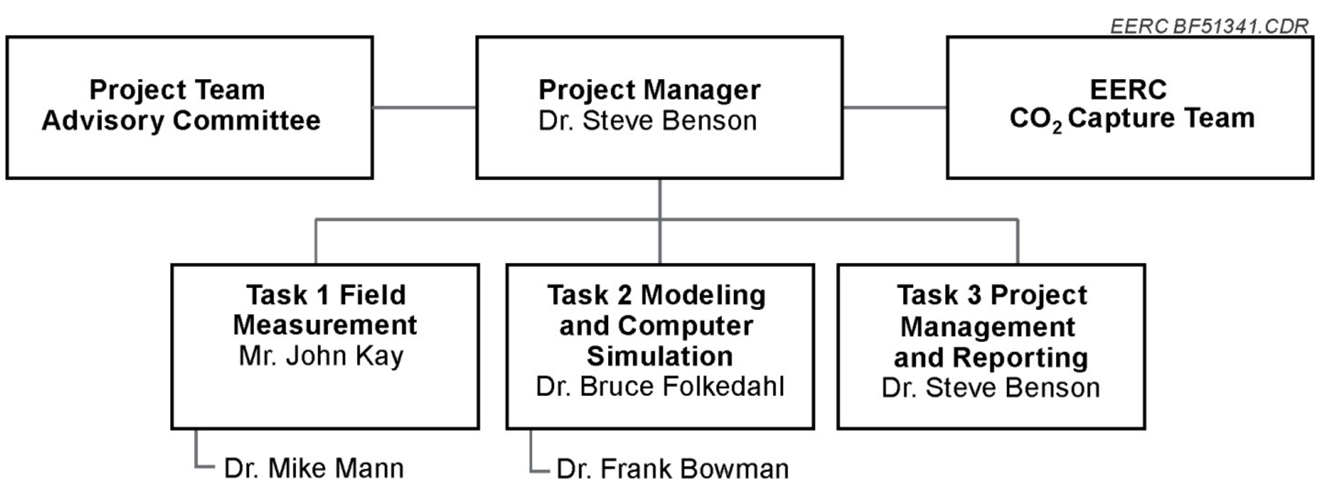
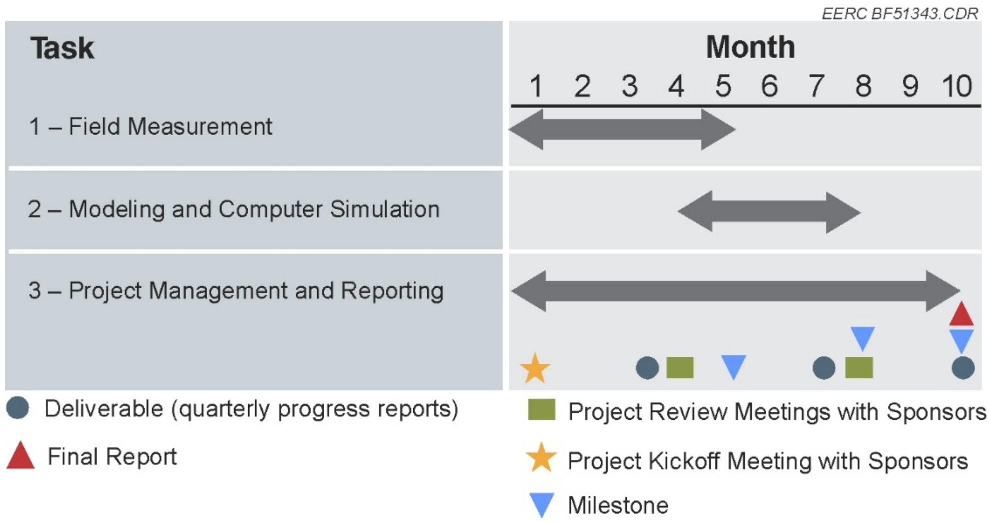


Figure 2. Project management and organizational chart.

TIMETABLE AND DELIVERABLES



BUDGET

CATEGORY	NDIC SHARE	INDUSTRY SHARE	TOTAL BUDGET
Labor	$252,793	$263,862	$516,655
Travel	$20,253	$19,357	$39,610
Supplies	$14,645	$11,997	$26,642
Communications	$406	$144	$550
Printing & Duplicating	$393	$149	$542
Laboratory Fees & Services			
Natural Materials Analytical Research Lab	$605	$645	$1,250
Particulate Analysis Lab	$801	$870	$1,671
Fuel Preparation Service	$293	$314	$607
Graphics Service	$2,504	$2,662	$5,166
Shop & Operations	$1,344	$ –	$1,344
SEM Lab	$5,963	$ –	$5,963
Total Project Costs – U.S. Dollars	**$300,000**	**$300,000**	**$600,000**

MATCHING FUNDS

The total estimated cost of the proposed project is $600,000. The EERC requests sponsorship of $300,000 from NDIC's, Lignite Research, Development and Marketing Program. The EERC anticipates matching NDIC funding from industrial sponsorship in the amount of $300,000. Mitsubishi Heavy Industries America has already signed on for the full $50,000 industrial sponsorship price. Several other electrical generation utilities have expressed interest in the program as well. The EERC is currently pursuing an additional $300,000 in federal cost share from DOE NETL. Should this DOE funding become available for the project, the scope of work will be increased to include potential pilot-scale validation of the modeling efforts. If the full funding is not secured, the scope of work will be amended commensurate with the funding available. Initiation of the proposed work is contingent upon the execution of a mutually negotiated agreement or modification to an existing agreement between the EERC and each of the project sponsors. If project funding cannot be secured through identified industrial consortium partners, this would delay the start of the project until new consortium members can be identified, but the EERC does not anticipate this will be a problem. The EERC will continue to secure more solid commitments, which will be in place prior to establishing a contract with NDIC.

TAX LIABILITY

The EERC is a special research center within UND, which is a state-controlled institution of higher education and is not a taxable entity; therefore, the EERC has no tax liability.

CONFIDENTIAL INFORMATION

No confidential material is included in this proposal.

APPENDIX A

RESUMES OF KEY PERSONNEL

DR. STEVEN A. BENSON
Associate Vice President for Research
Energy & Environmental Research Center (EERC), University of North Dakota (UND)
15 North 23rd Street, Stop 9018, Grand Forks, North Dakota 58202-9018 USA
Phone: (701) 777-5177, Fax: (701) 777-5181, E-Mail: sbenson@undeerc.org

Principal Areas of Expertise
Dr. Benson's principal areas of interest and expertise include development and management of complex multidisciplinary programs focused on solving environmental and energy problems associated with the development and utilization of fuel resources. These programs include 1) technologies to improve the performance of fuel resource recovery, refining, conversion and environmental control systems; 2) impact of fuel properties on combustion and gasification systems; 3) carbon dioxide separation and capture technologies, 4) advanced analytical techniques; 5) computer-based models to predict the performance of combustion and gasification systems; 6) technical and economic feasibility of fuel conversion technologies; and 7) state and national environmental policy.

Qualifications
Ph.D., Fuel Science, Pennsylvania State University 1987.
B.S., Chemistry, University of Minnesota, 1977.

Professional Experience
2015–Present: Associate Vice President for Research, EERC, UND. Dr. Benson assists the Vice President for Research in overseeing the activities of a team of scientists and engineers focused on research, development, demonstration, and commercialization of energy and environmental technologies. Dr. Benson has over 25 years of research and development experience in efficient and clean energy production systems.

2010–2014: Professor/Chair, Petroleum Engineering Department, and Director, Institute for Energy Studies, UND. Dr. Benson coordinated energy-related education and research activities that involve faculty, research staff, and students.

2008–Present: Professor, UND. Dr. Benson is responsible for teaching courses on energy production and associated environmental issues. Dr. Benson conducts research, development, and demonstration projects aimed at solving environmental, efficiency, and reliability problems associated with the utilization of fuel resources in refining/combustion/gasification systems that include transformations of fuel impurities, carbon dioxide separation and capture technologies, advanced analytical techniques, and computer-based models.

1999–2008: Senior Research Manager/Advisor, EERC, UND. Dr. Benson's was responsible for leading a group of about 30 highly specialized chemical, mechanical, and civil engineers along with scientists whose aim was to develop and conduct projects and programs on combustion and gasification system performance, environmental control systems, the fate of pollutants, computer modeling, and health issues for clients worldwide.

1994–1999: Associate Director for Research, EERC, UND, Grand Forks, North Dakota. Dr. Benson was responsible for the direction and management of programs related to integrated energy and environmental systems development. Dr. Benson led a team of over 45 scientists, engineers, and technicians.

1991–Present: President, Microbeam Technologies Incorporated (MTI). Dr. Benson is the founder of MTI, whose mission is to conduct service analysis of materials using automated methods. MTI began operations in 1992 and has conducted over 1450 projects for industry, government, and research organizations.

1989–1991: Assistant Professor of Geological Engineering, Department of Geology and Geological Engineering, UND. Dr. Benson was responsible for teaching courses on fuel geochemistry, fuel/crude behavior in refining, combustion and gasification systems, and analytical methods of materials analysis.

1984–1994: Senior Research Manager, Fuels and Materials Science, EERC, UND. Dr. Benson was responsible for management and supervision of research on the behavior of inorganic constituents in fuels in combustion and gasification.

1984–1986: Graduate Research Assistant, Fuel Science Program, Department of Materials Science and Engineering, Pennsylvania State University. Mr. Benson took course work in fuel science, chemical engineering (at UND), and ceramic science and performed independent research leading to a Ph.D. in Fuel Science.

1983–1984: Research Supervisor, Distribution of Inorganics and Geochemistry, Coal Science Division, UND Energy Research Center. He was responsible for management and supervision of research on coal geochemistry and ash chemistry related to inorganic constituents and mineral interactions and transformations during coal combustion and environmental control systems.

1977–1983: Research Chemist, U.S. Department of Energy Grand Forks Energy Technology Center, Grand Forks, North Dakota. He performed research on methods development for the characterization of coal and coal derived materials

Publications and Presentations
Editor of ten technical journal special issues
Author and coauthor of over 200 publications

Patents – Four patents issued and several applications pending:

7,574,968 – Method and Apparatus for Capturing Gas Phase Pollutants such as Sulfur Trioxide
7,628,969 – Multifunctional Abatement of Air Pollutants in Flue Gas
7,981,835 – System and Method for Coproduction of Activated Carbon and Steam/Electricity
8,277,542 – Method for Capturing Mercury from Flue Gas

Synergistic Activities

- Lignite Energy Council, Distinguished Service Award, Research & Development, 1997; College of Earth and Mineral Science Alumni Achievement Award, Pennsylvania State University, 2002; Lignite Energy Council, Distinguished Service Award, Research & Development, 2003; Lignite Energy Council, Distinguished Service Award, Government Action Program (Regulatory), 2005; Lignite Energy Council, Distinguished Service Award, Research & Development, 2008; Science and Technology Award, Impacts of Fuel Impurities Conference, 2014

- Provided testimony to the U.S. Senate Committee on the Environment and Public Works – Mercury Emissions Control at Coal-Fired Power Plants – 2008 and 2005

DR. BRUCE C. FOLKEDAHL

Senior Engineer, Renewables
Energy & Environmental Research Center (EERC), University of North Dakota (UND)
15 North 23rd Street, Stop 9018, Grand Forks, North Dakota 58202-9018 USA
Phone: (701) 777-5243, Fax: (701) 777-5181, E-Mail: bfolkedahl@undeerc.org

Principal Areas of Expertise

Dr. Folkedahl's principal areas of interest and expertise include biomass conversion to energy; biomass to fuels and chemicals; development of methodologies to mitigate the effects of inorganic components on the performance of combustion, gasification, and air pollution control systems; and fuel inorganic transformations and deposition and development of predictive models to assess these processes. He is also interested in the study and development of high-temperature materials for aggressive environments.

Qualifications

Ph.D., Materials Science and Engineering, Pennsylvania State University, 1997.
B.S., Computer Science, University of North Dakota, 1990.

Professional Experience

2001–Present: Senior Engineer, Renewables, EERC, UND. Dr. Folkedahl's responsibilities include studies of biomass combustion and gasification in conjunction with conventional combustion for electricity generation; research on the fundamental mechanisms of ash deposition and fouling during cofiring of biomass fuels with coal; process development for the conversion of biomass feedstocks to fuels, chemicals, and value-added products; and studies of corrosion and development of high-temperature materials to withstand aggressive combustion environments.

2000–2001: Product Manager, 3M Industrial Mineral Products Division, Little Rock, Arkansas. Dr. Folkedahl's responsibilities included managing a crushing and screening business unit 24-hr/day, 7-day/week manufacturing operation, including hiring, training, and directing 40 employees; managing a $12,000,000 annual budget; forecasting budgets; developing and implementing cost reduction plans; and developing automated labor-reducing equipment and routines.

1999–2000: Senior Product Engineer, 3M Industrial Mineral Products Division, St. Paul, Minnesota. Dr. Folkedahl's responsibilities included developing ceramer-coated roofing granules, developing automated dry powder-handling system for slurry-making process, investigating the mechanism of fluorine alkalinity reduction and coating enhancement in roofing granules, and investigating mechanisms of rust formation in mild steel storage tanks for roofing granules.

1994–1998: Graduate Assistant, Pennsylvania State University, University Park, Pennsylvania. Dr. Folkedahl's responsibilities included proctoring and grading exams and teaching lab classes. Thesis work consisted of development of a neural network model of inorganic ash viscosity in high-temperature systems; development of an image analysis program to identify graphitizability of cokes; and statistical cluster analysis of the chemical composition of ash deposits in electrical generation boilers.

1989–1999: Research Scientist, EERC, UND. Dr. Folkedahl's projects and responsibilities included corrosion studies of high-temperature alloys, modeling of slag and silicate material viscosities, and crystallization studies of coal. Other responsibilities included design, development, and maintenance of analytical software; development and implementation of new analysis techniques; and operation and performance analysis with x-ray diffraction, x-ray fluorescence, scanning electron microscopy, and processing and manipulation of raw data.

Publications and Presentations

Dr. Folkedahl has authored or coauthored numerous professional publications.

JOHN P. KAY
Principal Engineer, Emissions and Carbon Capture Group Lead
Energy & Environmental Research Center (EERC), University of North Dakota (UND)
15 North 23rd Street, Stop 9018, Grand Forks, North Dakota 58202-9018 USA
Phone: (701) 777-4580, Fax: (701) 777-5181, E-Mail: jkay@undeerc.org

Principal Areas of Expertise
Mr. Kay's principal areas of interest and expertise include applications of solvents for removing CO_2 from gas streams to advance technology and look toward transformational concepts and techno-economic assessments. He has 6 years of experience in field testing site management and sampling techniques for hazardous air pollutants and mercury control in combustion systems along with10 years of experience utilizing scanning electron microscopy (SEM), x-ray diffraction (XRD), and x-ray fluorescence (XRF) techniques to analyze coal, fly ash, biomass, ceramics, and high-temperature specialty alloys. He is also interested in computer modeling systems, high-temperature testing systems, and gas separation processes and is a FLIR Systems, Inc.-certified infrared thermographer.

Qualifications
B.S., Geological Engineering, University of North Dakota, 1994.
Associate Degree, Engineering Studies, Minot State University, 1989.

Professional Experience
2011–Present: Principal Engineer, Emissions and Carbon Capture Group Lead, EERC, UND. Mr. Kay's responsibilities include management of CO_2 separation research related to bench-, pilot-, and demonstration-scale equipment for the advancement of the technology. This also includes the development of cleanup systems to remove SO_x, NO_x, particulate, and trace elements to render flue gas clean enough for separation.

2005–2011: Research Manager, EERC, UND. Mr. Kay's responsibilities included the management and supervision of research involving the design and operation of bench-, pilot-, and demonstration-scale equipment for development of clean coal technologies. The work also involved the testing and development of fuel conversion (combustion and gasification) and gas cleanup systems for the removal of sulfur, nitrogen, particulate, and trace elements.

1994–2005: Research Specialist, EERC, UND. Mr. Kay's responsibilities included conducting SEM, XRD, and XRF analysis and maintenance; creating innovative techniques for the analysis and interpretation of coal, fly ash, biomass, ceramics, alloys, high-temperature specialty alloys, and biological tissue; managing the day-to-day operations of the Natural Materials Analytical Research Laboratory; supervising student workers; developing and performing infrared analysis methods in high-temperature environments; and performing field work related to mercury control in combustion systems.

1993–1994: Research Technician, Agvise Laboratories, Northwood, North Dakota. Mr. Kay's responsibilities included receiving and processing frozen soil samples for laboratory testing of chemical penetration, maintaining equipment and inventory, and training others in processing techniques utilizing proper laboratory procedures.

1991–1993: Teaching Assistant, Department of Geology and Geological Engineering, UND. Mr. Kay taught Introduction to Geology Recitation, Introduction to Geology Laboratory, and Structural Geology. Responsibilities included preparation and grading of assignments and administering and grading class examinations.

1990–1992: Research Assistant, Natural Materials Analytical Laboratory, EERC, UND. Mr. Kay's responsibilities included operating an x-ray diffractometer and interpreting and manipulating XRD data, performing software manipulation for analysis of XRD data, performing maintenance and repair of the XRD machine and sample carbon coating machine, preparing samples for XRD and SEM analysis, and performing point count analysis on the SEM.

Professional Memberships
ASM International
American Ceramic Society
Microscopy Society of America

Publications and Presentations
Has authored or coauthored numerous publications.

MICHAEL D. MANN, Ph.D.
Chester Fritz Distinguished Professor, Department of Chemical Engineering
Executive Director, Institute for Energy Studies, University of North Dakota

EDUCATION:

University of North Dakota, Energy Engineering, Ph.D. 1997
University of North Dakota, MBA, 1988
University of North Dakota, Chemical Engineering, M.S. 1981
Mayville State College (North Dakota), Chemistry and Mathematics, B.S., 1979

PROFESSIONAL EXPERIENCE

2014–Present	Executive Director, Institute for Energy Studies, UND
2009–2014	Associate Dean, College of Engineering and Mines, UND
2008	Interim Dean, School of Engineering and Mines, UND (Apr – Aug)
2006–Present	Distinguished Professor, Chemical Engineering, UND
2005–2013	Chair, Chemical Engineering, UND
1991–2006	Associate Professor, Chemical Engineering
2000–2005	Director, Engineering Doctoral Program
1999	Lecturer, Chemical Engineering, UND
1999–2005	Senior Research Advisor, Energy & Environmental Research Center (EERC)
1994–1999	Senior Research Manager, Advanced Processes and Technologies, EERC
1985–1994	Research Manager, Combustion Systems, EERC,
1982–1985	Research Engineer, Wastewater Treatment and Reuse, EERC
1981–1982	Operating Contractor, EG&G, Grand Forks Energy Technology Center (GFETC)

AREAS OF EXPERTISE

Technology development, system integration and life-cycle effects: including energy production from combustion and gasification, fuel cells, wind, and geothermal resources.

CURRENT RESEARCH

Geothermal Resource Development –
- Electric Power from Low Temperature Resources – DOE, Basin Electric, ND Industrial Comm.

Advanced Energy Systems –
- High Capacity Sorbent and Processes for CO_2 Capture – DOE
- Center for Gas Utilization – North Dakota Industrial Commission, Envergex LLC
- Performance of Materials in Hostile Environments – DOE
- Demonstration of the ORC for Low-Grade Heat Recovery – Montana-Dakota Utilities
- Development of Oxygen Carriers for Chemical Looping Systems – DOE, Envergex

SUNRISE – Sustainable Energy Research Institute –
- Development of Novel Membranes for Fuel Cell Applications – NSF EPSCoR

PUBLICATIONS:

Over 150 peer-reviewed publications and three patents. Graduated 14 Ph.D. and over 25 students. Currently supports two Ph.D. students and two M.S. students working on degrees in Energy Systems Engineering and Energy Engineering.

Professional Preparation

Brigham Young University	Chemical Engineering	B.S. ChE	1991
California Institute of Technology	Chemical Engineering	PhD. ChE	1997
California Institute of Technology	Environmental Engineering	Post Doctoral Scholar	1997

Appointments

2011-present Associate Chair, Department of Chemical Engineering, University of North Dakota

2011-present Associate Professor, Department of Chemical Engineering, University of North Dakota
2005-2011 Assistant Professor, Department of Chemical Engineering, University of North Dakota
1998-2005 Assistant Professor, Department of Chemical Engineering, Vanderbilt University

Five Products Related to the Proposed Project *(24 total peer-reviewed publications):*

1. Mohs, A. J. and Bowman, F. M., "Method for eliminating dispersion in moving center sectional method aerosol size distributions," *Aerosol and Air Quality Research*, 11, 21-30, 2011.
2. Jassim, E., Benson, S. A., Bowman, F. M. , Seames, W. S., "Influence of fragmentation on the behavior of pyrite particles during combustion," *Fuel Processing Technology*, 92, 970-976, 2011.
3. Bowman, F. M. and Eskelson, K., "Thermodynamic consistency of Raoult's law and Henry's law approaches for multiphase organic aerosol partitioning," *J. Atmos. Chem.*, 64, 179-193, 2010.
4. Lu, J. and Bowman, F. M. "A detailed aerosol mixing state model for investigating interactions between mixing state, semivolatile partitioning, and coagulation," *Atmospheric Chemistry and Physics*, 10, 4033-4046, doi:10.5194/acp-10-4033-2010, 2010.
5. Bowman, F. M. and Melton, J. A., "Effect of activity coefficient models on predictions of secondary organic aerosol partitioning," *J. Aerosol Sci.*, 35, 1415-1438, 2004.

Other Significant Products:

1. Brevik, K., Jean, K., Bowman, F., Bowen, B., "Impact of the You're Hired! program on student attitudes and understanding of engineering," *Proceedings of ASEE Annual Conference and Exposition*, 2015.
2. Van Eck, R., Hung, W., Bowman, F., & Love, S., "21st century game design: a model and prototype for promoting scientific problem solving," *Proceedings of the International Association of Science and Technology for Development's annual conference on Computers and Advanced Technology in Education*, 2009.
3. Bian, F. and Bowman, F. M., "A lumping model for composition- and temperature-dependent partitioning of secondary organic aerosols," *Atmospheric Environment*, 39, 1263-1274, 2005.
4. Sheehan, P.E. and Bowman, F.M., "Estimated effects of temperature on secondary organic aerosol concentrations," *Environmental Science and Technology*, 35, 2129-2135, 2001.
5. Bowman, F. M., Odum, J. R, Seinfeld, J. H. and Pandis, S. N., "Mathematical model for gas/particle partitioning of secondary organic aerosols, *Atmospheric Environment*, 31, 3921-3931, 1997.

Synergistic Activities:

1. **Funded Research:** PI/CoPI/I on 14 funded research grants for a total of $9,795,000 as a faculty member at UND. Currently Co-Director of new Center for Regional Climate Studies (CRCS), an interdisciplinary research center including collaborative projects with North Dakota tribal colleges and primarily undergraduate institutions.
2. **STEM Outreach:** Design of educational computer game for teaching scientific problem solving skills in middle schools. Contributor to annual Air Pollution Workshop for area high school students (120+ annually).

3. **Specialty Fields:** Atmospheric aerosols with expertise in secondary organic aerosol partitioning behavior, mathematical modeling of multicomponent aerosols, and air quality modeling of organic aerosols. Experienced with aerosol instrumentation for chamber studies of aerosol formation rates of individual aromatic and biogenic hydrocarbons. Also, atmospheric chemistry of ozone formation and chemical reaction mechanism analysis. Assessment of student learning, active teaching methods, educational air pollution models, and learning technologies.
4. **Awards:** NSF CAREER award, 2000; UND School of Engineering and Mines Professor of the Year, 2009; UND Faculty Spirit Achievement Award, 2012; UND Outstanding Student Organization Advisor Award, 2014; UND College of Engineering and Mines Outstanding Faculty Award, 2015.
5. **Reviewer:** Manuscript reviewer for *Aerosol Science and Technology*, *Atmospheric Environment*, *Chemical Engineering Education*, *Environmental Science and Technology, Journal of Geophysical Research, Journal of Environmental Engineering & Science*, Frontiers In Education Conference, American Society for Engineering Education Conference, National Center for Case Study Teaching in Science. Grant proposal reviewer for NSF, EPA, ACS-PRF, UK NERC, NASA.

Collaborators & Other Affiliations

Collaborators:

Steve Benson, University of North Dakota - UND; Bradley Bowen, North Dakota State University – NDSU; Kristin Brevik, North Dakota State College of Science – NDSCS; Xuefeng Chu, NDSU; Anne Denton, NDSU; Karen Eskelson, UND; Mark Hoffmann, UND; Woei Hung, UND; Esam Jassim, Prince Mohamad University; Kristi Jean, North Dakota State College of Science – NDSCS; Cindy Juntunen, UND; John Kay, Energy and Environmental Research Center-EERC; Andrei Kirilenko, UND; Gautham Krishnamoorthy, UND; Alena Kubatova, UND; Margaret Laumb, Microbeam Technologies; Sherita Love, UND; Jin Lu, California Air Resources Board; LaCosta Potter, North Dakota South East Education Cooperative; Don McCollor, EERC; Adam Mohs, Orin Remediation Technologies; Gretchen Mullendore, UND; David Roberts, NDSU; Wayne Seames, UND; Dennis Sisk, UND; Brian Tande, UND; Richard Van Eck, UND; Jianglong Zhang, UND; Xiaodong Zhang, UND; Haochi Zheng, UND

Graduate and Postdoctoral Advisor:

John Seinfeld, California Institute of Technology

Dissertation/Thesis Advisor of Graduate Students (total of 12 as primary advisor):

Ben Oster, POET Research
Prasanna Seshadri, Babcock & Wilcox
Kristin Brevik, North Dakota State College of Science

APPENDIX B

REFERENCES

REFERENCES

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Bowman, F.M.; Odum, J.R.; Seinfeld, J.H.; Pandis, S.N. Mathematical Model for Gas-Particle Partitioning of Secondary Organic Aerosols. *Atmospheric Environment* **1997**, *31* (23), 3921–3931.

Hamel, B.; Rhodes, R.; Benson, S.A.; McCollor, D.P. The Role of the Combustion Air Preheater in an Effective Multipollutant Control Strategy. Presented at the DOE–EPRI–EPA–A&WMA Power Plant Air Pollution Control "Mega" Symposium, Washington, DC, May 19–22, 2003.

Hurley, J.P.; Katrinak, K.A. *Determinations of Ash Formation and Deposition Mechanisms at Minnesota Power Clay Boswell Station;* Report for Minnesota Power and U.S. Department of Energy Cooperative Agreement No. DE-FC21-86MC106437; Energy & Environmental Research Center: Grand Forks, ND, July 1992.

Khakharia, P.; Brachert, L.; Mertens, J.; Anderlohr, C.; Huizinga, A.; Sanchez Fernandez, E.; Schallert, B.; Schaber, K.; Vlugt, T.J.H.; Goetheer, E. Understanding Aerosol Based Emissions in a Post Combustion CO_2 Capture Process: Parameter Testing and Mechanisms. *International Journal of Greenhouse Gas Control* **2015**, *34*, 63–74.

Laumb, M.; Benson, S.; Kay, J.; McCollor, D.; Bowman, F.; Sisk, D. *Assessment of Particulate Characteristics Upstream and Downstream of ESP and Wet FGD*; Final Report Prepared for Minnkota Power Cooperative, Inc., July 1, 2009.

Lighty, J.S.; Varanth, J.M.; Sarofim, A.F. Combustion Aerosols: Factors Governing Their Size and Composition and Implications to Human Health. J. *Air Waste Manage. Assoc.* **2000**, *50*, 1565–1618.

McCollor, D.M.; Benson, S.A.; Hamel, B.; Rhodes, R. Method and Apparatus for Separating Gas Phase Pollutants Such as Sulfur Trioxide from Combustion Gases by Injecting Particulate Material. Canadian Patent 2,541,973, Aug 20, 2011.

Moser, P.; Schmidt, S.; Stahl, K.; Vorberg, G.; Lozano, G.A.; Stoffregen, T.; Richter, T. The Wet Electrostatic Precipitator as a Cause of Mist Formation—Results from the Amine-Based Post-Combustion Capture Pilot Plan at Niederaussem. *International Journal of Greenhouse Gas Control* **2015**, *41*, 229–238.

Moser, P.; Schmidt, S.; Stahl, K.; Vorberg, G.; Lozano, G.A.; Stoffregen, T.; Rösler, F. Demonstrating Emission Reduction – Results from the Post-Combustion Capture Pilot Plan at Niederaussem. *Energy Procedia* **2014**, *63*, 902–910.