EXECUTIVE SUMMARY

In support of the U.S. Department of Energy (DOE) Advanced Research Program, conceptual systems and cost analyses were developed by the Parsons Corporation for coal processing plants to produce hydrogen while recovering carbon dioxide (CO_2) for offsite processing or sequestration. These plants had been referred to as "decarbonized fuel plants," but are now called "hydrogen fuel plants." The scope of work for this analysis entailed the following:

- Identifying alternative processes and technologies utilized for production of hydrogen from coal.
- Reviewing the technical and economic characteristics of developmental materials and technologies for separating hydrogen and oxygen from gas mixtures.
- Conceptualizing process plant designs that utilize developing technologies and materials, resulting in costs of product and CO_2 sequestration significantly lower than with conventional approaches.
- Comparing the costs of a hydrogen fuel plant with plants designed to produce hydrogen from coal utilizing conventional technology.
- Performing sensitivity analyses on the baseline conceptual hydrogen fuel plants to determine the effect of modifying plant design on cost of product.
- Presenting data and results on this study at periodic conferences and workshops.

Introduction

An alternative plant was conceived for producing hydrogen from coal utilizing a hydrogen separation device (HSD) being developed by Oak Ridge National Laboratory (ORNL). The HSD is based on a high-temperature membrane separation concept that can be designed to selectively separate hydrogen from other gases. By utilizing the HSD, it should be possible to separate hydrogen from CO_2 passively and economically.

This report is a compilation of a series of letter reports issued between 1999 and 2001 to document the activity and results from this investigation. It includes the following:

- An establishment of a baseline plant design for hydrogen production based on the ORNL membrane concept,
- A comparison of this design to the conventional methods of producing hydrogen from natural gas and coal, and
- An evaluation of the HSD based on gasifying a mixture of Wyodak coal and biomass.

Hydrogen Fuel from Coal Plants

Through mid-1999, designs and cost estimates for fuel plants utilizing the inorganic membrane were based on information derived from a 1997 conversation with Oak Ridge National Laboratory. The reporting and presentation of work associated with the membranes stimulated significant levels of interest in membrane applications, both within the DOE and in private industry. The primary report from this activity was a letter report prepared in June 1999. Nearly two years had passed since the initial information exchange, which led to a meeting held at Eastern Tennessee Technology Park (ETTP) in Oak Ridge, November 1999 to review the status of the properties and characteristics of the inorganic membrane for hydrogen transport. As a result of data gained from the meeting, assumptions applied to the membrane, which could have an impact on the baseline plant designs and on future membrane applications, were updated.

Utilizing the revised assumptions for the HSD, updated plant concepts were prepared for HSD operation at 572°F (300°C) and 1112°F (600°C). For comparisons, the initial plant operating at 1402°F (761°C) is also presented. A plant with HSD performance reduced from 95 to 80 percent hydrogen transport was also evaluated to show the impact of not reaching the HSD goal of 95 percent separation. Table ES-1 summarizes and compares the performance and economics of the four plants.

Table ES-1
Performance and Cost Summary Comparisons
Hydrogen Fuel Plants with Alternative HSD Temperatures

	1402°F Membrane (761°C)	**1112°F Membrane (600°C) Baseline Case**	**572ºF Membrane (300°C)**	**1112°F Membrane with 80% Hydrogen Transport**
HSD Exit Temperature	1402ºF (761ºC)	1112ºF (600ºC)	572ºF (300ºC)	1112ºF (600ºC)
Coal Feed	221,631 lb/h	221,631 lb/h	221,631 lb/h	221,631 lb/h
Oxygen Feed (95%)	231,218 lb/h	224,519 lb/h	218,657 lb/h	287,917 lb/h
Hydrogen Product Stream	35,205 lb/h	35,903 lb/h	36,565 lb/h	28,562 lb/h
CO_2 Product Stream	581,657 lb/h	582,566 lb/h	585,598 lb/h	583,220 lb/h
Sulfuric Acid Product	19,482 lb/h	19,482 lb/h	19,482 lb/h	19,482 lb/h
Gross Power Production	94 MW	84 MW	71 MW	131 MW
Auxiliary Power Requirement	76 MW	77 MW	76 MW	83 MW
Net Power Production	18 MW	7 MW	(6 MW)	48 MW
Effective Thermal Efficiency, HHV	80.2%	80.4%	80.3%	69.2%
Capital Cost, $1,000 (Year 2000)	$368,448	$359,791	$356,797	$385,650
Hydrogen Product Cost, $/MMBtu	$5.11	$5.06	$5.10	$6.02

The lower temperature favors hydrogen recovery but reduces the efficiency of the steam cycle. The 1112°F (600°C) plant was selected as the baseline design since this temperature is the operational goal of the membranes; in addition, this concept maintained a high hydrogen recovery while minimizing costs.

These designs were based on goals that have been set by membrane developers but not yet experimentally demonstrated. These goals include:

- Hydrogen Flux – The hydrogen flux was based on the R&D goal of 0.1 std cc/minute/ cm^2/cm Hg P_{H_2} differential.
- Separation Factor – The separation determines the hydrogen purity and is high for hydrogen, increasing with higher temperatures. Even at 300°C the separation factor would be above 200.
- Operating Pressure and Temperature – It was assumed that a 950 psi pressure differential can be contained by the inorganic membrane. The operational goal for the membranes is currently 600ºC, and a vessel design could be prepared today to operate with confidence up to 300ºC.
- CO Shift Properties – It was assumed that the shift reaction on the membrane surface goes to equilibrium without catalyst.

The 80 percent hydrogen transport case reduces the amount of hydrogen recovered but increases the amount of power produced in the topping cycle. The cost of hydrogen increases from the baseline case, but proportionally less than the reduction in hydrogen recovered.

Based on consistent financial parameters and technical parameters taken from the goals of the membrane developers, hydrogen can be produced ranging from $5.06 to $5.11 per million Btu including CO_2 capture. With 80 percent hydrogen transport, the cost increases to $6.02 per million Btu including CO_2 capture.

Hydrogen from Natural Gas and Coal-Based Plants

The previous work resulted in a baseline plant for production of hydrogen from coal utilizing the ORNL-developed inorganic membrane for separation of hydrogen from syngas. The purpose was to compare hydrogen cost from conventional methods, with and without CO_2 recovery, against the baseline hydrogen fuel plant. Table ES-2 summarizes and compares the performance and economics of the conventional hydrogen plants with the hydrogen fuel plants.

Table ES-2
Comparison of Hydrogen Cost from Conventional and Advanced Plant Designs

	Case 1 Hydrogen from Natural Gas without CO_2 Capture	Case 2 Hydrogen from Natural Gas with CO_2 Capture by Amine Process	Case 4 Conventional Hydrogen from Coal without CO_2 Capture	Case 5 Conventional Hydrogen from Coal with Maximum CO_2 Capture	Baseline Case Advanced Hydrogen Plant with CO_2 Capture 600°C Membrane
Plant Size, tons H_2/day (MMscfd) (Pressure, psia)	417.8 tpd (150 MMscfd) (346)	417.8 tpd (150 MMscfd) (346)	312.6 tpd (112 MMscfd) (346)	317.8 tpd (114 MMscfd) (346)	430.8 tpd (147 MMscfd) (346)
Coal Feed (dry basis)	N/A	N/A	2,500 tpd	2,500 tpd	2,500 tpd
Natural Gas Feed, MMBtuh (MMscfd)	2,868 MMBtuh (65.5 MMscfd)	2,640 MMBtuh (60.3 MMscfd)	N/A	N/A	N/A
Fuel Cost, $/MMBtu	$3.15/MMBtu	$3.15/MMBtu	$1.00/MMBtu	$1.00/MMBtu	$1.00/MMBtu
Plant Availability	90%	90%	80%	80%	80%
Cold Gas Efficiency[1]	74.2%	80.6%	57.7%	58.6%	79.5%
Equivalent Thermal Efficiency, HHV	83.9%	78.6%	62.3%	60.1%	80.4%
Steam Export?	220,000 lb/h	No	No	No	No
CO_2 Recovered, tpd (percent) (Pressure, psia)	N/A	2,609 tpd (71%) (30)	N/A	6,233 tpd (92%) (30)	6,362 tpd (94%) (20)
Net Power	(6 MW)	(15 MW)	38 MW	12 MW	7 MW
Total Plant Cost $1,000, Year 2000	$130,998	$142,370	$321,824	$374,906	$359,791
Cost of Hydrogen, $/MMBtu (¢/kscf)	$5.54/MMBtu (180 ¢/kscf)	$5.93/MMBtu (192 ¢/kscf)	$5.71/MMBtu (186 ¢/kscf)	$6.91/MMBtu (225 ¢/kscf)	$5.06/MMBtu (164 ¢/kscf)

[1] Cold gas efficiency equals HHV of the product gas divided by the HHV of the feed x 100.

Given that the R&D goals can be achieved, hydrogen production from the baseline hydrogen fuel plant, which includes CO_2 removal, would be competitive with hydrogen produced from both natural gas- and coal-based conventional technologies even without CO_2 removal. With only 80 percent hydrogen transport, hydrogen production would still be competitive with conventional coal-based technology.

Hydrogen Fuel from Wyodak Coal/Biomass Blend

The purpose of this study was to compare the economics of producing hydrogen from a Wyodak/biomass blend against producing hydrogen from bituminous coal for plants that have the same dry coal feedrate. Table ES-3 is a summary comparison of the performance and cost results. The costs of hydrogen from both feedstocks are approximately equal. This is due to a balance of capital charges, fuel costs, and byproduct credits.

Table ES-3
Performance and Cost Summary Comparisons
Hydrogen Fuel Plants with Alternative Feedstocks

	90% Wyodak 10% Biomass	Baseline Case Pittsburgh No. 8 600°C Membrane
Coal Feed	283,833 lb/h	221,631 lb/h
Biomass Feed	31,537 lb/h	N/A
Oxygen Feed (95%) to Gasifier	186,650 lb/h	165,818 lb/h
Oxygen Feed to Retentate Combustor	25,300 lb/h	58,701 lb/h
Water to Prepare Feed Slurry	114,009 lb/h	94,025 lb/h
Hydrogen Product Stream	33,337 lb/h	35,903 lb/h
CO_2 Product Stream	575,923 lb/h	582,566 lb/h
Sulfuric Acid Product	5,057 lb/h	19,482 lb/h
Gross Power Production		
Turbine Expander	55 MW	84 MW
Steam Turbine	28 MW	N/A
Auxiliary Power Requirement	(69 MW)	(77 MW)
Net Power Production	14 MW	7 MW
Net Plant Water Makeup	100,979 lb/h	198,150 lb/h
Effective Thermal Efficiency, HHV	79.8%	80.4%
Capital Cost, $1,000	$365,662	$359,791
Hydrogen Product Cost, $/MMBtu	$5.22 ($0.65 feedstock) $5.04 ($0.50 feedstock)	$5.06

The amount of hydrogen produced from the Wyodak/biomass blend is lowered by about 7 percent, primarily due to the higher level of CO_2 produced in the gasifier. This resulted in a lowered amount of reactive syngas (H_2 and CO) available for hydrogen production.

Total plant costs are roughly equal, resulting from a combination of increased and decreased equipment requirements. The cost adjustments to the hydrogen plant due to the changeover to the Wyodak/biomass blend are reflected in increased feedstock handling, increased oxygen plant size due to the higher water content (and associated increase in CO_2 content), and the need for a steam turbine that produces 28 MW from excess low-pressure steam. The capital costs were lower in sulfur control areas because of the low-sulfur feedstock, resulting in only 61 tpd sulfuric acid production from the blend versus 234 tpd from bituminous coal. This resulted in a lowering of byproduct credits.

1. INTRODUCTION

The Office of Planning and Environmental Analysis within the Office of Coal and Power Systems (C&PS), renamed Fuel and Power Systems for FY 2002, is responsible for evaluating the reasonableness of C&PS strategic goals, and views the evaluation of innovative systems in fossil energy power generation and liquid fuels production as key elements in that assessment. The Advanced Research Program within the C&PS supports basic research and the development of innovative systems in fossil energy power generation and liquid fuels production. Several research targets have been identified, including low-cost O_2 separation and high-temperature H_2 separation. In support of this program, conceptual systems and cost analyses were developed by the Parsons Corporation for a coal processing plant to produce hydrogen while recovering carbon dioxide (CO_2) for offsite processing or sequestration. This had been referred to as a "decarbonized fuel plant" and is now referred to as a "hydrogen fuel plant." The scope of work for this analysis entailed the following:

- Identifying alternative processes and technologies utilized for production of hydrogen from coal.
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With an increased interest in greenhouse gas sequestration and production of hydrogen from coal, conceptual designs and resulting economic analyses of syngas and hydrogen plants utilizing conventional technologies were also developed. Throughout the program, certain plant design and economic parameters remained constant to ensure normalized comparisons. These parameters are shown in Table 1-1 and Table 1-2. The conventional approaches included processes such as coal gasification, shift conversion, acid gas removal, and pressure swing adsorption to produce hydrogen. The results of previous studies indicated that the economics of producing syngas and hydrogen from coal by conventional methods is not presently cost competitive.[1,2,3]

Table 1-1
Consistent Design Parameters (Unless Noted in Text)

Coal	Pittsburgh No. 8
Gasifier Coal Feed	221,631 lb/h as received
Gasifier	E-Gas (Destec two-stage entrained) oxygen-blown
Hydrogen Product	High purity, 346 psia
Sulfur Recovery	Sulfuric acid
CO_2 Recovery	Low pressure

Table 1-2
Consistent Financial Parameters (Unless Noted in Text)

Cost Basis	Year 2000	
Capacity Factor	Coal-based – 80% Natural gas-based – 90%	
Delivered Cost of: Natural Gas Coal	 3.15 $/MMBtu 1.00 $/MMBtu	
Project Book Life	20 Years	
Capital:	% of Total	Cost (%)
Common Equity	20	16.5
Debt	80	6.3
Weighted Cost of Capital: (after tax)	6.4%	

An alternative plant was conceived for producing hydrogen from coal utilizing a hydrogen separation device (HSD). The HSD is based on a high-temperature membrane separation concept being developed by Oak Ridge National Laboratory (ORNL)[4] that can be designed to selectively separate hydrogen from other gases. By utilizing the HSD, it should be possible to separate hydrogen from CO_2 passively and economically.

This report is a compilation of a series of letter reports issued between 1999 and 2001 to document the activity and results from this investigation. Section 2 of this report establishes the baseline plant design for hydrogen production based on the ORNL membrane concept. Section 3 compares these designs to the conventional method of producing hydrogen from natural gas and coal. Section 4 evaluates the HSD based on gasifying a mixture of Wyodak coal and biomass.