DEVELOPMENT OF A NATIONAL CENTER FOR HYDROGEN TECHNOLOGY: A SUMMARY REPORT OF ACTIVITIES COMPLETED AT THE NATIONAL CENTER FOR HYDROGEN TECHNOLOGY[®] – YEAR 6

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DEVELOPMENT OF A NATIONAL CENTER FOR HYDROGEN TECHNOLOGY

A Summary Report of Activities Completed at the National Center for Hydrogen Technology[®] – Year 6

ABSTRACT

The Energy & Environmental Research Center (EERC) located in Grand Forks, North Dakota, has operated the National Center for Hydrogen Technology[®] (NCHT[®]) since 2005 under a Cooperative Agreement with the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). The EERC has a long history of hydrogen generation and utilization from fossil fuels, and under the NCHT Program, the EERC has accelerated its research on hydrogen generation and utilization topics.

Since the NCHT's inception, the EERC has received more than \$65 million in funding for hydrogen-related projects (\$24 million for projects in the NCHT, which includes federal and corporate partner development funds) involving more than 85 partners (27 with the NCHT). The NCHT Program's nine activities span a broad range of technologies that align well with the Advanced Fuels Program goals and, specifically, those described in the Hydrogen from Coal Program research, development, and demonstration (RD&D) plan that refers to realistic testing of technologies at adequate scale, process intensification, and contaminant control.

A number of projects have been completed that range from technical feasibility of several hydrogen generation and utilization technologies to public and technical education and outreach tools. Projects under the NCHT have produced hydrogen from natural gas, coal, liquid hydrocarbons, and biomass. The hydrogen or syngas generated by these processes has also been purified in many of these instances or burned directly for power generation. Also, several activities are still undergoing research, development, demonstration, and commercialization at the NCHT.

This report provides a summary overview of the projects completed in Year 6 of the NCHT. Individual activity reports are referenced as a source of detailed information on each activity.

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DEVELOPMENT OF A NATIONAL CENTER FOR HYDROGEN TECHNOLOGY

A Summary Report of Activities Completed at the National Center for Hydrogen Technology® – Year 6

EXECUTIVE SUMMARY

Formed in 2004 and founded upon the Energy & Environmental Research Center's (EERC's) more than 60 years of experience in hydrogen systems, the National Center for Hydrogen Technology® (NCHT®) project, under a Cooperative Agreement with the U.S. Department of Energy (DOE) National Energy Technology laboratory (NETL) develops and pursues commercialization of technologies that produce and utilize hydrogen for fuels and chemicals, as a coproduct with power, and for other uses. Since the NCHT's inception, the EERC has received more than \$65 million in funding of hydrogen-related projects (\$24 million for projects in the NCHT, which includes federal and corporate partner development funds) involving more than 85 partners (27 with the NCHT).

The NCHT's nine Year 6 activities span a broad range of technologies that align well with the Advanced Fuels Program goals and, specifically, address technical barriers described in the DOE Hydrogen from Coal Program research, development, and demonstration (RD&D) plan. Technical activities include development of hydrogen production and enrichment technologies by gasification and gas cleanup with domestic coals, especially cheap, abundant coals, and development of tools to increase efficiency and reliability of gasification systems through improved fuel selection and preparation, among others. Of particular note are NCHT efforts to provide a flexible gasifier facility capable of larger-scale, more realistic testing of advanced technologies (e.g., low-cost hydrogen separation membranes). In pursuing NETL's goal of proving the feasibility of a 40% efficient, near-zero-emission power facility that reduces the cost of electricity by 35% when compared to the base-case carbon capture technology, NCHT activities address such barriers as a "lack of demonstration" of technologies at a scale suitable to determine potential efficiencies and cost savings, complex process designs that could benefit from combining multiple steps into single vessels, and control of impurities that are detrimental to downstream processing and power generation equipment. This technical breadth and close working relationship with DOE and numerous partners endow the EERC with the capacity to quickly respond to evolving DOE needs, especially in areas such as warm-gas cleanup and hydrogen enrichment.

To a great extent, the NCHT project pursues technologies that permit it to leverage and extend the EERC's experience and unique facilities focused upon fossil fuel and hydrogen technology development. While the project exploits the expertise of its many partners, its core capabilities are provided by the EERC's more than 320 scientists, engineers, and support staff applying a 60-year history of research in hydrogen, including gasification. The EERC has one of the largest, single-site collections of pilot-scale gasifiers in the world – a site comprising over 245,000 square feet of laboratories, demonstration facilities, fabrication shops, and offices. The EERC has a long history of developing, testing, and integrating modular technologies for the production and utilization of hydrogen. Specifically, the EERC has unique, world-class

experience in hydrogen production from fossil fuels, renewable fuels, and the development of on-demand hydrogen fueling systems produced from a variety of liquid fuels, as well as gas separation and purification through conventional and advanced methods and utilization of hydrogen via direct combustion and in fuel cells. The work under the NCHT Year 6 projects is outlined in this summary report. Individual activity reports are referenced as a source of detailed information on each activity.

DEVELOPMENT OF A NATIONAL CENTER FOR HYDROGEN TECHNOLOGY

Summary Report of Activities Completed at the National Center for Hydrogen Technology® – Year 6

INTRODUCTION

Hydrogen is generally envisioned as a primary energy carrier of the future and a critical component in synthesis gas used to produce fuels and chemicals and, as such, can play a key role in the future energy security of the United States. Using hydrogen as a fuel in a fuel cell, turbine, or internal combustion engine (ICE) produces no harmful emissions, only water. However, the reality is that, with the exception of a few isolated prototypes, much of the infrastructure for hydrogen does not exist and has not been demonstrated. Significant advances are being made in laboratories throughout the world to develop technologies dealing with the various aspects of hydrogen production, including its generation, separation, purification, transportation, dispensing, and utilization. Advancing toward a hydrogen economy is not only about developing the individual components and methods, but also integrating and testing various technologies together for a complete hydrogen system.

The Energy & Environmental Research Center (EERC), working under agreement with the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL), has founded the National Center for Hydrogen Technology® (NCHT®) to develop a broad range of technologies required to advance the opportunity for a hydrogen economy within the United States. The EERC is helping accomplish this opportunity by building on its long 60-year history in coal and fossil fuel utilization in order to generate hydrogen from fossil fuels.

Multiple activities were performed under this agreement, such as optimized hydrogen production from coal, coal and biomass blends, and other solid feedstocks; separation of hydrogen from syngas; improved methods of generating hydrogen from natural gas; technology development to enable distributed hydrogen generation at gas stations from liquid fuels; and purification of syngas and combustion exhaust, among other tasks. These activities are well aligned with the goals and needs of NETL's Advanced Fuels Program, as depicted in the final report of the 2011 Advanced Fuels Program Peer Review and in the Hydrogen from Coal Research, Development, and Demonstration Plan, by addressing various challenges and technical barriers which include:

- **Scale-up concerns:** Many novel separation technologies have not been demonstrated at scales sufficient to confirm potential efficiency and cost benefits. To address these concerns, a few NCHT activities have partnered with hydrogen separation membrane and sorbent developers in modifying and applying its collection of gasifiers to provide a range of test conditions that approximate commercial-sized units, but at a scale and cost appropriate for the level of risk at this stage in development.
- **Complex process designs:** Process intensification – the integration of multiple process functions into a single step – possesses potential advantages of improved scalability, and efficiency and reduced costs. One NCHT activity has partnered in developing and demonstration a technology that performs reforming, shift, and hydrogen separation in

one vessel, while another activity and partner are developing a technology that simultaneously shifts and separates hydrogen from a coal-based syngas.

- Detrimental impurities: Efficient, inexpensive control of impurities to levels that can be tolerated by downstream cleanup, separation, and processing equipment is necessary to achieve Advanced Fuel Program goals. An NCHT activity has studied and modeled ash behavior to predict and control its behavior and impacts on downstream equipment, while another has partnered with a gas turbine manufacturer to provide a platform to test a coating that protects exposed surfaces to potential hydrogen impurities that damaged an existing commercial integrated gasification combined cycle (IGCC)-fed gas turbine.

Pursuit of these activities directly supports achieving NETL's target of a 40% efficient, near-zero emission power facility that has a cost of electricity that is 35% below a base-case IGCC with carbon capture and sequestration.

Concurrently, activities were completed in the areas of education and outreach to increase public acceptance and support needed to ensure the widespread use of hydrogen. These activities have been completed at the EERC with important commercial support from industrial partners and DOE.

Table 1 is a partial listing of some of the key partners and collaborators with the EERC that have supported or been involved in NCHT projects from 2005 to 2012. In conjunction with industrial partnerships, advancement of hydrogen into the energy mix is also reliant on public support. A component of the activities under the NCHT Program is to increase public support and acceptance. In order to accomplish this task, the EERC has held public events, designed and built a demonstration hydrogen-powered ice resurfer, developed an on-line course on hydrogen, and created a documentary about hydrogen with Prairie Public Broadcasting, Inc.

Table 1. Partial List of Partners of NCHT Activities

• Advanced Biomass Gasification Technologies, Inc.	• Kraus Global Inc.	• SGL Group – The Carbon Company
• Air Products and Chemicals, Inc.	• North American Coal Corporation	• Siemens Power Generation, Inc.
• Basin Electric Power Cooperative	• North Dakota Association of Rural Electric Cooperatives	• TXU Power
• Bobcat Company	• North Dakota Industrial Commission	• U.S. Army Corps of Engineers Construction Engineering Research Laboratory
• ConocoPhillips Company	• Porvair Filtration Group Ltd.	• U.S. Department of Energy
• Diversified Energy Corporation	• Prairie Public Broadcasting, Inc.	• University of Wyoming
• Electric Power Research Institute	• Pratt & Whitney Rocketdyne, Inc.	• Verendrye Electric Cooperative, Inc.
• ePower Synergies, Inc.	• Red River Valley Research Corridor	• Western Research Institute
• G F Truss, Inc.	• Resurface Corporation	• Xcel Energy, Inc.
• Great Point Energy	• Rio Tinto	• Xethanol Corporation
• Great River Energy		
• IdaTech LLC		
• Intellection Holding Pty Ltd.		

This report summarizes the main results of each of the nine completed activities from Year 6 of the NCHT, listed in Table 2. The overarching findings of each of these pieces of research and outreach point to the fact that hydrogen and fuel cells will be a growing piece of the energy mix including for use in vehicles, power generation, production of fuels and chemicals, and energy storage. Moreover, the research indicates that, in many instances, hydrogen can be generated and utilized economically and in the near future. More detailed information can be found in the specific topical reports for each activity, referenced throughout the document.

Table 2. Listing of Year 6 NCHT Projects

Activity Number	Title	Principal Investigator
1.4 (1)	Hydrogen Production and Purification from Coal and Other Heavy Feedstocks	Grant Dunham
1.10 (2)	Coal Ash Behavior in Reducing Environments (CABRE) III	Josh Stanislawski
1.12 (3)	Long-Term Demonstration of Hydrogen Production from Coal at Elevated Temperatures	Josh Stanislawski
1.13 (4)	Materials Testing of Coated Alloys in a Syngas Combustion Environment	Mike Swanson
1.14 (5)	Fluid-Bed Testing of GreatPoint Energy's Direct Oxygen Injection Catalytic Gasification Process for Synthetic Natural Gas (SNG) and Hydrogen Coproduction	Mike Swanson
1.15 (6)	Transport Reactor Development Unit Modification to Provide a Syngas Slipstream at Elevated Conditions to Enable Separation of 100 lb/d of Hydrogen by Hydrogen Separation Membranes	Steve Schlasner
3.2 (7)	Extended Operations of the Pratt & Whitney Rocketdyne Pilot-Scale Compact Reformer	Jay Almlie
3.5 (8)	Distributed H ₂ Supply for Fuel Cell Utility Vehicles	Jay Almlie
6.2.5	Outreach and Education for Hydrogen Production and Utilization	Tera Buckley

* Numbers in parentheses are reference numbers.

ACTIVITY 1.4 – HYDROGEN PRODUCTION AND PURIFICATION FROM COAL AND OTHER HEAVY FEEDSTOCKS

Activity 1.4 was a collaborative effort with Air Products and Chemicals, Inc. (APCI) to develop a pressure-swing adsorption (PSA) technology for purifying hydrogen contained in a “sour” (acid gas-containing) syngas produced from gasification of coal and other heavy feedstocks including petroleum coke, or “petcoke.” In a typical PSA-based hydrogen purification operation, separation of undesired syngas species from hydrogen is achieved by passing the syngas through a solid sorbent (maintained at moderate pressure) that selectively adsorbs the undesired species and allows the hydrogen to pass through. Regeneration of contaminant-saturated sorbent is affected by desorption of contaminants via purging with nitrogen or other gas under reduced pressure, after which the sorbent is ready for another cycle of syngas exposure and contaminant adsorption. For this effort, APCI was specifically interested in evaluating the performance of PSA sorbents developed for separation of the acid gas components hydrogen sulfide and carbon dioxide from a syngas.

Two separate sets of tests were conducted under this scope of work. In the first set, two APCI-provided sorbent samples (A and B) were exposed to sour syngas generated at the EERC via gasification of petcoke using the EERC entrained-flow gasifier (EFG). The sour syngas used in the tests had been generated previously in a scenario comprising petcoke gasification, syngas passage through a sour water–gas shift (WGS) catalyst bed, syngas cooling/condensation, syngas compression, and syngas dispensing into storage cylinders. In the second set of tests, sorbent samples were continuously exposed to dilute levels of HCl or NH₃. As a means of assessing sorbent performance after exposure to the test gases, CO₂ adsorption capacities for the fresh and spent sorbent samples were determined by thermogravimetric analysis (TGA), and elemental compositions of fresh and spent sorbents were determined by x-ray fluorescence (XRF) analysis. Spent sorbent samples were returned to APCI for additional characterization and analysis.

Sorbent exposure tests were conducted using the system shown in Figure 1. The system accommodates 10 packed beds, each containing up to 20–40 grams of sorbent. During exposure periods, syngas flow is continuously passed through each test bed using mass flow controllers. In the first set of tests, sorbents were exposed to the petcoke gasification-derived syngas for 813 hours at a pressure and temperature of 400 psig and 30°C, respectively. In the second set of tests, sorbents were continuously exposed to dilute levels of HCl and NH₃ under the conditions presented in Table 3.

Comparison of fresh and sour gas-exposed sorbents on the basis of CO₂ adsorption capacity indicated that continuous exposure to the sour petcoke gasification-derived syngas resulted in an average adsorption capacity reduction of 10%–15%. It appears that continuous sour gas exposure is an aggressive test of the stability of the sorbent material. XRF analysis of the sorbents showed that exposure resulted in deposition of iron, sulfur and, for most samples, nickel at the feed end of the sorbent column. This deposition was not directly responsible for the observed decreased CO₂ adsorption capacity. The presence on the sorbent of iron and nickel is most likely due to the decomposition of syngas-contained iron and nickel carbonyl. CO₂

Figure 1. Ten-bed syngas exposure unit at the EERC.

Table 3. Conditions for the Second Set of Exposure Tests

	Reactor 1	Reactor 2	Reactor 3	Reactor 4
Sorbent	B	B	A	A
50 ppm HCl, 500 ppm CO, balance N ₂	Yes	No	Yes	No
50 ppm NH ₃ , 50 ppm CO, balance N ₂	No	Yes	No	Yes
Temperature, °C (°F)	Ambient	60 (140)	60 (140)	Ambient
Pressure, psig	400	400	400	400
Hours of Exposure	623.5	751.5	623.5	751.5

adsorption capacity comparison of fresh and HCl- and NH₃-exposed sorbents indicated that exposure to these contaminants led to significant CO₂ capacity loss of up to 25%. These two sets of tests have provided further information on how syngas and some of its components affect the performance of PSA materials. For a full discussion of the results see the full report (1).

ACTIVITY 1.10 – COAL ASH BEHAVIOR IN REDUCING ENVIRONMENTS (CABRE) III

Because of widespread public concern related to air quality and global climate change, using the world's coal reserves will likely come under increased scrutiny over the next decade. While it is true that coal emits more greenhouse gases per unit energy produced than fuels like oil or natural gas, new technologies are being developed that will reduce coal-fired power plant emissions to near zero. Hydrogen production via coal gasification offers an opportunity to cleanly and efficiently produce fuels and energy from coal by enabling integration of carbon capture and sequestration technologies at lower costs than achievable with traditional combustion facilities. Hydrogen production in the United States is not a new concept, since there are economic business sectors that consume hydrogen at a significant level. Presently, natural gas is the most common hydrogen feedstock. Coal is not today a major source for purified hydrogen, but is an excellent energy medium which, when coupled with steam gasification and water–gas shift processing, becomes a very sustainable and cost-competitive mode of hydrogen production.

Coal gasification research at the EERC has been ongoing for over six decades. Although gasification of carbonaceous fuels is not a new concept, there is still limited experience with the technology, primarily because of the preference toward simpler and cheaper combustion facilities. As concern over global climate change mounts, more companies and utilities will be looking for cost-effective ways to deal with CO₂, and coal gasification will undoubtedly get more attention. To address this concern, successful design, implementation, and operation of new gasification facilities will require an increased understanding of the fate and behavior of fuelborne impurities or ash-forming components in reducing environments. More importantly, the economic implications related to system performance and reliability include slag flow control, slag attack on refractory, ash deposition on heat-transfer surfaces, corrosion and erosion of system materials, and gas cleanup. Minimizing the potential for these ash-related problems is fundamental to achieving maximum efficiency and safety in the design and operation of gasifiers to produce hydrogen, liquid fuels, chemicals, power, and CO₂.

The EERC Coal Ash Behavior in Reducing Environments (CABRE) III project was undertaken to address the need for greater understanding of ash-related challenges in reducing environments, thereby enabling development of strategies for economically and safely resolving these challenges. The EERC-led project was executed through a multiyear consortium involving multiple sponsors including ConocoPhillips, the North Dakota Industrial Commission (NDIC), and DOE NETL. The aim of the CABRE III Year 6 effort (the subject of this report) was to develop a model and associated fundamental information on ash behavior that can be used by researchers, designers, and operators of state-of-the-art gasification systems capable of handling a variety of fuels—particularly EFGs and fluidized-bed gasifiers (FBGs)—to:

- Operate a gasifier at maximum efficiency, thereby enhancing the quantity and quality of syngas products.
- Make efficiency improvements to full-scale operating commercial gasifier systems and/or gasifier designs.

- Select the optimum fuel for a specific gasifier design.
- Minimize gasifier downtime and extend gasifier lifespan.
- Facilitate troubleshooting.

The model was developed with data from several fuels selected by the sponsors, including bituminous coal, lignite, and petcoke. The data from these fuels were obtained using a small pilot-scale EFG and FBG at the EERC. Major features of the CABRE III model include its ability to:

- Predict inorganic transformations and phase partitioning for assessing impacts on specific gas cleanup equipment.
- Predict properties including standard temperature–viscosity curves and slag flow and thickness.
- Estimate deposition rates in the gasification cleanup equipment.
- Provide projected compositional analyses for all input and output streams across all process equipment, including major elements and trace elements of interest.
- Provide projected specific compositional analyses of deposit streams for various deposit zones: direct condensation on equipment surfaces (Zone A), homogeneous particulate deposition (Zone B), and entrained fly ash deposition (Zone C).
- Project extent of physical removal of ash in cyclones based on D_{50} cut points in EFGs and FBGs.
- Predict buildup of trace metals in gasifiers using ash and char recycle schemes.

Figure 2 shows the CABRE III model EFG definition input screen, which allows the user to define the parameters and operating conditions of the gasifier. There are separate tabs to input information about the gasifier, refractory, and gas cleanup equipment. The FBG input screen is very similar to the EFG input screen, except that the refractory tab in the EFG input screen is replaced with a bed material input tab, and the actual parameters input are also different to reflect FBG conditions. The view results screen (Figure 3) presents a results flow sheet. On this screen, the user can access results for any process equipment piece individually by clicking on the link for that equipment or click on the export results button to export the results to an Excel spreadsheet, Word document, or PDF. The arrangement is the same for an FBG except that the gasifier column has a slightly different design. The model generates summary and detailed tables and charts of stream compositions based on major elements (wt%) and selected trace elements (ppm). As examples, Figure 4 shows a graphical distribution of major and minor elements in modeled gasifier fly ash and slag samples, and Table 4 presents the same data in tabular form.

Gasifier Configuration Wizard

Enter Gasifier Definition Information

Diagram of a gasifier showing temperature zones and flow directions:

- Product Gas (outlet at top)
- Gasifier Outlet Temperature
- Top Zone Temperature
- Mid-Top Zone Temperature
- Midzone Temperature
- Mid-Bottom Zone Temperature
- Bottom-Zone Temperature
- Slag (outlet at bottom)
- Fuel Flow, Slurry Water Flow, Steam Flow, Oxidant Flow (input at bottom)

Parameters:

Parameter	Value	Unit
Fuel Rate	225	tonne/hr
Slurry Water	60	% solids
Gas Exit Temp	1500	°C
Pressure	60	abs atm
Top Zone	1650	°C
Mid Top Zone	1643	°C
Mid Zone	1645	°C
Mid Bot Zone	1640	°C
Bottom Zone	1590	°C
Oxidizer	Oxygen	
Oxidizer Rate	182	tonne/hr
Steam Flow	45.5	tonne/hr
Gasifier Height	18.3	m
Slag Fines Recycle	70	%
Amount Flyash	34.5	%
Syngas Cooling		
Temp In	1468	°C
Temp Out	538	°C

Step 1 of 5

Next >> Finish Cancel

Figure 2. EFG definition input screen.

The CABRE III model program runs on any MS Windows PC via an interactive user interface that provides a step-by-step guide to program input parameters. Among the many features of the interface, the user can start a new session based on a specific gasifier type (entrained flow or fluidized bed) and then can input and store data for that session. Although the current version of the program includes about four fuels in the database (the fuels selected by the sponsors of the project), users can input a fuel of their choice via an Excel spreadsheet or directly through the user interface. Blending options with additional fuels or fluxing agents have also been implemented in easily accessible click-of-the-mouse steps. The existing fuel database contains analytical information on the sponsor fuels and a few other selected coals, which allows easy input of fuel parameters for a desired simulation. A new feature of the CABRE III model is its user-friendly interface and ability to generate detailed reports that are easily exportable into Word documents, Excel spreadsheets, or PDF files. The user interface provides stepwise guides with built-in checks for efficient supply of required input data on fuels of interest to allow a successful execution of the model (2).

Figure 3. View results screen.

Figure 4. Distribution of major and trace elements in fly ash and slag.

Table 4. Distribution of Major and Trace Elements in Fly Ash and Slag

Distribution of Major Elements in Slag and Fly Ash			Distribution of Trace Elements in Slag and Fly Ash		
Oxide, wt%	Slag	Fly Ash	Element, ppm	Slag	Fly Ash
SiO ₂	48.05	48.29	Be	0.47	0.12
Al ₂ O ₃	16.95	15.27	B	0.00	0.00
Fe ₂ O ₃	9.04	7.65	F	0.00	0.00
TiO ₂	0.69	0.56	V	0.00	0.00
P ₂ O ₅	0.12	0.49	Mn	47.97	4.37
CaO	15.72	14.27	Co	3.04	0.22
MgO	5.73	6.47	Ni	8.07	0.95
Na ₂ O	1.29	2.45	Cu	0.00	0.00
K ₂ O	1.78	3.21	Zn	5.29	3.53
SO ₃	0.11	0.40	Ge	2.01	0.29
BaO	0.26	0.48	As	8.08	4.49
SrO	0.24	0.44	Se	0.50	0.22
MnO ₂	0.00	0.00	Cd	0.05	0.06
V ₂ O ₅	0.00	0.00	Sb	0.11	0.20
NiO	0.00	0.00	Hg	0.06	6.63e-3
			Pb	1.03	3.65

ACTIVITY 1.12 – LONG-TERM DEMONSTRATION OF HYDROGEN PRODUCTION FROM COAL AT ELEVATED TEMPERATURES

Sustainable hydrogen supply for current niche and future hydrogen applications can be accomplished using coal as an energy fuel coupled with efficient gasification technology. Advances in gasification performance, specifically the efficient production of clean synthesis gas, or “syngas,” that is optimized for hydrogen quantity and quality are being realized. Novel hydrogen separation membrane technologies are being developed to effectively remove impurities from coal-derived syngas and isolate a clean, high-quality flux of hydrogen gas. Research needs at this time include efficient, clean syngas production with optimized hydrogen production and the development of hydrogen separation membranes that can withstand long-term exposure to coal-derived syngas.

The EERC conducted a joint project with Western Research Institute (WRI) to assess the gasification performance of upgraded subbituminous and lignite coals and to evaluate the performance of hydrogen separation membranes on coal-derived syngas. WRI used a two-stage coal treatment process to upgrade a Wyoming Powder River Basin (PRB) coal and a North Dakota lignite. A first-stage process heated the coal to 250°–280°F to remove moisture, and the second-stage process heated the coal to temperatures between 250° and 550°F to volatilize mercury and, potentially, other trace metals. As a result, six different fuels were supplied to the EERC for gasification and hydrogen separation membrane testing: raw (or run-of-mine), dried, and upgraded.

The six coals were part of a matrix of gasification tests conducted on the EERC transport reactor development unit (TRDU), a type of FBG designed by KBR Inc. The TRDU can fire 200–500 lb/hour of fuel and effectively test real-world gasification performance and warm-gas cleanup techniques. The TRDU system was retrofitted with slipstream devices to expose two membranes to coal-derived syngas and note the impact of coal-derived impurities. This report details the performance of WRI’s upgraded coal in the EERC’s TRDU and presents the results of the warm-gas cleanup and hydrogen separation tests. The full activity report to DOE includes a thorough review of the fundamentals of coal gasification (3).

The treated fuels were shown to have a significant reduction in mercury and moisture. The raw and upgraded fuels were tested in the EERC’s TRDU, and each fuel was demonstrated to gasify well, with minimal operational issues. System upsets were only the result of mechanical failure and not the result of fuel or operational factors. Fuel feeding for the test runs progressed with minimal issues, and no differences were noted in the ability to process and feed the various raw, dried, and upgraded coals into the gasifier.

Gasification tests showed significant changes in CO and CO₂ concentrations as the gasifier was switched from raw to upgraded fuels. The dried PRB and lignite coals showed significantly increased CO levels, and CO₂ levels significantly decreased when the dried fuel was brought online. This change is expected as less energy is needed to evaporate water with the dried fuels, resulting in a syngas with increased heating value. This transition was also observed when

switching from the upgraded PRB to the raw lignite. Figure 5 shows the typical higher CO concentration and the lower CO₂ concentration as measured by a continuous emission monitor (CEM) analyzer during gasification of the upgraded PRB.

Smaller but significant changes in CO₂ concentration were observed when switching gasifier temperatures. As expected, the higher temperatures resulted in higher CO₂ concentration, increased carbon conversion, and reduced syngas heating value.

Mercury concentrations in the syngas for the treated PRB gasification tests were reduced by an average of 25% over mercury levels in the raw and dried test runs. With respect to particle-size distributions of ash samples collected during the test runs no major differences were observed. The elemental composition of the ash showed high levels of sulfur capture occurring in the filter ash under the air-blown test conditions. Otherwise, no significant difference was observed in the ash chemistry between the raw and treated fuel and no ash agglomeration issues were observed for any of the tests.

Water samples produced from the gasifier were analyzed for organic content. Lower levels of organics were observed on the dried and treated fuels as compared to the raw fuel runs. Significantly higher concentration organic material was produced during the steam–oxygen gasification tests.

Figure 5. Concentrations of syngas components during gasification of dried upgraded PRB coal showing high CO (top green line) and lower CO₂ (lower red line).

The warm-gas cleanup equipment, sorbents, and catalysts used were shown to be capable of removing sulfur down to less than 2 ppm, and the shift catalyst was able to reduce CO levels to below 1%. Water and tars were condensed out of the syngas prior to compression for the membrane exposure.

Finally, both of the hydrogen separation membranes successfully produced greater than 2 lb/day of hydrogen. Membrane 1 appeared to experience some performance degradation which may have been caused by coking. The coking could be attributed to a system upset and lack of steam available for the water–gas shift reaction. The membrane was exposed to oxygen at high temperature at the supplier’s laboratory to burn out the contaminant, and the membrane performance returned to expected levels. Membrane 2 developed a significant leak during the testing. Both membranes were shown to be capable of producing hydrogen from coal-derived syngas for the entire test period. Table 5 describes the membrane operation during selected test periods.

Table 5. Membrane Operating Conditions During Selected Test Periods

Operating Period	Membrane 1	Membrane 2
Start	January 18 – 16:00	January 18 –16:00
End	January 18 – 23:47	January 18 – 23:47
Membrane Inlet, °F	926	754
Membrane Temperature, °F	931	745
Permeate Exit, °F	51	53
Syngas Inlet, °F	919	919
Syngas Inlet Pressure, psi	407	214
Permeate Pressure, in. H ₂ O	65	72
Flux, scfh/ft ²	13.8	20.8
H ₂ Inlet, mol%	34.8	34.8
Wet H ₂ Inlet, mol%	34.8	34.8
Raffinate H ₂ , mol%	29.7	28.5
Inlet H ₂ , scfh	82.6	80.6
Raffinate H ₂ , scfh	64.0	60.1
Permeate H ₂ , scfh	20.2	18.3
Permeate H ₂ , lb/day	2.5	2.3
H ₂ Balance, %	105.2	98.0
Hydrogen Recovery, %	24.3	22.7
Theoretical Max Recovery, %	92.6	85.4
Partial Press. Differential, psi	140.8	73.4

ACTIVITY 1.13 – MATERIALS TESTING OF COATED ALLOYS IN A SYNGAS COMBUSTION ENVIRONMENT

Siemens Power Generation, Inc., has developed gas turbine technology for combustion of syngas/hydrogen fuels derived from IGCC systems utilizing coal. Turbine materials can undergo degradation because of new syngas hydrogen fuels. This project was intended to test coated coupons simulating turbine materials in a coal-derived syngas stream to see if carbonyls are deposited on the coupons.

The objective of this EERC project was to expand on the 2004–2008 Siemens testing program by evaluating the effectiveness of the new coating in resisting deposition of syngas-contained carbonyl compounds under realistic IGCC operating conditions and to identify where the coating could be applied in gas turbines and other process equipment surfaces that are exposed to carbonyl-laden reducing gases. While the Siemens tests involved most aspects of normal operation, the EERC tests added the component of high velocity to the syngas stream. The test program comprised syngas generation using the EERC high-pressure FBG running on PRB subbituminous coal from the Antelope Mine in Wyoming, and routing the syngas through the EERC thermal oxidizer system in which the coupons were installed. Prior to initiation of testing, the inlet of the EERC thermal oxidizer system was modified to incorporate a coupon holder for holding both coated and uncoated coupons in an environment representing conditions that would exist in the flow equalizers of the Puertollano plant. Testing was conducted according to a preapproved test plan developed with Siemens. Figures 6 and 7 illustrate key features of the FBG and thermal oxidizer (with coupon holder), respectively.

Two 5-day tests with over 200 hours of total exposure time were completed. The first week of testing was conducted in enriched air-blown mode, with coupon temperatures ranging from 128° to 272°F. Carbonyl sampling was conducted, but it was discovered, after the fact, that the methodology used was producing very low recoveries of iron and nickel carbonyl. Therefore, the data generated during this week of testing were not considered accurate. The second week of testing was conducted in oxygen-blown mode, with coupon temperatures ranging from 220° to 265°F. Two improved methods were used to measure carbonyl concentration during this week of testing. These methods produced results closer to equilibrium calculations. Since both weeks of testing mostly produced a product gas with approximately 15%–18% carbon monoxide, it was felt that actual carbonyl concentrations for Week 1 should be very similar to those measured during Week 2.

The revised carbonyl sampling methodology used during the second week of testing greatly improved the recovery of iron and nickel carbonyl in the sample. Even though the sampling results obtained from the first week were inaccurate, the results from the second week can be used as an estimate for the periods during which the gasifier was operating under similar conditions and producing similar product gas compositions. Specifically, Test Periods 2 and 3 from the first week were similar to the conditions run during the second week. For a product gas containing roughly 15%–18% CO and a coupon temperature of approximately 220°–270°F, the nickel carbonyl concentration should be about 0.05–0.1 ppm and the iron carbonyl concentration about 0.1–0.4 ppm. After each week of testing, the coupons were recovered from the coupon

Figure 6. EERC pressurized FBG system.

holder, examined, weighed, and shipped to Siemens for further analysis. It appears that coupons placed at the top of the coupon holder experienced significantly more weight gain than coupons placed further below, independent of whether the coupon was coated or not. Figure 8 shows coupons removed from the coupon holder after completion of Week 2 testing. The coating remained on the plates and was not worn off during either test, showing that the coating can withstand the velocities of a gas stream, which was not able to be tested in previous laboratory tests.

Figure 7. EERC thermal oxidizer with coupon holder.

Figure 8. Coated (light) and uncoated (dark) coupons after completion of Week 2 testing.

In the first run, hardly any deposition was observed. In the second run, noticeable deposition was found on the surface of the orifice plates as well on the inner sides of the holes. The coating was still in place beneath the deposition. It can be concluded that the deposition adheres well to the coating but that it cannot be removed from the orifice plate by chipping.

The difference between the two runs can probably be explained by different concentrations of iron and nickel carbonyls. In the second run, more carbonyls had formed because the addition of water vapor increased the formation rate. However, this addition might have also started the formation of other compounds such as iron hydroxides, iron oxides, and iron sulfides.

ACTIVITY 1.14 – FLUID-BED TESTING OF GREATPOINT ENERGY’S DIRECT OXYGEN INJECTION CATALYTIC GASIFICATION PROCESS FOR SYNTHETIC NATURAL GAS (SNG) AND HYDROGEN COPRODUCTION

The overall objective of Activity 1.14 was to utilize EERC pilot-scale gasification facilities to demonstrate key operating principles of the GreatPoint Energy (GPE) catalytic gasification concept for producing SNG and hydrogen from coal and other carbon resources. The GPE technology “refines” coal by employing a novel catalyst and milder operating conditions and less expensive reactor components than required for traditional gasification processes to “crack” carbon bonds and transform coal into pipeline-grade methane (natural gas) and relatively high-purity hydrogen. The GPE technology operates efficiently on low-cost carbon sources such as lignites, subbituminous coals, tar sands, petcoke, and petroleum residual oil. In addition, the GPE oxygen-blown catalytic coal gasification process eliminates troublesome ash removal and slagging problems, reduces maintenance requirements, and increases thermal efficiency, thereby significantly reducing the size of the required air separation plant—a system that alone accounts for 20% of the capital cost of most gasification systems.

The GPE concept is based on feeding coal and catalyst into a fluid-bed reactor with pressurized steam and a small amount of oxygen to “fluidize” the mixture and ensure constant contact between the GPE catalyst and carbon particles. In this environment, the catalyst facilitates multiple chemical reactions between carbon and steam on coal particle surfaces. These reactions generate a mixture of predominantly methane, hydrogen, and carbon dioxide. Product gases from the process are sent to a gas-cleaning system where CO₂ and other contaminants are removed. In a full-scale system, catalyst would be recovered from the bottom of the gasifier and recycled back into the fluid-bed reactor. In commercial application, by-products (such as sulfur, nitrogen, and CO₂) would be captured and sold into chemical and/or petroleum industry markets, resulting in near-zero hazardous air or water pollution. Methane and hydrogen products would be transported by pipeline to customers or stored. With warm-gas cleanup and hydrogen purification, the GPE technology could also generate a relatively pure CO₂ stream suitable for enhanced oil recovery (EOR) or sequestration.

Gasification tests were conducted at the EERC during May, July, and November 2010 and during August and September 2011 using feedstock mixtures of GPE catalyst and PRB coal or petcoke. Specific run conditions such as fuel feed rates, gasifier reactor temperature, reactor pressure, fluidization rates, and syngas quality production are not reported at the request of GPE. The EERC 600–1000-psi-rated 10–20-lb/hr FBG was modified for this project and used for all testing. This system can attain nominal gasification reaction temperatures between 1500° to 2000°F and recycle syngas while achieving full exit gas stream warm-gas cleanup. Table 6 shows syngas compositions generated during the September 2011 test, which utilized coal feedstock, syngas recycle, a sour shift catalyst bed, and a regenerable sulfur sorbent downstream of the gasifier to increase hydrogen yield for hydrogen separation membrane testing. Overall program results demonstrated methane and hydrogen yields consistently approaching 15 mol% and 50 mol%, respectively, in long-term (5–10-day continuous operation) tests conducted with both PRB coal and petcoke feedstocks. No significant bed agglomeration was observed, and carbon conversion was consistently greater than 80% while operating at temperatures of less than 1400°F, even with the shorter-than-desired reactor height (initial designs for the GPE

Table 6. September 2011 Average Gas Compositions, mol%

	Test 1	Test 2	Test 3
Gas Composition			
CO	0.3	0.2	0.3
CO ₂	25.5	26.3	25.0
H ₂	30.8	31.8	28.6
CH ₄	7.8	9.0	6.4
N ₂	35.9	32.7	40.4
H ₂ S	0.01	0.00	0.00
Gas Composition, N ₂ -free			
CO	0.5	0.3	0.5
CO ₂	39.8	39.1	41.9
H ₂	48.0	47.3	48.0
CH ₄	12.2	13.4	10.7
H ₂ S	0.02	0.00	0.00

gasification concept called for a height that could not be accommodated by the EERC pilot facility).

Activity 1.14 also included a test program to evaluate the performance of a hydrogen separation membrane. The objectives of the program—conducted in partnership with DOE NETL—were to validate hydrogen permeate, flux, and recovery achievable when using a single-membrane assembly with coal-derived syngas and accumulate operational hours with the membrane to enable evaluation of long-term performance. Motivation for the program derives from the possibility of using membranes to efficiently and economically effect the separation of fuel gas hydrogen and CO₂, thereby enabling cost-effective production of coal-based power, hydrogen, and/or chemicals, along with simultaneous CO₂ recovery for sequestration and/or EOR.

For the 100-hour membrane test, syngas was generated by the FBG using GPE-catalyzed PRB coal. Particulate was removed with a hot-gas filter vessel able to achieve near-absolute capture. WGS was achieved through use of Katalco K8-11 sour gas shift catalyst to maximize hydrogen and minimize CO concentrations in the syngas. Figure 9 shows the flow of process from gasifier syngas through a filter, the WGS beds, and the hydrogen separation membranes, with the warm-gas-conditioning train utilized, in which syngas flows from the filter (right) to the membrane system (left). For this test, Fixed Bed 1 and Fixed Bed 2 were used for WGS, with Bed 1 operating at about 300°C (575°F) and Bed 2 at about 275°C (525°F). RVS-1 solid sorbent from Sud-Chemie was used in Fixed Beds 3 and 4 to remove sulfur. The metallic Pd–Cu-based membrane tested was capable of achieving high flux rates and resistance to sulfur poisoning and was sized to take approximately 200 scfh of syngas from the gasifier, with the intent to demonstrate separation of hydrogen at the rate of 2 lb/day or more. The membrane operates at a temperature of 932°F and a pressure of up to 500 psi and was not designed to use a permeate sweep gas. Figure 10 shows sampling locations used during the membrane test. Key test results were an average hydrogen flux of 13.6 ft³ft⁻²h⁻¹, recovery of 54.5% of total hydrogen, and permeate of 2.54 lb day⁻¹. The membrane did not appear to suffer any performance degradation after exposure to the cleaned, warm syngas over a nominal 100-hour test.

Figure 9. Warm-gas-conditioning train.

Figure 10. Sampling locations.

ACTIVITY 1.15 – TRANSPORT REACTOR DEVELOPMENT UNIT MODIFICATION TO PROVIDE A SYNGAS SLIPSTREAM AT ELEVATED CONDITIONS TO ENABLE SEPARATION OF 100 lb/d OF HYDROGEN BY HYDROGEN SEPARATION MEMBRANES

Hydrogen is a key feedstock and chemical component for many industrial processes including ammonia production, oil refining, chemicals and pharmaceuticals production, food processing, semiconductor manufacturing, and power generation systems cooling. About 40–50 million tonnes per year of hydrogen is produced worldwide, and about one-third of this production is attributed to the United States. Hydrogen production is forecast to grow about 3.5% annually for the next 2 years, with the Asia–Pacific countries growing faster than other regions of the world. Longer-term hydrogen demand is uncertain, but, as in the recent past, will likely be influenced heavily by environmental concerns. Climate change issues, for example, are prompting calls to reduce power plant emissions of carbon dioxide and other greenhouse gases.

DOE has acknowledged the potential of hydrogen to reduce costs, improve efficiency, and reduce the complexity of coal-based clean electric power. Syngas production (from coal gasification or natural gas reforming), coupled with hydrogen separation and carbon sequestration technologies, represents one of the most economically viable near-term scenarios for large-volume, low-carbon hydrogen production for electric power generation. A 2010 DOE study,¹ indicates that hydrogen separation membranes offer the greatest efficiency improvement and cost savings of any single, alternative carbon capture technology employed in conjunction with IGCC technology. However, as described in another 2010 DOE publication,² a key barrier to commercial implementation of hydrogen membrane technologies is “lack of demonstration of novel technologies. . . at a scale sufficient to determine their potential for lower cost and efficient integration into advanced hydrogen-from-coal production systems.” Activity 1.15 was planned and executed to address this lack of larger-scale hydrogen membrane technology demonstration data through modification of the EERC TRDU gasifier system to enable its use in evaluating the performance of hydrogen separation membranes at a capacity of 100 lb/d hydrogen throughput.

Because most large gasifiers operate at a pressure of 400+ psig and the TRDU operating pressure is 120 psig, project activity centered on installation of a compressor system (including a surge tank) capable of pressurizing a slipstream of the TRDU syngas output to 500 psig. Prior to installation, project activity was focused on optimally siting the compressor within the TRDU battery limits, developing detailed compressor capacity and performance specifications for bid, and conducting a hazard and operability assessment to identify and resolve potential safety issues associated with compressor operation. Figure 11 shows the unit operations required for the overall membrane test system.

¹ U.S. Department of Energy Office of Fossil Energy National Energy Technology Laboratory. *Current and Future Technologies for Gasification-Based Power Generation Volume 2: A Pathway Study Focused on Carbon Capture Advanced Power Systems R&D Using Bituminous Coal, Revision 1*; DOE/NETL-2009/1389, Nov 2010.

² U.S. Department of Energy Office of Fossil Energy National Energy Technology Laboratory. *Hydrogen from Coal Program: Securing Our Future, Research, Development and Demonstration (RD&D) Plan for the Period 2010 through 2016*; External Draft, Sept 2010.

Figure 11. Block diagram of hydrogen separation membrane evaluation system.

As a result of Activity 1.15, the EERC TRDU system is now capable of supplying a 500-psig coal-based synthesis gas stream (that approximates a commercial-scale gasifier syngas stream) for use in evaluation of hydrogen separation membrane performance. TRDU-generated syngas streams can be produced to represent commercial-scale gasifier outputs obtained under a wide range of operating conditions and contain up to 100 lb/d of hydrogen. While the modified system does not attain the harshest conditions projected by DOE for future commercial gasifiers (such as 800+ psi syngas product pressure), its 500-psig 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 addition of a single compression 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 WGS to deliver a synthesis gas product stream of more than 45 scfm containing more than 100 lb/d of hydrogen at pressures of up to 500 psig.

ACTIVITY 3.2 – EXTENDED OPERATIONS OF THE PRATT & WHITNEY ROCKETDYNE PILOT-SCALE COMPACT REFORMER

Hydrogen continues to be a viable feedstock and chemical component for many industrial processes. Growth in demand for hydrogen increased energy costs and new environmental regulations will likely drive hydrogen producers to install new production technologies and modify existing facilities to increase production capacity, achieve improved efficiencies, and reduce emission levels to assure their competitiveness and compliance. Of the hydrogen production technologies that have been commercialized, conventional steam methane reforming (SMR) is the most prevalent, producing 80%–95% of the hydrogen generated in the United States today and about 45% worldwide. Conventional SMR is carbon dioxide-intensive. In many refineries, carbon dioxide emissions from hydrogen production units are second only to the large fluidized catalytic cracking (FCC) units. Thus there is an acute need for an inexpensive hydrogen production technology that is less carbon dioxide-intensive. Membrane- and sorbent-enhanced SMR are two concepts that have been investigated as means of enabling carbon dioxide capture.

Pratt & Whitney Rocketdyne (PWR) has a long history in the development of hydrogen-based technologies, primarily with respect to hydrogen use as a rocket engine fuel. A recent effort at PWR has resulted in the development of a potentially “disruptive” hydrogen production technology. The term “disruptive” is used because PWR believes this technology could disrupt the economics of today’s hydrogen production market. PWR approached the NCHT to assist in the development, testing, demonstration, and commercialization of this technology because of the EERC’s history of working with hydrogen technologies and bringing new technologies to the commercialization stage. PWR’s hydrogen production technology represents an alternative technology to conventional SMR. PWR’s technology applies process intensification concepts to arrive at a proprietary regenerative sorbent process capable of producing industrially useful quantities of hydrogen and possessing significant advantages over conventional SMR technology. These advantages include the following:

- Compact design – The PWR technology provides a 90% size reduction compared to a conventional SMR-fired box.
- Process integration/multifunctional reactor – The PWR hydrogen generator eliminates the complexity and costs of separate shift reactors.
- Modular – PWR generator components can be fabricated remotely from the construction site and then assembled on-site, which offers potential cost reduction and quality improvement.
- Improved efficiency – The PWR technology provides 5%–20% higher hydrogen yields than commercial SMR technology and accomplishes this without the large volume of export steam that is characteristic of conventional SMR technology.
- Less product cleanup – The PWR hydrogen generator potentially produces hydrogen at a higher concentration in the product stream than conventional SMR technology, which substantially reduces purification requirements for the product and, in some

applications, might eliminate the need for purification. The effect would be to reduce PSA size or cycle frequency, thus decreasing PSA capital cost or increasing its reliability, or possibly eliminate the PSA completely (PSA elimination would increase hydrogen recovery by a minimum of 10%).

- Reduced greenhouse gas emissions at less cost – The PWR hydrogen generator has the potential to favorably affect carbon dioxide emissions via its potentially greater efficiency (which means less energy and fewer carbon dioxide emissions per volume of hydrogen product than conventional SMR), and the higher carbon dioxide content of its flue gas versus conventional SMR flue gas, which translates to less energy required for carbon dioxide capture.
- Lower equipment cost – The above advantages translate into an estimated 30%–40% reduced equipment cost for the PWR hydrogen generator compared to conventional SMR technology.

The goal of this work was to advance the state of operability of the pilot-scale unit to the point of being able to generate hydrogen continuously for more than 30 hours. The technical team deemed the goal attainable based upon successes in achieving continuous solids flows and operational procedure advances achieved during the past year of development effort under NCHT funding. Two extended test operations were completed in December 2010. These test runs were completed during the periods of November 29, 2010 – December 3, 2010 and December 4, 2010 – December 8, 2010. These runs served to prove a repeatable degradation of catalyst performance. The test runs resulted in the collection of some of the most meaningful process data to date in this development program. The usefulness of the analysis of the results from the tests funded in Year 6 was to provide multiple data sets that lend insight into the causes of catalyst performance degradation.

Figure 12 shows a summary of the 13-hr hydrogen production period from the first December 2010 test (12/5/10). In this graph, it is evident that both CO₂ and H₂ production fell off near the end of the hydrogen production period. This is indicative of a progressive catalyst failure that causes progressively less hydrogen production with time. This degradation of performance was also noted previously in July 2010. Subsequent testing in the December 4, 2010 – December 8, 2010, time frame yielded very similar results within a slightly shorter period of time (5 hr). It is currently believed that the root causes of catalyst degradation are much more sensitive to temperature than previously understood. In fact, as a result of these tests, the operational procedure for the tests has been refined to narrow the temperature range of the hydrogen reactor and decrease the mean temperature of the hydrogen reactor.

Additional work performed after Year 6 focused on discovering the root causes of the catalyst deactivation. The data generated during the Year 6 tests simply helped the team understand at which conditions the reaction proceeds better. Year 6 NCHT funding allowed the project team to conduct two additional pilot-scale hydrogen production tests to verify and explore a previous observation of decreasing hydrogen yield with time. This behavior was

Figure 12. Hydrogen production, December 4, 2010 – December 5, 2010 (nitrogen-free basis).

repeated twice with similar shapes in the decreasing yield curve. These data will provide the team with information necessary to determine the root causes of the catalyst deactivation and to redefine pilot-scale unit design and operational procedures to preclude this catalyst deactivation.

The team objective of achieving 30 hours of continuous hydrogen production was not achieved because of the repeatable catalyst deactivation. This is the first point in the development program at which pilot-scale unit operations have advanced to the point where this behavior could be observed in a focused, exploratory method. Although the 30-hour-operation objective was not reached, the team viewed this work as a partial success because the process itself is now being evaluated, rather than the process support mechanisms. The full report was submitted to DOE in October 2011 (7). Additional work is now being carried out under separate funding sources.

ACTIVITY 3.5 – DISTRIBUTED H₂ SUPPLY FOR FUEL CELL UTILITY VEHICLES

Activity 3.5 is a continuation of work done previously under the NCHT Cooperative Agreement. Details of progress made during NCHT Years 1–5 were previously presented in a final report written to encompass only those years. The present report focuses on NCHT Year 6 results but repeats enough of previously reported results to aid in understanding Year 6 results. The intent of this activity was to utilize the EERC’s existing high-pressure water-reforming (HPWR) hydrogen production reactor system—designed and constructed in a prior project phase—as a basis to improve operational and production performance of the EERC overall hydrogen production demonstration unit, which comprises integrated unit operations for hydrogen production, purification, and dispensing into vehicle or other high-pressure storage tanks. Unlike traditional SMR-based processes that produce hydrogen at slightly above ambient pressures and then pressurize the hydrogen for storage and/or dispensing, the HPWR process produces high-pressure (up to 800 bar) hydrogen by reacting pressurized liquid feedstocks in a high-pressure reactor, thereby eliminating the high capital and operating costs of hydrogen compression. The HPWR reactor continuously produces a high-pressure, hydrogen-rich gas stream that is purified at pressure for dispensing into vehicles. In addition to eliminating the need for hydrogen compression, the small-scale compatibility of the HPWR design eliminates the need for hydrogen transportation from large-scale SMR facilities, since easily and inexpensively transportable and storable liquid feedstocks could be stored and reformed at refueling stations and other hydrogen point-of-use facilities. It has been estimated that hydrogen transportation costs \$4–\$9/gge (gallon of gasoline equivalent) and hydrogen compression, storage, and dispensing costs \$2–\$3/gge.¹

A primary Activity 3.5 objective was to provide valuable information regarding the real cost of hydrogen production for vehicle applications, with work focused on optimization of process variables in order to meet the target performance goals of the system (shown in Table 7) (8). Parameters that were to be pursued included higher hydrogen delivery pressure, higher hydrogen production rates, and the ability to refill a vehicle tank within a 5-minute time frame. Variables tested would include reactor aspect ratio, pressures, feed rates, temperatures, and residence times for the given delivery parameters. EERC-developed hydrogen production and purification unit operations (Figure 13) were to be integrated with 700-bar hydrogen storage

Table 7. Performance Characteristics

Fill Time	H ₂ Delivery Rate, kg/min	H ₂ Pressure, bar	H ₂ Purity/Compatibility
5 minutes	1.0	700	99.99%/ PEM ¹ fuel cell

¹ Proton exchange membrane.

¹ Schneider, J.; Richard, M.; Gambone, L.; McDougall, M.; Powers, C.; Patel, D.; Veenstra, M.; Barth, F.; Pregassame, J.; Damiani, C.; Webb, J.; Lynch, F. Evaluation of Fueling Performance Targets for Onboard 70-MPa Gaseous Hydrogen Storage Containers. In *Proceedings of the National Hydrogen Association 2006 Annual Meeting*; 2006.

Figure 13. 3-D model of the EERC scaled-up hydrogen on-demand system.

tank(s) and a fueling dispenser previously supplied by Krauss Global, Inc., of Winnipeg, Manitoba, to make a complete and functional hydrogen fueling system for small-scale demonstration purposes. From the demonstration unit, hydrogen production costs would be obtained along with the identification of applicable target markets.

Initial hydrogen production results at 350 bar were reported in the NCHT Years 1–5 final technical report. Operating the HPWR system with methanol as feedstock yielded a 350-bar (~5000-psig) product gas consisting of 73 mol% hydrogen, 25 mol% carbon dioxide, 1 mol% methane, and 1 mol% carbon monoxide. Conversion ranged from 74% to 100%, depending on methanol flow rate. A methanol flow rate of 0.09 kg/hr resulted in 100% conversion, while a methanol flow rate of 0.23 kg/hr resulted in 74% conversion. PSA tests proved the subsystem's capability to purify the reformat to ICE quality or better. These results served as lower-pressure validation of the system design. Higher-pressure validation at 700 bar was dependent upon acquisition and integration of a high-pressure hydrogen storage tank that would permit full functional checkout of the integrated system.

Acquisition and approval for use of the high-pressure tank proved more challenging than anticipated. After months of unsuccessful negotiations to procure a 300-liter, 700-bar, Type IV composite hydrogen fuel tank from Lincoln Composites, an industry leader in this cutting-edge hydrogen storage technology, the EERC contracted with Powertech Labs of Vancouver, British Columbia, to provide one tank and appropriate system integration hardware. The EERC also contracted for a comprehensive report on ongoing Powertech negotiations with the North Dakota State Boiler Inspector (NDSBI) for approval to use the tank with the HPWR system. In December 2011, the tank was received from Powertech Labs after the EERC received authorization from the NDSBI. The tank is shown in Figure 14. Although Powertech is currently

Figure 14. 700-bar Type IV tank delivered to the EERC by Powertech Labs.

working to win NDSBI approval to use the tank, the process is complicated by issues involving how best to comply with evolving manufacturing, installation, and inspection codes for high-pressure hydrogen storage tanks.

Efforts to resolve permitting issues with the installed Type IV tank continued to the end of this project. At the time of this report, the NDSBI had not signed the variance to permit use of this tank. The goal of utilizing the high-pressure hydrogen storage subsystem to enable high-pressure fueling demonstration and exploration of process improvements at higher pressure will need to be reached in subsequent testing of the HPWR system once use permits have been obtained. It is interesting to note that Type IV hydrogen storage tanks are formally approved for use in transport applications by the U.S. Department of Transportation (DOT).¹ It is hoped that that actions undertaken by this project—including direct and detailed interactions with North Dakota and California regulatory authorities—have helped to resolve Type IV hydrogen tank approval issues.

¹CSA America Inc.'s NGV2, *Basic Requirements for Compressed Natural Gas Vehicle (NGV) Fuel Containers*, ISO 11439, *Gas Cylinders – High Pressure Cylinders for the On-Board Storage of Natural Gas as a Fuel for Automotive Vehicles*, and FMVSS 304, *Compressed Natural Gas Fuel Container Integrity* are currently used as guidelines for approval of mobile hydrogen storage. SAE J2579, *Technical Information Report for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles*, is in the early stages of development, but will further refine DOT's approach to approval of mobile hydrogen storage tanks.

ACTIVITY 6.2.5 – OUTREACH AND EDUCATION FOR HYDROGEN PRODUCTION AND UTILIZATION

All new technologies face challenges with respect to social acceptability, especially those that may involve new risks, large-scale infrastructure, and significant government involvement—all features of the hydrogen economy. Perceptions of the benefits and risks are essential factors for determining public acceptance of any emerging technology, but are of particular importance for a path-breaking technology like hydrogen. Research indicates that the public awareness of hydrogen, and associated technologies such as fuel cells, is very low, with the exception of a few geographical areas where the local nature of the demonstration project or the effectiveness of communication campaigns increased awareness and generated public interest.¹ Despite low levels of awareness and knowledge, studies report that people have positive beliefs about and attitudes towards hydrogen and are generally accepting of its development as a fuel.¹ The discrepancy between a low knowledge level and high support for hydrogen indicates there is a need for educating the public about hydrogen.

Understanding the critical role the public can play in the ultimate deployment of hydrogen economy, the NCHT set out to provide objective information that stimulates the development of the hydrogen. Increased awareness about the hydrogen economy and its beneficial impact on national security, the environment, and the economy are being achieved through ongoing support and development of educational and outreach materials produced within this activity. In Year 6, this activity:

- Disseminated and promoted the use of NCHT educational materials such as the video and online course.
- Coordinated with other hydrogen or promotional programs to enhance and distribute NCHT educational materials.
- Supported hydrogen events at the EERC.

Hydrogen: Nature's Fuel Documentary

In collaboration with Prairie Public Broadcasting (PPB), the NCHT created the EERC's first full-length documentary entitled "*Hydrogen: Nature's Fuel*" (see DVD cover in Figure 15). This hour-long documentary tells the story of hydrogen through a series of intriguing interviews with those working on cutting-edge hydrogen technologies. The program explains to viewers every step of the process, including how hydrogen is created, how it is purified, how it is transported and dispensed, and how it is used in fuel cell vehicles and other end uses. The video is separated into thirteen distinct, yet integrated sections:

¹Ricci, M.; Bellaby, P.; Flynn, R. What Do We Know about Public Perceptions and Acceptance of Hydrogen? A Critical Review and New Case Study Evidence. *International Journal of Hydrogen Energy* **2008**, 33 (21), 5868–5880.

Figure 15. Hydrogen: Nature's Fuel DVD cover.

1. Introduction – Hydrogen is being used all around us, in data centers, warehouses, golf courses, and even breweries. This production takes viewers through all aspects of how these applications work.
2. Fuel cells – Through the insight of a University of California, Berkley, researcher, viewers see how hydrogen and oxygen combine in a fuel cell to make clean electricity. The only by-products are pure water and heat.
3. Hydrogen economy – Leading experts from the EERC's NCHT explain the past, present, and future hydrogen economy. Viewers see how a true hydrogen economy requires both inexpensive, plentiful sources of hydrogen as well as advanced technologies for using it.
4. Hydrogen production – Hydrogenics and the EERC tell viewers how hydrogen is made from a variety of domestic sources using different processes such as electrolysis, reformation, and gasification.

5. Storing renewable hydrogen – Sandia National Laboratory and Linde tell viewers how energy from the sun and water is being harvested and stored in the form of hydrogen.
6. Hydrogen fueling – Krause Global, an alternate fuel dispenser manufacturer, shows how hydrogen dispensers are different from gasoline dispensers.
7. Making fuel cells – Nuvera demonstrates how various-sized fuel cells are manufactured. Fuel cells are adaptable to the amount of power needed.
8. How do we compete? – Alteryx explains how fuel cells can compete with batteries and generators.
9. Battery or fuel cell? – Toro demonstrates how lawn equipment is quietly being powered by hydrogen.
10. Domestic energy – Sierra Nevada Brewery demonstrates how a 24/7 manufacturing facility can survive off the grid with hydrogen.
11. Vehicle of the future – The world's largest auto makers showcase their fuel cell vehicles. Also, viewers get an insider look at how New Flyer made the fuel cell buses used at the 2010 Vancouver Olympics.
12. Is it safe? – Hydrogen is no less safe than gasoline, it's just different. Viewers learn how hydrogen is being engineered to be as safe as, if not safer than, currently available technologies.
13. Hydrogen society – Iceland is capable of producing hydrogen from 100% renewable sources. Viewers see how this 100% renewable hydrogen is being used to power a touristic whale-watching ship in scenic Iceland.

Television Distribution

Hydrogen: Nature's Fuel premiered regionwide January 12, 2011, on Prairie Public Television, Fargo, North Dakota. As shown in Figure 16, the viewing area included all of North Dakota and parts of northwestern Minnesota and eastern Manitoba. To promote the premier, the NCHT sent a news release to regional media outlets on January 11, 2011. Announcements were also posted on the EERC's Facebook and Twitter accounts. On premier day, an e-mail blast was sent to the EERC's hydrogen industry contacts in Prairie Public Television's viewing area. As a result of the premier promotions, the stories about the documentary were featured in the *Grand Forks Herald*, Grand Forks Regional Economic Development Corporation blog, Areavoices.com, UND Press Room, *The Fargo Forum*, *FellCellWorks.com*, *Prairie Business* magazine, ThinkStage.com, the *University Letter*, and other industry blogs and online publications.

Figure 16. Public TV market centers.

Prairie Public Television continues to regularly air the documentary in its broadcast lineup. To further its national distribution, the documentary was posted to the National Educational Telecommunications Association (NETA) catalog on July 4, 2011. NETA provides a catalog and satellite feed so other public television stations can choose and download programming for broadcast. Stations are allowed to use the material for 3 years. From July 1 to December 30, 2011, the documentary had 204 telecasts in 19 markets, including Boston, Massachusetts; Minneapolis, Minnesota; Buffalo, New York; Knoxville, Tennessee; Charleston, North Carolina; Champaign, Illinois; Burlington, Vermont; Sioux Falls, South Dakota; Corpus Christi, Texas; Duluth, Minnesota; Salt Lake City, Utah; Flint, Michigan; Saginaw, Michigan; Toledo, Ohio; Medford, Oregon; Fairbanks, Alaska; Juneau, Alaska; Anchorage, Alaska; and Rochester, Minnesota.

Online Distribution

The documentary has been hugely popular online. Its greatest success is from PPB's YouTube channel. Since it was initially posted on January 15, 2011, it has over 32,000 views, which is equivalent to about 2200 views a month. The viewing rate has been relatively steady over the entire period of time and surpasses PPB's popular Prairie Home Companion pieces and is well above any energy-related piece ever created by PPB. Overall, online comments received about the documentary in PPB's YouTube channel have been very positive. Several people asked technical questions related to things such as storage and safety. Others provide their personal insights on what it will take to achieve the hydrogen economy.

To further increase exposure for the documentary, 13 separate segments based on the segments described above were produced. Each segment has its own title slide and ending credits. The segments can be viewed separately or watched in order to view the documentary in its entirety. The segments were posted on the NCHT Web site (Figure 17) and streamed from the EERC's YouTube channel. Improvements were made to the NCHT Web site video player to allow the video to be viewed on mobile devices. The most watched segment to date is the "Vehicle of the Future?" segment with over 120 views. Three chapter segments from a 30-minute NCHT video produced in 2006 entitled "Hydrogen: Fueling Our Future...Now!" were also posted on the EERC's YouTube channel and NCHT Web site.

At the request of interviewees, individual segments were provided to companies profiled in the documentary. Each featured company is allowed to use its segment for its own marketing purposes so long as the documentary is not modified. Examples of how companies chose to utilize their segments include Linde playing its segments at its trade show booths and Nuvera posting the entire documentary and its clip on its blog: www.nuvera.com/blog/?p=1447/.

DVD Distribution

In addition to online and broadcast distribution, actual copies of the documentary on DVD were distributed to various audiences including the following:

- The premier news release, e-mail blast, and thank you letters to documentary participants yielded 53 requests for the DVD.
- Eighty DVDs were distributed at the Fuel Cell & Hydrogen Energy Conference in Washington, D.C., on February 13–16, 2011, via the EERC booth. The documentary received positive comments from industry.
- PPB distributes DVDs on the EERC's behalf at various educational events in the region.
- Postcards were sent on February 13, 2011, to public libraries in North Dakota and Minnesota announcing that free DVDs were available to libraries upon request. As a result of the mailing, 29 libraries requested copies to add to their DVD collections.

Figure 17. Screen shot of the NCHT Hydrogen: Nature's Fuel page.

- Thirty DVDs were given to area high school educators at the PPB curriculum development workshop held March 3, 2011, in Fargo, North Dakota.
- The EERC worked with the California Fuel Cell Partnership (CAFCP) to distribute 140 DVDs at the National Science Teachers Conference on Science Education held March 10–13, 2011, in San Francisco, California. The DVDs were distributed via the CAFCP booth and supported lesson plans distributed by CAFCP. CAFCP reported a growing interest in hydrogen among high school science educators.

- DVDs were distributed to 130 elementary and secondary educators who attended the Lignite Education Seminar: Energy, Economics and Environment on June 20–23, 2011, at Bismarck State College in Bismarck, North Dakota.
- DVDs were distributed to 30 librarians at the North Dakota Librarians Association Annual Conference held September 21–24, 2011, in Minot, North Dakota.

Award Submissions

Because of the overwhelming success of *Hydrogen: Nature's Fuel*, PPB submitted it for a 2012 Telly Award. The Telly Awards honor the very best film and video productions and outstanding local, regional, and cable TV programs. Additional award submissions are planned for early 2012.

Fueling the Hydrogen Economy Online Course

Under a previous NCHT contract, the EERC and the University of North Dakota (UND) Division on Continuing Education developed an interactive online continuing education course entitled “Fueling the Hydrogen Economy.” The course was designed specifically for middle-to-high school educators; however, energy industry professionals have found it valuable as well. The course provides educators with required continuing education credits and may be used to satisfy the professional development requirements for some engineering fields.

Course Content

The course offers a unique blend of science disciplines. Students learn from and participate in self-checks, video/audio and text-based lectures, quizzes, animation, and graphic elements. Figure 18 shows a screen shot of a lesson with an interactive component. The course takes students on virtual field trips, where they gain access to teaching materials including lesson plans, handouts, and computer animations.

The course is split into eight lessons. Lesson titles include the following:

1. Hydrogen Basics
2. Hydrogen Production
3. Hydrogen Storage
4. Hydrogen Distribution
5. Safety Concerns
6. Fuel Cells
7. How Hydrogen Is Expected to Fit into the U.S. Energy Mix
8. What Will the Future Hydrogen Economy Look Like?

The University of
North Dakota

Division of Continuing Education

EERC
Energy & Environmental Research Center

Lesson 6
FUEL CELLS

Fuel Cell Vehicle History—The Early Days

Before we look at how a fuel cell is designed today, let's look at how the fuel cell has evolved. The concept of a fuel cell has been around since the 1800s, but a number of social, economic, environmental, and government pressures had to fall into place to spur the development seen today.

Click on the dates along the timeline.

Left: Francis Bacon's 5-kW Fuel Cell

Right: Harry Ihrig's Fuel Cell Tractor

Francis Bacon demonstrated a 5-kilowatt fuel cell that could power a welding machine. That same year, Harry Karl Ihrig demonstrated a 20-horsepower tractor that was the first vehicle ever powered by a fuel cell.

START BACK NEXT END

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Figure 18. Screen shot from the online course “Fueling the Hydrogen Economy.”

Course Support

UND continues to offer the course and promotes the course by posting it in online and printed course catalogs. The catalogs are mailed to educators in the tristate area during the fall and spring. NCHT has a page dedicated to the course on its Web site that explains the course content and how to register. In Year 6, NCHT continued to support the course by monitoring student course work via Blackboard and assessing their performance. During 2011, 12 students completed the course.

NCHT Building Tours

The EERC routinely hosts client meetings and industry events. Part of those events often includes tours of the NCHT facilities. For example, on October 18, 2011, the EERC and the UND College of Business and Public Administration hosted the Mellem Symposium. The theme was “The Business of Energy” and included a tour of the NCHT building. Hydrogen tours also include school classes from elementary through university levels.

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