



EERC[®]

Energy & Environmental Research Center

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March 28, 2013

Ms. Karlene Fine
Executive Director
North Dakota Industrial Commission
State Capitol
600 East Boulevard Avenue, Department 405
Bismarck, ND 58505-0840

Dear Ms. Fine:

Subject: EERC Proposal No. 2013-0135 Entitled “Advancing CO₂ Capture Technology:
Partnership for CO₂ Capture (PCO₂C) Phase III”

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) 777-4580 or by e-mail at jkay@undeerc.org.

Sincerely,

John P. Kay
Senior Research Manager

Approved by:

Dr. Gerald H. Groenewold, Director
Energy & Environmental Research Center

JPK/hmv

Enclosures



ADVANCING CO₂ CAPTURE TECHNOLOGY: PARTNERSHIP FOR CO₂ CAPTURE (PCO₂C) PHASE III

EERC Proposal No. 2013-0135

Submitted to:

Karlene Fine

**North Dakota Industrial Commission
State Capitol
600 East Boulevard Avenue, Department 405
Bismarck, ND 58505-0840**

Amount of Request: \$500,000
Total Amount of Proposed Project: \$5,398,000
Duration of Project: 24 months


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March 28, 2013

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**ADVANCING CO₂ CAPTURE TECHNOLOGY:
PARTNERSHIP FOR CO₂ CAPTURE (PCO₂C) PHASE III**

ABSTRACT

The overall goal of the Partnership for CO₂ Capture (PCO₂C) is to identify and help commercialize a range of CO₂ capture technology systems that can be integrated into the electric utility fleet to meet environmental emission constraints and requirements of CO₂ sequestration. Phase III will complement Phases I and II, performing continuing and new research for promising technologies. The fuel types considered will include all coal types, natural gas, petroleum coke, and/or biomass. The test program will deliver information on technical issues and challenges associated with the application of these technologies to the capture of CO₂ in both precombustion and postcombustion formats, being cognizant of the challenges of flue gas pretreating. A complete systems analysis and economic evaluation of the capture process will be performed as a function of technology type, coal type, and plant configuration to enable industries to make appropriate decisions to retrofit existing plants or build new plants.

The total estimated cost for the PCO₂C Phase III Program is \$5,398,000. The Energy & Environmental Research Center (EERC) will request approval to utilize \$2,699,000 through its Joint Program on Research and Development for Fossil Energy-Related Resources with the U.S. Department of Energy National Energy Technology Laboratory. The EERC is requesting \$500,000 from the North Dakota Industrial Commission to support the Phase III effort. Securing cost share from industrial sources is under way for the remaining balance of \$2,199,000. Phase III of the PCO₂C Program is scheduled to be completed in 24 months.

**ADVANCING CO₂ CAPTURE TECHNOLOGY:
PARTNERSHIP FOR CO₂ CAPTURE (PCO₂C) PHASE III**

PROJECT SUMMARY

The Energy & Environmental Research Center (EERC) has developed a premiere program to advance the most promising carbon capture technologies, the Partnership for CO₂ Capture (PCO₂C). Through this and other programs, world-class facilities have been designed, fabricated, and installed at the EERC. Over 30 private sector companies have contributed cash and technologies to both precombustion and postcombustion capture activities at the EERC. Because of the favorable response from industry and valuable information discovered in previous work, the EERC is proposing an additional round of funding. The proposed funding will allow the continued collaboration between industry partners, advance next-generation CO₂ capture technologies to the commercial scale, and provide tools and information that will aid industry-sponsored CO₂ capture-based efforts. The Phase III effort includes \$5,398,000 of funding to support a 2-year program that will allow for the evaluation of advanced CO₂ capture technologies in the postcombustion, precombustion, and oxycombustion platforms. The program is a follow-on to Phase II, which is currently wrapping up, as well as precombustion capture efforts also under way at the EERC.

The overall goal of the Phase III activity is to advance the state of CO₂ capture technology and create tools for managing CO₂ capture decisions through pilot-scale and systems engineering analyses. In order to meet this goal, the following objectives have been identified:

- Through pilot-scale demonstrations, find and evaluate promising precombustion and postcombustion CO₂ capture technologies.
- Evaluate CO₂ pretreatment technologies that can enhance the performance and reduce the cost of CO₂ capture systems.

- Continue the creation of systems engineering-based models using pilot-scale data and evaluations.
- Utilize the information gathered through the modeling and pilot-scale work to create economic-based decision tools that can aid owners and operators of CO₂ emission sources with capture-based strategies.

The fuel types to be considered will include lignite, subbituminous, bituminous, natural gas, petroleum coke, and/or biomass. Phase III will utilize the information gathered during Phases I and II of the program for the development of lower-cost and more effective capture technologies and also their integration into a total system that provides substantial economic and environmental benefits. The specific tasks to achieve the objectives of the project are listed below:

Task 1 – Postcombustion and Oxycombustion Technology Evaluation

Task 2 – Precombustion Technology Evaluation

Task 3 – Systems Engineering and Analysis and Support System Development

Task 4 – Management and Reporting

PROJECT DESCRIPTION

The proposed project is aimed at providing government and industry with key technical and economic information that can be used to examine the feasibility of technologies as a function of fuel type and system configuration. The technologies to be tested in pilot-scale systems at the EERC may include solvent scrubbing, oxygen-fired combustion, and other technologies such as gas separation membranes (GSMs).

The overall goal of this project is to demonstrate a range of CO₂ capture technologies while achieving high reductions in SO_x, NO_x, particulate, mercury, and other gas constituents to

meet environmental emission constraints and requirements of the CO₂ capture technologies. The technologies will be evaluated on a variety of flue gases derived from the combustion of lignite, subbituminous coal, bituminous coal, and biomass. In addition, other flue gases such as those derived from the combustion of fuel gas-derived gasification and natural gas utilization systems will also be considered for testing. The technology evaluation will draw upon the results and experience gained from Phases I and II of the PCO₂C Program.

OBJECTIVE

To meet the overall goal of the Phase III activity, objectives have been identified to advance the state of CO₂ capture technology and create tools for managing CO₂ capture decisions through pilot-scale and systems engineering analyses. The following objectives have been identified:

- Through pilot-scale demonstrations, find and evaluate promising precombustion and postcombustion CO₂ capture technologies.
- Evaluate CO₂ pretreatment technologies that can enhance the performance and reduce the cost of CO₂ capture systems.
- Continue the creation of systems engineering-based models using pilot-scale data and evaluations.
- Utilize the information gathered through the modeling and pilot-scale work to create economic-based decision tools that can aid owners and operators of CO₂ emission sources with capture-based strategies.

APPROACH

Testing efforts will involve the use of precombustion and postcombustion systems designed and constructed at the EERC. Several CO₂ capture technologies under development involve the use of GSM in a precombustion scenario and an adsorption column for gas–liquid contacting and a

stripper (or regenerator) column to regenerate the spent solvent and produce a nearly pure stream of CO₂ in a postcombustion scenario.

Precombustion tests will involve GSM, solvent-based technologies, solid sorbent, or other promising technologies that are identified. Pretreatment will also be considered.

Postcombustion tests will involve both solvent-based technologies and solid sorbent or other promising technologies that are identified. Oxy-firing may also be considered if the project team has an interest in further evaluation of that technology. Like precombustion testing pretreatment will also be considered.

Systems engineering analysis will be utilized to model and understand the different technology integration scenarios under consideration for use with CO₂ capture. Aspen software will be the primary tool and will be used with other engineering calculations and data collected during demonstration testing. This analysis will be used to determine the economic and technical feasibility of using different fuels when CO₂ capture is considered. These systems engineering studies will also be used to help modify the flexible scrubbing systems discussed above. In addition an enhanced decision support system (DSS) will also be developed. The EERC has developed, in conjunction with the Plains CO₂ Reduction (PCOR) Partnership, a Web-based DSS that can be utilized to link sources with potential targets within the PCOR Partnership region. This tool will be used as a starting point and will be enhanced to contain more information on capture technologies and performance.

SCOPE OF WORK

The EERC will work with technology developers as well as key industry stakeholders to evaluate technologies that are deemed to be promising advancements for the industry. This phase of the program will be divided into technology areas to include postcombustion, precombustion,

advanced oxycombustion, modeling/tools, and industrial applications. In order to maintain flexibility in the program, specific technologies are not proposed herein but will be determined by the advisory committee, which will consist of industry sponsors, the U.S. Department of Energy (DOE), and the EERC. A portion of the budget will be reserved for special topics that may arise as part of the test campaigns, modeling activities, or based on sponsor interests.

In order to meet the goals and objectives of this project, four tasks have been identified as follows:

Task 1 – Postcombustion and Oxycombustion Technology Evaluation

Task 2 – Precombustion Technology Evaluation

Task 3 – Systems Engineering and Analysis and Support System Development

Task 4 – Management and Reporting

Task 1 – Postcombustion and Oxycombustion Technology Evaluation

In this task, postcombustion and oxycombustion technologies chosen by the sponsor group or technologies brought to the program by members will be evaluated. Up to 15 weeks of testing is planned in the EERC technology demonstration combustion facilities. Eligible technologies are those that advance the state of postcombustion or oxycombustion CO₂ capture such as the following:

- Pretreatment
- Enabling technologies
 - Additives
 - Other
- Balance of plant
- Utilization
- Solvents (nonaqueous)
- Solvents (advanced amines)
- Solid sorbents
- Other

It is expected that most technologies will be allotted up to 3 weeks for testing unless the project team requests additional testing be conducted. A sample 2-week test plan is shown in Table 1. An example of the testing conducted during days 2 and 3 is given in Table 2 and shows parametric-style testing being conducted with typical test lengths of 3 to 4 hours for stable conditions to be reached. It would be expected that typically six, but up to eight, parametric tests could be completed in a 24-hour period depending on the technology. These parametric tests allow for the generation of plots showing CO₂ capture as a function of liquid-to-gas (L/G) ratio and heat input. This information will be compared to the performance of monoethanolamine (MEA), which has been run extensively in the EERC pilot-scale system, a method which is common practice in the determination of solvent performance. Conditions that could also be evaluated include concepts of partial capture where less than 90% capture is the focus, more evaluation of the emissions that may result from a given technology, and effects of contaminants on the technology (for example, solvent degradation). Analytical evaluation of technologies would be performed, if allowed by the vendor, to determine variables such CO₂-carrying capacities, stripping effectiveness, buildup of degradation products, and salt formation and composition.

Additional weeks will focus on maintaining specific conditions throughout the week to determine longer-term stability of the technology. For other technologies such as additives and sorbents, performance will be evaluated based on actual effect on CO₂ emissions and capture performance. The actual technologies to be tested will be decided by the project team. Technologies may also include CO₂ pretreatment (NO_x, SO_x, particulate) needed to achieve cost-effective CO₂ capture or partial capture of CO₂. Several CO₂ capture and pretreatment technology vendors have expressed interest in joining the program.

Table 1. Sample 2-week Postcombustion Test Plan

Day	Fuel	CO ₂ Pretreatment Technology	CO ₂ Capture Technology	Test Objective
1	Natural gas	System check	System check	System heat-up
2	Coal	Standard	Technology A	90% capture
3	Coal	Standard	Technology A	90% capture
4	Coal	Standard	Technology A	Partial capture
5	Coal	Standard	Technology A	Emissions
6	Coal	Standard	Technology A	Solvent degradation

Table 2. Example of a Daily Regimen for Days 2 and 3 (solvent testing)

Test	Test Length	Condition	Parameters
1	3–4 hours	Adjust to 90% capture for a given solvent flow rate and heat input	Includes gas flow rate, inlet gas temperature, stripper pressure, SO _x level, NO _x level, etc.
2	3–4 hours	Reduce flow rate	Parameters held steady
3	3–4 hours	Reduce flow rate	Parameters held steady
4	3–4 hours	Reduce flow rate	Parameters held steady
5	3–4 hours	Change heat input	Parameters held steady
6	≤4 hours	System maintenance (if needed)	
7	3–4 hours	Increase flow rate	Parameters held steady
8	3–4 hours	Increase flow rate	Parameters held steady
9	3–4 hours	Increase flow rate	Parameters held steady
10	3–4 hours	Repeat test or change condition	Parameters held steady
11	3–4 hours	Repeat test or change condition	Parameters held steady
12	≤4 hours	System maintenance (if needed)	

Industrial Applications of Technologies. The industrial applications program area within the postcombustion capture task will involve a determination of the feasibility of the technologies evaluated for application to other industrial emission streams such as cement kilns, fertilizer plants, natural gas combined cycle (NGCC) plants, gas processing, and other industrial processes. This will require pilot-scale testing while varying gas components by modifying combustion/gasification properties and spiking with certain gas components. These data will be used and compared to technology performance during “typical” coal-fired conditions. Correlations will be determined based on the pilot-scale data in order to modify the models to better predict economic and system performance. The results will be critical in determining

which technologies can best be used in certain industries and will allow a more technical approach when deciding levels of capture required. The number of tests will be determined by the project team.

Task 2 – Precombustion Technology Evaluation

In this task, precombustion technologies will be evaluated as chosen by the project team. Up to 6 weeks of testing is planned in the EERC gasification facilities. An example test summary for a week of pilot-scale evaluation can be found in Table 3, with parametric testing being conducted in a manner similar to the postcombustion activities. Technologies may include but not be limited to the following:

- Pretreatment
- Enabling technologies
- Balance of plant
- Utilization
- Membranes
- Physical solvents
- Solid sorbents
- Others
 - Electrical swing adsorption (ESA)

Details of technology performance with regard to CO₂ capture efficiency and cost will be provided.

Table 3. Sample Test Plan for Precombustion Technologies

Day	Fuel	CO ₂ Pretreatment Technology	CO ₂ Capture Technology	Test Objective
1	Natural gas	System check	System check	System heat-up
2	Coal	Standard	Membrane	Membrane performance
3	Coal	Standard	Membrane	Membrane performance
4	Coal	Standard	Membrane	Membrane performance
5	Coal	Standard	Physical solvent	Solvent degradation
6	Coal	Standard	Physical solvent	Solvent degradation

Task 3 – Systems Engineering and Analysis and Support System Development

The main goal of this task is to enhance existing advanced models and tools that will predict the behavior of CO₂ capture technologies. This information can be used by project sponsors in their decision-making processes involving CO₂ capture. Large-scale demonstrations of CO₂ capture technologies can be very costly and time consuming to deploy. Methods to make decisions in technology development steps are needed to speed up the deployment of advanced CO₂ capture concepts.

The focus of the systems engineering effort will be to provide additional information on promising technology from the laboratory and into commercial application. Aspen Plus will be the primary tool, utilizing the theoretical CO₂ capture models that were created during Phase I and Phase II of the program. These models will be modified to reflect the ideas and data generated from the pilot- and full-scale evaluations.

An enhanced DSS will also be developed as part of this task. The EERC has developed, in conjunction with the PCOR Partnership, a Web-based DSS system that can be utilized to link sources with potential targets within the PCOR Partnership region. This tool will be used as a starting point and will be enhanced to contain more information on capture technologies and performance. Some of the key questions that will be addressed by the capture-based DSS are as follows:

- What capture technologies are options for my plant configuration or industrial application?
- What are potential opportunities for CO₂ near my plant (the focus will be on the PCOR Partnership region)?
- How will partial capture affect my operations?

- What is needed to get my coal plant CO₂ emissions near NGCC levels?
- What are the initial economic needs for a CO₂ capture project?

Task 4 – Management and Reporting

Task 4 is the management and reporting task. Its success will be demonstrated by the timely and cost-effective accomplishment of contractual deliverables and milestones. Task 4 includes three main activities:

1. Management and Summary Progress Reporting: Summary reports will be provided on a regular basis. Additionally, regular conference calls with project participants will be conducted to allow for the exchange of information and input on test plans.
2. Presentations and Travel: Also incorporated into the management task are two detailed project presentations at sites to be selected by the Project Team Advisory Committee. This will also include conferences for presenting results.
3. Final Report: This project will provide a detailed final report discussing all of the project results.

EQUIPMENT

A portable Fourier transform infrared (FT-IR) spectroscopy instrument will be purchased to monitor and evaluate levels and concentrations of flue gas constituents that may be emitted to the atmosphere. FT-IR will assist in the understanding of the complex chemistry between flue gas and solvent. Additionally, upgrades and modifications to existing pilot facilities will also be carried out to improve the control and quality of the processes involved in testing CO₂ technologies.

DELIVERABLES

The main deliverables of this project will be progress reports and final technical and executive summary reports that will include the results of all of the tasks. The final report will include the following:

- Results from testing precombustion, postcombustion, and oxycombustion technologies
- Results of evaluating system integration approaches
- CO₂ capture feasibility studies
- CO₂ capture economic sensitivity analysis
- Results of special topic evaluations
- Access to the Web-based CO₂ Capture DSS

Quarterly reports and other reports will be generated when necessary. A summary of the other deliverables from this program follows:

- Information on mechanisms of CO₂ capture and its integration into overall systems.
- Collaborative research between stakeholders with an interest in developing cost-effective capture technologies.
- Immediate access to data in interim reports.
- Data and information that can be used to make decisions for future CO₂ capture projects.

FACILITIES

World-class facilities at the EERC include postcombustion technology, oxyfuel combustion, and precombustion systems. The specific systems are described briefly as follows.

Postcombustion Systems

The EERC, with cooperation from industry sponsors, has designed and built two systems that are currently available for postcombustion capture testing. The first system is a solvent absorber–stripper system used to capture CO₂ from the flue gas generated by a solid fuel combustion system. This capture system was designed to be flexible to allow for the evaluation of multiple solvent types. The second system is a moving-bed solid sorbent system. The solid sorbent system is also flexible in terms of capacity and can be operated at a smaller scale for proof-of-concept evaluations.

The solvent-based capture system, shown in Figure 1, consists of two main columns, each constructed from 10-in.-i.d. stainless steel column sections of varying lengths bolted together to achieve a desired total height. Koch–Glitsch IMTP 25 316L stainless steel random packing is loaded in the columns to enhance the liquid–gas contact area and promote better CO₂ absorption and regeneration. Sulzer’s advanced structured packing is also available for use in the system. Packing height, size, and type can easily be modified to accommodate different solvents and test conditions. The columns are designed to handle up to 130 scfm of flue gas generated by the combustion test facility (CTF). A demister is installed near the top of the absorber column to keep the flue gas flowing through the column from carrying solvent through with the exhaust stream. The system is also equipped with a water wash column to minimize solvent emissions.

Oxycombustion Systems

The oxy-fired combustion system is a retrofitted system on the same pilot-scale combustion system (CTF), providing flue gas to the solvent and solid sorbent capture equipment. The combustor is fired at a rate of 550,000 Btu/hr and is uniquely equipped to develop an understanding of heat-transfer issues along with fouling and slagging problems that may arise

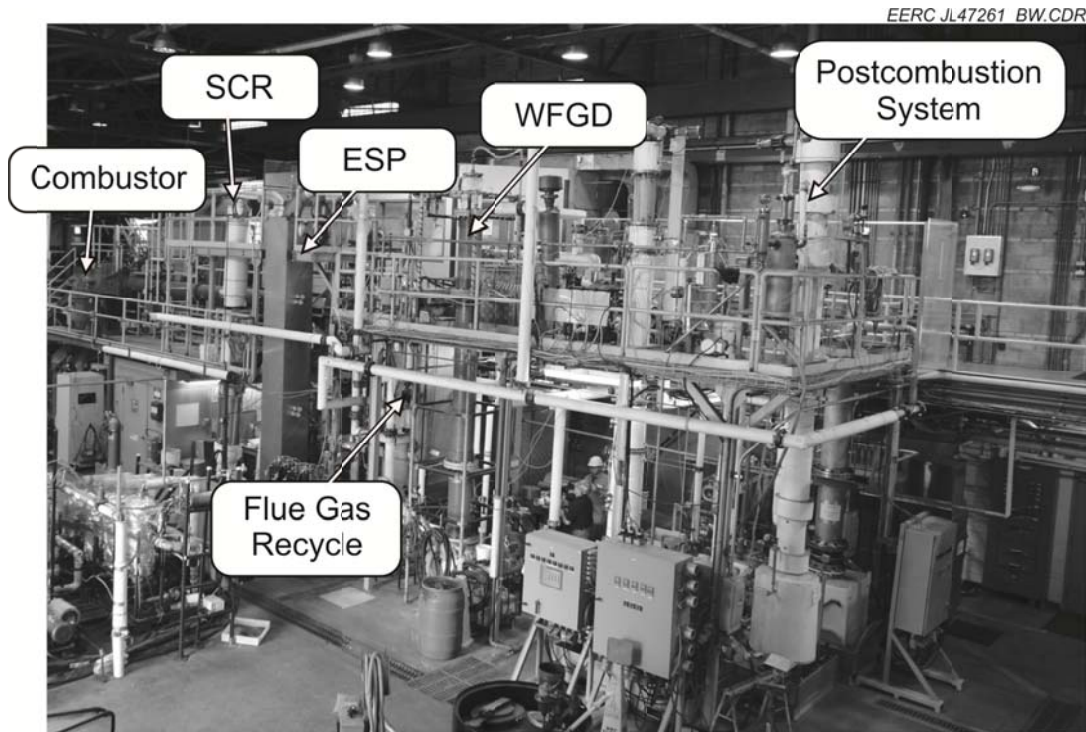


Figure 1. Photo of the CTF and capture equipment.

because of the CO₂-rich atmosphere in the furnace and convective pass. In addition, the CTF has the ability to operate with various types of burners and a suite of gas cleanup systems that include electrostatic precipitators (ESPs), fabric filtration, selective catalytic reduction (SCR), spray dryer absorbers (dry scrubbers), and wet scrubbers. Flue gas concentrations of O₂, CO₂, and SO₂ are obtained simultaneously at the furnace exit and stack. All system temperatures, pressures, and flue gas analyses are recorded continuously to the system's computer-controlled data acquisition system. The oxyfuel system has the capability to produce 140 scfm of flue gas with CO₂ concentrations as high as 90%. This system includes a range of options for recycling various amounts of flue gases containing a range of oxygen levels to as high as 35% O₂ for enriched combustion testing.

Precombustion Systems

The EERC has multiple gasification systems capable of gasifying coal, biomass, and other solid or liquid feedstocks. Of these, six of the systems are expected to see primary use over the next several years. Table 4 lists the systems and the basic characteristics of each.

The six systems each have warm-gas cleanup capabilities. The EERC has a bench-scale warm-gas cleanup train that is portable and can be placed at the back end of each gasifier. The system is capable of reducing sulfur levels to as low as 0.010 ppm, particulate to less than 0.1 ppmw with ceramic/metal candle filters, and fixed-bed reactors for reducing mercury or other contaminants. Water–gas shift reactors including sour, high-temperature, and low-temperature shift can be inserted at any location in the cleanup train. The EERC, through its National Center for Hydrogen Technology[®] (NCHT[®]), developed the warm-gas cleanup testing capability. The bench-scale cleanup train is fully operational.

Table 4. Summary of Gasification Systems

Gasifier Name	Type	Scale	Feed Rate, lb/hr	Syngas Production, scfm	System Pressure, psi	Gasifier Nominal Temp, °F	Warm-Gas Cleanup Capability
CFBR ¹	Fluidized bed	Bench	4	8 on air, 1.5–2 on O ₂	150	1525	Full stream
TRDU ²	Transport reactor	Pilot	200–500	400 on air, 250 on O ₂	120	2000	Slipstream (5%)
EFG ³	Entrained flow	Bench	4–16	16–20	300	2730	Full stream
HPFBG ⁴	Fluidized bed	Bench	4–20	30–40	600–1000	1600–1800	Full stream
Carbonizer	Fluidized bed	Pilot	100–150	150 on air	150	1200–1800	Slipstream
AFBG ⁵	Fixed bed	Pilot	33–70	35–75 on air	Ambient	1300–1550	Cold-gas only

¹ Continuous fluid-bed reactor.

² Transport reactor development unit.

³ Entrained-flow gasifier.

⁴ High-pressure fixed-bed gasifier.

⁵ Advanced fixed-bed gasifier.

Gas separations using hydrogen/CO₂ separation membranes can be performed at elevated temperatures without the need to quench the syngas. The membrane can be inserted at any point in the cleanup train to simulate the desired operating conditions but would normally be installed after the sulfur removal and shift reactors, depending on the sensitivity of the membrane to sulfur. If needed, a small slipstream of the syngas from any gasifier can be pulled for testing.

STANDARDS OF SUCCESS

The ability to assess the success of the project is based primarily on the EERC's quality management system (QMS). To ensure successful projects, the EERC adheres to an organizationwide QMS. It is authorized and supported by EERC management to define the requirements and the organizational responsibilities necessary to fulfill governmental and client requirements relating to quality assurance/quality control (QA/QC), applicable regulations, codes, and protocols.

BACKGROUND

Coal will continue to play a major role in meeting energy demands well into the 21st century. EERC research is ensuring that coal can be utilized as cleanly and efficiently as possible in existing facilities as well as with emerging technologies. Coal research at the EERC pursues a scientific understanding of the physical, chemical, and mineralogical nature of coal and its associated earth materials as the foundation for predictively engineering coal conversion and power systems. The EERC team has more than five decades of basic and applied research experience producing energy from all ranks of coal, with particular emphasis on low-rank coals. As a result, the EERC has become the world's leading low-rank coal research center. EERC research programs are designed to embrace all aspects of energy-from-coal technologies from

cradle to grave, beginning with fundamental resource characterization and ending with waste utilization or disposal in mined land reclamation settings.

CO₂ Is an Environmental Concern

In 1992, international concern about climate change led to the United Nations Framework Convention on Climate Change (UNFCCC), the ultimate objective of which is the “stabilization of greenhouse gas concentrations in the atmosphere at a level that mitigates anthropogenic interference with the climate system” (1). Research by DOE and the International Energy Agency (IEA) has suggested that carbon separation and sequestration can play an important role in reducing CO₂ in the atmosphere in the first part of the twenty-first century (2).

Currently, global climate change is perceived by many as the largest environmental challenge facing the world. An increased level of CO₂ in the atmosphere has been interpreted as the dominant contributor to the apparent increase in global warming. The primary sources of anthropogenic CO₂ are fossil-fueled power plants, automobile engines, and furnaces used in residential and commercial buildings. Ninety-seven percent of anthropogenic CO₂ emissions come from energy-related tasks (3). CO₂ emissions from coal-fired power plants contributed more than one-third of the anthropogenic CO₂ emissions in the United States in 2004. A breakdown of stationary U.S. CO₂ emissions is outlined in Table 5, which shows that CO₂ from coal-fired electric utilities is the single largest contributor of all stationary emitters. Because of the abundant supply of coal, especially lignite, subbituminous, and bituminous coals, the United States will rely on the use of fossil fuels for its energy needs for many years to come, thus sustaining or increasing the level of CO₂ emissions. Since lignites produce more CO₂ per unit of energy compared to the other ranks of coal, they will be the most impacted by any move to force CO₂ removal from power plants.

Table 5. Annual U.S. CO₂ Emissions

Sources	U.S. Total Tonnes
Power Generation (1)*	2,239,700,000
Coal (1)	1,868,400,000
Natural Gas (1)	299,100,000
Oil (1)	72,200,000
Industries	324,789,000
Refinery (2)	184,918,000
Iron and Steel (3)	54,411,000
Cement (3)	42,898,000
Ammonia (3)	17,652,000
Aluminum (3)	4,223,000
Lime (3)	12,304,000
Ethanol (3)	8,383,000
Total	2,564,489,000

* Numbers in parentheses are references.

CO₂ Capture

The three main options for reducing CO₂ emissions from fossil fuel-based energy systems are 1) increasing fuel conversion efficiency, 2) switching to a fuel with a lower fossil carbon content, and 3) capturing and storing the CO₂ emitted from the fossil fuel (4). Options 1 and 2 are currently not sufficient options for reducing CO₂, as the United States relies, and will continue to rely, heavily on coal for energy production. Reduction of anthropogenic CO₂ emissions is focused on CO₂ separation and subsequent sequestration, which includes capture and separation, transportation, and storage. Sixty percent of the total cost for CO₂ sequestration occurs in the capture and separation step, with the remaining 40% coming from transportation and storage (2). It is technically feasible to separate CO₂, but the costs associated with the method are currently too high to be practical because of the large energy requirements of these systems.

Postcombustion Capture (4)

Removal of CO₂ from low-pressure (<2 psig), low-CO₂-concentration (<15 vol%) flue gases takes place following the pollution control devices, as shown in the schematic in Figure 2.

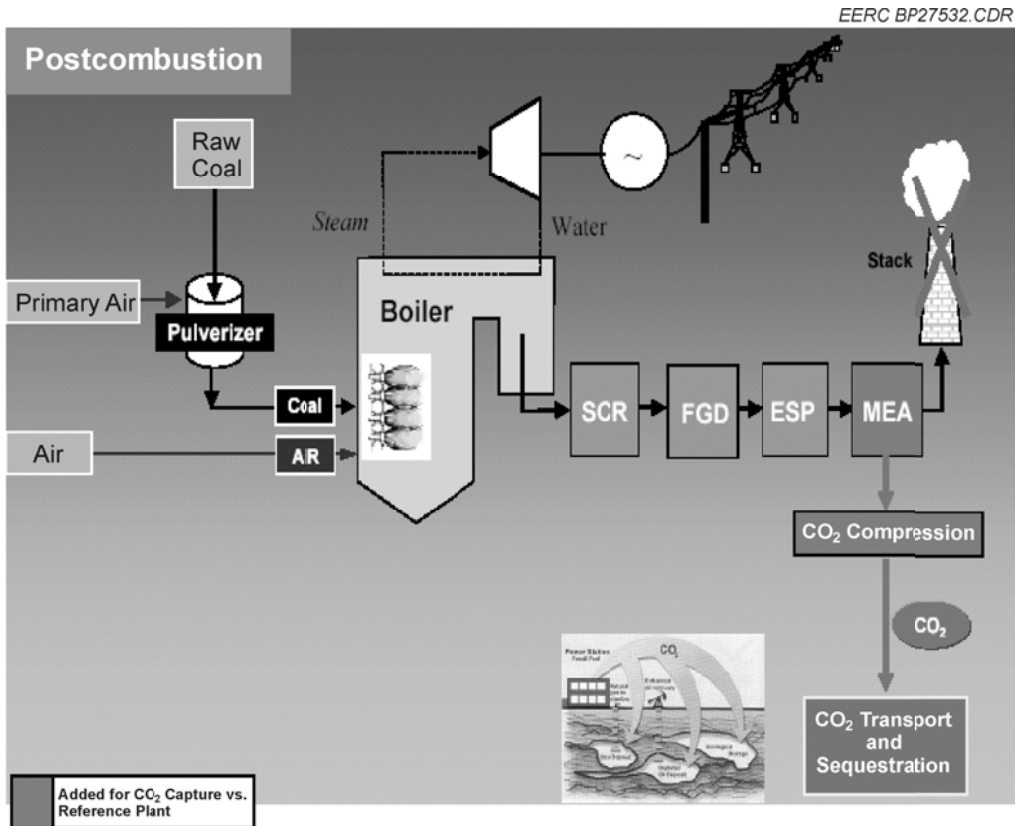


Figure 2. Schematic for postcombustion CO₂ capture (5).

Several types of processes have been or are being developed to separate and remove CO₂ from a flue gas stream. Figure 3 summarizes the basic types of processes. In general, when postcombustion capture is being considered, three main categories of technologies are being considered that can be employed within the next 5 to 10 years:

1a. Absorption (amine-based)

i. Fluor Daniel Econamine FGSM

- 30% MEA solution incorporating additives to control corrosion and (oxidative and thermal) degradation; more than 20 commercial plants ranging in size from 5 to 400 tons CO₂/day.

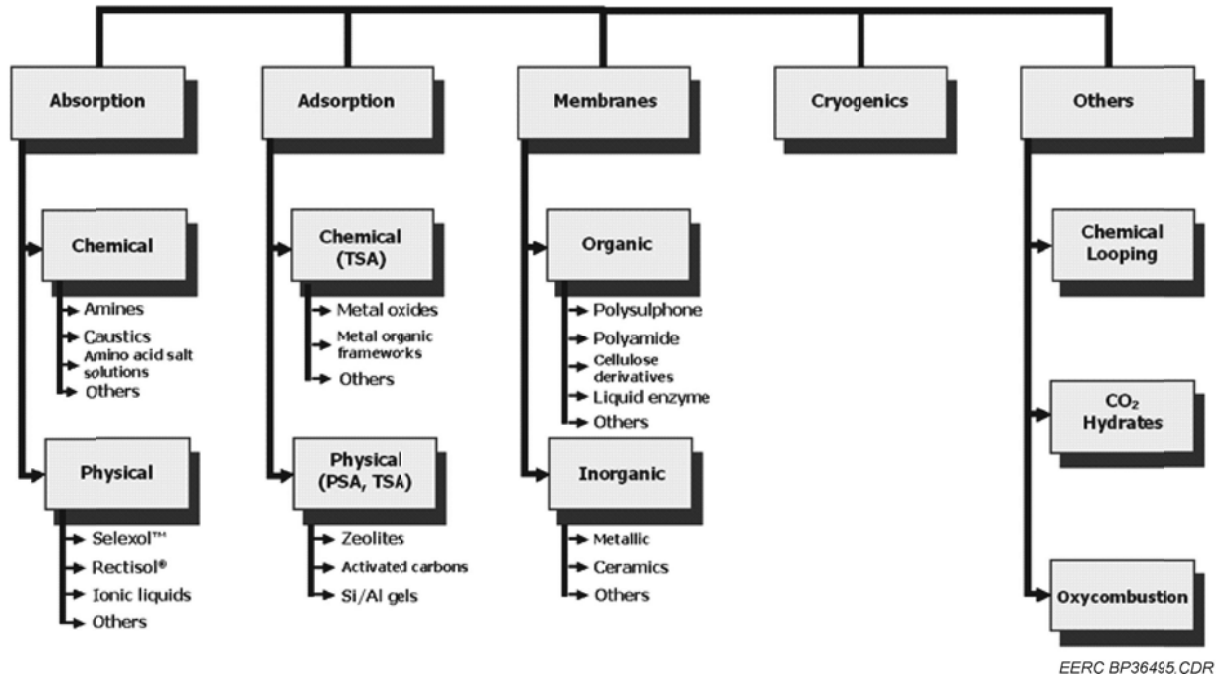


Figure 3. CO₂ capture and separation technology types.

- ii. ABB-Lummus Global
 - 15%–20% MEA solution; four commercial plants ranging in size from 150 to 850 tons CO₂/day.
- iii. Mitsubishi Heavy Industries (MHI)
 - KS-1 – sterically hindered amines; two commercial plants: ~210 and 30 ton CO₂/day.
- iv. Cansolv
 - Mixture of amines; commercial plant case study at NSC (Japan).
- v. HTC Pure Energy
 - Mixture of amines with a focus on a modular 1000-ton/day system.
- vi. DOW/Alstom Power
 - Advanced amine process.

- vii. Hitachi
 - Proprietary mixture of amines.
- viii. Huntsman Chemical
 - Proprietary mixture of amines with bench- and small-pilot-scale data.
- ix. Praxair
 - Mixture of amines.

1b. Absorption (ammonia-based)

- i. Powerspan
 - ECO₂ Ammonia Process – 1-MW slipstream pilot plant.
- ii. Alstom
 - Chilled ammonia – American Electric Power (AEP) demonstration; We Energies pilot plant and other slipstream demonstrations.

2. Adsorption (solid sorbents)

- i. Research Triangle Institute (RTI) international dry carbonate process
- ii. ADA-ES carbon-based amine-enriched sorbents
- iii. National Energy Technology Laboratory (NETL) amine-enriched sorbents
- iv. Süd-Chemie
- v. TDA Research, Inc.
- vi. Metal organic frameworks (MOFs)
- vii. Zeolites

3. Membranes

- a. Thermally optimized polymer membrane
- b. Inorganic nanoporous membrane

- c. Molecular gate membrane (Research Institute of Innovative Technology for the Earth [RITE])
- d. Kvaerner hybrid membrane absorption system (Kvaerner Process Systems)
- e. Enzymatic liquid membranes (Carbozyme)
- f. CO₂-selective membrane (Media and Process Technology, University of Southern California)
- g. Membrane water–gas shift reactor (Eltron Research/SOFCo/Chevron Texaco)

Precombustion

Precombustion removal refers to near-complete capture of CO₂ prior to fuel combustion and is usually implemented in conjunction with gasification (of coal, coke, waste, residual oil, biomass) or steam/partial oxidation reforming of natural gas to produce syngas. Syngas contains CO and H₂. Subsequent conversion via the water–gas shift reaction produces CO₂ from CO, resulting in H₂-rich syngas. This syngas (often with N₂ added for temperature control) can be combusted in gas turbines, boilers, or furnaces. Figure 4 is a flow sheet showing precombustion CO₂ removal.

Typical CO₂ stream concentrations before capture are 25 to 40 vol% at pressures of 363 to 725 psia. The high partial pressure of CO₂, relative to that in combustion flue gas, enables easier separation through solvent scrubbing. In refineries and ammonia production facilities, where H₂-rich syngas is produced by gas reforming, CO₂ is recovered during acid gas removal using chemical solvents (e.g., Benfield or MDEA [methyldiethanolamine] processes described in the postcombustion section). Pressure swing adsorption (PSA) is also used, but the CO₂-rich stream may have significant residual fuel value that makes it attractive for in-plant use.

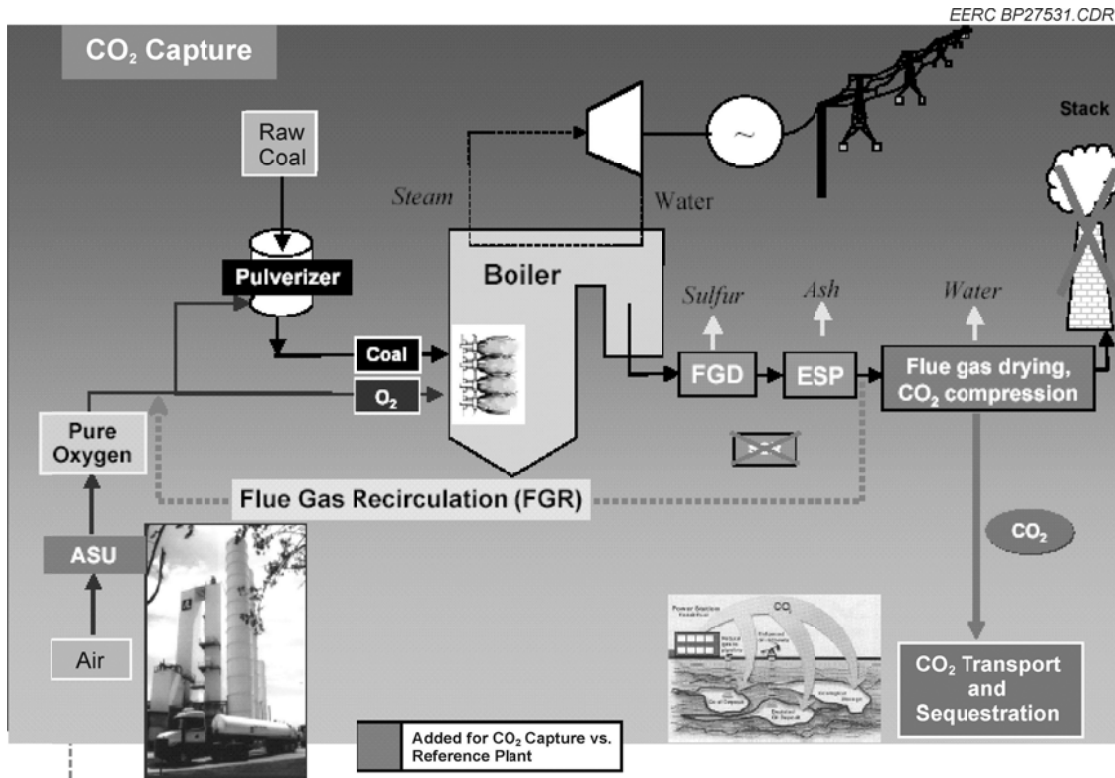


Figure 4. Schematic of an oxygen combustion system (5).

Oxycombustion

Substitution of oxygen and recycled flue gas for all of the combustion air has been proposed to produce a CO₂-rich flue gas requiring minimum separation for use or sequestration.

Conventional air combustion processes in boilers or gas turbines produce flue gas that contains predominantly N₂ (>80 vol%) and excess O₂ in addition to CO₂ and water. Separation technologies must separate CO₂ from these other components. If the air is replaced by oxygen, the nitrogen content of the flue gas approaches zero (assuming minimal air leakage into the system), and the flue gas contains predominantly CO₂ along with a small amount of excess oxygen and combustion water. The CO₂ can be recovered by compressing and cooling, followed by dehydration. The adiabatic flame temperature can be moderated by recirculating a part of the recovered CO₂.

The levels of noncondensable impurities and thermodynamics limit recovery of CO₂ and affect the purity of the product stream. The concentration of CO₂ can be targeted to a specific intended end-use application such as sequestration. For enhanced coalbed methane (ECBM) recovery or saline aquifer sequestration, only condensation of moisture may be required because some constituents (e.g., N₂) can be present and a supercritical, dense-phase fluid is not required. Under this scenario, zero emissions would be possible. Where a supercritical fluid is required for enhanced oil recovery (EOR) or deep reservoir injection, noncondensable contaminants such as N₂, NO_x, O₂, and Ar are removed by flashing in a gas–liquid separator.

Oxygen combustion has several advantages. The volume of flue gas reaching downstream systems is one-third to one-fifth that of conventional coal boilers. The process produces a flue gas stream containing more than 80 vol% CO₂, depending upon the fuel composition, purity of oxygen from air separation, and air leakage into the boiler. Impurities such as SO₂, NO_x, particulate, trace elements, and mercury become concentrated in the flue gas, thus reducing capital and operating costs for contaminant removal. NO_x may be low enough to eliminate further control, and capital and operating cost savings (for control systems) may offset air separation capital and operating costs.

Issues with oxygen combustion center principally around the high cost for air separation, which is currently attainable at a very large scale only by cryogenic distillation. Relative to coal gasification, combustion requires up to three times the amount of oxygen because all of the carbon is converted to CO₂. The air separation unit (ASU) capacity (and parasitic power load) likewise will be commensurately larger. Other issues include expected lower flue gas exit temperature (that may increase the risk of low-temperature corrosion from condensation of

sulfuric acid), burner operation, flame stability, levels of unburned carbon, flame luminosity and length, and changes in slagging/fouling characteristics under the different atmosphere.

Retrofit applications would be designed to maintain the same steam outlet conditions. The higher heat capacity of the gas should potentially facilitate greater heat absorption while producing lower flue gas temperature. Higher heat absorption would result in higher boiler efficiency, but this would be offset by higher auxiliary power load for fan power to the recycle gas for temperature control.

Development efforts involving conventional pulverized coal testing with oxygen combustion are at the scale of several hundred kilowatts and less. Developers and testing organizations include CANMET, Mitsui Babcock, American Air Liquide, Babcock & Wilcox, Foster Wheeler North America, and the EERC.

Oxygen firing in circulating fluid-bed boilers may have an advantage over pulverized coal (pc) firing in that a significant degree of temperature control can be achieved by recirculating solids, but this has not been proven. Lower flue gas recycle would reduce parasitic power load for fans. In addition, higher O₂ concentrations may be possible, resulting in a smaller boiler island size and reduced capital cost. Development issues center around continuous solids recirculation. Currently, testing is at the large pilot scale, with development efforts being conducted by ALSTOM Power, ABB-Lummus Global, Praxair, and Parsons Energy.

Economics of CO₂ Capture

Several studies have been completed in the past that have estimated the cost of capturing CO₂ from coal-fired power plants. Although advanced solvents are currently thought of as being the most readily available technology, there are still many unanswered questions about the economics of these systems. For most of the advanced solvents under development, the

economics are still unknown as only small-scale data are available. A study by the University of New South Wales was completed that compared the economics of a conventional solvent (MEA) to an advanced solvent (MHI's KS1) (6). This study shows a good example of what advanced solvents can do in terms of decreasing the costs of capturing CO₂. Figure 5 from this analysis shows the breakdown of costs for capturing CO₂ with a conventional MEA solvent vs. the advanced MHI KS1 solvent. This analysis shows how advanced solvents can reduce the amount of energy required, therefore reducing the overall cost of the capture system.

The results of the study show that the biggest area for reducing cost is in the reduction of the energy required for the system. This is shown in Figure 6. This is accomplished by designing a solvent with favorable thermodynamics. Discovery of favorable kinetics can reduce capital cost significantly. When looking at the cost to capture CO₂, this study predicted that for a conventional MEA solvent, it would cost \$55–\$74/ton of CO₂ captured, depending on the level

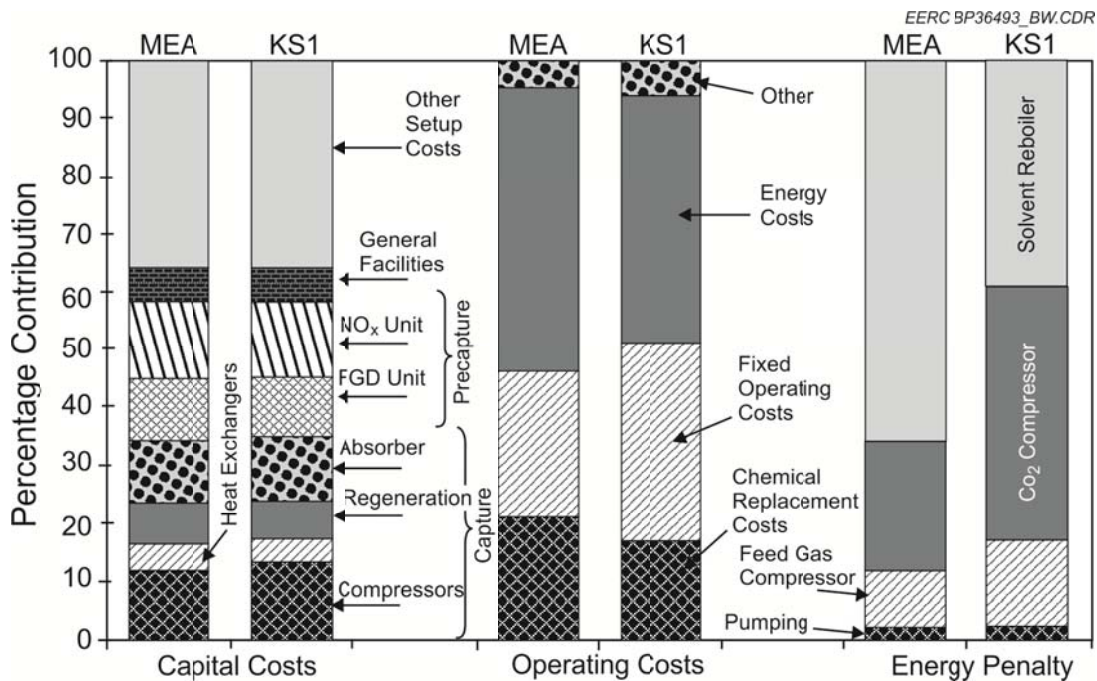


Figure 5. Capital and operating costs and estimates of energy penalties for MEA and KS1 solvents.

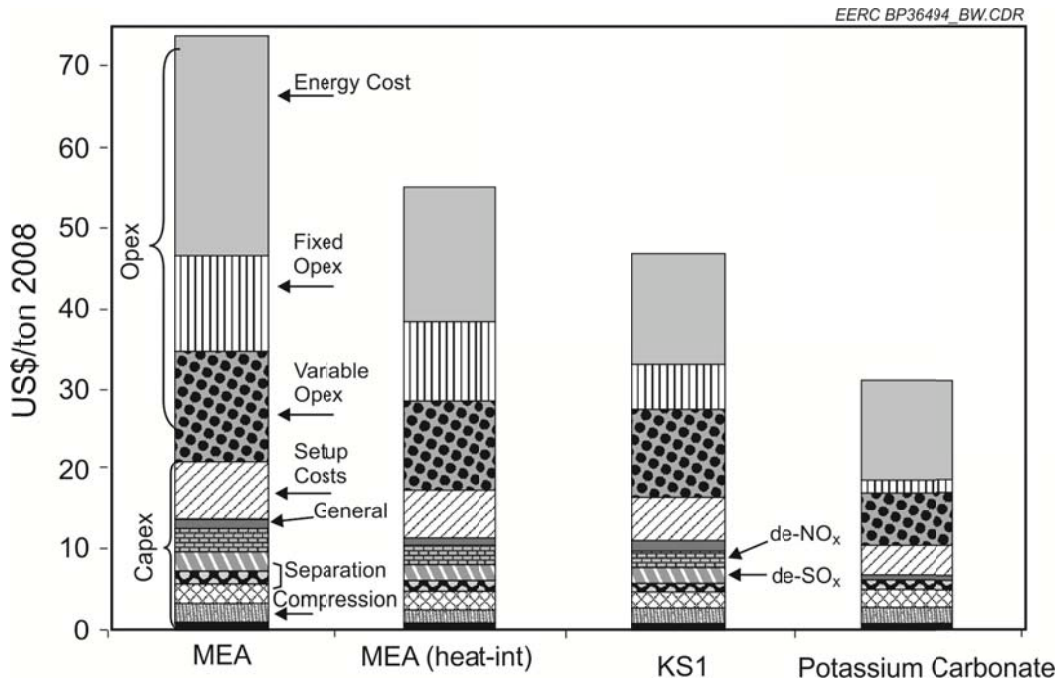


Figure 6. CO₂ capture cost breakdown.

of heat integration. Just by switching to an advanced solvent, the cost can be reduced to \$30–\$47/ton in this example. Many solvents exist, and the economics for each are dependent on the properties that were discussed above, creating a wide variety of cost estimates. These data show the importance of advanced solvents and support the statement that it will not be a “silver bullet” approach for capturing CO₂; several CO₂ capture technologies will need to be used on a site-by-site evaluation. Further cost reductions can be realized if capital equipment costs can be decreased. This can be accomplished by increasing the mass-transfer rate between the CO₂ and the liquid solvent.

Key Results from Previous Phases

The postcombustion program is a continuation of the PCO₂C effort currently wrapping up the Phase II efforts. In Phase I of PCO₂C, the EERC conducted pilot-scale demonstrations of selected CO₂ separation and capture technologies for fossil fuel- and biomass-fired systems.

PCO₂C Phase I was aimed at providing partners with key technical and economic information on the feasibility of capture technologies as a function of fuel type and system configuration. The technologies tested in the pilot-scale systems at the EERC included solvent scrubbing, solid sorbents, and oxygen-fired combustion. Work conducted during Phase II of PCO₂C has been focused on the most promising technologies identified during Phase I as well as several new technology advancements under development. The aim of Phase II is lower-cost and more effective capture technologies whose integration into an advanced system provides substantial economic and environmental benefits.

Phase I – Postcombustion. The PCO₂C Program has evaluated six different solvents, a solid sorbent, a novel gas contactor, a range of oxycombustion methods, and other novel technologies. Many other results have been realized through this program as well, such as information and systems engineering models to understand the life cycle of solvent-based systems as well as their integration into large-scale power plants. Some of the key results of the modeling and pilot-scale evaluations can be seen in Figure 7, which also shows an economic analysis for a 500-MW greenfield plant with several CO₂ capture system options. Advanced equipment has also been evaluated to reduce the capital costs associated with postcombustion capture. The main system evaluated is an advanced contactor that can use a range of solvents as the chemical component. This would allow for a versatile technology that enables advancements for postcombustion capture. The pilot-scale data have been used to perform an economic analysis to predict the capital savings over a traditional solvent-based system. The results of this preliminary analysis show that the system has the potential to reduce the capital costs by up to 50%.

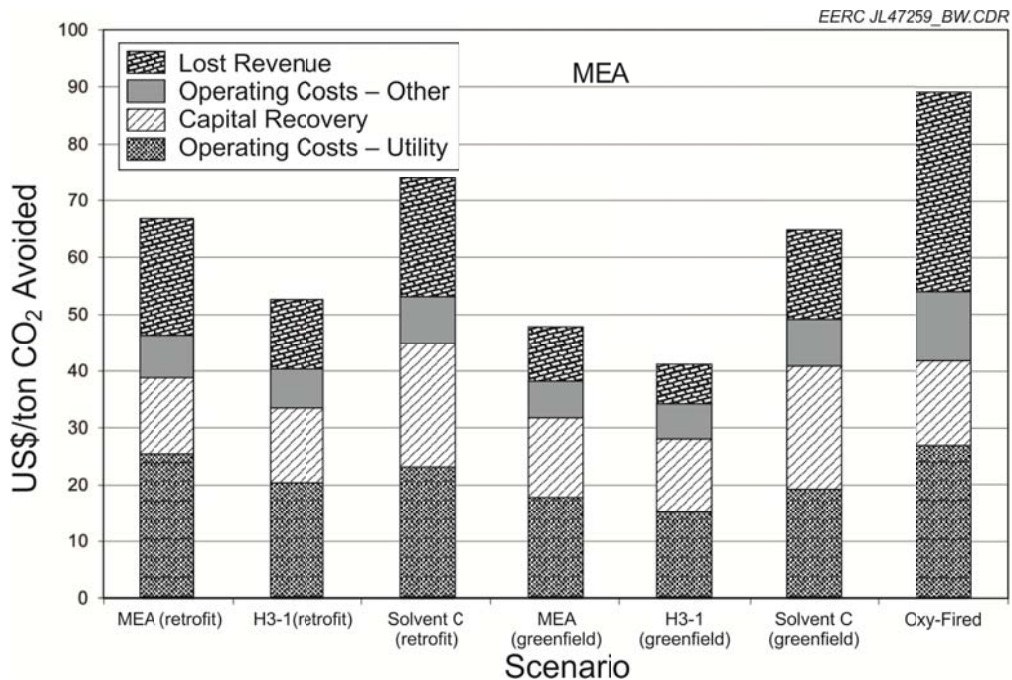


Figure 7. Cost of CO₂ avoided based on PCO₂C pilot-scale evaluations and advanced modeling.

Phase II – Postcombustion. Testing during Phase II of the program was designed to enhance the economic evaluations completed during Phase I. The tests were concentrated on more advanced amines and other advanced enabling technologies, including the following:

- MEA (30 wt%) with Sulzer Advanced Mellapak™ CCTM packing
- Hitachi H3-1 solvent
- Huntsman advanced solvent
- Cansolv next-generation solvent
- ION Engineering solvent
- NETL solid sorbent
- C-Quest

Preliminary findings suggest several solvent technologies require much lower amounts of regeneration energy when compared to MEA. Figure 8 contains the results for a solvent designated Solvent A. At a L/G ratio of 0.88, the energy requirement at 90% CO₂ capture is less than 80% of that required for MEA.

More substantial reductions in energy requirements were observed with other technologies also evaluated in Phase II. Figure 9 contains the results for tests where the solvent provided by ION Engineering was evaluated. The results of testing the ION Engineering technology indicated that regeneration of this solvent requires nearly 50% of the energy required for MEA at 90% capture and a L/G ratio of 0.88.

Additional Phase II activities included life cycle assessments, economic modeling, steam cycle integration options, evaluation of solvents under NGCC conditions, and the evaluation of degradation products. This information will be available to support Phase III activities.

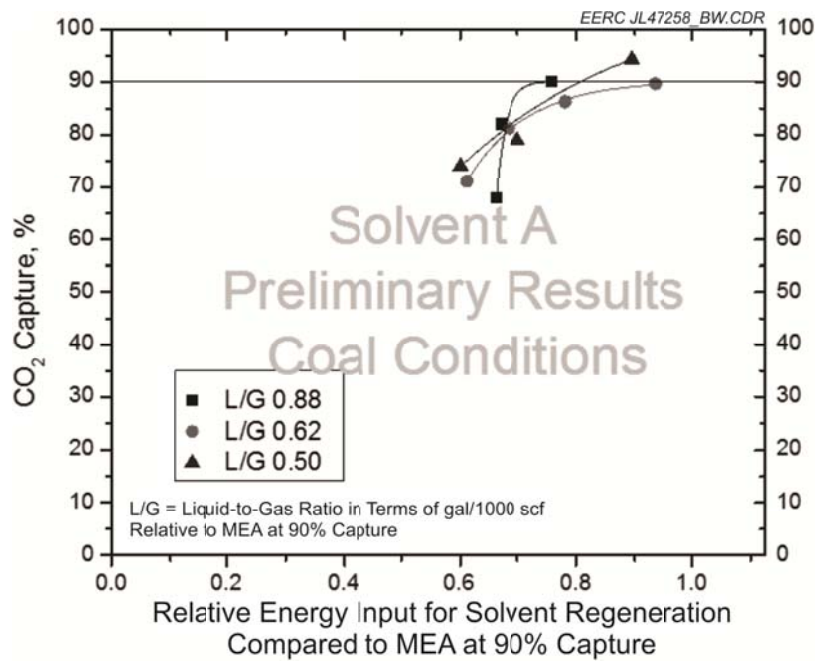


Figure 8. Relative energy input for Solvent A compared to MEA.

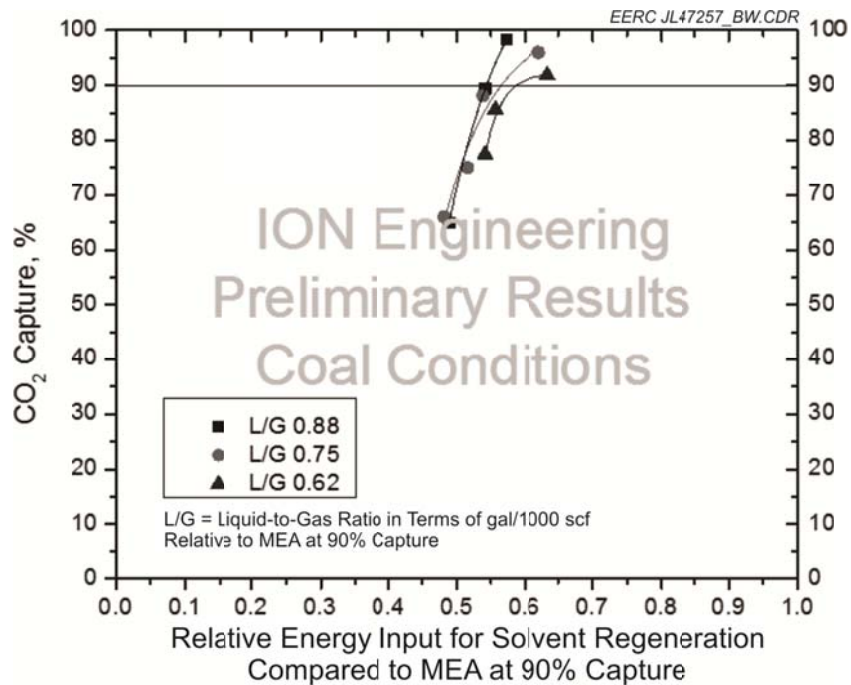


Figure 9. Relative energy input for ION Engineering solvent compared to MEA.

Precombustion

A concurrent EERC precombustion capture program has focused on membranes, physical solvents, sorbents, and unique regeneration techniques covering PSA, temperature swing adsorption (TSA), and ESA. Through this work, pilot-scale systems have been put in place with a wide range of capabilities. The key to driving CO₂ capture technologies to the marketplace is being able to quickly evaluate these systems at a pilot-scale level that most closely matches industrial-quality gas. The systems developed at the EERC are all used with a variety of fuels, allowing for the understanding of flue gas (or syngas) impurities and the impact they may have on the technologies. This understanding can provide substantial economic benefits when installing commercial systems.

The precombustion programs have also made great strides in the evaluation of technologies currently under development. Several pilot-scale evaluations have taken place to

look at using membranes to capture CO₂ vs. physical solvents. A number of membranes have been evaluated under coal-derived syngas at various pressures. The results were used to develop a model to predict the savings of using membranes over the more traditional physical solvent used. Table 6 shows the results of such an analysis. The analysis shows an additional 33 MW of power can be produced if membranes were used instead of a physical solvent-based system. As membrane technologies increase in scale, further analysis can be performed.

QUALIFICATIONS

The EERC is a research facility that operates as a business unit of the University of North Dakota (UND). EERC contract funding in fiscal year 2012 was \$32.1 million. The EERC has worked with over 1225 clients in all 50 states and 52 countries. The EERC has a multidisciplinary staff of around 300 who have expertise and partnerships in a broad spectrum of energy and environmental programs, including over 50 years of research experience on lignite properties and variability; gasification processes; ash-related impacts; the fate of pollutants including Hg, particulate, and acid gases; Hg sampling, measurement, and speciation; development, demonstration, and commercialization of combustion and environmental control systems; conducting field testing and demonstrations; and advanced analysis of materials.

Table 6. Energy Balance to Determine the Benefits of Membranes over Physical Solvents for Precombustion Capture, MW

Hierarchy Block	Membrane Case	Solvent Case
Power	316	318
Air Separation Unit	-55	-57
CO ₂ Compression	-4	-24
Selexol™ Regeneration	0	-13
Total	257	224

The project manager and principal investigators are many of the same team members who contributed greatly to the successful completion of many tasks in Phase I and Phase II. Details of their qualifications can be found in the enclosed resumes. The EERC has a staff of fabricators from the various crafts and trades (welders, machinists, electricians, instrumentation and controls, etc.) who have extensive talent and experience with all aspects of producing and modifying combustion, gasification, and gas cleanup systems. As a result, it is anticipated that little outsourcing will need to be done and the control of the resource allocation and scheduling can be handled internally. Additionally, quality control is maintained in-house. Many of these people serve dual roles at the EERC, with the fabricators being the operators of the systems when they are complete. This unique situation has resulted in the integration of the fabricator/operators in the early stages of the mechanical design process alongside the engineers and designers. There is a great deal of transparency in the management of projects, so all members of the team feel motivated to contribute.

VALUE TO NORTH DAKOTA

In North Dakota, over 18,000 jobs, \$1.8 billion in business volume, and \$75 million in tax revenue are generated by the lignite industry each year. North Dakota produces over 30 million tons of lignite annually, and thousands of tons of lignite is fired by North Dakota power plants daily (4). North Dakota's economy depends on lignite production and use. Lignite combustion produces more CO₂ per Btu of energy as compared to other coals; thus a low-cost, effective means of separating CO₂ will be critical to ensure lignite's future use if regulations limit CO₂ emissions in the future.

MANAGEMENT

This project will be executed by the EERC (Table 7), with guidance from the project team made up of the industrial sponsors, the North Dakota Industrial Commission (NDIC), and DOE. Mr. John Kay will be responsible for overall task management and strategic studies. Other task managers have been assigned for each of the tasks discussed above and include Mr. Brandon Pavlish and Mr. Joshua Stanislawski. The PCOR Partnership team along with Mr. Michael Holmes and Mr. Jason Laumb will serve as project advisors. Figure 10 provides an overview of the project management structure. Resumes for key personnel can be found in Appendix A.

Table 7. Key Personnel

Name	Role	Hours
John Kay	Project Manager	2972
Brandon Pavlish	Principal Investigator	2965
Joshua Stanislawski	Principal Investigator	3035
Michael Holmes	Project Advisor	700
Jason Laumb	Project Advisor	815

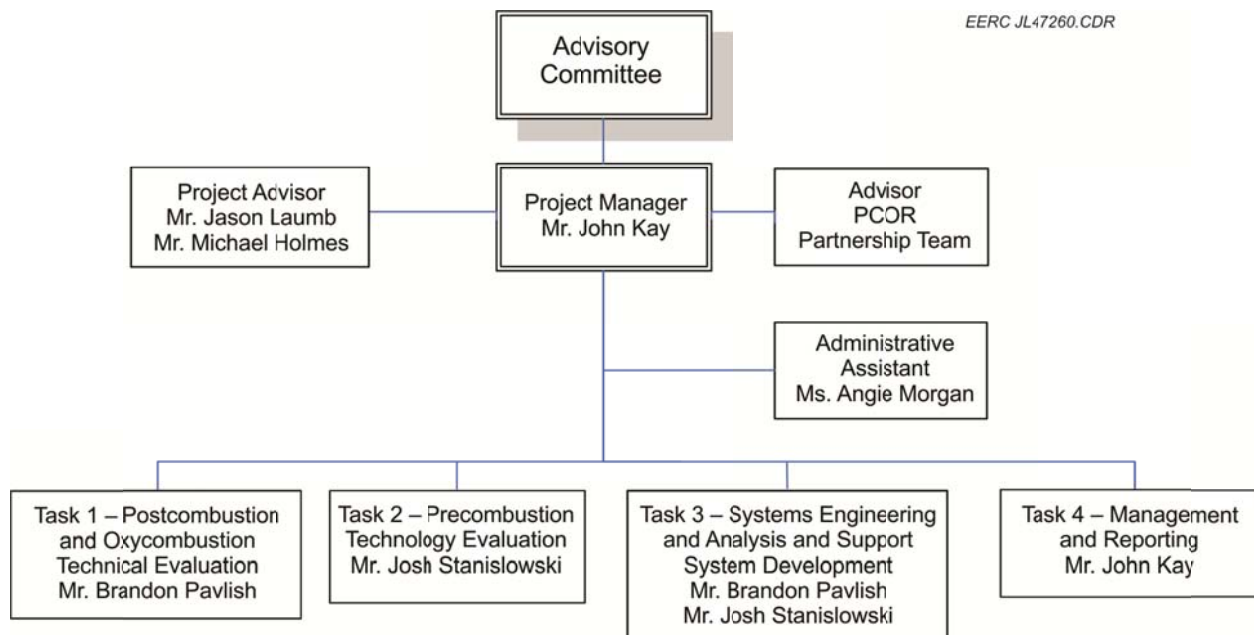


Figure 10. Overview of management structure.

PROJECT SCHEDULE

The proposed tasks for Phase III will take 24 months to complete, with a proposed start date of July 1, 2013, and an end date of June 30, 2015. An overview of the schedule for the project is shown in Table 8.

Table 8. Schedule of Tasks

Tasks	Duration
1 – Postcombustion and Oxycombustion Technical Evaluation	1–20 months
2 – Precombustion Technology Evaluation	1–20 months
3 – Systems Engineering and Analysis/Support Systems Development	1–22 months
4 – Management and Reporting	1–24 months

BUDGET/MATCHING FUNDS

The EERC is requesting \$500,000 from NDIC to support the PCO₂C Phase III effort. The total estimated cost for Phase III is \$5,398,000; of this, the EERC will request \$2,699,000 from DOE through the EERC's Joint Program on Research and Development for Fossil Energy-Related Resources. The remaining \$2,199,000 required to complete the program will consist of funding through a consortium of industrial participants. Interest has been generated for Phase III by the participants of Phase II which include the following:

- CO₂ Capture Project (bp, Chevron, eni, BR Petrobras, Shell, and Suncor)
- Arthur J. Gallagher
- Atco Power, Inc.
- Baker Hughes
- Black & Veatch Corporation
- Constellation Power Source Generation, Inc.
- C-Quest Technologies
- GE Global Research
- Hitachi Power Systems America, Ltd.
- Huntsman Petrochemical Corporation
- Metso Power
- Midwest Generation
- Minnesota Power
- Nebraska Public Power District

- PPL Montana, LLC (Puget Sound Energy, Portland General Electric, Avista, PacificCorp)
- SaskPower
- TransAlta Utilities Corporation
- Cansolv Technologies, Inc.
- Sulzer, Ltd.

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 the current industrial consortium members, this would delay the start of the project until new consortium members can be found, but the EERC does not anticipate this to happen. Budget information is found in Appendix B. A letter of commitment can be found in Appendix C.

TAX LIABILITY

The EERC—a research organization within UND, which is an institution of higher education within the state of North Dakota—is not a taxable entity.

CONFIDENTIAL INFORMATION

No confidential information is included in this proposal.

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APPENDIX A
RESUMES OF KEY PERSONNEL



JOHN P. KAY

Senior Research Manager

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 amine solutions for removing CO₂ from gas streams and field testing site management. He has 10 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, high-temperature specialty alloys, and biological tissue. 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. For the last six years he has been involved in field testing site management and sampling techniques for mercury control in combustion systems.

Qualifications

B.S., Geological Engineering, University of North Dakota, 1994.

Associate Degree, Engineering Studies, Minot State University, 1989.

Professional Experience

2011–Present: Senior Research Manager, EERC, UND. Mr. Kay's responsibilities include management of CO₂ 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.



BRANDON M. PAVLISH

Research Manager

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) 777-5065, Fax: (701) 777-5181, E-Mail: bpavlish@undeerc.org

Principal Areas of Expertise

Mr. Pavlish's principal areas of interest and expertise include management of and technical direction for multidisciplinary science and engineering research teams focused on a wide range of integrated energy and environmental technologies. Specific program areas of interest include clean and efficient use of low-grade fuels, development of advanced power systems, gas separation technologies, carbon dioxide sequestration, activated carbon technologies, and emission control related to mercury, sulfur, and particulates. Projects emphasize a cradle-to-grave approach from resource assessment to optimum utilization systems, to minimization of emissions, and to waste management featuring by-product utilization. Currently, Mr. Pavlish is managing several large projects, including the Partnership for CO₂ Capture, that deal with the evaluation and demonstration of CO₂ capture technologies focusing on increasing integration and efficiency to push technologies into the commercial marketplace.

Qualifications

M.S., Chemical Engineering, University of North Dakota, 2012.

B.S., Chemical Engineering, University of North Dakota, 2006.

Professional Experience

2008–Present: Research Manager, EERC, UND. Mr. Pavlish's responsibilities include managing projects in the areas of gas separation technologies, carbon dioxide sequestration, activated carbon technologies, and emission control, including preparing proposals, establishing and maintaining contacts with industry and government organizations, managing staff and project activities, designing and conducting experiments, performing calculations and interpreting data, leading the preparation of technical reports and papers, and presenting research at national and international conferences and in other venues.

2006–2008: Research Engineer, EERC, UND. Mr. Pavlish's responsibilities included preparing proposals, interacting with industry and government organizations, researching literature, designing and conducting experiments as a principal investigator, performing calculations and interpreting data, writing technical reports and papers, managing projects, and presenting information. Activities ranged from project management to field testing management at full-scale power plants, to pilot-scale studies, to laboratory investigations that examined both fuel and system characteristics and their impacts on overall technology performance. Projects focused on Hg control technology evaluation and CO₂ capture development and feasibility.

2002–2006: Student Engineer, EERC, UND. Mr. Pavlish's responsibilities included the following:

- Performed a broad range of engineering functions including literature research, conducting experiments (laboratory- and bench-scale testing), pilot-scale testing, sampling and sample tracking, tracking project activities, data reduction, writing and presenting technical results, proposal writing, presenting at conferences, and preparation of technical papers and project reports.
- Specific EERC intern/coop experience in hydrogen involved the preparation of the hydrogen short course, literature searches, ChemCad simulations related to hydrogen production, hydrogen production via ethanol + water, and catalyst reactions.
- During intern/coop at the EERC, Mr. Pavlish was involved in numerous projects focused on emission control. The primary focus of the work completed during this time was mercury control technologies and included pilot- and bench-scale testing, data reduction, proposal writing, technical reporting, and presentation.

Professional Memberships

American Institute of Chemical Engineers

Publications and Presentations

Has coauthored numerous publications.



JOSHUA J. STANISLOWSKI

Research Manager

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) 777-5087, Fax: (701) 777-5181, E-Mail: jstanislawski@undeerc.org

Principal Areas of Expertise

Mr. Stanislawski's principal areas of interest and expertise include fossil fuel combustion for energy conversion with emphasis on trace element control, gasification systems analysis, combustion and gasification pollution control, and process modeling. He has extensive experience with process engineering, process controls, and project management. He has a strong background in gauge studies, experimental design, and data analysis.

Qualifications

M.S., Chemical Engineering, University of North Dakota, 2012.

B.S., Chemical Engineering, University of North Dakota, 2000.

Six Sigma Green Belt Certified, August 2004.

Professional Experience:

2008–Present: Research Manager, EERC, UND, Grand Forks, North Dakota. Mr. Stanislawski manages projects in the areas of gasification, gas cleanup, hydrogen production, liquid fuel production, and systems engineering.

2005–2008: Research Engineer, EERC, UND, Grand Forks, North Dakota. Mr. Stanislawski's areas of focus included mercury control technologies and coal gasification. His responsibilities involved project management and aiding in the completion of projects. His duties included design and construction of bench- and pilot-scale equipment, performing experimental design, data collection, data analysis, and report preparation. He also worked in the areas of low-rank coal gasification, warm-gas cleanup, and liquid fuels production modeling using Aspen Plus software.

2001–2005: Process Engineer, Innovex, Inc., Litchfield, Minnesota.

- Mr. Stanislawski was responsible for various process lines including copper plating, nickel plating, tin-lead plating, gold plating, polyimide etching, copper etching, chrome etching, and resist strip and lamination. His responsibilities included all aspects of the process line including quality control, documentation, final product yields, continuous process improvement, and operator training. He gained extensive knowledge of statistical process control and statistical start-up methodology. Mr. Stanislawski was proficient with MiniTab statistical software and utilized statistical analysis and experimental design as part of his daily work.

- Mr. Stanislawski designed and oversaw experiments as a principal investigator; wrote technical reports and papers, including standard operating procedures and process control

plans; presented project and experimental results to suppliers, customers, clients, and managers; created engineering designs and calculations; and performed hands-on mechanical work when troubleshooting process issues. He demonstrated the ability to coordinate activities with varied entities through extensive project management and leadership experience.

1998–2000: Student Research Assistant, EERC, UND. Mr. Stanislowski worked on a wide variety of projects, including data entry and programming for the Center for Air Toxic Metals[®] (CATM[®]) database, contamination cleanup program development, using aerogels for emission control, and the development of a nationwide mercury emission model.

Publications and Presentations

Has coauthored several publications.



MICHAEL J. HOLMES

Deputy Associate Director 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) 777-5276, Fax: (701) 777-5181, E-Mail: mholmes@undeerc.org

Principal Areas of Expertise

Mr. Holmes's principal areas of interest and expertise include fuel processing for production of syngas for coproduction of hydrogen, fuels, and chemicals with electricity in gasification systems and process development and economics for advanced energy systems and emission control (air toxics, SO₂, NO_x, H₂S, and particulate technologies). He has managed numerous large-scale projects in these areas. Mr. Holmes is the program manager of the National Center for Hydrogen Technology at the EERC and is working under agreement with the U.S. Department of Energy National Energy Technology Laboratory and over 85 partners to develop a broad range of technologies required to advance the opportunity for a hydrogen economy. In addition, Mr. Holmes is currently serving as a board member for the National Hydrogen Association Board of Directors (an executive committee member) and the Mountain States Hydrogen Business Council.

Qualifications

M.S., Chemical Engineering, University of North Dakota, 1986.

B.S., Chemistry and Mathematics, Mayville State University, 1984.

Professional Experience

2005–Present: Deputy Associate Director for Research, EERC, UND. Mr. Holmes currently oversees fossil energy research areas at the EERC, including coproduction of hydrogen, fuels, and chemicals with electricity in gasification systems, advanced energy systems, and emission control technology projects involving mercury, SO₂, NO_x, H₂S, and particulate.

2001–2004: Senior Research Advisor, EERC, UND. Mr. Holmes was involved in research in a range of areas, including emission control, fuel utilization, process development, and process economic evaluations. Specific duties included marketing and managing research projects and programs, providing group management and leadership, preparing proposals, interacting with industry and government organizations, designing and overseeing effective experiments as a principal investigator, researching the literature, interpreting data, writing reports and papers, presenting project results to clients, and presenting papers at conferences.

1986–2001: Process Development Engineer (Principal Research Engineer), McDermott Technology, Inc., Alliance, Ohio. Mr. Holmes' responsibilities included project management and process research and development for projects involving advanced energy systems, environmental processing, combustion systems, fuel processing, and development of new process measurement techniques. He also served as Project Manager and Process Engineer for projects involving evaluation of air toxic emissions from coal-fired power plants; development of

low-cost solutions for air toxic control focused on mercury emissions; development of wet and dry scrubber technologies; demonstration of low-level radioactive liquid waste remediation; in-duct spray drying development; development of improved oil lighter burners; limestone injection multistaged burning; the ESO_x process; the SO_x-NO_x-Rox Box™ process; and the limestone injection dry-scrubbing process.

Professional Memberships

Fuel Cell and Hydrogen Energy Association

- Board of Directors, 2011

National Hydrogen Association

- Board Member, 2004–2011
- Executive Committee Member, 2009–2010
- Cochair of Hydrogen from Coal Group, 2008–2010

Subbituminous Energy Coalition

- Board Member, 2003–2008

Mountain States Hydrogen Business Council

- Board Member, 2009–2010

Tau Beta Pi

Patents

Holmes, M.J.; Pavlish, J.H.; Olson, E.S.; Zhuang, Y. High Energy Dissociation for Mercury Control Systems. U.S. Patent 7615101 B2, 2009.

Holmes, M.J.; Pavlish, J.H.; Zhuang, Y.; Benson, S.A.; Olson, E.S.; Laumb, J.D. Multifunctional Abatement of Air Pollutants in Flue Gas. U.S. Patent 7628969 B2, 2009.

Olson, E.S.; Holmes, M.J.; Pavlish, J.H. Sorbents for the Oxidation and Removal of Mercury. U.S. Patent Application 2005-209163, Aug 22, 2005.

Olson, E.; Holmes, M.; Pavlish, J. Process for Regenerating a Spent Sorbent. International Patent Application PCT/US2004/012828, April 23, 2004.

Madden, D.A.; Holmes, M.J. Alkaline Sorbent Injection for Mercury Control. U.S. Patent 6,528,030 B2, Nov 16, 2001.

Madden, D.A.; Holmes, M.J.; Alkaline Sorbent Injection for Mercury Control. U.S. Patent 6,372,187 B1, Dec 7, 1998.

Holmes, M.J.; Eckhart, C.F.; Kudlac, G.A.; Bailey, R.T. Gas Stabilized Reburning for NO_x Control. U.S. Patent 5,890,442, Jan 23, 1996.

Holmes, M.J. Three-Fluid Atomizer. U.S. Patent 5,484,107, May 13, 1994.

Bailey, R.T.; Holmes, M.J. Low-Pressure Loss/Reduced Deposition Atomizer. U.S. Patent 5,129,583, March 21, 1991.

Awards

Lignite Energy Council Distinguished Service Award, Government Action Program (Regulatory), 2005.

Lignite Energy Council Distinguished Service Award, Research and Development, 2003.

Publications and Presentations

Has authored or coauthored more than 120 publications and presentations.



JASON D. LAUMB

Senior Research Manager

Energy & Environmental Research Center (EERC), University of North Dakota (UND)

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Phone: (701) 777-5114, Fax: (701) 777-5181, E-Mail: jlaumb@undeerc.org

Principal Areas of Expertise

Mr. Laumb's principal areas of interest and expertise include biomass and fossil fuel conversion for energy production, with an emphasis on ash effects on system performance. He has experience with trace element emissions and control for fossil fuel combustion systems, with a particular emphasis on air pollution issues related to mercury and fine particulates. He also has experience in the design and fabrication of bench- and pilot-scale combustion and gasification equipment.

Qualifications

M.S., Chemical Engineering, University of North Dakota, 2000.

B.S., Chemistry, University of North Dakota, 1998.

Professional Experience

2008–Present: Senior Research Manager, EERC, UND. Mr. Laumb's responsibilities include leading a multidisciplinary team of 30 scientists and engineers whose aim is to develop and conduct projects and programs on power plant performance, environmental control systems, the fate of pollutants, computer modeling, and health issues for clients worldwide. Efforts are focused on the development of multiclient jointly sponsored centers or consortia that are funded by government and industry sources. Current research activities include computer modeling of combustion/gasification and environmental control systems, performance of selective catalytic reduction technologies for NO_x control, mercury control technologies, hydrogen production from coal, CO₂ capture technologies, particulate matter analysis and source apportionment, the fate of mercury in the environment, toxicology of particulate matter, and in vivo studies of mercury–selenium interactions. Computer-based modeling efforts utilize various kinetic, systems engineering, thermodynamic, artificial neural network, statistical, computation fluid dynamics, and atmospheric dispersion models. These models are used in combination with models developed at the EERC to predict the impacts of fuel properties and system operating conditions on system efficiency, economics, and emissions.

2001–2008: Research Manager, EERC, UND. Mr. Laumb's responsibilities included supervising projects involving bench-scale combustion testing of various fuels and wastes; supervising a laboratory that performs bench-scale combustion and gasification testing; managerial and principal investigator duties for projects related to the inorganic composition of coal, coal ash formation, deposition of ash in conventional and advanced power systems, and mechanisms of trace metal transformations during coal or waste conversion; and writing proposals and reports applicable to energy and environmental research.

2000–2001: Research Engineer, EERC, UND. Mr. Laumb’s responsibilities included aiding in the design of pilot-scale combustion equipment and writing computer programs that aid in the reduction of data, combustion calculations, and prediction of boiler performance. He was also involved in the analysis of current combustion control technology’s ability to remove mercury and studying in the suitability of biomass as boiler fuel.

1998–2000: SEM Applications Specialist, Microbeam Technologies, Inc., Grand Forks, North Dakota. Mr. Laumb’s responsibilities included gaining experience in power system performance including conventional combustion and gasification systems; a knowledge of environmental control systems and energy conversion technologies; interpreting data to predict ash behavior and fuel performance; assisting in proposal writing to clients and government agencies such as the National Science Foundation and the U.S. Department of Energy; preparing and analyzing coal, coal ash, corrosion products, and soil samples using SEM/EDS; and modifying and writing FORTRAN, C+, and Excel computer programs.

Professional Memberships

American Chemical Society

Publications and Presentations

Has coauthored numerous professional publications.

APPENDIX B

BUDGET

ADVANCING CO₂ CAPTURE TECHNOLOGY
 PARTNERSHIP FOR CO₂ CAPTURE PHASE III
 NDIC
 PROPOSED PROJECT START DATE: 7/1/13
 EERC PROPOSAL #2013-0135

BUDGET

CATEGORY	NDIC TOTAL	NONFEDERAL TOTAL	FEDERAL TOTAL	PROJECT TOTAL
TOTAL LABOR	\$ 450,136	\$ 1,298,848	\$ 1,983,418	\$ 3,732,402
TRAVEL	\$ -	\$ -	\$ 58,409	\$ 58,409
EQUIPMENT > \$5000	\$ -	\$ -	\$ 188,900	\$ 188,900
SUPPLIES	\$ 20,715	\$ 10,650	\$ 78,162	\$ 109,527
COMMUNICATIONS	\$ 346	\$ 104	\$ 2,153	\$ 2,603
PRINTING & DUPLICATING	\$ 179	\$ 72	\$ 2,153	\$ 2,404
FOOD	\$ -	\$ 800	\$ -	\$ 800
FEES – ASPEN SOFTWARE	\$ -	\$ 256,000	\$ -	\$ 256,000
OPERATING FEES				
Fuels & Materials Research Lab.	\$ 5,345	\$ -	\$ 12,855	\$ 18,200
Analytical Research Lab.	\$ -	\$ -	\$ 95,979	\$ 95,979
Combustion Test Svcs.	\$ -	\$ 461,584	\$ -	\$ 461,584
Particulate Analysis	\$ -	\$ -	\$ 102,134	\$ 102,134
Process Chem. & Dev. Lab.	\$ 19,805	\$ -	\$ 5,088	\$ 24,893
Fuel Prep. and Maintenance	\$ 3,474	\$ -	\$ 27,984	\$ 31,458
Continuous Fluidized-Bed Reactor	\$ -	\$ 129,438	\$ -	\$ 129,438
Graphics Support	\$ -	\$ -	\$ 12,975	\$ 12,975
Shop & Operations Support	\$ -	\$ 41,504	\$ -	\$ 41,504
Research Information Systems	\$ -	\$ -	\$ 128,790	\$ 128,790
TOTAL PROJECT COST - US DOLLARS	\$ 500,000	\$ 2,199,000	\$ 2,699,000	\$ 5,398,000

LABOR CATEGORIES	LABOR HOURS			
	NDIC	NONFEDERAL	FEDERAL	PROJECT
Research Scientists/Engineers	4,239	6,685	14,351	25,275
Research Technicians	-	-	2,097	2,097
Mechanics/Operators	-	5,600	-	5,600
Senior Management	-	3	810	813
Technical Support Services	120	96	1,252	1,468
TOTAL PROJECT COST SHARE	9.3%	40.7%	50.0%	100.0%

APPENDIX C
LETTER OF COMMITMENT

March 28, 2013

Ms. Karlene Fine
Executive Director
North Dakota Industrial Commission
State Capitol
600 East Boulevard Avenue, Department 405
Bismarck, ND 58505-0840

Dear Ms. Fine:

Subject: Cost Share for EERC Proposal No. 2013-0135 Entitled “Advancing CO₂ Capture Technology: Partnership for CO₂ Capture (PCO₂C) Phase III”


The Energy & Environmental Research Center (EERC) is conducting complementary research and development efforts under a multimillion-dollar 5-year Cooperative Agreement with the U.S. Department of Energy (DOE) entitled “Joint Program on Research and Development for Fossil Energy-Related Resources.” Through this joint program, nonfederal entities can team with the EERC and DOE in projects that address the goals and objectives of DOE’s Office of Fossil Energy.

The proposed project to the North Dakota Industrial Commission (NDIC) Lignite Research Council entitled “Advancing CO₂ Capture Technology: Partnership for CO₂ Capture (PCO₂C) Phase III” is a viable candidate for funding under this program. Therefore, the EERC intends to secure \$2,699,000 of cash cost share for the proposed project through its Cooperative Agreement with DOE providing NDIC commits \$500,000 cash cost share. The EERC is actively seeking the remaining \$2,199,000 of cost-share funding through a consortium of industrial partners for a project total of \$5,398,000.

Once the EERC has a commitment from NDIC, the EERC will submit a proposal to DOE for its concurrence. 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 you have any questions, please contact me by phone at (701) 777-5157 or by e-mail at jharju@undeerc.org.

Sincerely,



John A. Harju
Associate Director for Research

JAH/hmv