# Integrated Hydrogen Production, Purification and Compression System

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*This presentation does not contain any proprietary or confidential information*

**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

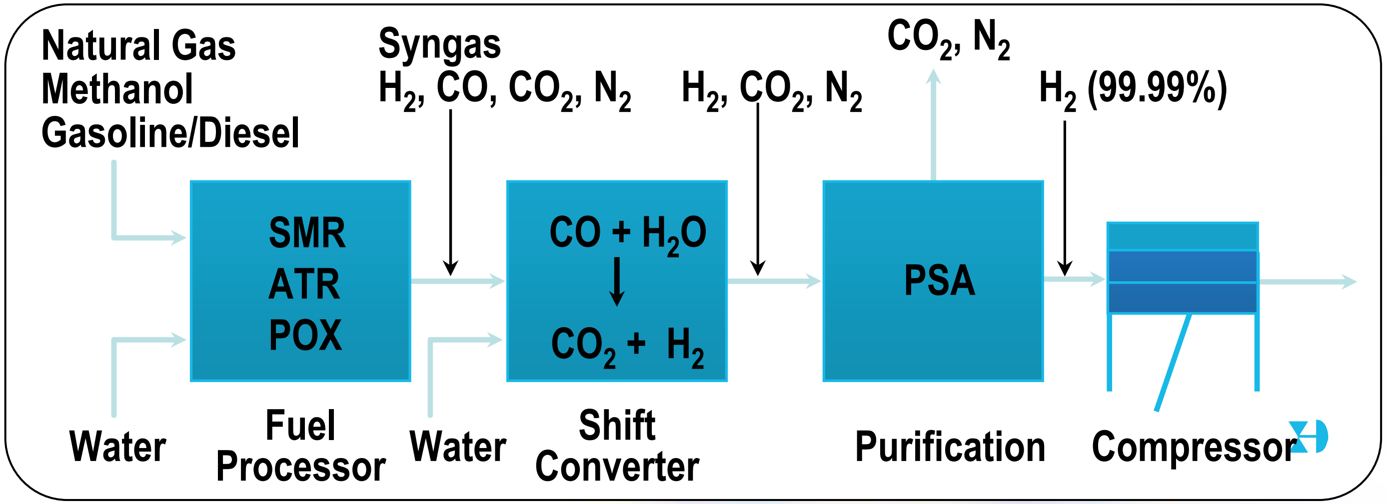
# Program Objectives

- **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

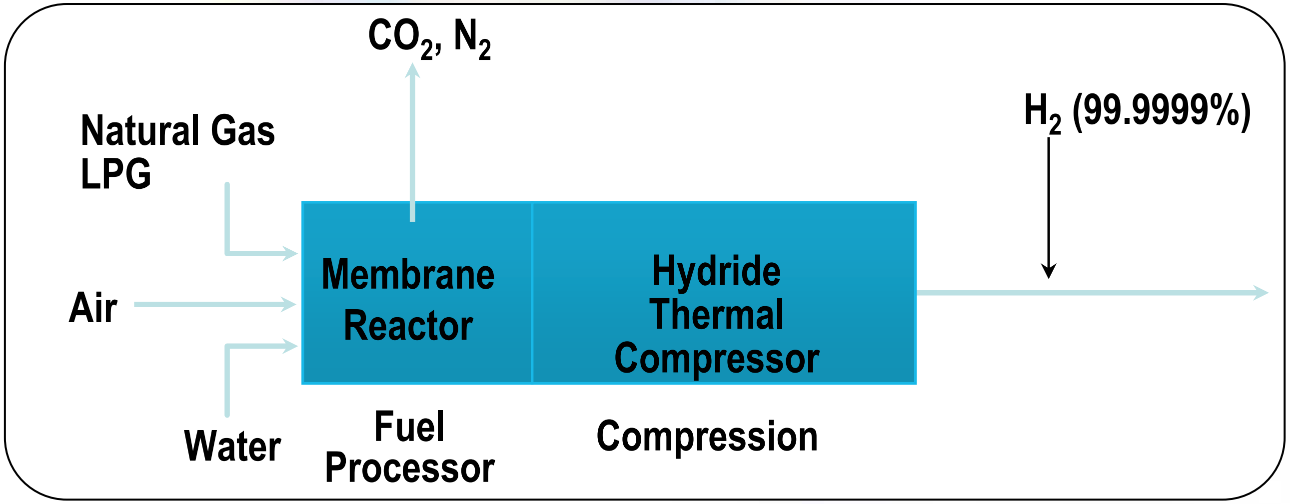
- Integrate the membrane reformer developed by Membrane Reactor Technology (MRT) and the MHC system developed by HERA USA in a single package
  - Lower capital cost compared to conventional fuel processors by
    - *reduced component count and sub-system complexity*
    - *thermal integration of all 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

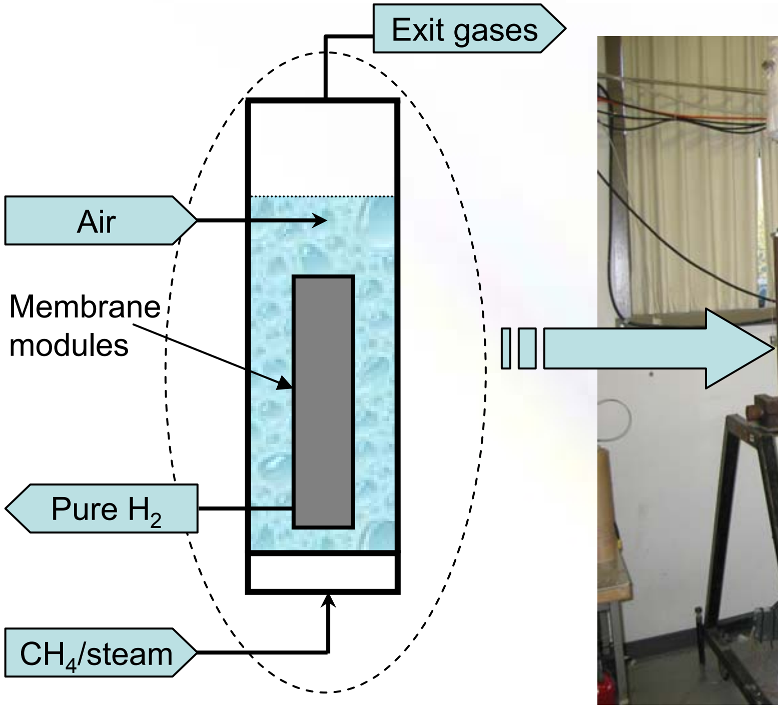


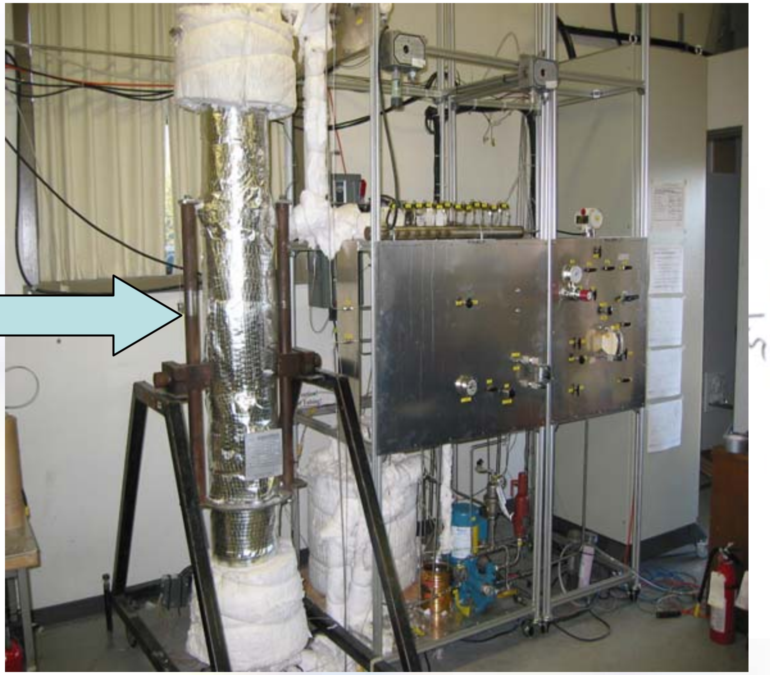

Conventional

Proposed System



# Membrane Reactor Configuration



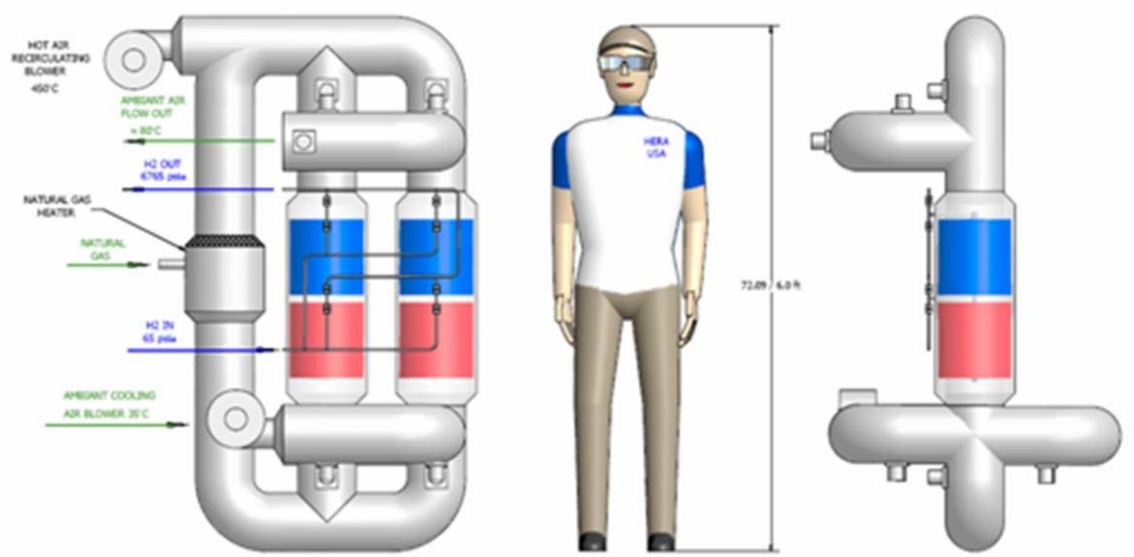
**Reactor Test Stand**

Typical membrane module

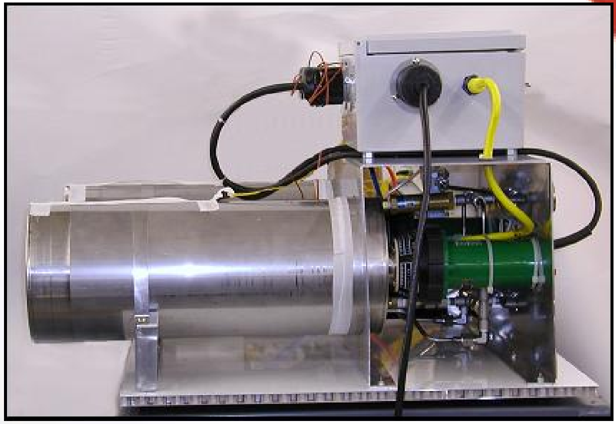
- Fluidized bed reactor (well-mixed catalyst particles; uniform temperature)
- Thermodynamic equilibrium shift of reforming and shift reactions
- Oxidant (air) added to supply part or all of the energy needed for reforming
- $H_2$ withdrawn with vacuum to increase production

# Compressor Configuration





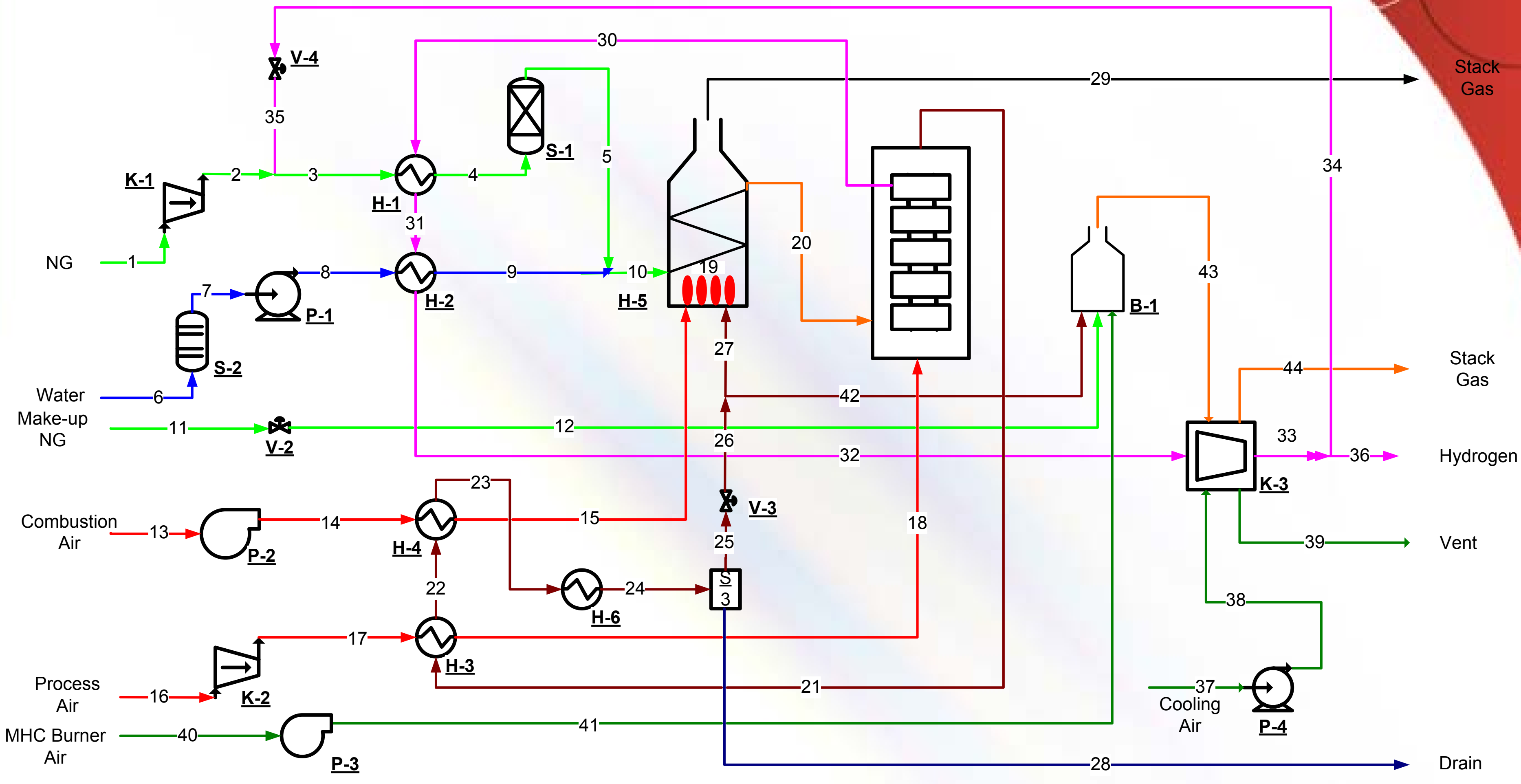

Hot Gas Metal Hydride Compressor (MHC)



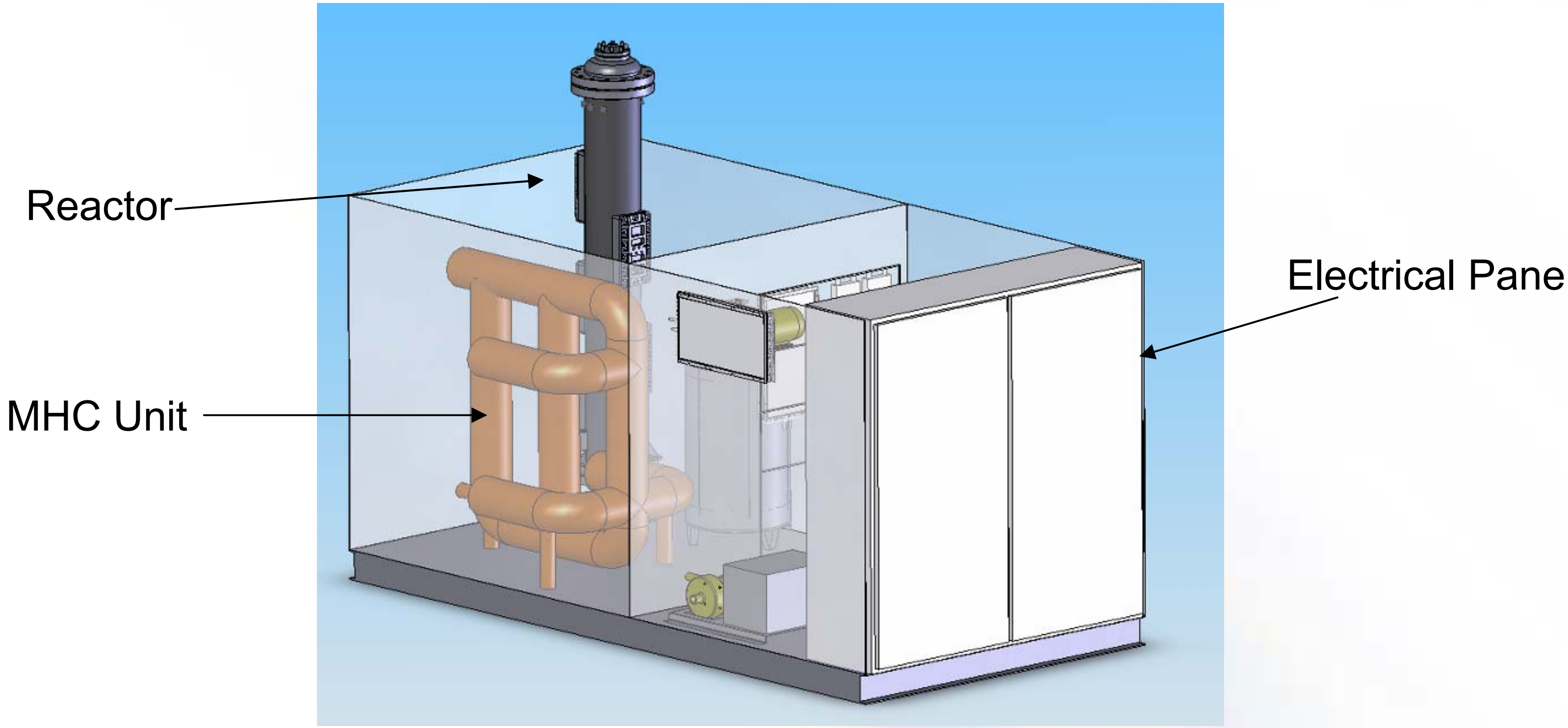
Experimental
Hot Gas Heated MHC

- 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 (2nd 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

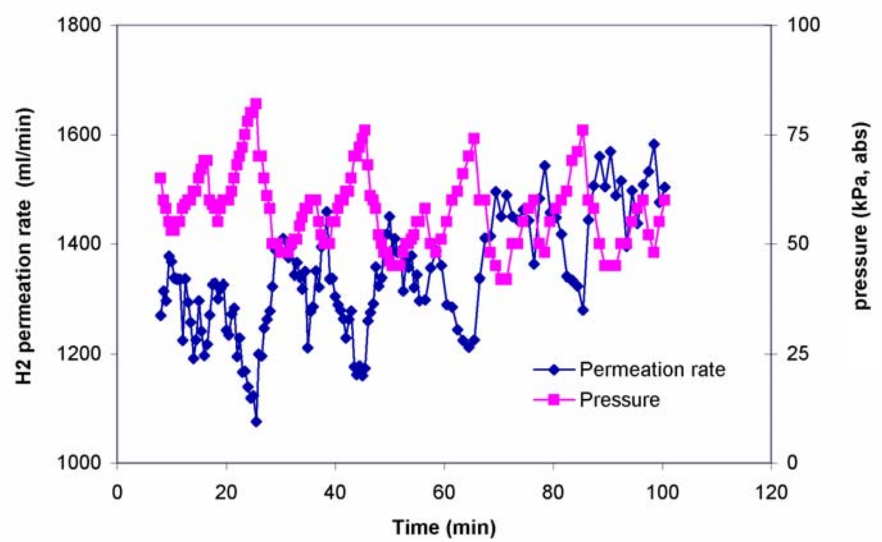
# SMR vs. ATR Analysis

- 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**