Propal to the North Dakota Industrial Commission for the DEVELOPMENT OF BIOMIMETIC MEMBRANES FOR NEAR-ZERO PC POWER PLANT EMISSIONS

Submitted to:

Ms. Karlene Fine, Executive Director

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

Funding amount requested: $260,000

Submitted by:

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PROPOSAL FOR DEVELOPMENT OF BIOMIMETIC MEMBRANES FOR NEAR-ZERO PC POWER PLANT EMISSIONS

ABSTRACT

Cost-effective capture of CO_2 from coal-fired power plant flue gas has not been demonstrated commercially. In fact, the only commercial technology that currently could be used to capture CO_2 from a coal-fired power plant is traditional amine scrubbing, usually performed with monoethanolamine (MEA). Carbozyme Inc. has developed a biomimetic CO_2 capture technology that appears to offer significant cost and performance advantages over MEA scrubbing systems. The Carbozyme technology is based on separation of CO_2 from a mixed gas stream by carbonic anhydrase, an enzyme found in plants and animals. The process features a layer of carbonic anhydrase contained between two membranes, called a contained liquid membrane (CLM). The CO_2 from a mixed-gas stream permeates across this liquid membrane to a sweep gas. Laboratory-scale testing has shown the CLM permeator to be very stable and performance data indicate that the Carbozyme process could capture CO_2 at avoidance costs that are only 60% of the avoided costs of monoethanolamine (MEA) or chilled ammonia absorption processes. (Smith, et al., 2006) Testing has been performed on natural gas at the laboratory scale; funding in the amount of $260,000 is requested from the North Dakota Lignite Research Council (NDLRC) to fund the evaluation and demonstration of the ability of the CLM permeator to capture CO_2 from flue gas produced during the combustion of lignite at a pre-pilot scale. The monies requested from the NDLRC will provide cost share for a $4.8-million cooperative agreement with the U.S. Department of Energy that is being performed to further develop and scale up the Carbozyme process for the capture of CO_2 from power plant flue gas. Testing of the Carbozyme CLM permeator will be performed on 40,000-Btu/h and 500,000-Btu/h combustion systems at the Energy & Environmental Research Center (EERC). The resulting data will be used to validate and further scale up the technology. The study offers the opportunity to

significantly advance the state-of-the-art in a critically important research area. Efficient capture of CO_2 from power plants can not only dramatically reduce greenhouse gas emissions, but could provide another source of CO_2 for enhanced energy recovery operations. In North Dakota, the establishment of enhanced oil recovery operations using CO_2 could ultimately lead to the sequestration of millions of tons of CO_2 a year into deep geological formations while producing oil that could be valued as high as $14 billion.

PROJECT SUMMARY

Funding in the amount of $260,000 is requested from the North Dakota Lignite Research Council (NDLRC) to provide cost share for a $4.8-million U.S. Department of Energy (DOE) award (Fossil Energy Techline, 2006) being performed to further develop and scale up the Carbozyme enzyme-based, contained-liquid membrane (CLM) technology for capture of CO_2 from power plant flue gas. Cost-effective capture of CO_2 from coal-fired power plant flue gas has not been demonstrated commercially and the only commercial technology that currently could be used to capture CO_2 from a coal-fired power plant is traditional amine scrubbing, usually performed with monoethanolamine (MEA). The Carbozyme process is a biomimetic CO_2 capture technology that appears to offer significant cost and performance advantages over commercially available MEA scrubbing systems.

This study offers the opportunity to significantly advance the state-of-the-art in a research area of critical importance to the nation. Not only could CO_2 emissions be dramatically reduced, but efficient capture of CO_2 from power plants will provide another source of CO_2 for enhanced energy recovery operations. In North Dakota, the establishment of enhanced oil recovery operations using CO_2 could ultimately lead to the sequestration of millions of tons of CO_2 a year into deep geological formations while producing oil that could be valued as high as $14 billion.

The goal of the work proposed to the NDLRC is to scale up and evaluate the ability of the Carbozyme CLM permeator to extract CO_2 specifically from lignite-derived flue gas. The permeator performance will be considered successful if it is shown to capture 90% of the CO_2 produced by combustion of lignite at a purity of at least 95%. Empirical data and process engineering projections based on laboratory-scale test beds indicate that the Carbozyme CLM permeator will perform to these standards.

The testing will be performed at the Energy & Environmental Research Center (EERC) in the EERC's conversion and environmental process simulator (CEPS) and combustion test furnace (CTF). The CEPS is a modular, 40,000-Btu/h pilot-scale system capable of simulating conditions of both the radiant and convective sections of a full-scale utility boiler. It generates realistic combustion test results for a variety of fuels (natural gas, coal, biomass and waste materials) and combustion conditions. The CTF is a 550,000-Btu/h, pc-fired system designed to generate data representative of that produced in a full-scale utility boiler.

The CEPS and CTF will be configured with pollution control devices to reduce SO_2, NO_x, and particulate levels in the flue gas steam reaching the CLM permeator. In addition, a condensing heat exchanger will be installed between the baghouse and the permeator to reduce the gas temperature to the appropriate level before it enters the permeator. The CHE will also serve to reduce the concentration of acid gases and fine particulates prior to CO_2 separation. Test points to be evaluated will include both steady-state and upset conditions to determine their effect on permeator performance during combustion tests of 250-hr duration. Fine particulate and acid aerosol levels in the permeator feed will be measured, as will the levels of CO_2 in the flue gas and sweep gases leaving the CLM permeator. Data reduction will include an evaluation of the ability of the pollution control train to reduce fine particulate and acid-gas aerosols to levels meeting the requirements of the CLM permeator. Identical 250-hr test matrices will be performed for both 120-m^2 and 400-m^2 permeators to validate successful scaleup, with the 120-m^2 permeator test performed on the CEPS and the 400-m^2 permeator test performed on the CTF. Reports detailing the test results and drawing conclusions from them will be submitted as contractually required.

PROJECT DESCRIPTION

Objectives

Funding in the amount of $260,000 is requested from the North Dakota Lignite Research Council (NDLRC) to provide cost share for a $4.8-million U.S. Department of Energy (DOE) award (Fossil Energy Techline, 2006) being performed to further develop and scale up the Carbozyme enzyme-based, contained-liquid membrane (CLM) technology for capture of CO_2 from power plant flue gas. The Carbozyme CLM technology is a biomimetic process that is based on separation of CO_2 from a mixed gas stream by carbonic anhydrase, an enzyme found in virtually all plants and animals. The process features a layer of carbonic anhydrase contained between two membranes, with the CO_2 from a mixed-gas stream permeating across this liquid membrane to a sweep gas. Laboratory-scale testing has shown the CLM permeator to be very stable and performance data indicate that the Carbozyme process could capture CO_2 at avoidance costs that are only 60% of the avoided costs of monoethanolamine (MEA) or chilled ammonia absorption processes. (Smith, et al., 2006) Testing has been performed on natural gas at the laboratory scale; the monies requested from the NDLRC will be used to fund the evaluation and demonstration of the ability of the CLM permeator to capture CO_2 from flue gas produced during the combustion of lignite at a pre-pilot scale.

The primary goal of the research is to show that the Carbozyme CLM technology can achieve performance coincident with the U.S. Department of Energy (DOE) CO_2 capture technology targets of a 90% capture rate and less than a 20% increase in the cost of energy (COE) by 2012. (NETL CO_2 capture website, 2007) Several objectives must be met to accomplish this overall project goal, including demonstration and evaluation of the ability of a Carbozyme CLM permeator to capture CO_2 from a variety of flue gases at a pre-pilot scale, scaling up the CLM permeator system design from laboratory-scale to multiple units organized as a skid and having membrane surface areas ranging from 120 m^2 to 400 m^2, implementing a flue gas pretreatment conditioner that will ensure that the flue gases meet the CLM technology acceptance standards, validating the technology necessary to produce carbonic anhydrase enzymes cost effectively, and performing a commercialization study that will maximize the commercial potential of the Carbozyme technology by incorporating business acumen into the technical efforts.

Methods

Commercialization and subsequent widespread application of the Carbozyme CLM technology to capture CO_2 from coal-fired power plants will require scaleup, validation, and optimization testing, followed by demonstration and verification testing. The proposed work addresses the first step: scaleup of the process to a pre-pilot scale and testing on various flue gases produced from combustion of natural gas as well as coal. The technical approach and work plan have been designed to collect the data necessary to perform detailed systems and economic analyses and to continue to scale up the process to a full-scale application.

To collect the necessary data, the CLM permeator work effort has been organized into eight tasks that will be performed over a 3-yr time frame. These tasks include flue gas pretreatment system specification, enzyme development, identification and final selection of a membrane manufacturer, permeator scale-up development, permeator skid scaleup, engineering and economic analysis, commercialization study, and management and reporting. (Note: Our current membrane suppliers, Celgard, Charlotte, NC, is a prime candidate to manufacture permeator modules). This proposal requests funding that will be applied to the permeator skid scaleup and feed stream conditioning tasks specifically as they pertain to lignite-fired systems.

Anticipated Results

The availability of a commercially viable CO_2-capture technology will be a necessity if carbon emissions are managed in the future and/or existing CO_2 sources for enhanced oil recovery require augmentation. The Carbozyme CLM technology is a novel approach for CO_2 control at conventional coal-fired power plants. This study will provide the data required for its further scaleup and eventual commercialization and widespread application.

Facilities, Resources, and Techniques to be Used

The workhorse of the testing will be the EERC's conversion and environmental process simulator (CEPS). The CEPS is a modular pilot-scale system capable of simulating conditions of both the radiant and convective sections of a full-scale utility boiler. It generates realistic combustion test results for a variety of fuels (natural gas, coal, biomass and waste materials) and combustion conditions. CEPS is also used to test small-scale versions of pollution control technologies, including baghouse and wet scrubber technologies. The downfire design is rated for a nominal coal feed rate of 2 kg/h, with a heat input of 40,000 Btu/h. Other solid or liquid fuels can be fed with slight system modifications. The CEPS is designed to maintain the flue gas (approximately 0.23 m^3/min, or 8 scfm) generated by the combustion of the fuel at a maximum of 1500EC (2732EF) in the radiant zone. Heating elements line the main furnace, convective pass section, and baghouse chambers. The entire system is lined with either ceramic or refractory material, eliminating the possibility of reaction with and contamination of metal surfaces. There is ample access for sampling, observation, and optical diagnostics through access ports located throughout the CEPS. A PC displays and records temperatures, gas flows, feed rates and flue gas compositions. Flue gas (O_2, CO_2, CO, SO_2, and NO_x) compositions are sampled from ports in the radiant section and after the collection device. CEPS is a sealed system maintained under a slight vacuum with an eductor. Figure 1 shows the CEPS main and convective pass sections, heat exchangers, and baghouse.

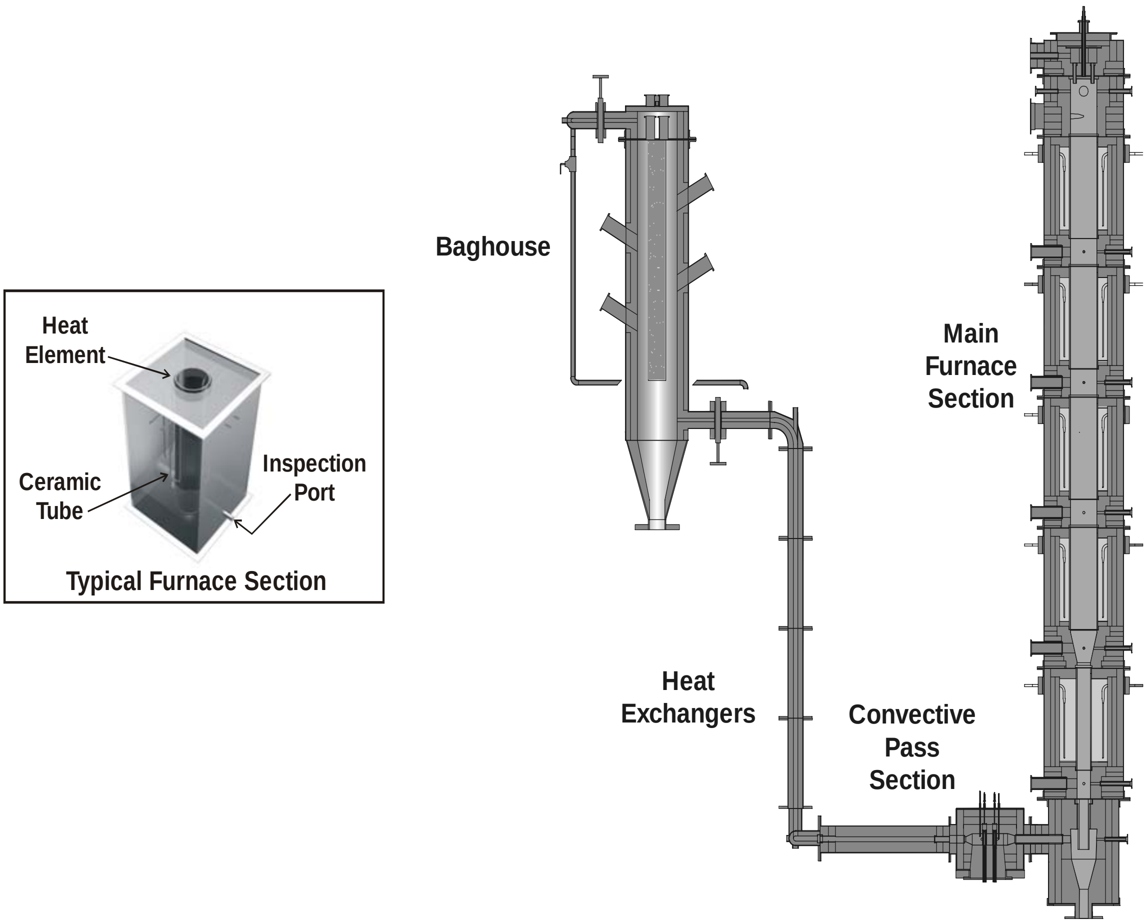

Figure 1. Schematic of the EERC's CEPS.

Additional testing of the larger-scale permeator system may be performed on the EERC's combustion test facility (CTF), shown in Figure 2. The CTF is a 550,000-Btu/h, pc-fired system designed to generate data representative of that produced in a full-scale utility boiler. The combustor is oriented vertically to minimize wall deposits and has a refractory lining to ensure

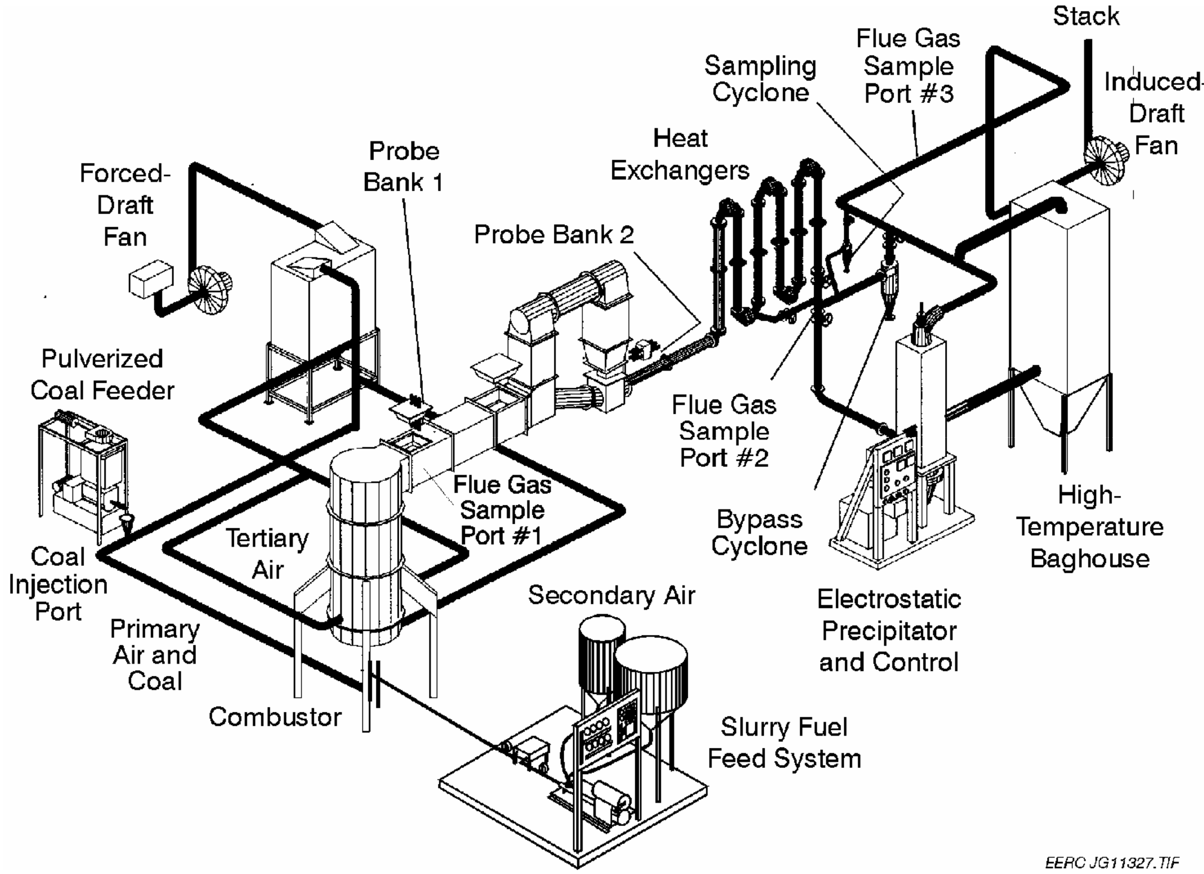

Figure 2. Schematic of the EERC's CTF and auxiliary systems.

adequate flame temperature for complete combustion. The coal nozzle of the CTF fires axially upward from the bottom of the combustor and secondary air is introduced concentrically to the primary air with turbulent mixing. In addition, tertiary air is supplied above the base of the combustor. Coal is introduced to the primary air stream via a screw feeder controlled by an Acrison automatic feed system ejector. An electric air preheater is used for precise control of the combustion air temperature. The CTF is also equipped with a single-wire, tubular ESP.

The CTF instrumentation permits system temperatures, pressures, flow rates, flue gas constituent concentrations, and ESP operating data to be monitored continuously and downloaded to a data acquisition system. After passing through sample conditioners to remove the moisture, the flue gas is typically analyzed for O_2, CO_2, SO_2, and NO_x. Each of these analyzers is regularly calibrated and maintained to provide accurate flue gas concentration measurements.

Both the CEPS and the CTF and the associated operations staff are available for use on this project.

The CEPS and CTF will be configured with pollution control devices to reduce SO_2, NO_x, and particulate levels in the flue gas steam reaching the CLM permeator. In addition, a condensing heat exchanger will be installed between the baghouse and the permeator to reduce acid gas aerosols and other fine particulate prior to CO_2 separation. Test points to be evaluated will include both steady-state and upset conditions to determine their effect on permeator performance during combustion tests of 250-hr duration. Fine particulate and acid aerosol levels in the permeator feed will be measured, as will the levels of CO_2 in the flue gas and sweep gases leaving the CLM permeator. Data reduction will include an evaluation of the ability of the pollution control train to reduce fine particulate and acid-gas aerosols to levels meeting the requirements of the CLM permeator. Identical 250-hr test matrices will be performed for both 120-m^2 and 400-m^2 permeators to validate successful scaleup, with the 120-m^2 permeator test performed on the CEPS and the 400-m^2 permeator test performed on the CTF. Reports detailing the test results and drawing conclusions from them will be submitted as contractually required.

Environmental and Economic Impacts

CO_2 is a greenhouse gas. In 2003, the Bush Administration, through the DOE, launched an initiative to achieve reductions in CO_2 emissions in the United States through a variety of means, including capture and sequestration in geological formations. The proposed project addresses CO_2 capture, aiming to offer a cost-effective method to reduce the CO_2 emissions from North Dakota's coal-fired facilities and providing a stream that can be put to beneficial use in terms of enhanced oil recovery (EOR) or enhanced coalbed methane production.

With respect to local environmental impact in the vicinity of the EERC, the test matrix will be designed and implemented according to applicable state and federal regulations to ensure that the environmental impact of all project activities is minimal.

Ultimate Technological and Economic Impacts

Cost-effective capture of CO_2 from coal-fired power plant flue gas has not been demonstrated commercially. The proposed work offers the opportunity to significantly advance the state-of-the-art in a research area of critical importance to the nation. Not only could CO_2 emissions be dramatically reduced, but efficient capture of CO_2 from power plants will provide another source of CO_2 for enhanced energy recovery operations. The establishment of CO_2 EOR operations in North Dakota could ultimately lead to the sequestration of millions of tons of CO_2 each year into deep geological formations while producing up to 280 million barrels of incremental oil in currently unitized fields (Lynn D. Helms, Director, NDIC OGD personal communication, 2003). At a price of $50/barrel, the value of this oil would be $14 billion.

Why the Project Is Needed

An effective comprehensive greenhouse gas reduction program incorporates both emissions reductions and CO_2 capture and sequestration. The most common commercially-available CO_2 capture process is based on MEA scrubbing. However, there are challenges to applying MEA scrubbing to a gas stream, including solvent loss through heat-stable salt formation caused by reaction with SO_2 and NO_x, volatility into the treated gas stream, and degradation; sensitivity of the MEA solvent to oxygen; and high energy consumption during solvent regeneration. Flue gas from conventional coal-fired power systems is typically dilute, at atmospheric pressure, and is contaminated with impurities, notably SO_2 and NO_x, making it very expensive to treat using MEA scrubbing. The combustion of lignite in particular provides a challenging opportunity for CO_2 capture from its flue gas because of its high inherent CO_2 content.

This study will produce the engineering and economic data needed for demonstration and, ultimately, commercialization of the novel and cost-effective Carbozyme CLM permeator technology for conventional coal-fired power plants firing not only subbituminous or bituminous coal, but also lignite.

STANDARDS OF SUCCESS

The Carbozyme CLM permeator testing program will be considered successful if it shows that the process achieves the DOE target values of at least 90% separation at a cost of energy increase of less than 20% by 2012. Standards of success specific to this proposal are the ability to capture 90% of the CO_2 produced by combustion of lignite at a purity of at least 95%.

BACKGROUND

The Carbozyme CLM technology has been under development for many years, originally under funding from the National Aeronautics and Space Administration and most recently from the DOE. Because the process details are considered to be confidential, a summary of the process and prior work related to its development is included as Appendix A.

QUALIFICATIONS

Key personnel who will be involved with the permeator scaleup and conditioning treatment testing are Melanie Jensen and Jason Laumb, chemical engineers from the Energy & Environmental Research Center (EERC) at the University of North Dakota, and Dr. Michael C.

Trachtenberg, President and CEO of Carbozyme Inc. Both Ms. Jensen and Mr. Laumb have considerable coal combustion and flue gas separation and cleanup experience. Ms. Jensen has worked in the areas of high-pressure/high-temperature reaction engineering and system design, flue gas cleanup with emphases on NO_x and mercury, and is the EERC's point person for CO_2 capture and separation technologies, serving as the task leader for this area within the Plains CO_2 Reduction (PCOR) Partnership. She is also a member of the DOE's CO_2 Capture and Transportation working group within the regional partnerships. Mr. Laumb is a Research Manager who supervises projects, personnel, and equipment involved with the combustion and gasification testing of various fuels and wastes. He also manages projects related to coal composition, coal ash formation, deposition of ash in conventional and advanced power systems, and mechanisms of trace metal transformations during coal or waste conversion.

Dr. Trachtenberg designed the technology and has managed its development over the last 10 years. He is an experienced scientist with over 120 publications and 3 patents and has been a principal investigator and research director for over 30 years. The technology is biomimetic, meaning that it uses the mammalian cardiovascular and cardiopulmonary systems as a model design to optimize the chemical and mass transfer efficiencies. He holds a Bachelor of Arts degree from the City College of New York and Doctorate in Neuroscience from the University of California at Los Angeles. He supervises several very experienced chemical engineers and biochemists working on this project.

Details regarding the credentials of Dr. Trachtenberg, Ms. Jensen, and Mr. Laumb can be found in Appendix B.

VALUE TO NORTH DAKOTA

Successful conduct of the proposed CO_2 capture demonstration can provide tremendous environmental and economic benefits to the state of North Dakota. The project will develop the information needed to greatly reduce CO_2 emissions within the state as well as assist in planning for the most economically favorable fate of the CO_2. As was discussed in the Economic Impacts sections of the proposal, the value of the oil that is estimated to be available in the state for EOR operations could be as high as $14 billion. North Dakota's coal-fired power facilities are located near potential EOR opportunities. This fortunate juxtaposition could provide for a competitive advantage for North Dakota facilities if carbon management is mandated in the future.

MANAGEMENT

Dr. Trachtenberg is the principal investigator. He is supported by Mr. John Koenst, PE, a very experienced chemical engineering project manager and Mr. John Marciszewski, who is skilled in project management, critical path management and design structure matrix analyses. At a technical level, they are supported by Dr. Robert Cowan, Environmental Engineer, and Mr. David Smith, Project Engineer. John Koenst is responsible for weekly contact with each of the subcontractors – EERC, Siemens Power Generation, Novozymes NA, and Visage Energy. He and John Marciszewski will map progress on the critical path to make sure that the milestones are achieved on schedule and on budget.

TIMETABLE

Appendix C includes a confidential project milestone plan that will serve as the baseline for tracking project performance and identifies critical path project milestones for the entire three-year project. The funding requested from the Lignite Research Council would be applied to activities during Years 1 and 2 of the project.

BUDGET

Carbozyme Inc. is requesting a total of $260,000 from the Lignite Research Council for testing of the CLM permeator on flue gas produced during the combustion of lignite. The funding is requested as $130,000 each year for Years 1 and 2 of the three-year project. Because the detailed financial and resource plans for this project are considered confidential, these elements are included in Appendix C.

TAX LIABILITY

None. Carbozyme Inc. is a New Jersey company and has no tax liability with the State of North Dakota.

CONFIDENTIAL INFORMATION

No confidential information is included in the main body of this proposal. However, Appendix A is to be considered a confidential document as it contains detailed information about the Carbozyme CLM permeator technology. Appendix C is also considered confidential as it contains proprietary references and facts to the project budget and implementation plans.

APPENDICES

Appendix A consists of detailed, confidential information about the Carbozyme CLM technology. Appendix B contains the biographical sketches of key personnel who will contribute to the project. Appendix C includes confidential details about the budget, resource plans, and project schedule.

REFERENCES

Fossil Energy Techline, October 23, 2006, http://www.fossil.energy.gov/news/techlines/2006/06061-Sequestration_Research_Grants.html.

Helms, L.D., Director, NDIC OGD, personal communication with J. Sorensen of EERC, 2003.

National Energy Technology Laboratory Carbon Sequestration CO_2 Capture website, http://www.netl.doe.gov/technologies/carbon_seq/core_rd/co2capture.html (accessed March 24, 2007).

Smith, D.A.; Dumortier, R.; Bau, L.; Trachtenberg, M.C. Flue Gas CO_2 Capture. Presented at the Fifth Annual Conference on Carbon Capture & Sequestration, Alexandria, VA, May 2006; Paper 039.

APPENDIX B

Biographical Sketches of Key Personnel

BIOGRAPHICAL SKETCH
Melanie D. Jensen

Education and Training

B.S., Chemical Engineering, University of North Dakota (UND), 1983
B.A., Anthropology, UND, 1978.

Research and Professional Experience

1985–Present: Research Engineer, Energy & Environmental Research Center (EERC), UND, Grand Forks, ND. Performs research in the areas of carbon sequestration, reaction engineering, coal combustion, reburning, hazardous waste treatment, gas-phase particulate and mercury collection, photocatalytic processes, fuel production from biomass, contaminated water cleanup, and phytoremediation. Designs, develops, operates, and/or evaluates complex processes and equipment, including high-pressure/high-temperature coal conversion systems, low-temperature plasma systems, and multicolumn sorption systems. Identifies promising carbon sequestration opportunities by matching major sources with applicable CO_2 separation and capture technologies and nearby geologic and/or terrestrial sinks. Evaluates and compares various characterization, remediation, and decontamination technologies for application to waste treatment and cleanup programs. Tracks, reduces, and interprets data generated during research projects. Develops statistically designed experimental matrices, analyzes the results, and derives models describing system behavior. Develops integrated, multiproject programs to meet both the immediate and long-term needs of clients; prepares or assists with the preparation of proposals and supporting documentation; develops comprehensive QA/QC plans; and prepares patent applications. Project management activities include detailed program planning; scheduling of equipment and personnel, budget monitoring, maintenance of project schedules, preparation of reports, papers, and presentations; and communicating with clients. Disseminates results to a variety of audiences through the preparation of technical reports, peer-reviewed papers/journal articles, and posters and slide presentations.

Relevant Publications

Steadman, E.N.; Harju, J.A.; Fischer, D.W.; Botnen, L.S; Daly, D.J.; Jensen, M.D.; O'Leary, E.M.; Smith, S.A.; Sorensen, J.A.; Nelson, C.R. The Plains CO_2 Reduction (PCOR) Partnership – Developing CO_2 Sequestration Opportunities for the Central Interior of North America. 8th International Conference on Greenhouse Gas Control Technologies, Trondheim, Norway, June 2006.

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Patent

Rindt, J.R.; Hetland (Jensen), M.D. Direct Coal Liquefaction Process. U.S. Patent No. 5256278, October 26, 1993.

Synergistic Activities

Task Leader for carbon capture, separation, compression, and transportation on the Plains CO_2 Reduction Partnership, one of seven DOE carbon sequestration partnerships

Member of the DOE carbon sequestration partnership program Capture and Transportation Working Group

BIOGRAPHICAL SKETCH
Jason D. Laumb

Education and Training

M.S., Chemical Engineering, University of North Dakota (UND), 2000. Thesis: “Predicting Slag Viscosity from Coal Ash Composition”

B.S., Chemistry, UND, 1998.

Research and Professional Experience

2001–Present: Research Manager, Energy & Environmental Research Center (EERC), UND, Grand Forks, ND. 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. Aided 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. Also involved in the analysis of current combustion control technology’s ability to remove mercury and studying the suitability of biomass as boiler fuel.
1998–2000: SEM Applications Specialist, Microbeam Technologies, Inc., Grand Forks, ND. Gained 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 NSF and DOE; preparing and analyzing coal, coal ash, corrosion products, and soil samples using SEM/EDS; and modifying and writing FORTRAN, C+ and Excel computer programs.
1998–2000: Graduate Teaching Assistant, UND. Transport phenomena and unit operations, administered and graded exams, graded homework, and answered student questions.

Relevant Publications

Benson, S.A.; Crocker, C.R.; Galbreath, K.C.; Gunderson, J.R.; Holmes, M.J.; Laumb, J.D.; Olderbak, M.R.; Pavlish, J.H.; Yan, L.; Zhuang, Y.; Mackenzie (Zola), J.M. *Pilot- and Full-Scale Demonstration of Advanced Mercury Control Technologies for Lignite-Fired Power Plants*; Final Report (Oct 1 – Dec 31, 2004) for U.S. Department Energy National Energy Technology Laboratory Cooperative Agreement No. DE-FC26-03NT41897 and multiclients; EERC Publication 2005-EERC-02-05; Energy & Environmental Research Center: Grand Forks, ND, Feb 2005.

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Gupta, H.; Benson, S.A.; Fan, L.-S.; Laumb, J.D.; Olson, E.S.; Crocker, C.R.; Sharma, R.K.; Knutson, R.Z.; Rokanuzzaman, A.S.; Tibbetts, J.E. Pilot-Scale Testing of Activated High-Sodium Lignite Chars for NO_x Reduction Simulated and Actual Flue Gas. *AIChE* **2005,** in review.

Laumb. J.D.; Benson, S.A. Slipstream Mercury Studies. In *Proceedings of Western Fuels Symposium: 19th International Conference on Lignite, Brown, and Subbituminous Coals*; Billings, MT, Oct 12–14, 2004.

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Benson, S.A.; Olson, E.S.; Dunham, G.E.; Laumb, J.D. *Characterization of Coal-Derived Mercury Sorbents*; Final Report for Subcontract No. 1783-UND-DOE-0350, DOE Award No. DEFC26-98FT40350; EERC Publication 2001-EERC-01-05; Energy & Environmental Research Center: Grand Forks, ND, Jan 2001.

Jensen, R.R.; Benson, S.A.; Laumb, J.D. *Advanced Power Systems Analysis Tools*; Final Report for U.S. Department of Energy Cooperative Agreement No. DE-FC26-98FT40320; EERC Publication 2001-EERC-08-05; Energy & Environmental Research Center: Grand Fork, ND, Aug 2001.

Laumb, J.D.; Benson, S.A.; Toman, D.L.; Timpe, R.C. Bench-Scale Studies of SCR Catalyst Blinding. Presented at the Engineering Foundation Conference Power Production in the 21st Century: Impacts of Fuel Quality and Operations, Snowbird, UT, Oct 28 – Nov 2, 2001.

Synergistic Activities

Gasification of Lignite to Produce Hydrogen, Power, and Liquid Fuels project – Responsible for the design and construction of pilot-scale equipment to remove and/or separate hydrogen, sulfur, ammonia, carbon dioxide, and mercury from syngas.

BIOGRAPHICAL SKETCH
Michael C. Trachtenberg

Education and Training

Postdoctoral Fellow in Anatomy/Surgery, Harvard Medical School, Boston, Massachusetts 1969
Postdoctoral Fellow in Neurosurgery, Massachusetts General Hospital, Boston, Massachusetts 1969
Ph.D. Anatomy / Neurobiology, The University of California, Los Angeles, California 1967
B.A. Psychology / Biology, The City College of New York, New York, New York 1962

Research and Professional Experience

1991–present Chairman, CEO and Chief Scientific Officer. Carbozyme, Inc., Monmouth Junction, NJ.
2000-present Director. The Sapient's Institute, Monmouth Junction, NJ
1994-present Program Director. The Sapient's Institute, Monmouth Junction, NJ
1999-present Visiting Scientist. Department of Plant Biology and Pathology. Rutgers University, New Brunswick, NJ
1985-1991 Vice President, Research and Development. NeuroGenesis, Inc./MATRIX Technologies, Inc., Houston, Texas
1978-1984 Associate Professor of Surgery (Neurological) Associate Professor of Physiology and Biophysics, Director, Neurosurgical Research. The University of Texas Medical Branch, Galveston, Texas
1974-1978 Director, Neurobiology Laboratories, Research Physiologist. Boston Veterans Administration Hospital
1971-1973 Instructor in Anatomy/Psychiatry. Harvard Medical School, Boston, Massachusetts

Publications
Journal Articles (Selected)

1. Trachtenberg MC, Bao L, Goldman SL. **2004** Flue gas CO_2 capture by a green liquid membrane. *GHGT-7*. Vancouver, BC, CN
2. Trachtenberg, MC, Bao L., Goldman, SL, Smith DA. Dynamic maintenance of CO_2 levels in closed environments. **2004** Intl. Conf. Environ. Sys. Colorado Springs, CO, July SAE 2004-01-2376.
3. Trachtenberg M.C., Cowan R.M., Goldman S.L.: **2003**. CO_2 capture using enzyme based membrane reactors. *AIChE J.*
4. Trachtenberg M.C., Cowan R.M., Goldman S.L., Ge, J-J, Qin Y-J, McGregor M.L.: Enzyme based membrane reactor for CO_2 capture. **2003** *33rd Intl. Conf. Environ. Sys.* July, Vancouver, BC, CAN, SAE 2003-01-2499.
5. Cowan R.M., Ge J-J., Qin Y-J., McGregor M.L., Trachtenberg M.C.: CO_2 capture by means of an enzyme-based reactor. **2003** *Ann. NY Acad. Sci.* **984**:453-470.
6. Ge J-J, Cowan R.M., Tu C-K, McGregor M.L., Trachtenberg M.C.: 2002 Enzyme-based CO_2 capture for advanced life support. **2002** *Life Support & Biosphere Science* **8**:181-189.
7. Trachtenberg M.C., Ge J-J., Cowan R.M., Qin Y-J.: CO_2 capture by enzyme-based facilitated transport. *32nd Intl. Conf. Environ. Sys.* July, San Antonio, TX, SAE **2002**-01-2267, 2002.

8. Ge J-J, Trachtenberg M.C., Cowan R.M., McGregor M.L.: Enzyme-based facilitated transport: Use of vacuum induced sweep for enhanced CO_2 capture. *31st Intl. Conf. Environ. Sys.* July, Orlando, FL, SAE **2001**-01-2305, 2001.
9. Trachtenberg M.C., McGregor M.L., Tu C-K., Laipis P.J., Willson R.C., Kennedy J.F., Paterson M., Rudolph F.B.: Enzyme-enhanced membranes for gas separation. *29th Intl. Conf. Environ. Sys.* Denver, CO, **July 1999**. SAE 1999-01-1961.
10. Trachtenberg M.C., Tu C-K., Landers R.A., Willson R.C., McGregor M.L., Laipis P.J., Kennedy J.F., Paterson M., Silverman D.N., Thomas D., Smith R.L., Rudolph F.B.: Carbon dioxide transport by proteic and facilitated transport membranes. *Life Support & Biosphere Sciences*, **6**:293-302.**1999**.

Abstracts (Selected)

1. Trachtenberg MC, Bao L, Goldman SL. **2004** CO_2 transfer across liquid membrane facilitated by carbonic anhydrase. *AIChE* Annual Meeting, Austin, TX. Nov.
2. Trachtenberg MC, Bao L, Goldman SL. **2004** Flue gas CO_2 capture by a green liquid membrane. *GHGT-7*. Vancouver, BC, CN, Sept.
3. Trachtenberg, MC, Bao L., Goldman, SL, Smith DA. Dynamic maintenance of CO2 levels in closed environments. **2004** *Intl. Conf. Environ. Sys.* Colorado Springs, CO, July 2004-01-2376.
4. Trachtenberg MC, Bao L, Smith DA, Goldman SL. **2004** Air revitalization in ALS and EVA. *Advanced Life Support Air Revitalization Element Workshop*. Gainesville, FL, Jan.
5. Cowan RM, Goldman SL, Trachtenberg MC. **2004** Carbon dioxide management for advanced life support and EVA. *Habitation.* Orlando, FL, Jan.
6. Trachtenberg MC, Cowan RM, Goldman SL. **2003** CO_2 capture using enzyme based membrane reactors. *AIChE Ann. Meeting.* San Francisco, CA, Nov.
7. Trachtenberg M.C.: **2003** Faciltated transport enzyme catalyzed membrane reactor for CO_2 capture. *SAMAP* Oct. Emden, Germany
8. Trachtenberg M.C., Cowan R.M., Goldman S.L.: **2003** Enzyme based membrane reactor for CO_2 capture. *Am. Chem. Soc.* Ann. Meeting, New York, NY, Sept.
9. Trachtenberg M.C., Cowan R.M., Goldman S.L., Qin Y-J., Ford E.: **2003** Carbon Dioxide Extraction from Flue Gas. *North Am. Memb. Soc.*, Jackson Hole, WY. May
10. Trachtenberg M.C., Cowan R.M., Goldman S.L., Ge J-J., Qin Y-J., McGregor M.L.: Enzyme Based CO_2 Capture. **2003** *Am. Chem. Soc.* Spring Meeting. Apr.
11. Trachtenberg M.C., Cowan R.M., Goldman S.L., Ge J-J, Qin Y-J, McGregor M.L.: Enzyme Based Membrane Reactor For CO_2 Capture. **2003** *Bioastronautics Investigators Workshop*, Galveston, TX. Jan.
12. Qin Y-J., Ge J-J., Cowan R.M., Trachtenberg M.C.: Facilitated Membrane for Natural Gas Sweetening. **2002** *AIChE* Ann. Meeting, Nov. Indianapolis, IN
13. Trachtenberg M.C., Cowan R.M., Ge J-J., Qin Y-J., McGregor M.L.: Sequestration of CO_2. *Protection and Restoration of the Environment VI*, Skiathos Isl., Greece, Jul. 2002.
14. Qin Y-J., Ge J-J., Cowan R.M., Trachtenberg M.C.: Biomimetic Liquid Membrane for CO_2 Removal from Natural Gas. *North American Membrane Soc.* Long Beach, CA, May 2002.
15. Ge J-J., Qin Y-J., Cowan R.M., Trachtenberg M.C.: High Efficiency Capture Of CO_2 From Mixed Gas Streams. *Am. Chem. Soc.* Fuel Chemistry Div. Orlando, FL, Apr. 2002

16. Ge J-J., Qin Y-J., Trachtenberg M.C.: Enzyme-Based Hollow Fiber Contained Liquid Membrane for CO_2 Removal. *AIChE*, New Orleans, LA, Mar. 2002
17. Trachtenberg M.C., Qin Y-J., Cowan R.M., Ge J-J.: CO_2 Capture and Sequestration. *NSF Workshop on CO_2 Capture and Sequestration*, New Orleans, LA, Mar. 2002
18. Trachtenberg M.C., Ge J-J., Qin Y-J., McGregor M.L., Cowan R.M.: Enzyme Based Membrane Reactor for CO2 Capture. *American Society for Gravitational and Space Biology*. Alexandria, VA, November 2001
19. Trachtenberg M.C., Ge J-J., Cowan R.M., Qin Y-J., McGregor M.L.: CO_2 Capture by Enzyme-Based Facilitated Transport. *Advanced Membrane Technology*. Barga, Italy, October 2001.
20. Trachtenberg M.C., Ge J-J., Cowan R.M., McGregor M.L.: Efficient CO_2 separation by enzyme-based facilitated transport. *North American Membrane Soc.* Lexington, KY, May 2001.
21. Trachtenberg M.C.: Carbon dioxide capture and sequestration: Implications for the New Jersey coast. *Impact of Climate Change on New Jersey*, New Brunswick, NJ, February 2001.
22. Trachtenberg M.C., Ge J-J., Cowan R.M., McGregor M.L.: Biomimetic strategy for carbon dioxide capture. *Bioastronautics Investigators' Workshop*, Galveston, TX, Jan. 2001
23. Trachtenberg M.C.: Enzyme-Based CO_2 Removal from Air. NASA JSC *Inspection 2000*, Houston, TX 2000.
24. Trachtenberg M.C., Cowan R.M., Ge J-J., Tu C-K.: Separation of CO_2 from air by a carbonic anhydrase (II) bioreactor. *4th International Life Support and Biosphere Science Conf.* Baltimore, MD. July. 2000
25. Trachtenberg M.C., McGregor M.L., Willson R.C., Tu C-K.: Reduction, capture and remediation of carbon dioxide. *5th International Conference on Protection and Restoration of the Environment.* July 2-6, 2000, Thassos Island, Greece
26. Trachtenberg M.C., Tu C-K., McGregor M.L., Willson R.C., Koenst J.W.: Enzyme-enhanced membranes for gas separation. *EVA Pacing and Advanced Technologies Conf.,* Auburn, SC, Nov. 1999
27. Trachtenberg M.C., Tu C-K., Landers R.A., Willson R.C., McGregor M.L., Laipis P.J., Kennedy J.F., Silverman D.N., Thomas D., Rudolph F.B.: Carbon dioxide transport by proteic and facilitated transport membranes. *3rd* Intl. *Life Support and Biosphere Sciences Conf.*, Orlando, FL, 1998.
28. Trachtenberg M.C., Landers R.A., Tu C-K., Laipis P.J., Willson R.C., McGregor M.L., Smith R.L., Silverman D.N., Rudolph F.B.: Biochemical capture and removal of carbon dioxide. *Adv. Life Support*, NASA JSC, 1997.

PATENTS (RELEVANT)

1. Trachtenberg M.C.: Enzyme systems for gas processing. U.S. Pat. No. 6,143,556, Nov. 7, 2000.
2. Trachtenberg M.C.: Enzyme systems for processing gas. Canadian Pat. No. 2,222,030, Apr. 17, 2007