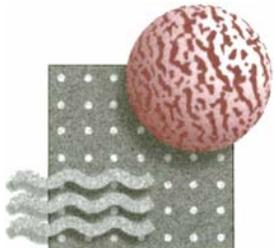

Carbon Molecular Sieve Membrane as Reactor/Separator for Water Gas Shift Reaction

DE-FG36-05G015092

This presentation does not contain any proprietary, confidential, or otherwise restricted information



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Pittsburgh, PA 15238
Date: June 11, 2008

PDP25

Overview

Project Start Date

7/1/05

Project End Date

6/30/07

(1 yr no cost extension submitted)

Percent Complete

85%

Delivery of 99.999% H₂ with high H₂ recovery ratio is difficult through a membrane-based process

Demonstration of the membrane reactor-based process in a significant scale

Economic analysis for production cost

Total project funding

- DOE Share: \$1,530,713.
- Contractor Share: \$382,678.

Previous Funding received:

\$100K(FY05), \$225K(FY06), \$566K(FY07)

Funding received in FY08

\$325K

No catalyst development activities due to funding limitation in the beginning of the project

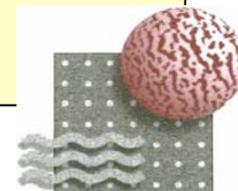
Professor Theo T. Tsotsis

University of Southern California,
Catalytic membrane reactor expert

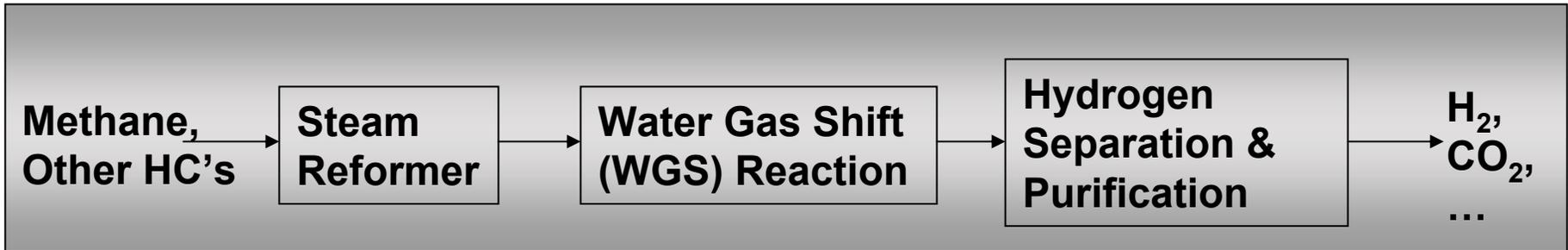
Dr. Babak Fayyaz-Najafi

Chevron ETC,
End User Participant

Dr. Hugh Stitt, Johnson Matthey,
Catalyst Manufacturer

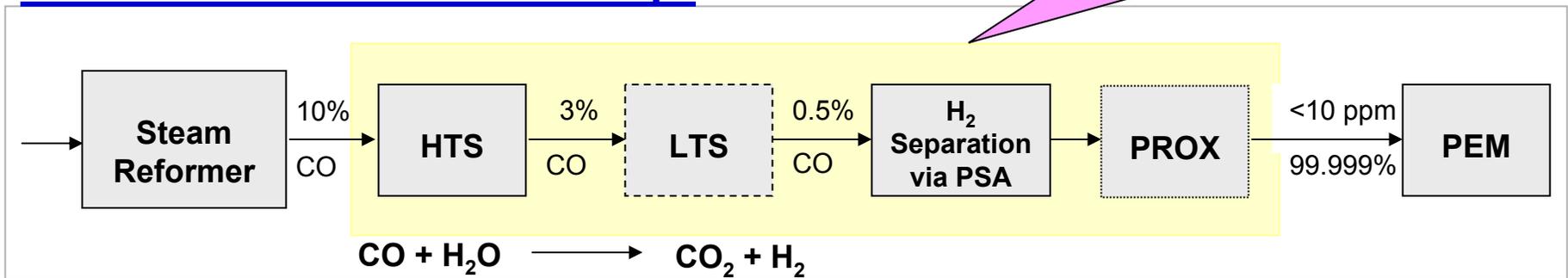


Hydrogen Production from Steam Reforming

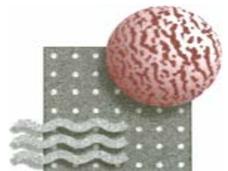


Our Project Focus
Improve Production Efficiency and Streamline Unit Operations involving CO Conversion/H₂ Separation & Purification

Conventional Process Concept



HTS: High Temperature Shift
LTS: Low Temperature Shift
PROX: Preferential Oxidation
PEM: Proton Exchange Membrane Fuel Cell



Overall Technical Approach

1. Bench-Scale Verification (Yr I&II, Phase I)	2. Pilot Scale Testing* (Yr III, Phase I)	3. Field Demonstration (Phase II)
1.1 Evaluate membrane reactor: use existing membrane & catalyst via math simulation	2.1 Prepare membranes, module, and housing for pilot-scale testing	3.1 Fabricate membranes and membrane reactors and prepare catalysts
1.2 Experimental verification: use upgraded membrane & existing catalyst via bench unit	2.2 Perform pilot scale testing and demonstration	3.2 Prepare site and install reactor
1.3 Validate membrane and membrane reactor performance & economics	2.3 Perform economic analysis & technical evaluation	3.3 Perform field test
	2.4 Prepare field testing	3.4 Conduct system integration study
		3.5 Finalize economic analysis & refine performance simulation

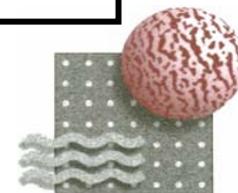


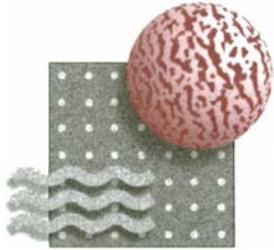
Technology development team



End user participant

*current stage of the project





Distributed hydrogen production

Objectives and Technical Approach for Yr III

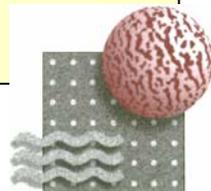
Based upon the lab results obtained from Yr I&II in the performance of our membrane and membrane reactor, we have focused on below in Yr III:

- **Process Synthesis to**

- deliver 99.999% H₂ purity
- achieve capital cost reduction, and
- overcome intrinsic deficiencies of membrane and membrane reactor technologies;

- **Establishing PDU testing facility at USC and pilot demonstration and field testing unit at M&P to**

- verify the performance based upon process simulation, and
- provide experimentally substantiated inputs for H₂A analysis
- perform H₂A analysis



TECHNICAL ACCOMPLISHMENTS – Yr III

❑ Process Synthesis for Distributed H₂ Production based upon WGS/MR

A distributed hydrogen production process has been synthesized based upon our WGS/MR + Polishing to produce hydrogen with high overall conversion (80-85%) and 99.999% purity.

❑ High H₂ Recovery vs High H₂ Purity is no longer a Choice

Based upon the lab experimental results, our simulation indicates 90% hydrogen recovery at 99% purity is achievable with our HiCON process. A PDU unit has been assembled to experimentally verify this simulation by the end of Yr III.

❑ Production of 99.999% with Operating-Cost Free Polishing Step

Our experimental result demonstrated that 99.999% purity H₂ was produced with an adsorption-based polishing step. Through integration with the HiCON process, this polishing step can be operated without additional operating cost.

❑ Process Flow Diagram and Heat Integration with PRO/II

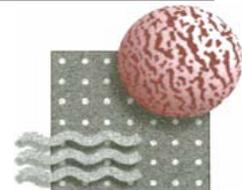
PRO/II design package was used for the development of the process flow diagram based upon our HiCON process. The finalized design with optimized heat integration will be used as input for H2A analysis.

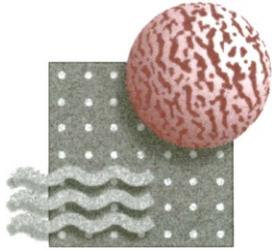
❑ Performing H2A Analysis

A preliminary H2A analysis has been performed based upon our simulation result. Once the experimental results from the PDU unit become available, we will finalize the process flow diagram and the H2A analysis.

❑ Assembly of Pilot Testing Unit

A stand-alone pilot testing unit is under construction, which will be used for in-house pilot testing (under Phase I) and field demonstration (under Phase II if budget is available).





M&P Ceramic MEMBRANES - Low cost

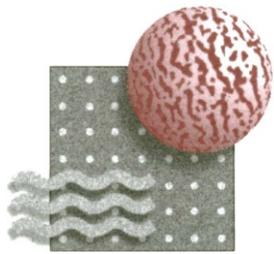
Our Commercial Ceramic Membranes/Bundles and their Substrate



Proposed module for gas phase applications



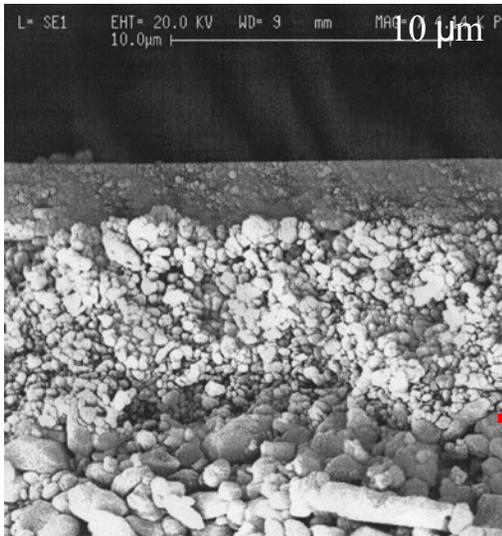
The low cost ceramic membrane was used as substrate for the hydrogen selective membrane developed for this project.



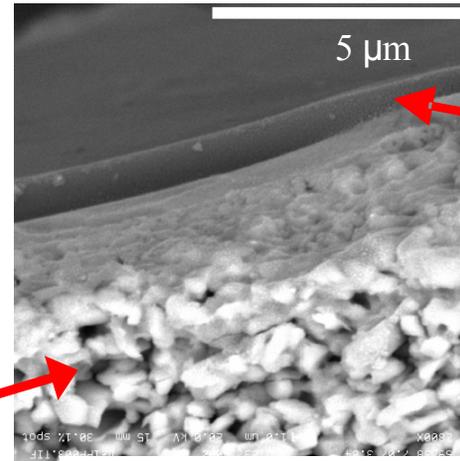
M&P Emerging Inorganic Membranes

M&P's Core Technology: Thin film deposition on porous substrates

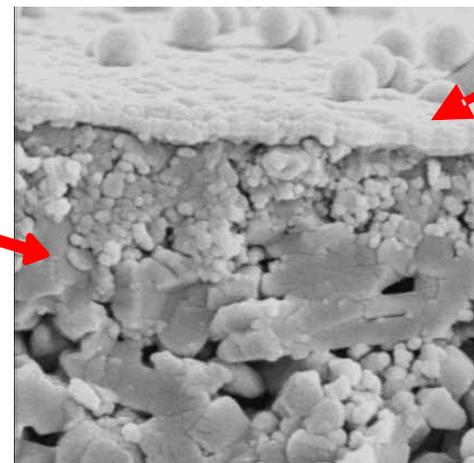
Inorganic Substrate



Ceramic Substrate

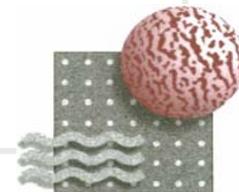


Carbon molecular sieve (porous)



Palladium (dense)

Emerging membranes used by our proposed hydrogen production process



Limitation of membrane-based separation and reactor process

- High H₂ purity vs high H₂ recovery vs High recovery efficiency are incompatible
- 100% conversion is theoretically possible, but practically unattainable

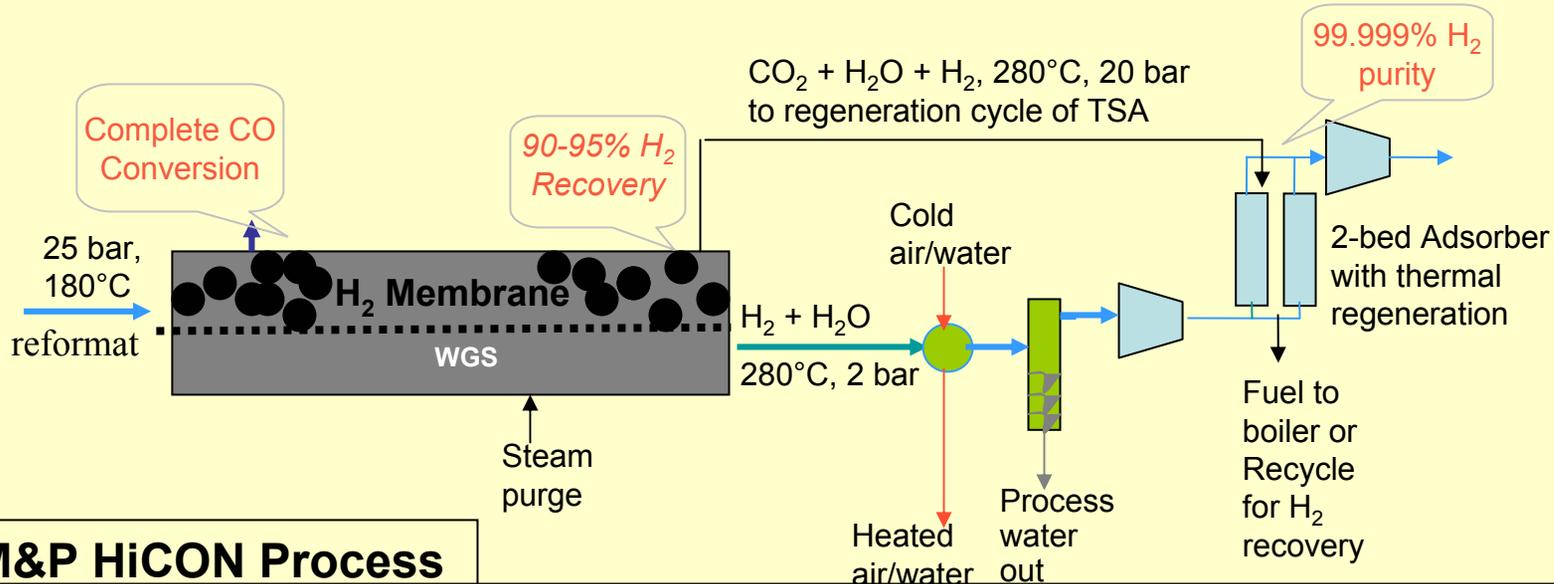


How did we overcome these deficiencies via membrane properties process synthesis ?

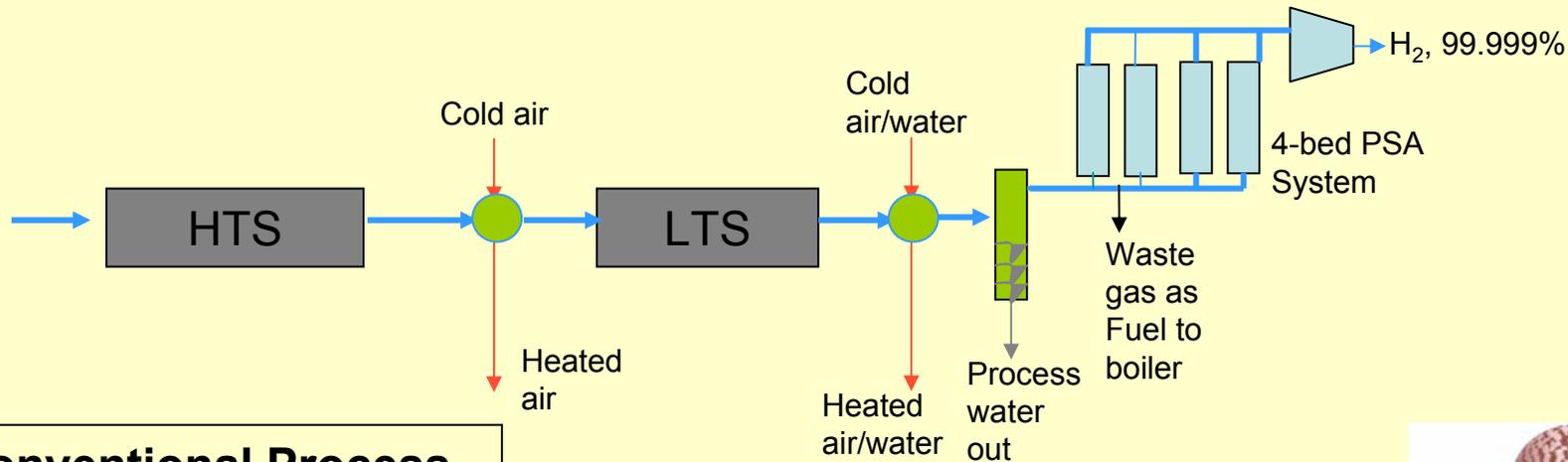
- Using a uniquely formulated membrane for enhancing conversion to achieve nearly complete conversion
- Using adsorption as a no (operating) cost polishing step in order to achieve high purity with high recovery.
- Additional recovery potential of the unrecovered hydrogen from the reject of our membrane process.



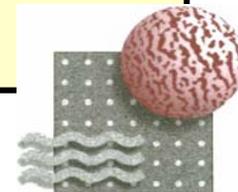
HICON Process: CO Conversion, H₂ Recovery and Polishing Step



M&P HiCON Process

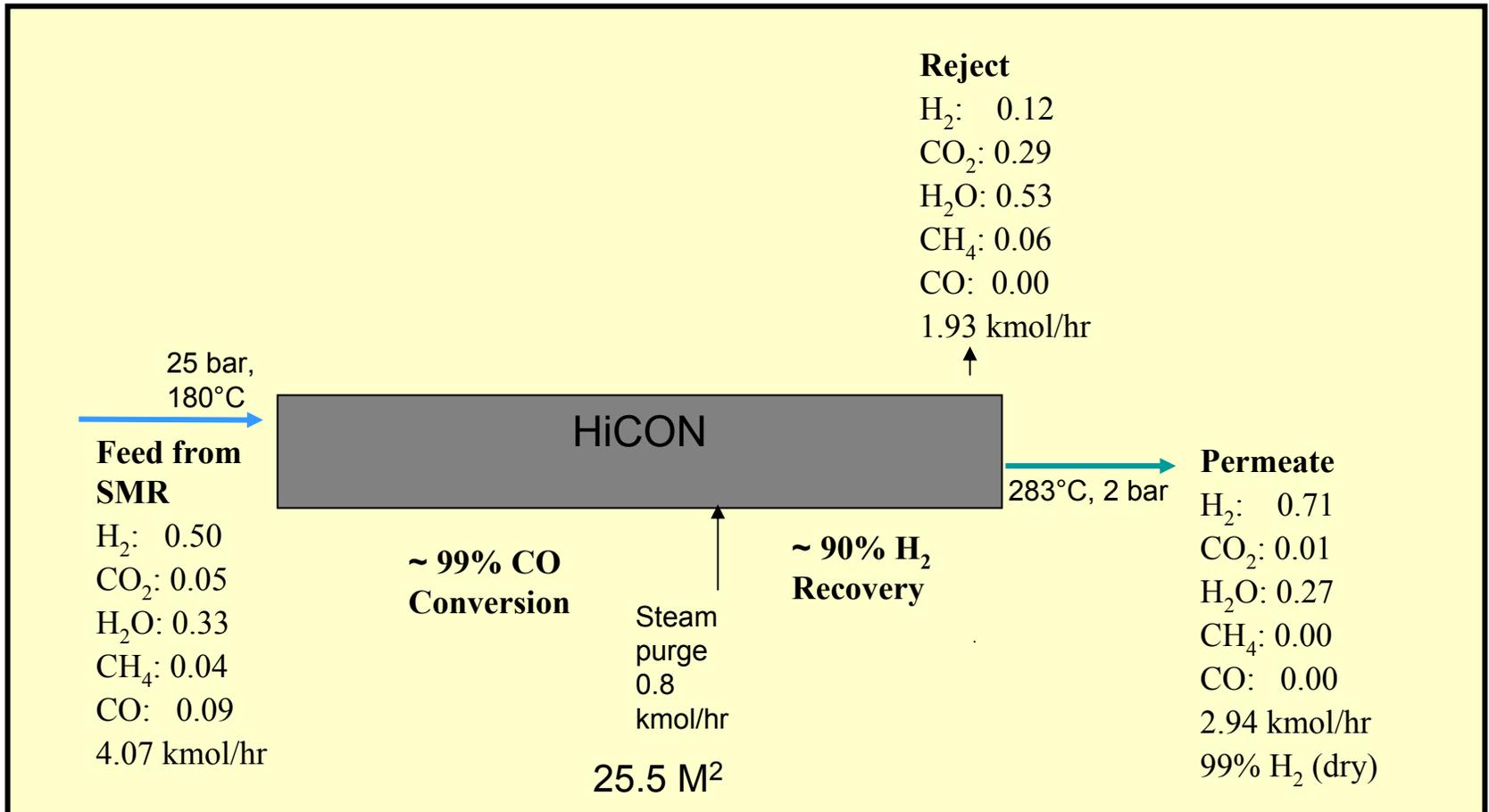


Conventional Process

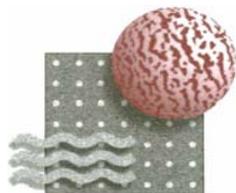


Stream composition, size, temperature & pressure And membrane surface area requirement

Basis: 100 kg/day production



Membrane reactor is under adiabatic operation (i.e., no temperature control is required).



Process Development Unit at USC

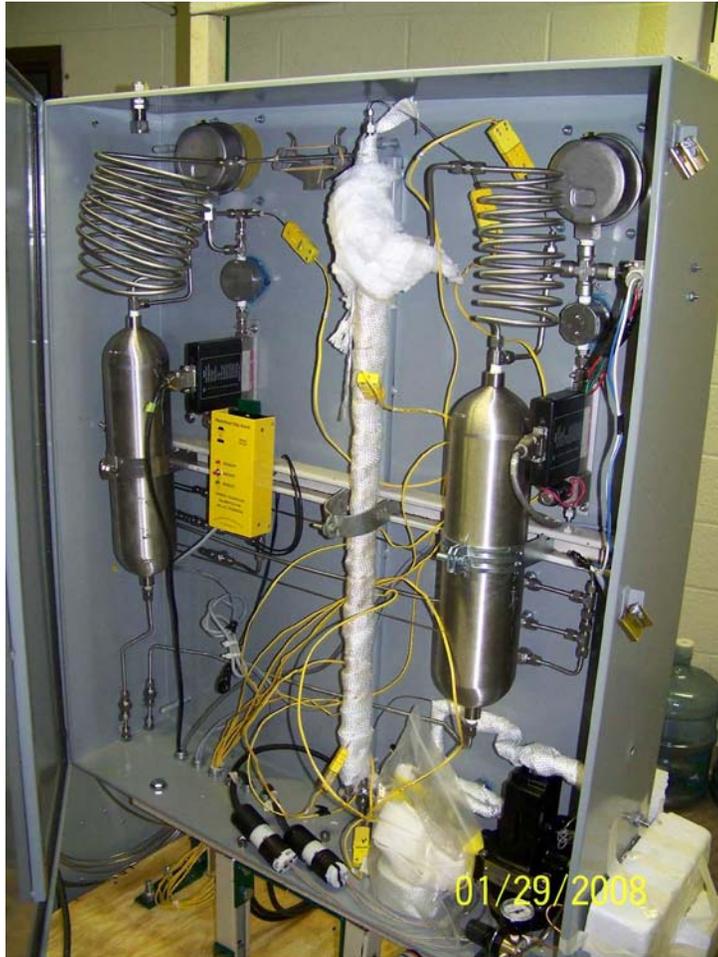
using
30" L full-scale
Single Tube
Membrane Reactor



This facility is completely installed and is currently under operation. This facility will provide experimental data generated from a full scale membrane tube for process simulation and H₂A analysis. Experimental data will be available during the meeting

M&P HiCON Process

Demonstration and Field Testing Unit



Control Panel

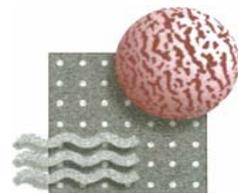
Main Unit

L: inside

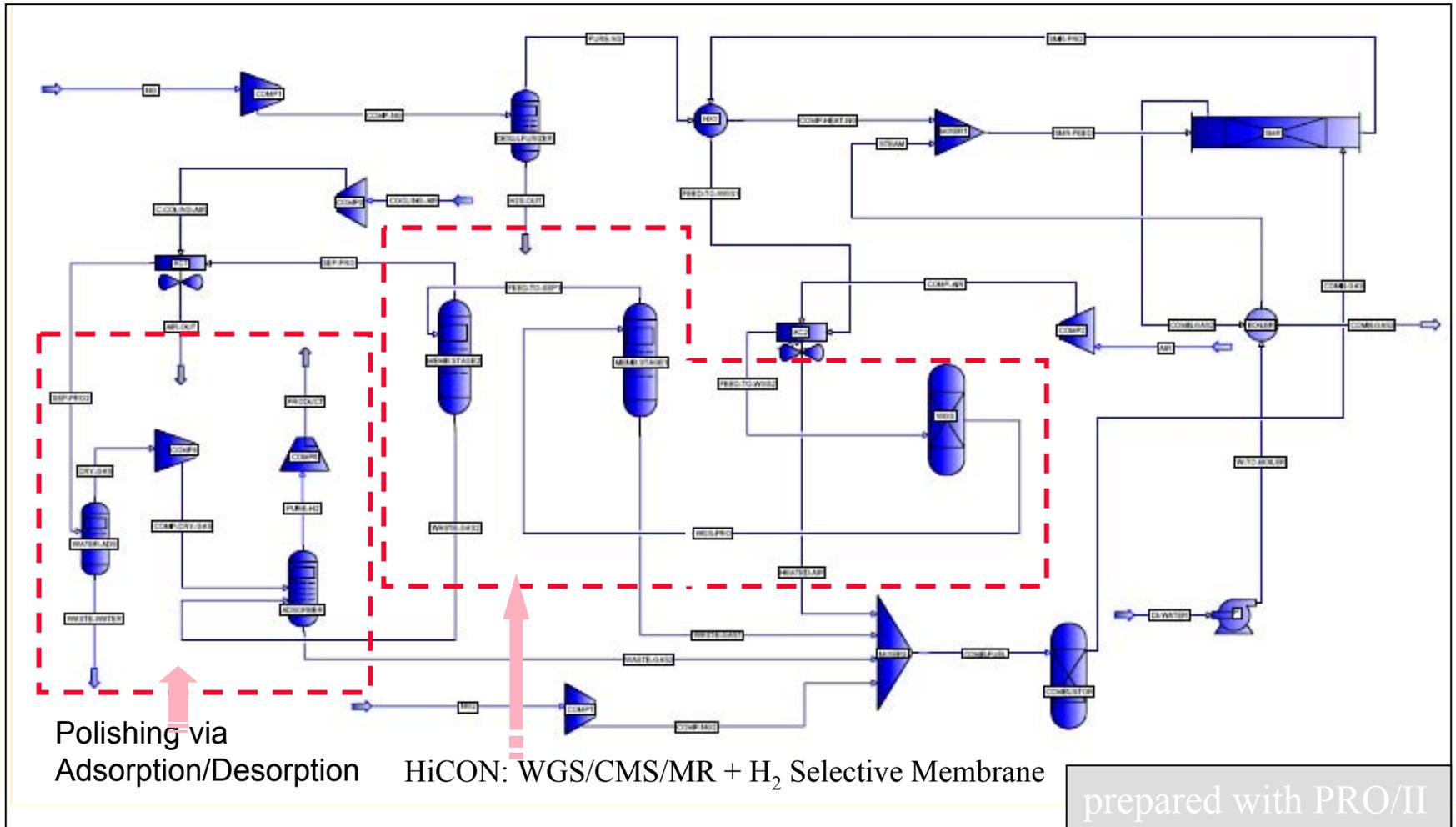
R: overview

This unit is currently under construction. This unit will be used for demonstrating the HiCON Process, a process for hydrogen production beyond the reformer.

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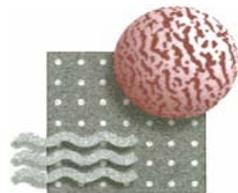


Our HiCON Process Flow Diagram



Process simulation and heat integration are actively pursued by us using PRO/II. Saxon Engineering has been retained for engineering evaluation and capital cost estimate. The results will be fed to H2A analysis.

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H2A Inputs

- **Total production initial capital investment (installed):**

\$1,020,000

\$1,116,000 with option

- **Primary feedstock usage :
(excluding fuel usage)**

2.4 kg NG/kg H₂ , or

3.4 Nm³ NG/kg H₂ or

1.23 E+05 kJ/kg H₂

- **Total other energy usage:**

0.50 kWh/kg H₂ for NG Compression, and

2.70 kWh/kg H₂ for H₂ Compression, and

0.7 Nm³/kg H₂ for Fuel Usage

3.50 E+04 kJ/kg-H₂ Total

- **Total yearly operating costs excluding energy:**

\$0.67/kg H₂ excluding utilities

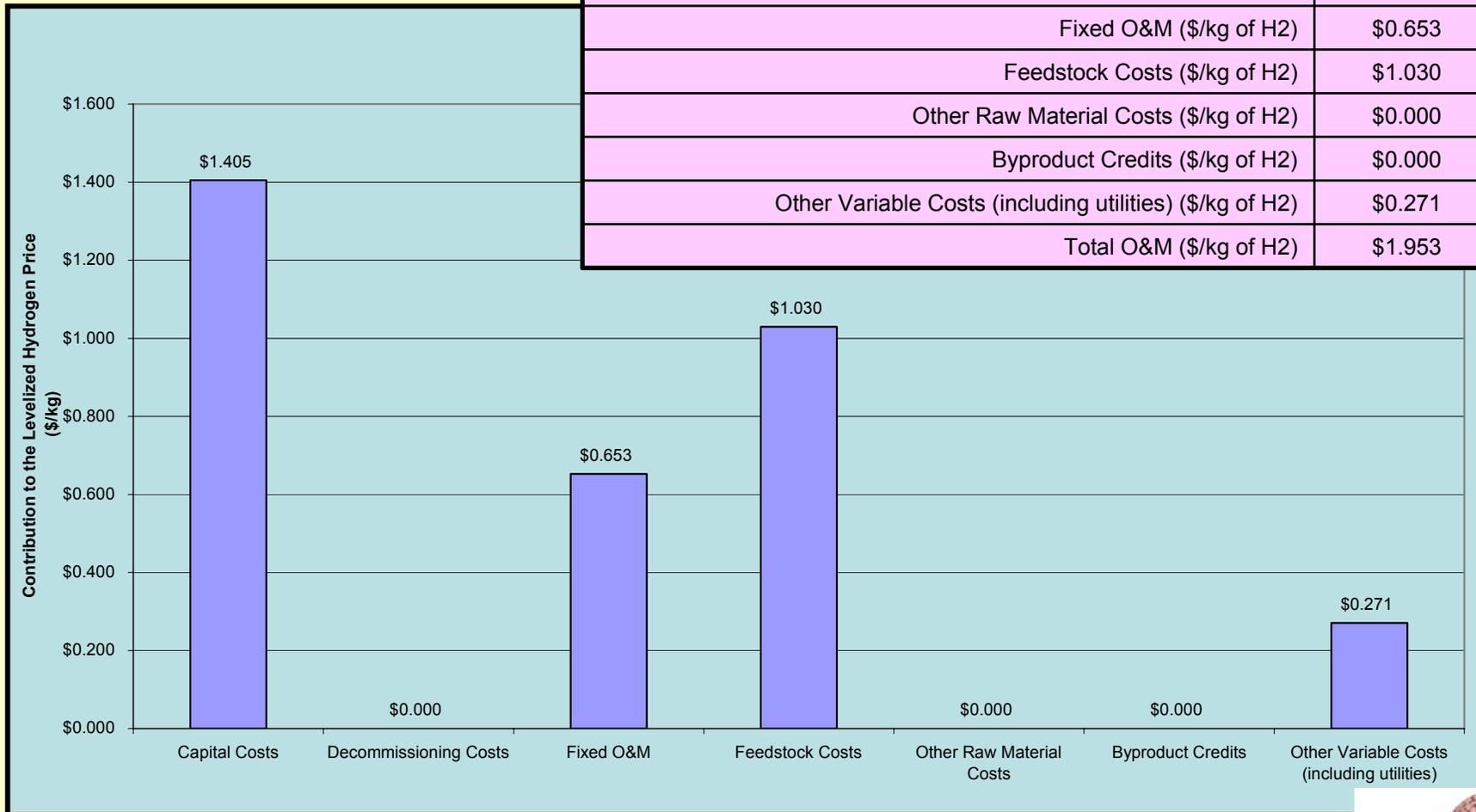


INPUT AND OUTPUT FOR ENERGY & WATER

<i>Energy efficiencies for individual process steps</i>	Values	Basis
Production System Feedstock Consumption (kJ Feedstock (LHV)/kg of H2)	146595.6	9.31 kmol/hr for 52.1 kg-H2/hr. This feedstock includes the use of methane as fuel in addition to the use of methane as feedstock for H2.
Production Unit Hydrogen Efficiency (%)	83.7%	93% Methane conversion and 90% H2 recovery
Production Electricity Consumption (kWhe/kg of H2)	0.497	25900 watt/52.1 kg-H2/hr for NG compression, 3 stages
Hydrogen Leak from Production System (%)	0%	
Production Step Efficiency (%)	82.3%	
Compression, Storage and Dispensing Feedstock Consumption (kJ (LHV)/kg of H2)	0.0	
Compression, Storage and Dispensing Electricity Consumption (kWhe/kg of H2)	2.7	according to Ariel, 9 stages, <270F
Hydrogen Leak from Compression, Storage and Dispensing Systems (%)	0%	
Compression, Storage and Dispensing Step Efficiency (%)	92.0%	based upon LHV of H2
Total H2 Leak (%)	0%	
Total System Efficiency (%)	75.7%	
Process water consumption (L/kg of H2)	8.1	3:1 ratio, 23.4 kmol/hr, credit from retentate not accounted for yet

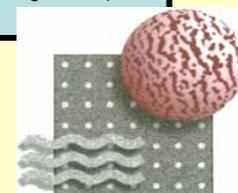
Hydrogen Selling Price and Cost Contribution (year 2005\$)

<i>Hydrogen Selling Price and Cost Contributions (Year 2005 \$)</i>	
Required Hydrogen Cost (\$/Year 2005)/kg of H2	\$3.358
Capital Costs (\$/kg of H2)	\$1.405
Decommissioning Costs (\$/kg of H2)	\$0.000
Fixed O&M (\$/kg of H2)	\$0.653
Feedstock Costs (\$/kg of H2)	\$1.030
Other Raw Material Costs (\$/kg of H2)	\$0.000
Byproduct Credits (\$/kg of H2)	\$0.000
Other Variable Costs (including utilities) (\$/kg of H2)	\$0.271
Total O&M (\$/kg of H2)	\$1.953



Upgrading via optimization with PRO/II is continuing. Updated results will be available in our poster.

Media and Process Tech Inc.



Future Work

Remainder of FY 2008

- Complete PDU testing using a single, full-scale hydrogen selective membrane and synthetic feed to generate performance database for H₂A analysis.
- Complete pilot scale testing to demonstrate the optimized HiCON process.
- Complete the H₂A economic analysis for hydrogen production via the developed HiCON process.

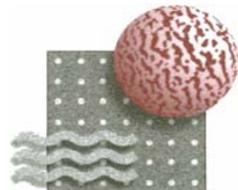
FY 2009 and Beyond

- Depending upon the budget availability, the field demonstration with the pilot scale unit as originally planned will be pursued.



Other Potential Opportunities of HiCON Process

- HiCON via CMS/MR is uniquely suitable for gasified products (such as from biomass) containing high CO, and/or sulfur and other poisons.
- Our HiCON can deliver H₂ product at 99% purity with 90 to 95% recovery for the downstream polishing step.
- Purification with simple adsorption/thermal regeneration at no operating cost to meet the PEM feedstock spec. This option overcomes the barrier associated with the membrane-based technology.



ACKNOWLEDGEMENT

US DOE Project Managers

- Rick Farmer, Sara Dillich, Arlene Anderson
- Jill Grubber, Carolyn Elam

Our Project Team Members

- Theo T. Tsotsis, University of Southern California
- Babak Fayyaz-Najafi & John Wind, Chevron ETC
- Hugh Stitt, Johnson Matthey
- Richard J. Ciora, Jr. Media and Process Tech Inc.

