EERC
Energy & Environmental Research Center

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October 1, 2014

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

Dear Ms. Fine:

Subject: EERC Proposal No. 2015-0043 Entitled "Demonstration of Pilot-Scale Hydrogen and CO_2 Separation Membrane Technology on Lignite-Derived Syngas"

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) 777-5087 or by e-mail at jstanislowski@undeerc.org.

Sincerely,

Joshua J. Stanislowski
Research Manager

Approved by:

Thomas A. Erickson, Interim Director
Energy & Environmental Research Center

JJS/kal

Enclosures

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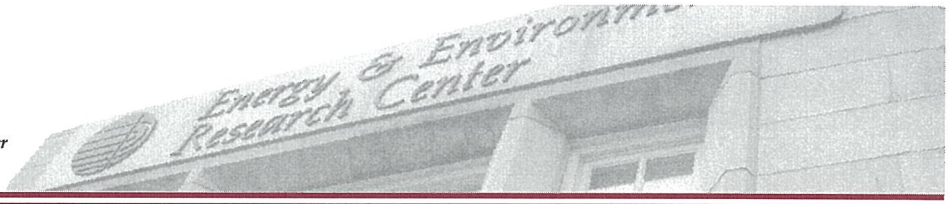

DEMONSTRATION OF PILOT-SCALE HYDROGEN AND CO_2 SEPARATION MEMBRANE TECHNOLOGY ON LIGNITE-DERIVED SYNGAS

EERC Proposal No. 2015-0043

Submitted to:

Karlene Fine

North Dakota Industrial Commission
600 East Boulevard Avenue
State Capitol, 14th Floor
Bismarck, ND 58505-0840

Amount of Request: $225,000
Total Amount of Proposed Project: $2,039,608
Duration of Project: 21 months

Submitted by:

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October 1, 2014

TABLE OF CONTENTS

Continued . . .

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF TABLES

DEMONSTRATION OF PILOT-SCALE HYDROGEN AND CO_2 SEPARATION MEMBRANE TECHNOLOGY ON LIGNITE-DERIVED SYNGAS

ABSTRACT

The Energy & Environmental Research Center (EERC) has developed a project with Praxair, Inc., and the state of Wyoming to demonstrate advanced membrane separation technology for coal-derived syngas streams. The goal of the project is to conduct a pilot-scale demonstration of advanced hydrogen and CO_2 separation technology on low-rank coal using warm-gas cleanup techniques and hydrogen separation membranes. Syngas will be generated on the EERC's transport reactor development unit (TRDU) using Powder River Basin (PRB) and lignite coal. The hydrogen content of the syngas generated will be maximized through a water–gas shift (WGS) catalyst bed, and then sulfur will be removed prior to membrane separation. Approximately half of the syngas generated from the 1-MW-thermal TRDU will be separated in the pilot-scale membrane.

Thirty days of testing is anticipated on the system, divided into three 5-day test campaigns. A minimum of 5 days will be dedicated to lignite coal testing. The EERC has existing federal flow-through funding in the amount of $1,329,608 from Praxair and funding of $450,000 from the state of Wyoming that we anticipate to be matched with the proposed $225,000 from the Lignite Energy Council (LEC) and with $35,000 from other industrial sponsors. The total project cost is anticipated to be $2,039,608.

Five separate tasks will be performed to enable the demonstration of the technology. Tasks 1 and 2 will involve membrane acquisition and installation, and additional modifications to the transport reactor and warm-gas cleanup testing will be needed to facilitate the test runs. Tasks 1 and 2 are currently under way with existing sponsorship. The test runs will occur in Task 3, and the data derived will be used in an economic analysis to be conducted in Task 4. Task 5 is for management and reporting.

DEMONSTRATION OF PILOT-SCALE HYDROGEN AND CO_2 SEPARATION MEMBRANE TECHNOLOGY ON LIGNITE-DERIVED SYNGAS

PROJECT SUMMARY

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and the data derived will be used in an economic analysis to be conducted in Task 4. Task 5 is for management and reporting.

Successful demonstration of the technology will help provide additional options for low-cost hydrogen and CO_2 separation systems. The hydrogen generated can be sold as a product, used in a low-carbon power generation setting, or utilized for chemical processes that need hydrogen enrichment, including ammonia synthesis.

PROJECT DESCRIPTION

Goal

The goal of the proposed project is to conduct a pilot-scale demonstration of coal-to-hydrogen production technology using warm-gas cleanup techniques and hydrogen separation membranes. Five separate tasks will be performed to enable the demonstration of the technology. Tasks 1 and 2 will involve membrane acquisition and installation, and additional modifications to the TRDU and warm-gas cleanup system will be needed to facilitate the test runs. The test runs will occur in Task 3, and the data derived will be used in an economic analysis to be conducted in Task 4. Task 5 is for management and reporting. Tasks 1 and 2 are currently under way with the project sponsors, and Tasks 3 and 4 will begin in December 2014.

Task 1 – Acquisition and Installation of Hydrogen Separation Membranes

In this task, the EERC will receive the pilot-scale hydrogen CO_2 separation membranes. The membranes will be installed at the back end of the EERC's TRDU. The EERC will add heaters and heater controllers to maintain membrane temperature during operation. The membranes will operate as high as 500°C, so high-temperature materials will be needed. Gas piping, meters, thermocouples, and controls will also be acquired to properly meter and monitor the gas flow,

temperature, and pressure through each membrane. Analytical equipment will be installed so that each stream can be adequately characterized.

Task 2 – Modification of the Transport Reactor System for Membrane Testing

The TRDU located at the EERC is a pilot-scale gasification unit capable of producing 400 lb/day of hydrogen. A detailed description of the TRDU and hot-gas filter vessel (HGFV) can be found in Appendix B. Certain modifications will have to be made to the pilot-scale transport reactor gasifier in order for it to generate syngas at sufficient pressure and hydrogen concentrations for adequately testing the membranes. Warm-gas cleanup techniques will be used to condition the syngas prior to H_2/CO_2 separation. An existing bubbling fluid-bed gasifier (FBG) at the EERC will be converted to operate as WGS reactor. The operating pressure of the TRDU is limited to 120 psig, so a compressor will be used to bring the gas to the pressure specification required by the membrane and to allow syngas to be recycled back to the gasifier to eliminate nitrogen purges on the TRDU, thereby significantly increasing the hydrogen partial pressure in the syngas. The EERC will also install two fixed-bed reactors for removing sulfur from the syngas prior to membrane separation. A flow measurement and control device will also be required to be purchased and installed in order to measure and control the flow of syngas into the membrane skid.

Task 3 – Hydrogen and CO_2 Separation Testing on the TRDU Gasifier

Three 5-day test campaigns totaling up to 600 hours of run time on the TRDU are anticipated for this project. PRB coal from Wyoming and lignite coal will be acquired for the test runs. Operating conditions will be chosen based on sponsor input. Operational data from the TRDU for each fuel will be collected and included in the reporting. The performance of the warm-gas cleanup (WGCU) train will also be evaluated. Hydrogen flux measurements on the membrane

materials will be made, and the impact of impurities on membranes will be quantified. A continuous emission monitor (CEM) and two gas chromatographs (GCs) will continuously monitor the compositions of the permeate and raffinate streams. Solid samples will be taken from the system and analyzed. Gas bag samples will be taken from the permeate side of the membrane to evaluate the hydrogen purity of the effluent on an off-line GC. Gas bag samples will also be taken upstream of the membrane in an effort to determine the level of trace metals in the syngas. A continuous mercury monitor (CMM) can also be used to quantify mercury levels in the gas stream. The EERC will use Dräger tubes to measure the membrane feed gas for levels of chlorine, cyanide, and ammonia.

The test protocol on the gasifier and membrane system will be determined by the project sponsors. The EERC test setup will be flexible so that a wide variety of conditions can be tested such as temperature, pressure, gas composition, and impurity levels. The tests will be adequate to demonstrate the readiness for design of a larger-scale unit. Membrane performance will be determined as a function of operating conditions. The membrane transport performance will be compared to Sievert's law to determine its performance versus theoretical values. The impact of syngas contaminants, including H_2S, water, and CO, will also be compared to performance of the system.

After the testing is complete, the EERC will remove the membrane modules and package them for shipping to the membrane provider. The membrane provider will then perform a postmortem analysis on the membrane module to determine the extent of any impurities deposited.

Task 4 – Process Modeling and Economic Evaluation

In this task, Aspen Plus® will be used to model the process and aid in determination of the economics of membrane usage on coal-derived syngas. Aspen will be used to build a model that starts with the gasifier and continues through to the hydrogen and CO_2 separation process. The properties of Wyoming coal can be directly entered into the model to aid in the evaluation of gasifier performance. Of specific interest will be the costs associated with compressing and sequestering CO_2. Aspen Process Economic Analyzer will be used in conjunction with Aspen Plus to develop the costs associated with CO_2 separation and compression. The model will be built so that the impacts of various coal types can be analyzed. Models with advanced membrane schemes will be compared to conventional technologies to determine the potential benefit of hydrogen and CO_2 separation membranes under both hydrogen production scenarios and integrated gasification combined cycle (IGCC) scenarios.

Task 5 – Management and Reporting

All data will go through a rigorous quality assurance/quality control process to ensure reporting accuracy. Computer data logs, process log books, and analytical results will be used to compile the results of the testing into a report format.

Progress reports will be issued 1 month after the conclusion of each calendar quarter to inform the sponsors of the project progress and present results as they become available.

At the completion of the project, a comprehensive final report will be produced that details the results from each of the tasks and provides a concise summary of the results of the project. The findings will be used to determine the path forward for a demonstration-scale system.

The results of this study will be presented to user groups at the final seminar organized by the University of Wyoming School of Energy Resources. The EERC also plans to prepare and give a presentation at a minimum of one conference to discuss progress and results of this study.

STANDARDS OF SUCCESS

Success of the technologies will be judged by the ability to effectively separate a stream of hydrogen and CO_2 derived from lignite coal using a transport gasifier in conjunction with a warm-gas cleanup train and hydrogen separation membranes. The ability of the gasifier to operate continuously on lignite coal with no fuel-related operational issues will be evaluated. A syngas must be produced with a hydrogen concentration greater than 30% at pressures of 250 psi or greater after compression. Sulfur and chlorine in the gas stream must be reduced to levels of less than 1 ppm prior to hydrogen separation. Specific goals for the performance of the membranes will include the U.S. Department of Energy's (DOE's) stated goals of >300 scfh/ft^2 of membrane material by 2015 and <\$1000/ft^2 for membrane module cost. Overall efficiency improvements with warm-gas cleanup and hydrogen separation membranes will be calculated, with the goal of achieving improved efficiencies over traditional physical solvent processes.

A successful test program will meet all of the deliverables and milestones listed in the statement of work section in a timely manner. Successful demonstration of hydrogen separation membranes on coal-derived syngas at the pilot scale will result in justification for scale-up to a demonstration-scale system. The EERC will work closely with the membrane providers after conclusion of a successful project to work on the detailed design of the demonstration-scale system. The membrane providers will be working to develop the exact details of the commercialization plan, including investment opportunities, demonstration sites, and securing suppliers for the necessary materials. The expertise provided by the EERC will enable successful

membrane integration with a syngas stream from a commercial-scale gasifier. The testing performed in this program will enable the EERC to advise the membrane providers on the syngas cleanliness required to be achieved before membrane separation. The inputs from the demonstration-scale system will be used to design a full-scale membrane system that could either replace a physical solvent in an existing unit or be constructed as part of a grassroots plant.

BACKGROUND

Two main applications for hydrogen separation membranes employed at large scale are envisioned. Large-scale hydrogen production facilities could provide fuel for fuel cell vehicles. Power generation facilities with CO_2 capture could employ hydrogen separation membranes to reduce the cost of separation. Both scenarios are likely to employ coal gasification to produce the hydrogen.

Membranes for Hydrogen Production for Transportation Applications

DOE views hydrogen as an energy carrier of the future because it can be derived from domestic resources that are clean and abundant and because hydrogen is an inherently clean fuel. According to DOE, the deployment of hydrogen technologies could lead to the creation of 675,000 green jobs in the United States (1). Coal gasification plants can separate hydrogen from the synthesis gas, purify the carbon for storage, and burn the hydrogen to produce power in an IGCC configuration. In this type of configuration, the only major emission from the plant is water. Hydrogen can also play a key role as a transportation fuel. If all vehicles in Los Angeles were converted to hydrogen, the urban smog problems would be virtually eliminated. Hydrogen fuel cell technologies have undergone rapid development over the past decade, and the technology exists today to produce commercial hydrogen fuel cell vehicles that have a transportation range of up to 280 miles (2). The main challenges that remain today are the

economical production of hydrogen, economical production of fuel cell vehicles, and development of hydrogen transportation, storage, and dispensing infrastructure.

The National Hydrogen Association views hydrogen as the best pathway to both reduce oil consumption in the United States and reduce transportation-based CO_2 emissions. Three different vehicle market penetration scenarios for light-duty vehicles are considered (3): 100% gasoline internal combustion engine vehicles (ICEVs), plug-in hybrid electric vehicles (PHEVs), and hydrogen fuel cell vehicles. In Figure 1, each scenario is compared to the annual oil consumption for that time period. It can be seen that if nothing changes and the United States continues to rely solely on gasoline-powered vehicles, annual oil consumption is predicted to increase from 4 billion barrels per year (bby) to over 7 bby by the year 2100. With a significant market penetration of PHEVs, oil consumption can be reduced to about 2.5 bby by 2100. However, with 98% market penetration of fuel cell vehicles, dependence on oil is virtually eliminated. While the

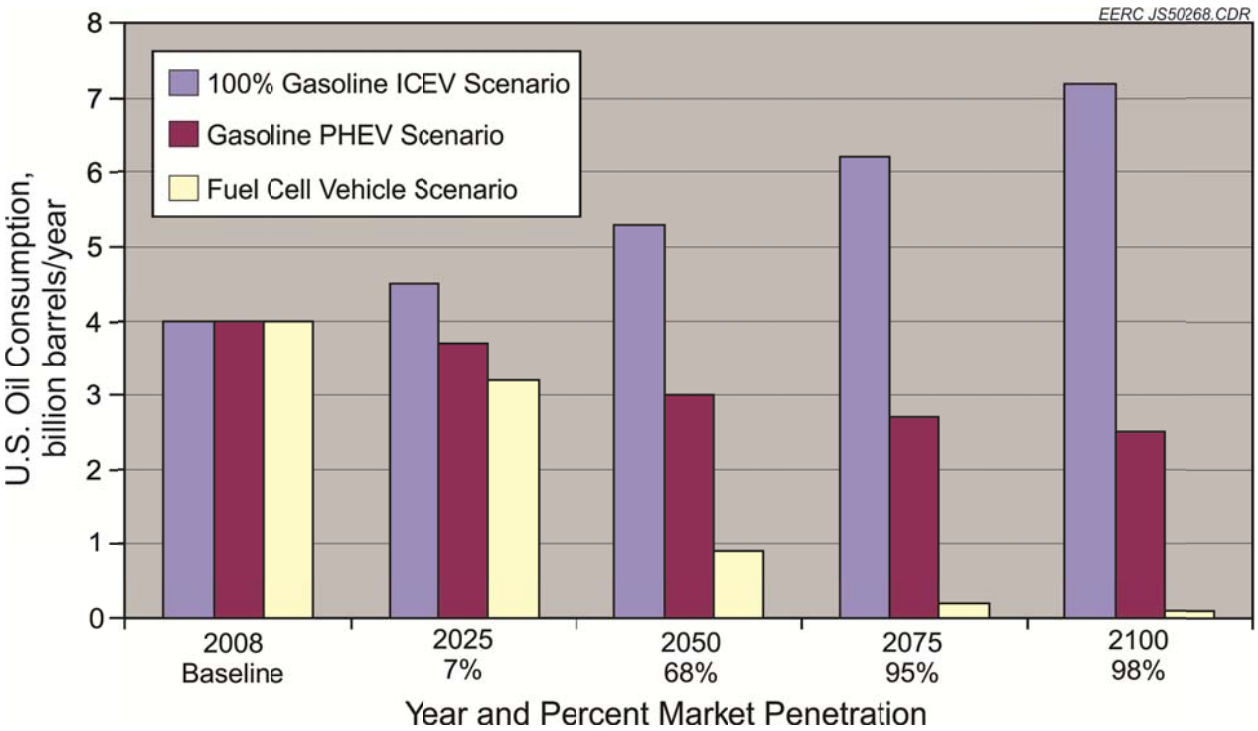


Figure 1. U.S. oil consumption for various vehicle scenarios (light-duty vehicles only) (3).

future of transportation will certainly be a mix of several technologies, this graph illustrates that hydrogen is one of the only pathways toward eliminating the use of oil.

Figure 2 shows a similar set of scenarios, but compares the market penetration with annual CO_2 emissions from vehicles (3). It should be noted that the study assumes hydrogen production is occurring with carbon capture and storage or hydrogen is supplied from a renewable source. The graph shows that CO_2 emissions from vehicles will almost double by the year 2100 if gasoline vehicles continue to be used exclusively. A reduction in CO_2 emissions is achieved if the course of PHEVs is followed. However, with the fuel cell vehicle scenario, CO_2 emissions are reduced by over 80% in the year 2100. This illustrates that hydrogen is a potential fuel pathway in a carbon-constrained world. Increased production of natural gas and coal will be needed to meet these targets, and the data assume that the hydrogen production facility is equipped with carbon capture technology.

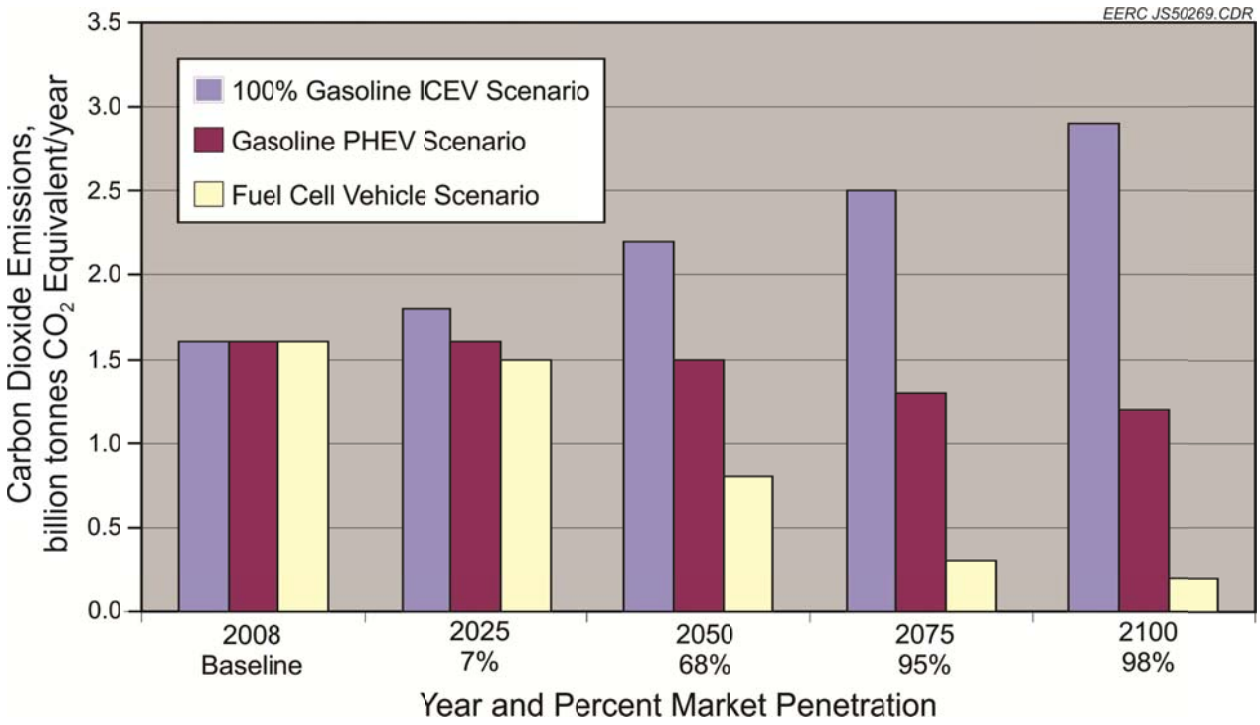


Figure 2. CO_2 emissions for various vehicle scenarios (3).

Membranes Integrated with Power Systems

Coal gasification is of significant interest to the future of power generation in the United States because it can be performed more efficiently and with less emissions than conventional combustion. IGCC systems fire the syngas produced directly in a gas turbine and recover the heat produced, resulting in more efficient conversion of energy to electricity than a conventional steam cycle. Currently, gasification systems produce electricity at a higher cost than conventional combustion systems. One significant advantage of gasification over combustion is the ability to capture CO_2 at a much lower cost and energy penalty. The CO_2 in gasifier syngas streams is at much higher concentration and typically at elevated pressure; therefore, less energy is required to perform the separation. When the cost of CO_2 capture is considered in the overall capital and operating cost of a power system, gasification units can have advantages in the cost of electricity (COE) over conventional combustion. Figure 3 compares COE for gasification versus conventional power systems with and without CO_2 capture (4). The figure shows that for conventional power systems, COE is significantly less if CO_2 capture is not required. In the cases where CO_2 capture is needed, the IGCC plant produces electricity at a lower cost than pc systems. The cost of natural gas combined cycle (NGCC) is heavily dependent on the price of natural gas. With recent natural gas prices as low as $2/MMBtu, the current cost of NGCC is significantly lower than the competing technologies.

The cost of gasification with CO_2 capture utilizing technologies that are commercially available today is still relatively high compared to COE production with no capture. Advanced technologies are needed to further reduce the costs of capture and improve the overall efficiency of the plants. Several critical research pathways and technologies have been identified by the DOE National Energy Technology Laboratory (NETL) that will greatly improve the efficiency

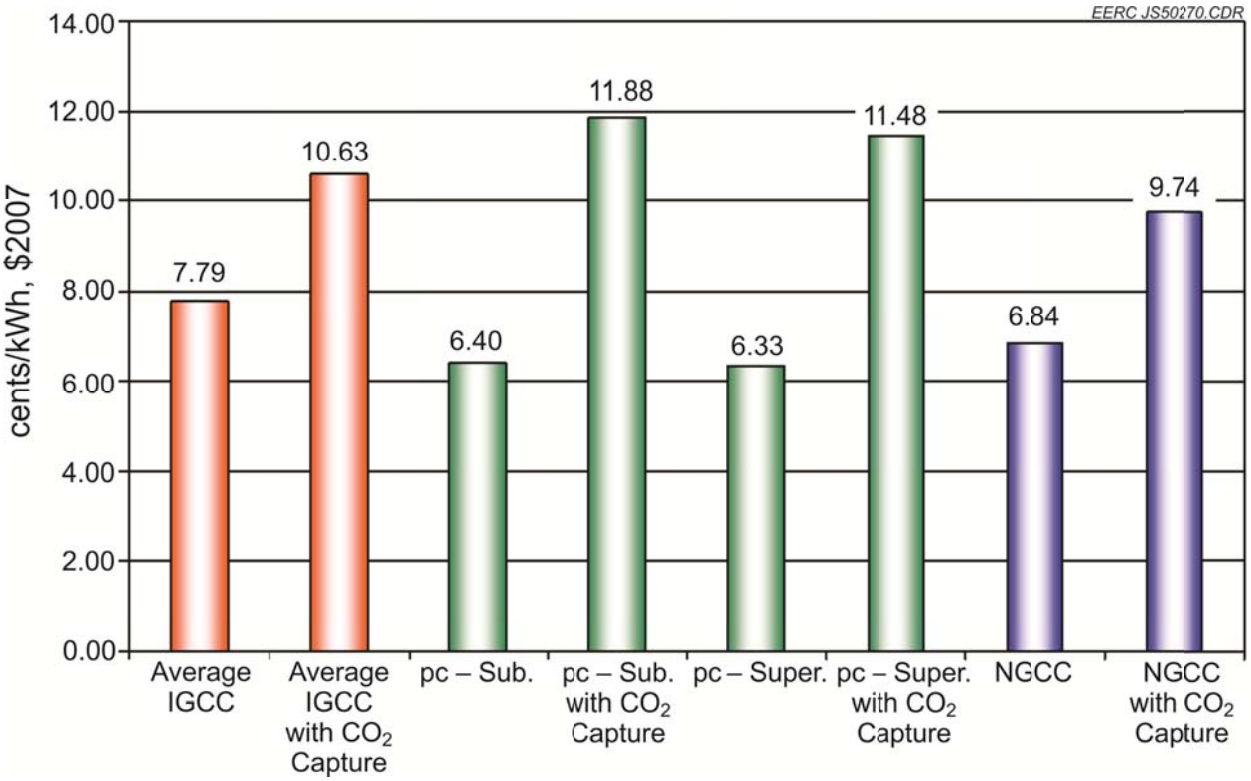


Figure 3. Comparison of COE for gasification vs. conventional systems with and without CO_2 capture (4) (pc = pulverized coal, Sub. = subcritical, and super. = supercritical).

of gasification-based power systems. Figure 4 depicts the technology advancements and incremental increase in net plant efficiency if each technology is implemented (5). The figure indicates that the technology with the highest potential for reducing the cost of gasification systems is hydrogen and CO_2 separation using hydrogen-selective membranes. According to NETL, the implementation of membrane technology can result in a nearly 3% efficiency point increase for a gasification system over using a conventional Selexol™ process. If all of the advanced pathway technologies are realized, the efficiency of an IGCC system with hydrogen separation membrane technology and CO_2 capture and compression could reach 40%. IGFC technologies could push the efficiency over 50%.

EERC JS50271.CDR

Case Title	Efficiency (% HHV)	Delta* Efficiency (% points)	TPC** ($/kW)	Delta* TPC** ($/kW)	20-yr Levelized COE (¢/kW-hr)	Delta* COE (¢/kW-hr)
Reference IGCC	30.4	0	2,718	0	11.48	0
Adv. "F" Turbine	31.7	1.3	2,472	-246	10.64	-0.84
Coal Feed Pump	32.5	0.8	2,465	-7	10.54	-0.10
85% CF	32.5	0.0	2,465	0	10.14	-0.40
WGCU/Selexol	33.3	0.8	2,425	-40	10.00	-0.14
WGCU/H_2Membrane	36.2	2.9	2,047	-378	8.80	-1.20
AHT-1 Turbine	38.0	1.8	1,855	-192	8.14	-0.66
ITM	38.3	0.3	1,724	-131	7.74	-0.40
AHT-2 Turbine	40.0	1.7	1,683	-41	7.61	-0.13
90% CF	40.0	0.0	1,683	0	7.36	-0.25
IGCC Pathway		+9.6%pts (+32%)		-1,035 (-38%)		-4.12 (-36%)
Advanced IGFC	56.3	+26%pts +85%	1,759	-959 (-35%)	7.45	-4.03 (-35%)

* Delta shown is the incremental change as each new technology is added to previous case configuration
** TPC is reported in January 2007 dollars and excludes owner's costs

Figure 4. Advanced gasification pathways toward improving efficiency and reducing COE for IGCC systems (5) (HHV = higher heating value, TPC = total power cost, CF = capacity factor, AHT = advanced hydrogen turbine, and IGFC = integrated gasification fuel cell).

Coal Gasification Fundamentals

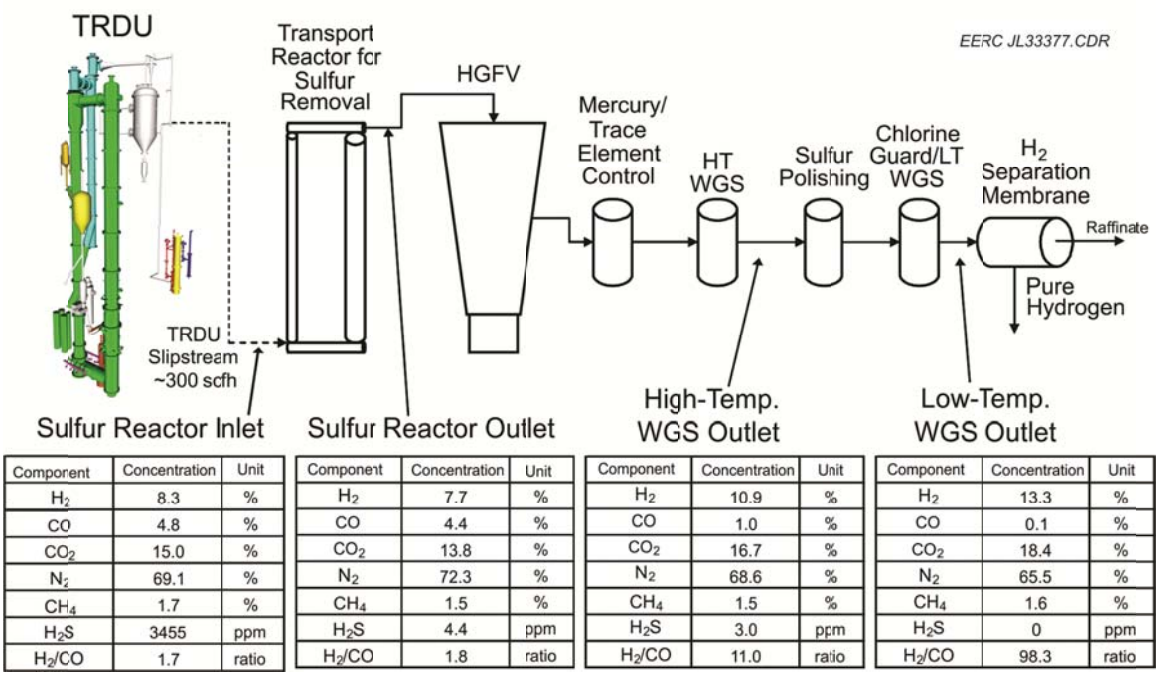
Coal gasification is a process in which coal is reacted with steam and oxygen at temperature and pressure to form H_2 and CO. Pressures can range from atmospheric pressure to 1200 psi, and temperatures range from about 1200° to over 2900°F. In addition to the typically desired products, H_2 and CO, many other by-products are formed during gasification such as CO_2,CH_4, H_2S, COS, HCl, NH_3, higher hydrocarbons, tars and oils, and particulate matter. The biggest challenge with any gasification system is dealing with the inorganic components in the coal and matching gasifier design to fuel-specific properties and desired end products. Gasifiers are typically configured as fixed beds, fluidized beds, moving beds, or entrained flow. Each gasifier type has strengths and weaknesses depending on the fuel used and the desired end products.

Gas Cleanup Fundamentals

Conventionally, cold-gas cleanup methods have been employed to remove contaminants from coal gasification syngas streams. Methods such as Rectisol® or Selexol are commercially available and highly effective at removing contaminants, but are also very costly from a capital and operational perspective. Significant economic benefits can be realized by utilizing warm- or hot-gas cleaning techniques. DOE has stated that thermal efficiency increases of 8% over conventional techniques can be realized by integrating WGCU technologies (6) into IGCC plants. Hydrogen separation membranes typically operate at WGCU temperatures, so they are a good match for IGCC projects looking to employ WGCU and carbon capture.

Work has been performed at the EERC in conjunction with DOE to develop methods to remove contaminants from syngas to levels suitable for a hydrogen separation membrane. The WGCU train is capable of removing sulfur, particulate, chlorine, and trace metals including mercury at temperatures above 400°F. All of the technologies utilized are considered either commercial or near-commercial in development. One such test involved gasification of Texas lignite in the EERC's TRDU, with a slipstream of gas being sent to the WGCU train (7). Figure 5 shows the test setup and a sampling of the results from the test.

Sulfur in the form of hydrogen sulfide and carbonyl sulfide was removed in a transport-style gas–solid contactor at temperatures between 600° and 1000°F. The system was capable of reducing sulfur to single-digit ppm levels in the syngas. Particulate was removed in a HGFV that provided near-absolute filtration using candle filters. Mercury and trace elements were removed with a proprietary sorbent. A high-temperature WGS catalyst significantly increased the hydrogen concentration in the gas stream while reducing CO. A sulfur-polishing bed removed hydrogen sulfide to concentrations below 0.2 ppm. A chlorine guard bed was used in front of the



Component	Concentration	Unit
H_2	8.3	%
CO	4.8	%
CO_2	15.0	%
N_2	69.1	%
CH_4	1.7	%
H_2S	3455	ppm
H_2/CO	1.7	ratio

Component	Concentration	Unit
H_2	7.7	%
CO	4.4	%
CO_2	13.8	%
N_2	72.3	%
CH_4	1.5	%
H_2S	4.4	ppm
H_2/CO	1.8	ratio

Component	Concentration	Unit
H_2	10.9	%
CO	1.0	%
CO_2	16.7	%
N_2	68.6	%
CH_4	1.5	%
H_2S	3.0	ppm
H_2/CO	11.0	ratio

Component	Concentration	Unit
H_2	13.3	%
CO	0.1	%
CO_2	18.4	%
N_2	65.5	%
CH_4	1.6	%
H_2S	0	ppm
H_2/CO	98.3	ratio

Figure 5. Gasification and gas cleanup process diagram with test results (7).

low-temperature WGS catalyst to prevent poisoning. Carbon monoxide was reduced to 0.1% in a low-temperature shift bed, and hydrogen was maximized. If the system were run under oxygen-fired conditions, the resulting syngas would contain combined H_2 and CO_2 levels greater than 90%. After passing through the cleanup train, the syngas was ready for hydrogen and CO_2 separation in a hydrogen separation membrane.

Principles of Hydrogen Separation Membranes

Most hydrogen separation membranes operate on the principle that hydrogen selectively penetrates through the membrane because of the inherent properties of the material. The mechanism for hydrogen penetration through the membrane depends on the type of membrane in question. Most membranes rely on the partial pressure of hydrogen in the feed stream as the driving force for permeation, which is balanced with the partial pressure of hydrogen in the permeate stream. Kluiters has categorized membranes into five main types that are commercial

or appear to have commercial promise: dense polymer, microporous ceramic, porous carbon, dense metallic, and dense ceramic (8). Each membrane type has advantages and disadvantages, and research organizations and companies continue to work to develop better versions of each (9). Figure 6 illustrates the basic operating principles of hydrogen separation membranes for use in coal-derived syngas (7). This figure shows a dense metallic tubular membrane, but plate-and-frame-style membranes have also been developed. The "syngas in" stream refers to the feed gas into the membrane module. The permeate stream has permeated through the membrane wall and, in this case, is made up of mostly hydrogen. The raffinate stream is what is left of the feed stream once the permeate is separated. A sweep gas such as nitrogen may be used on the permeate side to lower the partial pressure of hydrogen and enable more hydrogen to permeate the membrane.

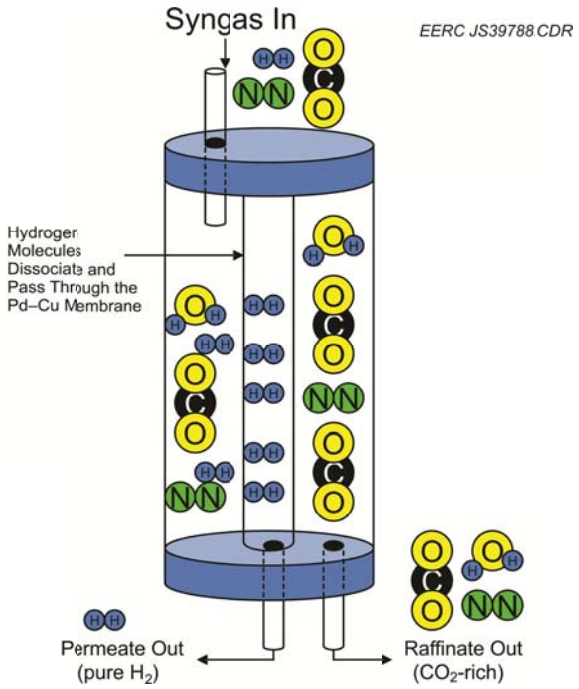


Figure 6. Illustration of the operating principle of hydrogen separation membranes (7).

The mechanisms for hydrogen transport through each membrane type are different. However, the performance of each membrane is gauged by two main principles: hydrogen selectivity and hydrogen flux. Hydrogen selectivity is defined by Equation 1 (8):

$$\alpha_{A/B} = \frac{y_A / y_B}{x_A / x_B} \qquad \text{[Eq. 1]}$$

where α is the selectivity factor of Component A over Component B in the mixture, y_A and y_B are the fractions of those components in the permeate, and x_A and x_B are the fractions of those components in the feed. Components A and B are usually defined so that a higher selectivity factor refers to better membrane performance. A selectivity factor of 1 means there is no component separation.

Hydrogen flux is a measure of the rate of permeation of hydrogen through a membrane wall. The general equation for flux is shown by Equation 2 (8, 10):

$$J_x = \frac{P(p^n_{x,\,feed} - p^n_{x,\,permeate})}{t} \qquad \text{[Eq. 2]}$$

where J_x represents the flux of Species x, P_x represents the permeability of Species x, $p_{x,feed}$ and $p_{x,permeate}$ are the partial pressures of Species x in the feed and permeate streams, t is the membrane thickness, and n is the partial pressure exponent. The value of n is usually between 0.5 and 2 and, like the value of P, depends on the transport mechanism assumed. When n = 1, the equation is called Fick's law. For hydrogen transport through a metal membrane, the value of n is usually 0.5, and the equation reduces to what is referred to as Sievert's law. Sievert's law is a useful way of measuring membrane performance because it takes into account the membrane thickness and partial pressure of hydrogen on each side of the membrane.

Since most membranes operate on a partial pressure differential, there will always be some hydrogen left behind in the raffinate stream. Therefore, an additional measurement of performance is the recovery or yield, as shown by Equation 3 (8):

$$S = \frac{q_p}{q_f} \qquad \text{[Eq. 3]}$$

where S is the yield, qp is the permeate flow, and qf is the feed flow. There are numerous other ways to quantify the yield, including calculating the volume reduction in the raffinate or the percentage hydrogen recovery from the feed.

The five basic types of membranes mentioned earlier each have inherent advantages and disadvantages, depending on the desired operating conditions and necessary product specifications. With data presented by Kluiters (8) and modified with Adhikari (10) and Ockwig (11), Table 1 compares, in general, the relative operational performance of these five membrane types. Typical operational temperature will vary by specific membrane type, but it can be seen

Table 1. Properties of Five Hydrogen-Selective Membranes (8, 10, 11)

	Dense Polymer	Micro-porous Ceramic	Dense Ceramic	Porous Carbon	Dense Metallic
Temperature Range, °C	<100	200–600	600–900	500–900	300–600
H_2 Selectivity	Low	Moderate	Very high	Low	Very high
H_2 Flux	Low	High	Moderate	Moderate	High
Known Poisoning Issues	HCl, SO_x, CO_2	–	H_2S	Organics	H_2S, HCl, CO
Example Materials	Polymers	Silica, alumina, zirconia, titania, zeolites	$SrCeO_{3-\delta}$, $BaCeO_{3-\delta}$	Carbon	Palladium alloys, Pd–Cu, Pd–Au
Transport Mechanism	Solution/ diffusion	Molecular sieving	Solution/ diffusion	Surface diffusion, molecular sieving	Solution/ diffusion

that the dense polymer membranes are only applicable at low temperature. Dense ceramic and dense metallic membranes have the highest hydrogen selectivity, and hydrogen flux is highest with dense metallic or microporous ceramic membranes. While dense metallic membranes seem to have the best performance relative to hydrogen, they are also very susceptible to poisoning from many compounds found in syngas, and metal alloys can be very expensive. Dense ceramic membranes also have high potential for commercial applications. They are less susceptible to poisoning than metallic membranes and, depending on the material, can be significantly less expensive. Development work is under way with each of these membrane types to increase the resistance to poisoning and reduce cost.

Bench-Scale Test Results

Testing was performed at a bench scale on Praxair's hydrogen separation membrane technology using coal-derived syngas produced in EERC gasifiers. Three separate weeklong test campaigns were performed using both a transport gasifier and an entrained-flow gasifier for syngas production. The small-scale membranes met DOE's target of 2.0 lb/day hydrogen production on each gasifier type. In addition, the membranes exhibited good durability and resistance to sulfur and other coal-derived contaminants over the test periods. Based on these results and other laboratory tests, Praxair was selected for follow-on testing at the pilot scale, with separation rates up to 100 lb/day hydrogen.

QUALIFICATIONS

Key Personnel

Mr. Joshua Stanislowski, a Research Manager at the EERC, will serve as the project manager for program. Mr. Stanislowski has managed gasification projects at the EERC for the past 8 years, including the evaluation of dozens of bench-scale hydrogen separation membranes. He holds

M.S. and B.S. degrees in Chemical Engineering from the University of North Dakota (UND), with his thesis work focused on the impact of coal-derived impurities on the performance of hydrogen separation membranes. Prior to his current position, Mr. Stanislowski served as a process engineer for Innovex, Inc. His principal areas of expertise include fossil fuel conversion with emphasis on hydrogen separation and CO_2 capture, gasification system analysis, pollution control, and process modeling. He has extensive experience with Aspen software and systems engineering, process controls, and project management.

Mr. Tyler Curran, a Research Engineer at the EERC, will serve as the principal investigator for the project. Mr. Curran works in the area of process engineering and design related to conversion of coal and biomass to fuels, chemicals, and energy, including designing processes and equipment for gasification and pyrolysis of coal and biomass, optimizing syngas chemistry, developing purification methods, designing thermocatalytic reactors for conversion of syngas and thermochemical process products to fuels and chemicals, and engineering support on advanced pilot systems for testing and developing alternative fuels and energy forms. Mr. Curran has designed and built numerous control systems for hydrogen separation membranes. He received his B.S. degree in Mechanical Engineering from UND. Prior to his position at the EERC, he worked as a Mechanical and Electrical Engineer at Hawkes Manufacturing.

Dr. Michael L. Swanson, a Senior Research Manager at the EERC, will serve as project advisor. Dr. Swanson is currently involved with the demonstration of advanced power systems such as pressurized fluidized-bed combustors and IGCC, with an emphasis on hot-gas cleanup issues. Dr. Swanson received a Ph.D. degree in Energy Engineering, a M.B.A., and M.S. and B.S. degrees in Chemical Engineering, all from UND. Dr. Swanson's principal areas of expertise include pressurized fluidized-bed combustion, IGCC, hot-gas cleanup, coal reactivity in low-

rank coal combustion, supercritical solvent extraction, and liquefaction of low-rank coals. Dr. Swanson is a member of the American Institute of Chemical Engineers and the American Chemical Society. In addition, he has authored or coauthored over 80 publications.

Resumes for key personnel can be found in Appendix A.

EERC

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

VALUE TO NORTH DAKOTA

In order to secure lignite's future in energy production, novel and innovative technologies are needed to improve efficiency and reduce the CO_2 footprint of the fuel. Advanced, highly efficient technologies such as gasification combined with hydrogen separation membranes provide a promising route for continued use of lignite at higher efficiency with lower cost and with lower CO_2 emissions. Additionally, the growing oil and gas industry in North Dakota has a need for increased supplies of both power and hydrogen. Demonstration of an advanced technology that can utilize the state's abundant resources to provide valuable products is critical to ensure continued, increased, and responsible lignite use for decades to come. North Dakota will also have a need for CO_2 in the future in order to maintain high levels of oil production. Hydrogen separation membranes separate the CO_2 from the energy containing hydrogen while

keeping the CO_2 at system pressure and, therefore, minimize the CO_2 compression needs for enhanced oil recovery.

MANAGEMENT

The overall project manager will be Mr. Josh Stanislowski. Mr. Tyler Curran will act as the principal investigator, and Dr. Michael Swanson will be the project advisor. Mr. Curran will be responsible for leading Tasks 1 and 2. Mr. Stanislowski will lead Tasks 3–5. All key personnel will be responsible for interpretation of results and writing reports. Resumes of all key personnel are enclosed in Appendix A.

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

Several milestones and decision points have been identified for the program. Milestones include completion of membrane installation, completion of TRDU modifications, acquisition of fuels, completion of test runs and process modeling, and periodic reporting. Decision points for the project include finalizing test configuration and membrane integration design, determining the test plan with project sponsors, determining modeling inputs, and determining if the membrane meets performance goals. The timing of the milestones and decision points is indicated on the time line shown in the next section.

TIMETABLE

A time line for the project activities is shown in Figure 7. Tasks 1 and 2 which are currently under way (initiated in January 2014) will be completed in the second quarter of calendar year

	2014												2015								
Project Activity	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
Task 1 – Acquisition and Installation of Hydrogen Separation Membranes								A									a				
Task 2 – Modification of the Transport Reactor System for Membrane Testing					B												b				
Task 3 – Hydrogen and CO_2 Separation Testing on the TRDU Gasifier													c	C			d	D			
Task 4 – Process Modeling and Economic Evaluation																		e		e	
Task 5 – Management and Reporting													q			q			q, E		f, q, E

Milestones		**Decision Points**	
a	Complete Membrane Installation	A	Finalize Membrane Test Configuration
b	Complete TRDU Modifications	B	Finalize Membrane Integration Design
c	Acquire Fuel	C	Finalize Test Plan
d, e	Complete Test Runs Complete Process Model	D	Determine Inputs for the Process Model
f	Final Report	E	Determine if Membrane Meets DOE Performance Goals
q	Quarterly Reports	F	Provide Recommendations for Commercialization and Further Study

Figure 7. Project schedule.

2015. Tasks 3 and 4 will be initiated in December 2014 and continue to the end of the project (September 2015). Task 5 is ongoing and will continue throughout the life of the project. Milestones and decision points are also included in the time line.

BUDGET/MATCHING FUNDS

The total estimated cost of the proposed project is $2,039,608. The EERC is requesting sponsorship of $225,000 from LEC. The EERC anticipates matching LEC funding with existing federal flow-through sponsorship in the amount of $1,329,608 from Praxair and $450,000 from the state of Wyoming. In addition, the EERC will also match $35,000 from industrial sponsors. Letters of support from Brown Coal Innovation Australia Limited and Dakota Gasification Company can be found in Appendix C.

TAX LIABILITY

The EERC, a department within the University of North Dakota, is a state-controlled institution of higher education and is not a taxable entity; therefore, it has no tax liability.

CONFIDENTIAL INFORMATION

No confidential material is included in this proposal.

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APPENDIX A

RESUMES OF KEY PERSONNEL

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: jstanislowski@undeerc.org

Principal Areas of Expertise
Mr. Stanislowski'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. Stanislowski 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. Stanislowski'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. Stanislowski 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. Stanislowski was proficient with MiniTab statistical software and utilized statistical analysis and experimental design as part of his daily work.

– Mr. Stanislowski 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.

TYLER J. CURRAN
Research Engineer
Energy & Environmental Research Center (EERC), University of North Dakota (UND)
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Phone: (701) 777-5097, Fax: (701) 777-5181, E-Mail: tcurran@undeerc.org

Professional Areas of Expertise

Mr. Curran's principal areas of interest and expertise include classical synthesis of mechanical mechanisms and machines; design of energy conversion systems; process design and modeling; parametric computer modeling and simulation; finite element modeling and simulation; fluid power systems, internal combustion engines, electric motors, and hydrogen fuel cells; mechanical power trains; design for precision machining and specialized manufacturing processes; and electronic controls, programmable logic controllers, and wireless control devices.

Qualifications

B.S., Mechanical Engineering, University of North Dakota, 2004.
Registered Professional Engineer, North Dakota.
Proficient in Pro Engineer, Solid Edge, Cadkey, Ansys, and Mathematica. Senior Design Project: Hydrogen Fuel Cell Car Powertrain System Design, 2003–2004.

Professional Experience

2008–Present: Research Engineer, EERC, UND, Grand Forks, North Dakota. Mr. Curran works in the area of process engineering and design related to conversion of coal and biomass to fuels, chemicals, and energy. His responsibilities include designing processes and equipment for gasification and pyrolysis of coal and biomass, optimizing syngas chemistry, developing purification methods, designing thermocatalytic reactors for conversion of syngas and thermochemical process products to fuels and chemicals, and engineering support on advanced pilot systems for testing and developing alternative fuels and energy forms.

2005–2008: Mechanical and Electrical Design Engineer, Hawkes Manufacturing, East Grand Forks, Minnesota. Mr. Curran's responsibilities included design, redesign, research, and testing, evaluation of new and existing products, mechanical synthesis of mechanisms, structures, and fluid power systems programmable electronic controls, wiring harnesses, actuators, and sensors, project management, and cost analysis.

2003: Engineering Intern, American Crystal Sugar Company, East Grand Forks, Minnesota. Mr. Curran's responsibilities included ultrasonic testing and visual inspection of process heat exchangers, creating detailed inspection reports for vessels tested in five factories, and creating a detailed standardized testing procedure.

Professional Memberships
American Society of Mechanical Engineers
Pyrotechnics Guild International

Publications and Presentations
Has coauthored several publications.

DR. MICHAEL L. SWANSON
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) 777-5239, Fax: (701) 777-5181, E-Mail: mswanson@undeerc.org

Principal Areas of Expertise

Dr. Swanson's principal areas of interest and expertise include pressurized fluidized-bed combustion (PFBC), integrated gasification combined cycle (IGCC), hot-gas cleanup, coal reactivity in low-rank coal (LRC) combustion, supercritical solvent extraction, and liquefaction of LRCs.

Qualifications

Ph.D., Energy Engineering, University of North Dakota, 2000. Dissertation: Modeling of Ash Properties in Advanced Coal-Based Power Systems.
M.B.A., University of North Dakota, 1991.
M.S., Chemical Engineering, University of North Dakota, 1982.
B.S., Chemical Engineering, University of North Dakota, 1981.

Professional Experience

2004–Present: Adjunct Professor, Chemical Engineering, UND.

1999–Present: Senior Research Manager, EERC, UND. Dr. Swanson is currently involved in the demonstration of advanced power systems such as PFBC and IGCC, with an emphasis on hot-gas cleanup issues.

1997–1999: Research Manager, EERC, UND. Dr. Swanson managed research projects involved with the demonstration of advanced power systems such as PFBC and IGCC, with an emphasis on hot-gas cleanup issues.

1990–1997: Research Engineer, EERC, UND. Dr. Swanson was involved with the demonstration of advanced power systems such as PFBC and IGCC, with an emphasis on hot-gas cleanup issues.

1986–1990: Research Engineer, EERC, UND. Dr. Swanson supervised a contract with the U.S. Department of Energy to investigate the utilization of coal–water fuels in gas turbines, where he designed, constructed, and operated research projects that evaluated the higher reactivity of LRCs in short-residence-time gas turbines and diesel engines.

1983–1986: Research Engineer, EERC, UND. Dr. Swanson designed, constructed, and operated supercritical fluid extraction (SFE) and coal liquefaction apparatus; characterized the resulting organic liquids and carbonaceous chars; and prepared reports.

1982–1983: Associated Western Universities Postgraduate Fellowship, Grand Forks Energy Technology Center, U.S. Department of Energy, Grand Forks, North Dakota. Dr. Swanson designed and constructed an SFE apparatus.

Publications and Presentations
Has authored or coauthored numerous publications.

APPENDIX B

DESCRIPTION OF EQUIPMENT

Transport Reactor Development Unit (TRDU)

The pilot-scale TRDU has an exit gas temperature of up to 980°C (1800°F), a gas flow rate of 400 scfm (0.153m^3/s), and an operating pressure of 120 psig (9.3 bar). The TRDU system can be divided into three sections: the coal feed section, the TRDU, and the product recovery section. The TRDU proper, as shown in Figure B-1, consists of a riser reactor with an expanded mixing zone at the bottom, a disengager, and a primary cyclone and standpipe. The standpipe is connected to the mixing section of the riser by an L-valve transfer line. All of the components in the system are refractory-lined and designed mechanically for 150 psig (11.4 bar) and an internal temperature of 1090°C (2000°F). Detailed design criteria and a comparison to actual operating conditions on the design coal are given in Table B-1.

The premixed coal and limestone feed to the transport reactor can be admitted through three nozzles, which are at varying elevations. Two of these nozzles are located near the top of the mixing zone (gasification), and the remaining one is near the bottom of the mixing zone (combustion). During operation of the TRDU, feed is admitted through only one nozzle at a time.

The coal feed is measured by an rpm-controlled metering auger. Oxidant is fed to the reactor through two pairs of nozzles at varying elevations within the mixing zone. For the combustion mode of operation, additional nozzles are provided in the riser for feeding secondary air. Hot solids from the standpipe are circulated into the mixing zone, where they come into contact with the nitrogen and the steam being injected into the L-valve. This feature enables spent char to contact steam prior to the fresh coal feed. This staged gasification process is expected to enhance process efficiency. Gasification or combustion and desulfurization reactions are carried out in the riser as coal, sorbent, and oxidant (with steam for gasification) flow up the reactor. The solids circulation into the mixing zone is controlled by fluffing gas in the standpipe, J-leg aeration flows, and the solids level in the standpipe.

The riser, disengager, standpipe, and cyclones are equipped with several internal and skin thermocouples. Nitrogen-purged pressure taps are also provided to record differential pressure across the riser, disengager, and cyclones. The data acquisition and control system scans the data points every ½ s and saves the process data every 30 s. The bulk of entrained solids leaving the riser are separated from the gas stream in the disengager and circulated back to the riser via the standpipe. A solids stream is withdrawn from the standpipe via an auger to maintain the system's solids inventory. Gas exiting the disengager enters a primary cyclone. The dipleg solids are recirculated back to the standpipe through a loop seal at the bottom of the dipleg. Gas exiting this cyclone enters a jacketed-pipe heat exchanger before entering the hot-gas filter vessel (HGFV). The warm, particulate-free gases leaving the HGFV are vented directly into a thermal oxidizer where they are combusted.

Hot-Gas Filter Vessel

This vessel is designed to handle all of the gas flow from the TRDU at its expected operating conditions. The vessel is approximately 48 in. i.d. (121.9 cm) and 185 in. (470 cm) long and is designed to handle gas flows of approximately 325 scfm at temperatures up to 815°C (1500°F) and 120 psig (8.3 bar). The refractory has a 28-in. (71.1-cm) i.d., with a shroud

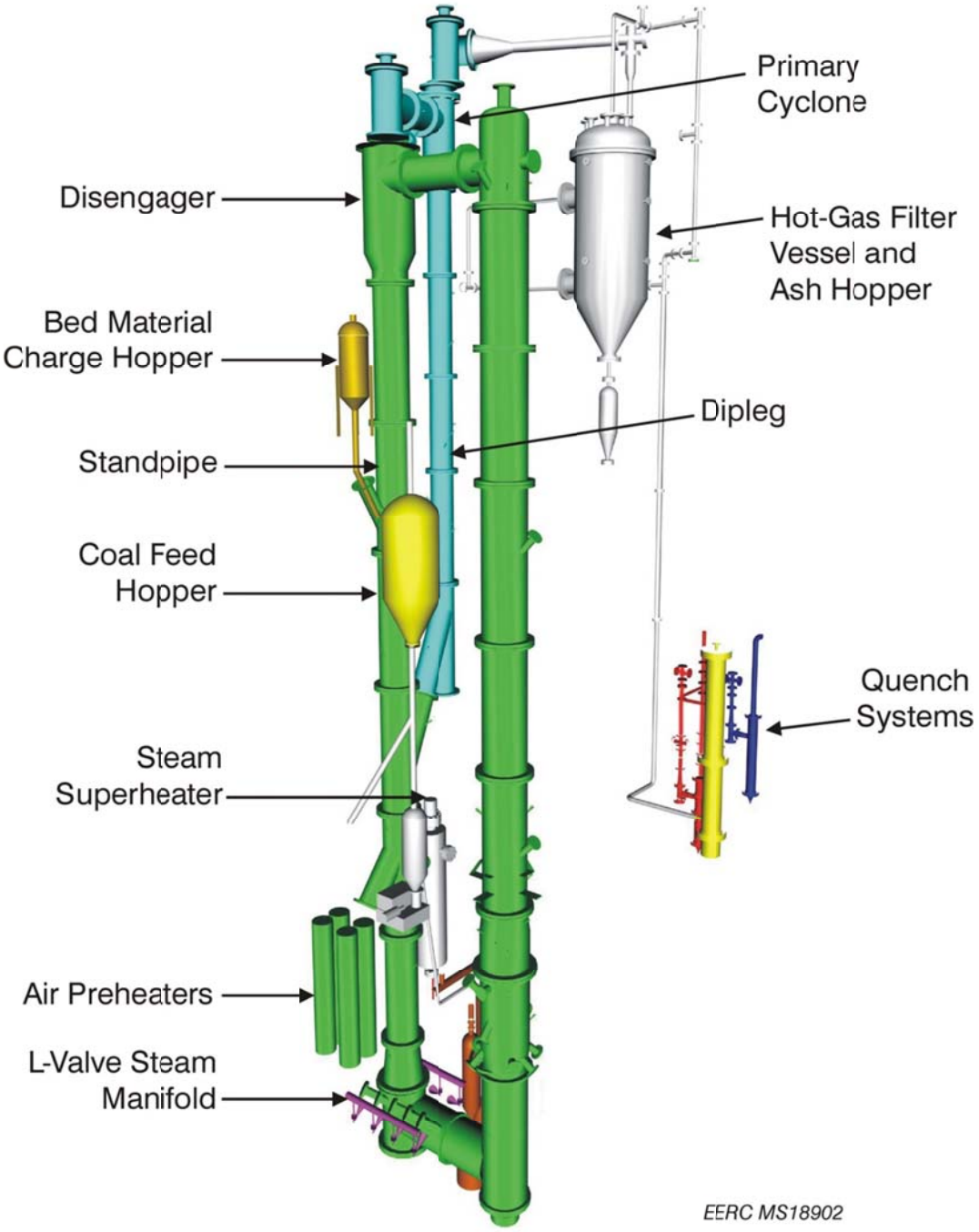

Figure B-1. Schematic of the TRDU.

Table B-1. Summary of TRDU Design and Operation on the Design Coal

Parameter	Design	Actual
Coal	Illinois No. 6	Illinois No. 6
Moisture Content, %	5	8.5
Pressure, psig	120 (9.3 bar)	120 (9.3 bar)
Steam/Coal Ratio	0.34	0.34
Air/Coal Ratio	4.0	2.3
Ca/S Ratio, mol	1.5	2.0
Air Inlet Temperature, °C	427	180
Steam Preheat, °C	537	350
Coal Feed Rate, lb/hr	198 (89.9 kg/hr)	220 (99.9 kg/hr)
Gasifier Temperature, maximum °C	1010	950
T, maximum °C	17	60 to 100
Carbon Conversion,[1] %	>80	76.5
HHV[2] of Fuel Gas, Btu/scf	100	110
Heat Loss as Coal Feed, %	19.5	13
Riser Velocity, ft/sec	31.3	25
Heat Loss, Btu/hr	252,000	320,000
Standpipe Superficial Velocity, ft/sec	0.1	0.38

[1] Carbon conversion = (wt carbon feed − wt carbon removed)/wt carbon feed * 100.
[2] Higher heating value.

diameter of approximately 22 in. (55.9 cm). The vessel is sized such that it could handle candle filters up to 1.5 m long; however, 1-m candles have been utilized in the 540°C (1000°F) gasification tests to date. Candle filters are 2.375-in. (6-cm) o.d. with 4-in. (10.2-cm) center line-to-center line spacing. The filter design criteria are summarized in Table B-2.

The total number of candles that can be mounted in the current geometry of the HGFV tube sheet is 19. This enables filter face velocities as low as 2.0 ft/min to be tested using 1.5-m candles. Higher face velocities are achieved by using fewer candles. The majority of testing has been performed at a face velocity of approximately 4.0 to 4.5 ft/min. This program has tested an Industrial Filter & Pump (IF&P) ceramic tube sheet and Fibrosic and REECER SiC candles, silicon carbon-coated and SiO_2 ceramic fiber candles from the 3M company, along with sintered metal (iron aluminide) and Vitropore silicon carbon ceramic candles from Pall Advanced Separation Systems Corporation. In addition, granular SiC candles from U.S. Filter/Schumacher and composite candle filters from McDermott Technologies and Honeywell were tested. Current testing has focused on Pall's iron aluminide metal filters. Also, candle filter fail-safes from Siemens-Westinghouse Science and Technology Center have been tested.

Table B-2. Design Criteria and Actual Operating Conditions for the Pilot-Scale HGFV

Operating Conditions	Design	Actual
Inlet Gas Temperature	540EC	450E–580EC
Operating Pressure	150 psig (10.3 bar)	120 psig (8.3 bar)
Volumetric Gas Flow	325 scfm (0.153 m^3/s)	350 scfm (0.165 m^3/s)
Number of Candles	19 (1 or 1.5 meter)	13 (1 meter)
Candle Spacing	4 in. 6 to 6 (10.2 cm)	4 in. 6 to 6 (10.2 cm)
Filter Face Velocity	2.5–10 ft/min (1.3 to 2.3 cm/s)	4.5 ft/min (2.3 cm/s)
Particulate Loading	<10,000 ppmw	< 38,000 ppmw
Temperature Drop Across HGFV	<30EC	25EC
Nitrogen Backpulse System Pressure	Up to 600 psig (42 bar)	250 to 350 psig (17 to 24 bar)
Backpulse Valve Open Duration	Up to 1-s duration	¼-s duration

The ash letdown system consists of two sets of alternating high-temperature valves with a conical pressure vessel to act as a lock hopper. Additionally, a preheat natural gas burner attached to a lower inlet nozzle on the filter vessel can be used to preheat the filter vessel separately from the TRDU. The hot gas from the burner enters the vessel via a nozzle inlet separate from the dirty gas.

The high-pressure nitrogen backpulse system is capable of backpulsing up to four sets of four or five candle filters with ambient-temperature nitrogen in a time-controlled sequence. The pulse length and volume of nitrogen displaced into the filter vessel are controlled by regulating the pressure (up to 600 psig [42 bar]) of the nitrogen reservoir and controlling the solenoid valve pulse duration. A recently installed heat exchange surface now allows the hot-gas filter to operate in the 500° to 1200°F range instead of the higher temperature range of 800° to 1000°F utilized in previous testing. This additional heat exchange surface was added to allow gas cooling to the temperature where Hg removal is likely to occur. Ports for obtaining hot high-pressure particulate and trace metal samples both upstream and downstream of the filter vessel were added to the filter system piping.

Hot-Side Syngas Compressor

While capable of generating a slipstream that would expose test membranes to a range of conditions, the TRDU has a maximum operating pressure of 120 psig, which is substantially less than the desired +400-psi pressures of gasifiers. To address this limitation, the EERC modified the TRDU downstream equipment to include a compressor capable of providing a stream of about 250 scfm at more than 500 psig for periods of more than 8 hours. The compressor is installed at the EERC and is operational. Of the syngas stream, more than 90 scfm can be sent to the membrane for separation to produce 200 lb/d of hydrogen, with the remainder returned to the gasifier to satisfy purge requirements. Figure B-2 displays a block diagram of system modifications. While the modified system does not attain the harshest conditions projected by the

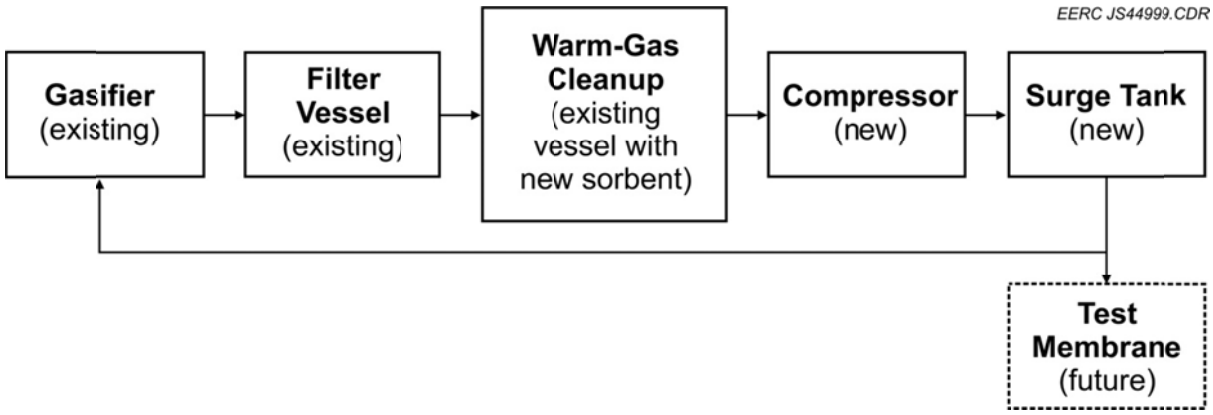

Figure B-2. Block diagram of proposed system.

U.S. Department of Energy for future commercial gasifiers (such as +800-psi syngas product pressure), its 500-psia design pressure places it in the range of existing gasifiers. It should be noted that the compressor can be modified to achieve +800-psi exhaust pressure merely by the addition of a single stage, if such pressures are desired in the future.

Ultimately, the modified TRDU system can perform cold- or warm-gas (up to 450°F) cleanup, with or without water–gas shift to produce a synthesis gas product stream of more than 45 scfm containing more than 100 lb/d of hydrogen at pressures up to 500 psig. Compressor specifications are listed as follows:

- Suction pressure: 135–140 psig
- Discharge pressure: 500 psig
- Capacity: 250 scfm
- Suction temperature: 450°–500°F from gasifier, 60°–80°F from quench system
- Site elevation: 830 feet
- Ambient temperature: 100°F (assuming indoor location)
- Interstage temperature: must be kept at or above 450°F
- Driver: electric, 208 V, 3Ø, 60 Hz
- HazLoc rating: Class I, Division II, Group B (in accordance with the requirements of National Fire Protection Association 70)
- Corrosives: H_2S up to 7500 ppm, NH_3 up to 3600 ppm, HCl up to 5 ppm

APPENDIX C

LETTERS OF SUPPORT

BROWN COAL
INNOVATION
AUSTRALIA

Positioning brown coal for a brighter future

30th September 2014

Mr. Jason Laumb
Senior Research Manager
Energy & Environmental Research Center
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

Project Entitled "Demonstration of Pilot-Scale Hydrogen and CO2 Separation Membrane Technology on Lignite-Derived Syngas"

Dear Mr. Laumb:

This letter is in response to your request for participation in the Energy & Environmental Research Center (EERC) project "Demonstration of Pilot-Scale Hydrogen and CO2 Separation Membrane Technology on Lignite-Derived Syngas"

We feel this is an excellent program that will be of significant benefit to the lignite and brown coal industry. Hydrogen production from brown coal is an area of great commercial relevance to a low-emissions future, and a major demonstration-scale production facility is planned in Australia, to commence operation in the next few years. It is my understanding that the research to be undertaken under the above program will develop important tools and information for end users of membrane separation technologies, a prospective option for reducing the cost of hydrogen production.

We understand funding for this proposed project will be from the U.S. Department of Energy (DOE), state governments, and industry. Given the relevance to the use of brown coal in Australia, BCIA is willing to consider providing funding up to $10,000 for a trial of the membrane technology on syngas derived from Australian brown coal. Such funding would be subject to BCIA receiving a full proposal for the work to be undertaken, and would be conditional on the approval of the application by both BCIA's Board and Research Advisory Committee.

I can certify that any cash contribution made by our organization would be with nonfederal dollars.

We strongly encourage all stakeholders to consider funding the proposed work. We look forward to working with DOE, PraxAir, LEC, the EERC, and other sponsors of this program.

Yours sincerely,

Dr. Phil Gurney
Chief Executive Officer

Brown Coal Innovation Australia Limited
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Email info@bcinnovation.com.au | ABN 51 141 273 261

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BISMARCK, NORTH DAKOTA 58503

Great Plains SYNFUELS

September 30, 2014

Mr. Joshua Stanislowski
Research Manager
Energy & Environmental Research Center
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

Dear Mr. Stanislowski:

Subject: Project Entitled "Demonstration of Pilot-Scale Hydrogen and CO_2 Separation Membrane Technology on Lignite-Derived Syngas"

This letter is in response to your request for participation in the subject Energy & Environmental Research Center (EERC) project. We feel this is an excellent program that will be of significant benefit to the lignite and brown coal industry. The program will develop important tools and information for end users of membrane separation technologies.

We understand funding for this proposed project will be from the U.S. Department of Energy (DOE), state governments, and industry. This letter certifies that any cash contribution made by our organization will be with nonfederal dollars. Therefore, Dakota Gasification Company pledges cash support in the amount of US $25,000.

We strongly encourage the North Dakota Lignite Energy Council (LEC) to consider funding the proposed work. We look forward to working with DOE, PraxAir, LEC, the EERC, and other sponsors of this program.

Sincerely,

Dave Sauer
Senior VP and COO
Dakota Gasification Company

/bk

cc: Bob Fagerstrom
Mark Foss
Matthew Greek
Michael Holmes - EERC
Steve Johnson
Jason Laumb - EERC
Steven Liebelt
Kimberly Miller
Ken Rutter
Paul Sukut
Valerie Weigel

APPENDIX D

BUDGET

DEMONSTRATION OF PILOT-SCALE HYDROGEN AND CO_2 SEPARATION
MEMBRANE TECHNOLOGY ON LIGNITE-DERIVED SYNGAS
NDIC LIGNITE ENERGY COUNCIL
PROPOSED PROJECT START DATE: 12/1/14
EERC PROPOSAL #2015-0043

BUDGET

CATEGORY	NDIC LEC Share	Matching Funds Total	Project Total
Labor	$ 170,431	$ 1,027,013	$ 1,197,444
Travel	$ 6,368	$ 10,064	$ 16,432
Equipment > $5000	$ -	$ 395,000	$ 395,000
Supplies	$ 7,525	$ 115,521	$ 123,046
Other*	$ 439	$ 3,018	$ 3,457
Laboratory Fees & Services			
Natural Materials Analytical Research Lab	$ -	$ 30,872	$ 30,872
Fuels & Materials Research Lab	$ -	$ 26,680	$ 26,680
Analytical Research Lab	$ -	$ 5,786	$ 5,786
Fuel Preparation Service	$ -	$ 32,938	$ 32,938
Continuous Fluidized-Bed Reactor Service	$ 23,713	$ 144,101	$ 167,814
Graphics Service	$ 1,141	$ 2,159	$ 3,300
Shop & Operations Fee	$ 5,874	$ 21,456	$ 27,330
Technical Software Fee	$ 8,756	$ -	$ 8,756
Freight	$ 753	$ -	$ 753
Total Project Costs – U.S. Dollars	$ 225,000	$ 1,814,608	$ 2,039,608

Labor Categories	Labor Hours		
	NDIC LEC	Matching Funds	Total
Research Scientists/Engineers	887	6,474	7,361
Research Technicians	69	392	461
Mechanics/Operators	600	3,120	3,720
Senior Management	36	188	224
Technical Support Services	64	517	581

*May include costs such as food, printing, communications, or other miscellaneous expenses.