Integrated Hydrogen Production, Purification and Compression System

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May 16, 2006

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PD2

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Overview

Timeline

- Project start date - April 1, 2005
- Project end date - June 31, 2008*
- Percent complete: 23

* *Revised with extension*

Budget

- Total project funding - $3,840,009
  - DOE share - $2,854,202
  - Team share - $985,807
- Funding received in FY05
  - $306,339
- Funding for FY06 - $600,000

Barriers addressed

- Production Barriers
  - Fuel Processor Capital Costs
  - Operation and Maintenance
- Delivery Barriers
  - Reliability and Costs of Hydrogen Compression

Partners

- Key partners:
  - MRT and HERA USA
- Other collaboration/interactions:
  - Safety experts
  - Product certification experts
  - Pd membrane suppliers

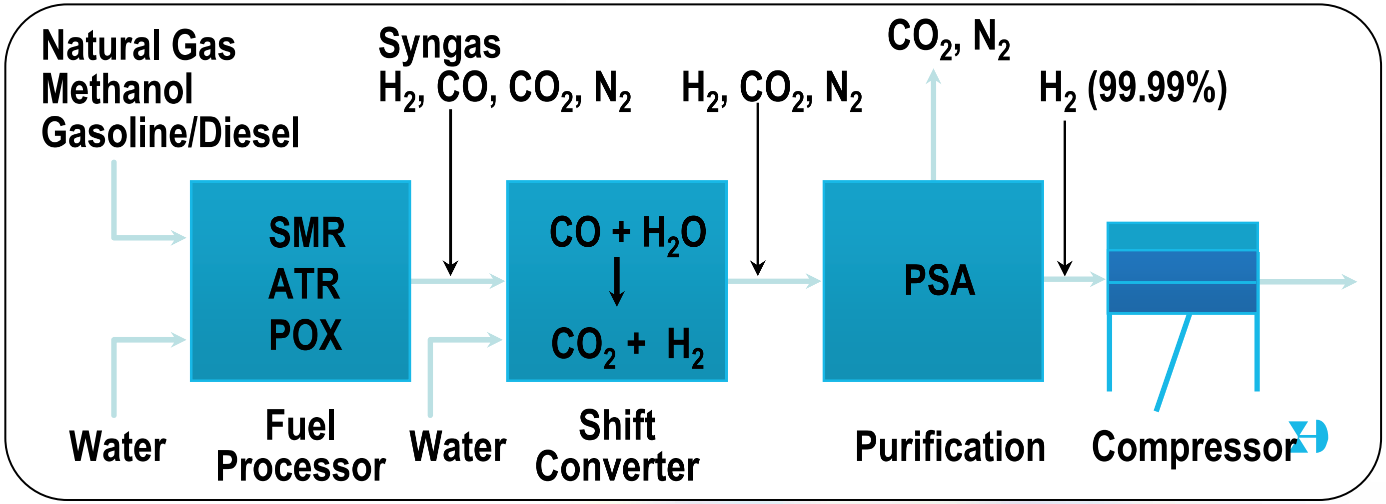
Program Objectives

- **Goal**: To demonstrate a low-cost option for producing FCV quality hydrogen that can be adopted to meet the ultimate DOE cost and efficiency targets for distributed production of hydrogen
- **Objective**: To develop a fuel processor system that directly produces high pressure, high-purity hydrogen from a single integrated unit
  - **Task 1(FY05):** Perform a detailed techno-economic analysis, verify feasibility of the concept and develop a test plan
  - **Task 2 (FY06-07):** Build and experimentally test a Proof of Concept (POC) integrated reformer / metal hydride compressor (MHC) system
  - **Task 3(FY07-08):** Build an Advanced Prototype (AP) system with modifications based on POC data and demonstrate at a commercial site
  - **Task 4 (FY08):** Complete final product design capable of achieving DOE 2010 H2 cost and performance targets

Approach

- Integrate the membrane reformer developed by Membrane Reactor Technology (MRT) and the MHC system developed by HERA USA in a single package
  - Lower capital cost compared to conventional fuel processors by
    - *reduced component count and sub-system complexity*
    - *thermal integration of all reactions/processes in a single package*
    - *integrated, thermal MHC without rotating machinery, which results in high reliability and low maintenance*
  - High efficiency achieved by
    - *directly producing high-purity hydrogen using high temperature, H2 selective membranes*
    - *improved heat and mass transfer due to inherent advantages of fluidized catalyst bed design*
    - *equilibrium shift to enhance hydrogen production in the reformer by lowering the partial pressure of hydrogen in the reaction zone*
    - *improved thermal efficiency and lower compression energy by integrating compression with the reactor system*

Current Forecourt Fueling Station Scenario



Natural Gas
Methanol
Gasoline/Diesel

Syngas
H_2, CO, CO_2, N_2

H_2, CO_2, N_2

CO_2, N_2

H_2 (99.99%)

SMR
ATR
POX

$CO + H_2O \downarrow CO_2 + H_2$

PSA

Water

Fuel Processor

Water

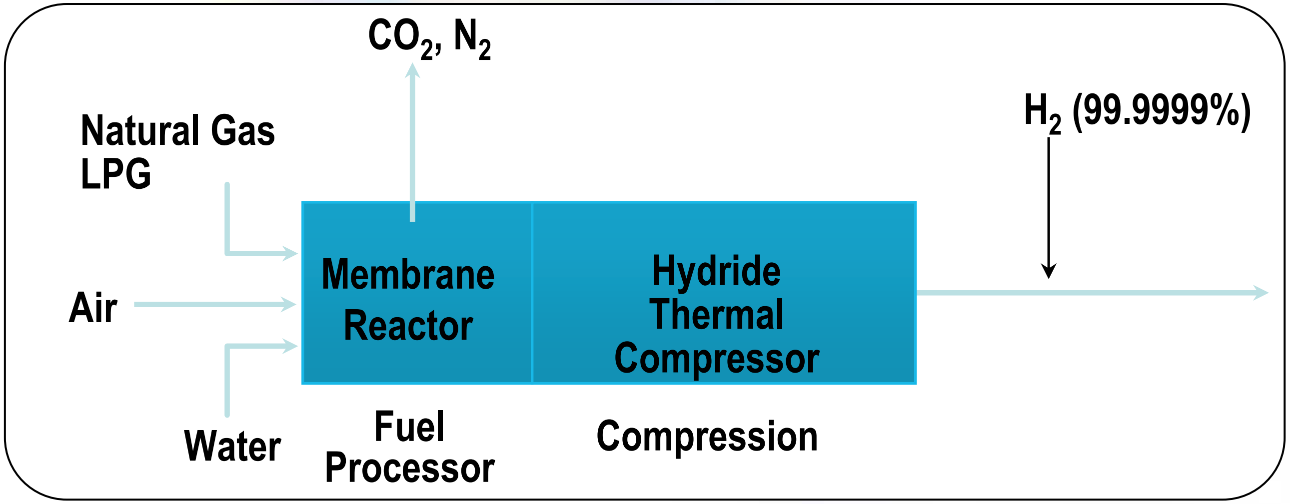
Shift Converter

Purification

Compressor

Conventional

Proposed System



CO_2, N_2

Natural Gas
LPG

Air

Water

Membrane Reactor

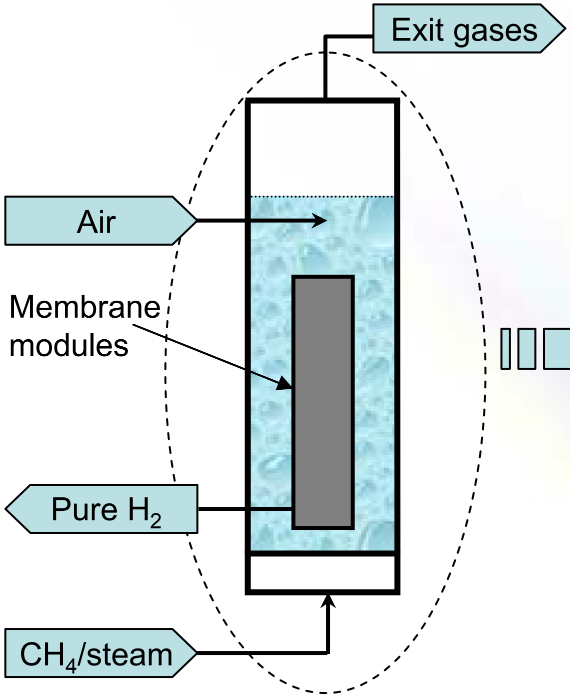
Hydride Thermal Compressor

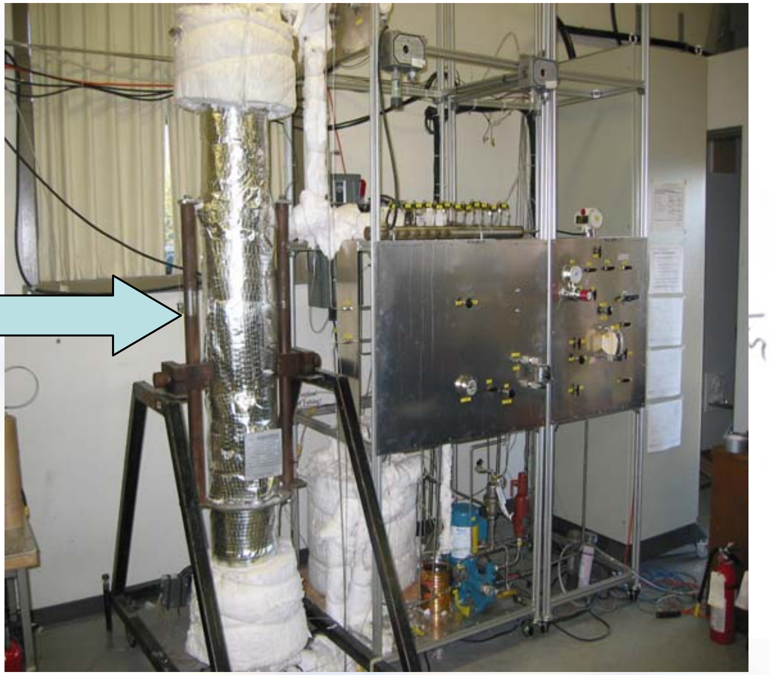
H_2 (99.9999%)

Fuel Processor

Compression

Membrane Reactor Configuration



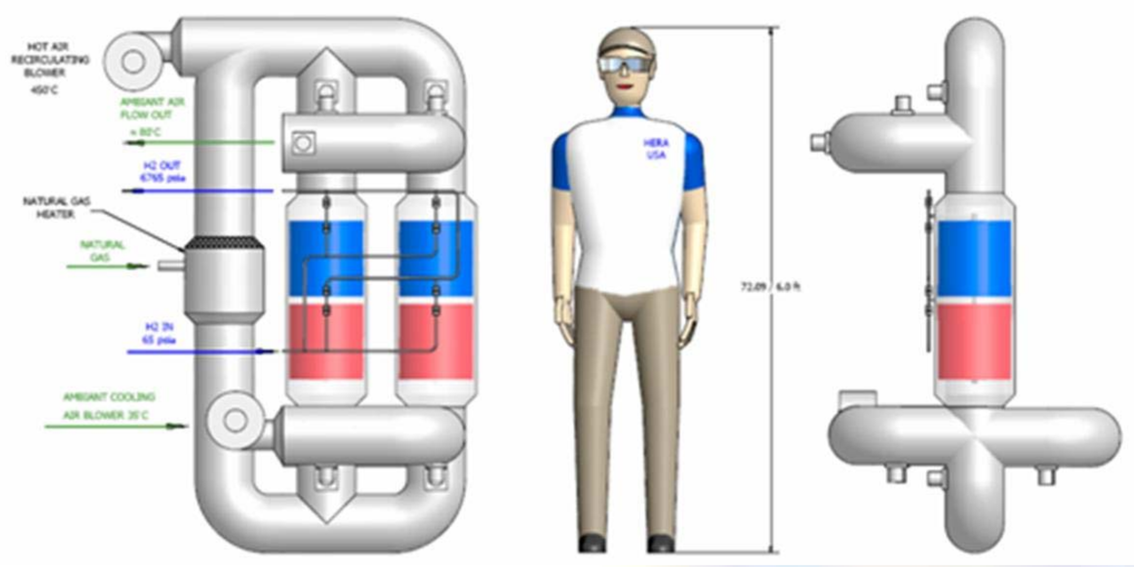


Reactor Test Stand

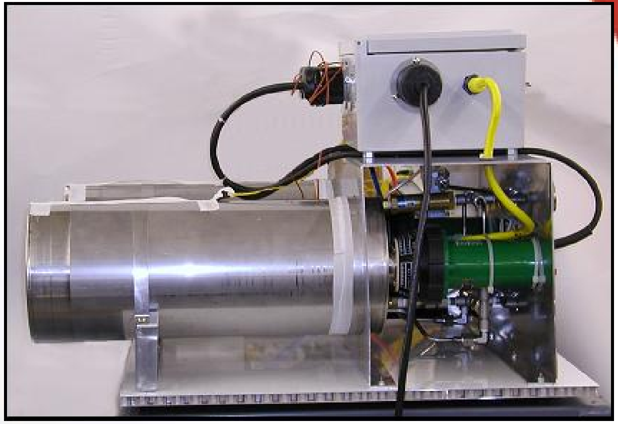
Typical membrane module

- Fluidized bed reactor (well-mixed catalyst particles; uniform temperature)
- Thermodynamic equilibrium shift of reforming and shift reactions
- Oxidant (air) added to supply part or all of the energy needed for reforming
- H_2 withdrawn with vacuum to increase production

Compressor Configuration



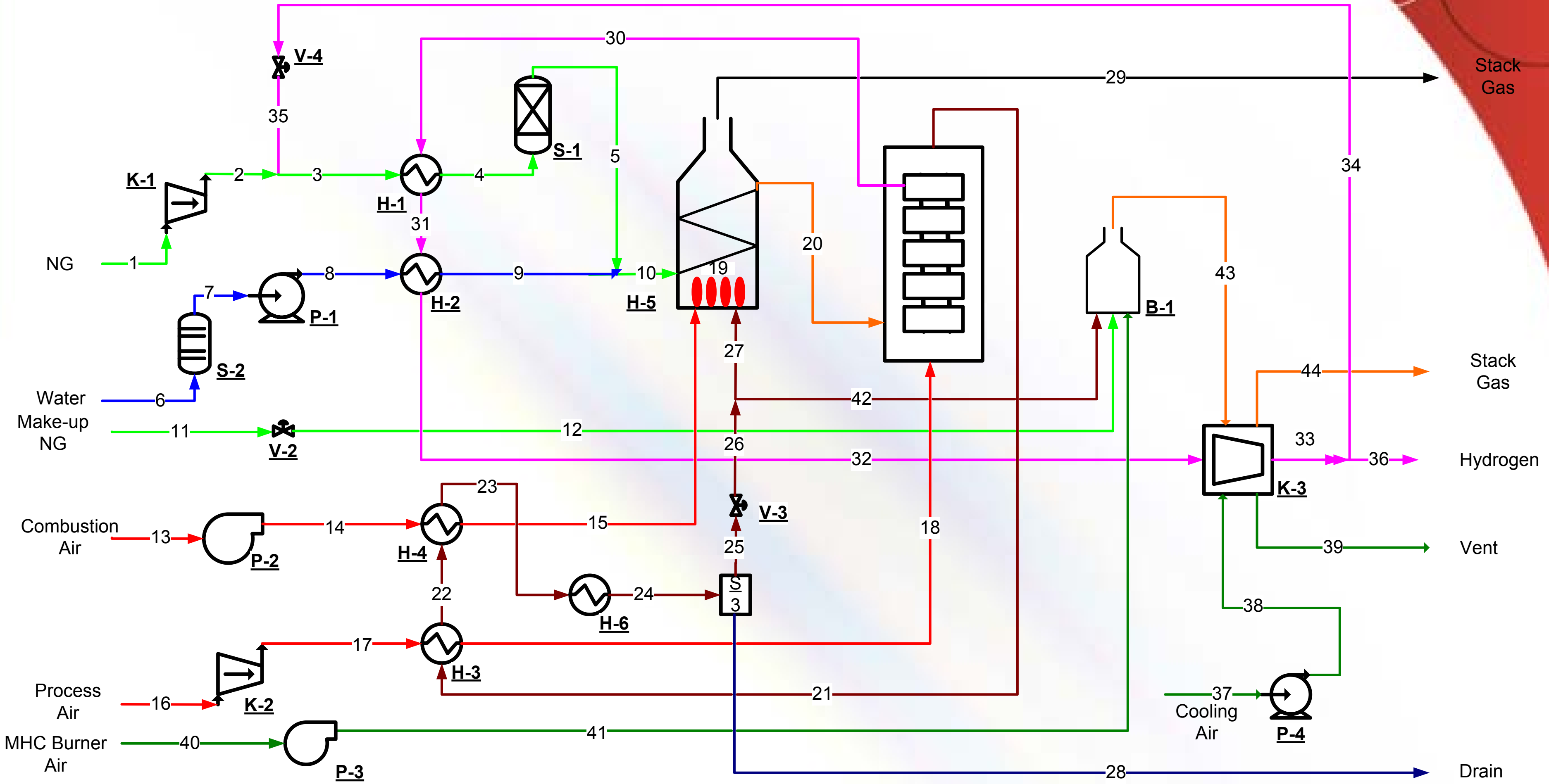
Hot Gas Metal Hydride Compressor (MHC)



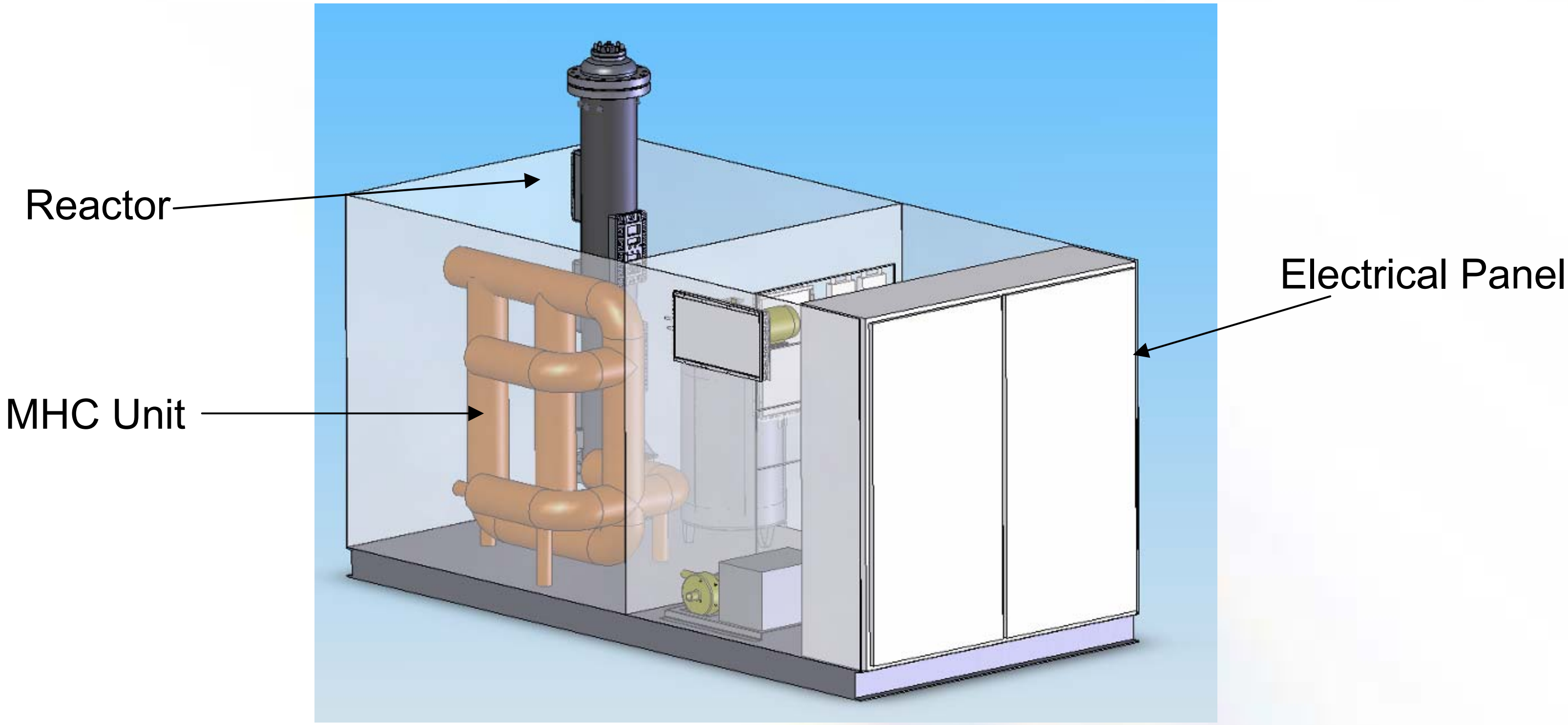
Experimental
Hot Gas Heated MHC

- Metal Hydride Compressor provides sub-atmospheric inlet operation
- New hot gas design concept uses higher-temperature heating
  - Improves efficiency and reduces number of stages to lower cost, (compared to liquid-based heating and cooling system)

Schematic of the POC System



Skid Layout of Integrated POC Unit



LENGTH:	12 ft
WIDTH:	6 ft
HEIGHT:	6'-6" (10' including reactor)

ENCLOSURE COMPARTMENTS:

1) electrical panel
2) cool box
3) hot box

Project Milestone Cost Targets

Attribute	**POC System (1st gen.)**	**AP System (2^{nd} gen.)**	**DOE Final Commercial System**
Nominal H_2 rated capacity	15 Nm^3/hr	15 Nm^3/hr	Up to 670 Nm^3/hr
Nominal H_2 rated capacity	1.4 kg/hr	1.4 kg/hr	Up to 62.5 kg/hr (1500 kg/day)
H_2 Product Pressure	100 barg (1500 psig)	435 barg (6500 psig)	100 barg (1500 psig)
Product H_2 purity	Fuel cell grade[1]	Fuel cell grade[1]	Fuel cell grade[1]
Cost of H_2 produced	$4.72/kg[2]	$2.81/kg[2]	$1.50/kg at a production volume of 200 units/yr.
Capital Cost (DMDL)	<$US 500k for one unit @ 15 m^3/hr output	<$US 400k for one unit @ 15 m^3/hr unit	Refer to cost of H_2 produced

1 Hydrogen purity that meets CaFCP and/or other H_2 fuel product quality guidelines
2 Hydrogen cost target assumes scaling capacity from 15 to 670 Nm^3/hr at a production volume of 200 units/yr.

Summary of Technical Accomplishments

- Various reformer-membrane configurations and options were studied and reformers with integral membranes and planar architecture were chosen because of
  - High membrane area / catalyst volume ratio; more compact reactors; and ease of fabrication
- ATR and SMR systems were compared using modeling techniques and by experimentation
- Different options for heat integration between the reactor (FBMR) and compressor (MHC) modules were explored using process simulation
- Experimental evaluation of a combined FBMR-MHC system completed
  - Designed and tested a lab-scale MHC integrated with the lab FBMR unit
- Detailed design of reformer / compressor components completed
- Efficiency versus capital cost calculation and economic analysis of the system completed using H2A model and proprietary analysis tools

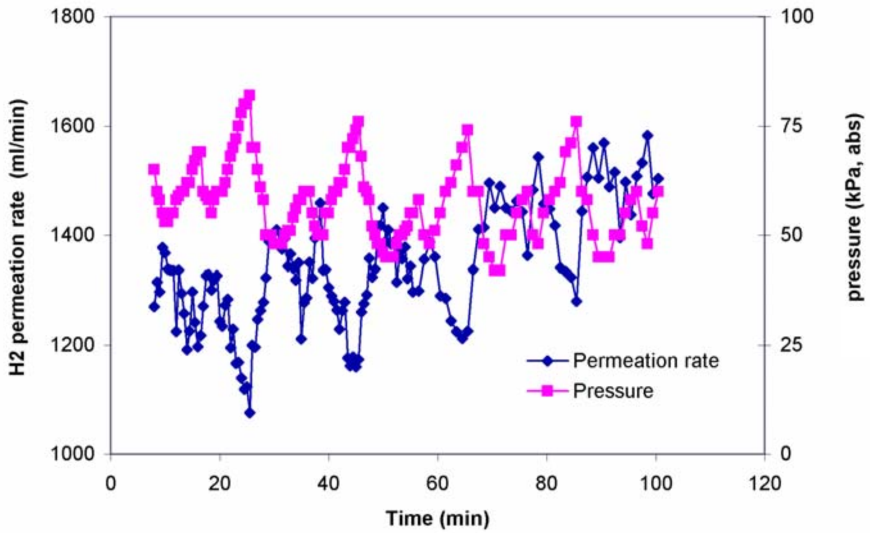
SMR vs. ATR Analysis

- SMR reactor is 30% larger and heavier than ATR due to extra heat transfer surface area needed
- ATR Air Compressor costs are offset by the additional cost for the larger SMR reactor
  - Incremental Air Compressor power requirements are only 1.5 kW or \$0.07/kg H2
- Reformer efficiencies for both ATR and SMR systems were within 2%
  - 75% on an LHV basis for reformer alone
  - Minimum 55% overall system efficiency (including compression) for POC
- Heat flux and heat transfer area requirements for a future SMR reactor with <15 micron membranes is a limiting design factor
- In ATR design, fluidized catalyst provides better heat transfer & unique ATR design minimizes N2 dilution effect at membrane

Hot Gas Heating System for Compressor

- Advantages:
  - Two stages instead of four or five reduces the number of heat exchangers, associated hydride beds and hydrogen circuit complexity
  - Higher efficiency
  - Lower capital cost and small footprint
- Challenges:
  - Large diameter gas piping must be detonation resistant
  - Locating / fabricating components for circulating hot gas

FBMR-MHC pilot-scale performance tests. The MH compressor maintained vacuum conditions at the membrane outlet while hydrogen flux responded to changes in suction pressure.



Delivered H2 Cost Estimates (1st Gen. plant design)

		Base case	Case 1	Case 2	Case 3
flowsheet		POC	POC	POC	POC
H2 capacity	Nm3/hr	15	15	50	670
H2 delivery pres.	psig	1500	6500	6500	6500
volume	units/yr	1 proto	20	200	200
Natural Gas Cost	$US/kg	1.86	2.07	2.07	2.07
Electricity Cost	$US/kg	0.44	0.44	0.44	0.44
O&M (except Membrane Replacement)	$US/kg	0.75	0.57	0.40	0.33
Membrane Replacement	$US/kg	2.40	0.71	0.62	0.59
Property Taxes + Insurance	$US/kg	1.15	0.70	0.27	0.11
Capital Recovery	$US/kg	4.24	3.73	1.29	0.43
Total	**$US/kg**	**10.84**	**8.22**	**5.09**	**3.97**

Estimated Cost Reduction with Advanced Prototype

		Case 2	**Case 8**
flowsheet		POC	AP
H2 capacity	Nm3/hr	50	50
H2 delivery pres.	psig	6500	6500
volume	units/yr	200	200
Natural Gas Cost	$US/kg	2.07	1.88
Electricity Cost	$US/kg	0.44	0.42
O&M (except Membrane Replacement)	$US/kg	0.40	0.30
Membrane Replacement	$US/kg	0.62	0.23
Property Taxes + Insurance	$US/kg	0.27	0.23
Capital Recovery	$US/kg	1.29	0.99
Total	**$US/kg**	**5.09**	**4.04**

Tighter integration, higher efficiency

2 years versus 1 year

Key Results

EXPERIMENTAL FINDINGS

- The 25-micron membranes, catalyst, and reactor conditions proposed for the POC delivered acceptable performance and produced < 1ppm CO, <5 ppm CO2, < 2 ppm CH4 at the end of life [equipment detection level limited]
- 25-micron membrane modules are now produced without flaws and 100% of theoretical flux through improved production process
- An FBMR successfully operated at steady state with sub-atmospheric H_2 discharge supplied by a hot air heated MHC

Key Results

SYSTEM ECONOMICS

- Technically viable design developed for a single complete POC unit - 15 Nm^3/hr H_2 at 1500 psig with delivered hydrogen cost of ~10.84 $/kg
- Cost for a scaled up version (670 Nm^3/hr at 6500 psig) of the POC unit in volume production (200 units/yr.) is estimated to be $3.97/kg H_2
- The MHC cost accounted for between 18-27% of the total direct material and labor costs for 15-50 Nm^3/hr hydrogen
- Balance of plant equipment (BOP) costs account for 38 to 55% of the equipment cost
  - BOP cost reduction will be a focus through the development stages

Status and Future Work

- Task 2 – Proof of Concept prototype (Apr. 06 – Mar. 07)
  - Complete POC design, safety review and parts ordering
    - Detailed design (P&ID), and safety review in progress
    - Complete production details finalized; ordering parts for reactor
  - Fabrication / assembly / testing
    - Vendors selected, test plan developed
  - Deliverable: Report summarizing POC test results
- Task 3 – Advanced Prototype unit (Mar. 07 – Mar. 08)
  - Design / fabrication / assembly / testing / report
- Task 4 – Develop concept for mass production (Apr. 08 – June 08)
  - Deliverable: Report providing final design to meet DOE targets

Summary

Accomplishments

- Significant progress made through experimental testing of individual components as well as the integrated system at bench scale
  - Compressor cyclic operation had no adverse effect on membrane reactor
- Extensive modeling, simulation and design efforts to compare various options and to arrive at the best integrated system design for POC
- Economic analysis completed to establish cost estimates for various cases with varying product pressures, plant capacities and unit production volumes

Plans

- Build and test for 3 months a 15 Nm^3/hr POC unit capable of delivering H_2 at 1500 psig to obtain baseline data
- Identify optimization opportunities for the BOP in Task 2
- Use data and operational experience with the POC to further optimize the overall system and to complete a design for the AP unit

Thank You!

Questions?

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Risks and Uncertainties

- Unknown robustness and life of critical items, e.g., thin membranes, rotating equipment & high-temperature switching valves
- Several prototype MHC units have been built, however
  - Capacities as large as 15 Nm^3/hr have not yet been attempted
  - Hot gas heating system needs to be developed and tested
- Need considerable operational experience with an integrated system for optimization / process improvements
- Further analysis of volume discount factors required to reduce the uncertainty associated with the delivered hydrogen cost estimates
- **Nevertheless, there are still two more complete design cycles in the project with scope for improvements to hit the cost targets**