DOE Hydrogen Program

Integrated Hydrogen Production, Purification and Compression System

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Project ID # PDP_29_Tamhankar

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Overview

Timeline

- Project start date – April 1, 2005
- Project end date – TBD
- Percent complete: 60
- Phase 1 completion: June 2009

Barriers addressed

- Production Barriers
  - Capital and O&M Costs
- Delivery Barriers
  - Reliability and Costs of Hydrogen Compression

Budget

- Total project cost:
  - Phase 1 - $ 3,347,408
  - Phase 2 - $ 986,274 (estimate)
- DOE share – 65%
- Phase 1 Funding:
  - FY08: $ 310,834
  - FY09: $ 0

Partners

- Key partners:
  - MRT
  - Ergenics Corp.
- Other collaboration/interactions:
  - University of British Columbia
  - National Research Council
  - Noram Engineering

Program objectives

Develop an integrated system that directly produces high pressure, high-purity hydrogen from a single unit.

Phase 1:

- **Task 1:** Verify feasibility of the concept, perform a detailed techno-economic analysis, and develop a test plan
- **Task 2:** Build and experimentally test a Proof of Concept (POC) integrated membrane reformer / metal hydride compressor system

Phase 2:

- **Task 3:** Build an Advanced Prototype (AP) system with modifications based on POC learning and demonstrate at a commercial site
- **Task 4:** Complete final product design capable of achieving DOE 2010 H_2 cost and performance targets

Targets for Phase 1

POC performance

- Production capacity of 15 Nm3/hr
- Hydrogen output pressure of 100 bar
- Hydrogen purity of 99.99% (Fuel cell grade)
- Production unit efficiency of 71% and compression efficiency of 69% (at compression ratio of 216)
- Continuous run time of >400 hr

Techno-economic analysis

- Feasibility of hydrogen gas cost of $4.72/kg

Milestones and decision points

	Key Task	Milestones	GO / NO GO Decision Points	Date
Phase 1	Techno-economic assessment	Concept validated at lab scale	Feasibility of system integration confirmed	Feb-06
		Preliminary system design and economic model developed	Potential of achieving the cost target of \$2/kg H_2 for a commercial system verified	
	Proof Of Concept (POC) prototype	Unit commisioned with output capacity of 15 Nm^3/hr, FC grade H_2 at 100 bar	Integration of FBMR & MHC proven. System operability demonstrated	Jun-09
		Test data gathered and analyzed	Initial gas cost target of \$4.72/kg H_2 at FBMR and MHC efficiencies of 71 and 69% respectively validated	
Phase 2	Advanced Prototype	Unit commisioned with output capacity of 15 Nm^3/hr or higher, FC grade H_2 at 435 bar	System operability demonstrated; improvements over POC validated	TBD
		Test data gathered and analyzed	Intermediate gas cost target of \$2.81/kg H_2 at DOE LHV efficiency validated	
	Final system design for mass production	Commercial system designed and mass production concept defined	Feasibility of achieving final cost target of \$2/kg at 1500 kg/day and 500 units/yr scale demonstrated - Dec. 2009	TBD
		Final cost estimation and economics assessment completed		

Novel approach to low-cost, forecourt H2 production, purification and compression

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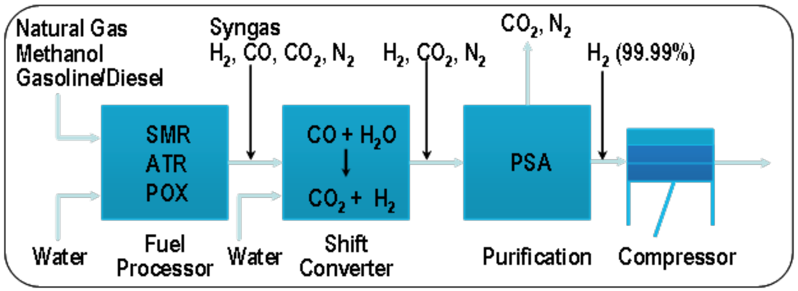
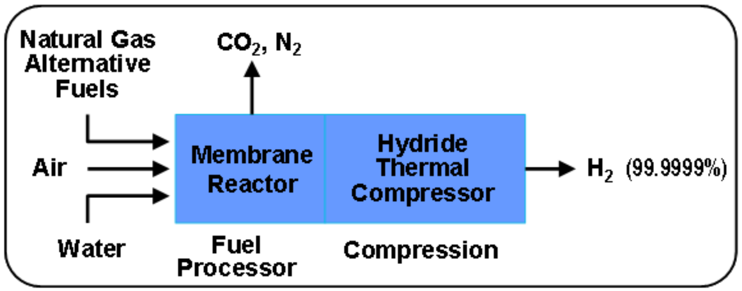
Integrate the membrane reformer developed by Membrane Reactor Technology (MRT) with the metal hydride compressor (MHC) developed by Ergenics in a single package



Conventional



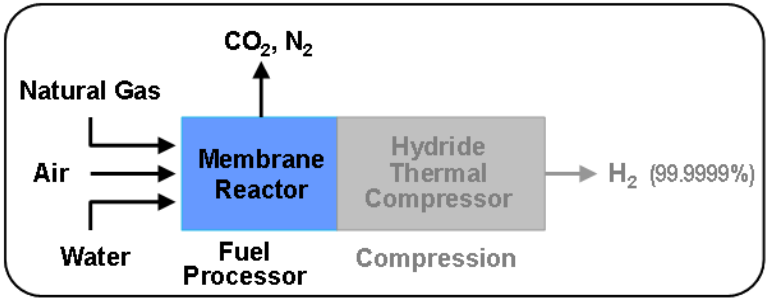
Proposed System

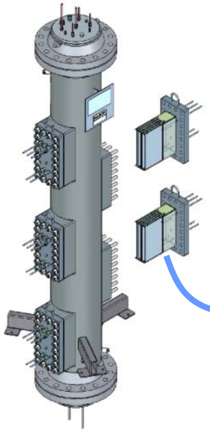
- Lower capital cost compared to conventional fuel processors by reducing component count and sub-system complexity.
- Increase efficiency by:
  - directly producing high-purity hydrogen using high temperature, H_2 selective membranes; increased flux due to suction provided by the hydride compressor
  - improved heat and mass transfer due to inherent advantages of fluid bed design
  - equilibrium shift to enhance hydrogen production in the reformer by lowering the partial pressure of hydrogen in the reaction zone
  - using excess heat from reformer to provide over 20% of compression energy

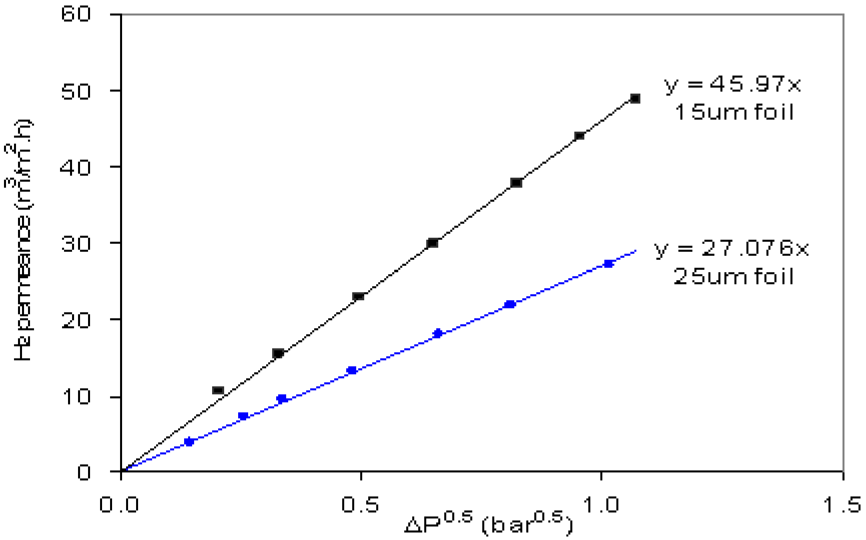
Reformer design is compact and allows uniform temperature and a high H_2 flux

Auto-thermal Fluidized Bed Membrane Reformer (FBMR)

- Reformer vessel design enables the use of lower cost metals (e.g. carbon steel)
- Novel membrane assemblies ease installation and maintenance



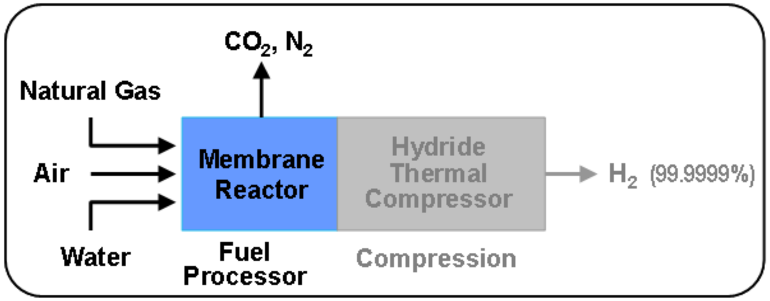




New Membrane Design

- Membranes operate at 550ºC, 25 bar
- Large area, planar membrane modules installed and tested in multiple POC runs; modules included two membrane sizes (6” and 4¼” x 11” x ¼”), both with double-sided 25µm foils
- Thinner, higher-flux membranes (15µm foil) for reduced cost successfully tested in lab

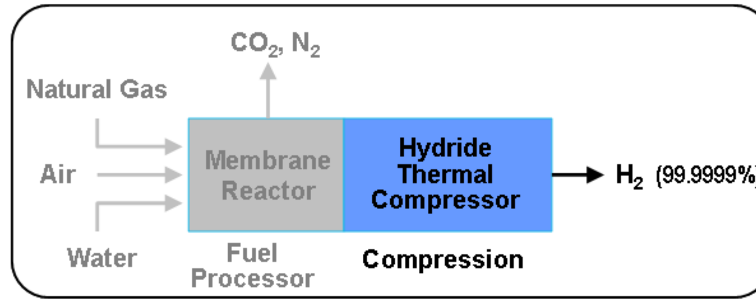
FBMR performance
Full membrane load results



- July 2008 Campaign (FBMR alone)
  - Over 65 hours at reforming conditions at both 20 and 25 barg
  - Maximum production rate observed was 9 Nm3/hr
  - Maximum methane conversion of over 60% achieved
  - Axial temperature gradients less than 10°C
  - Reactor effluent (ROG) successfully routed to process burner to preheat reactor feeds and to generate steam
- Purity issues observed during operation and shutdown
  - Discussions with membrane supplier revealed that foil quality diminished due to exceeding width tolerances on current foil rolling machine
    - Decision made to temporarily reduce module width from 6” to 4.25”
    - New rolling machine for high quality 6” foil to be operational in Fall 2009
  - Other potential mechanisms under investigation in parallel with 3rd parties

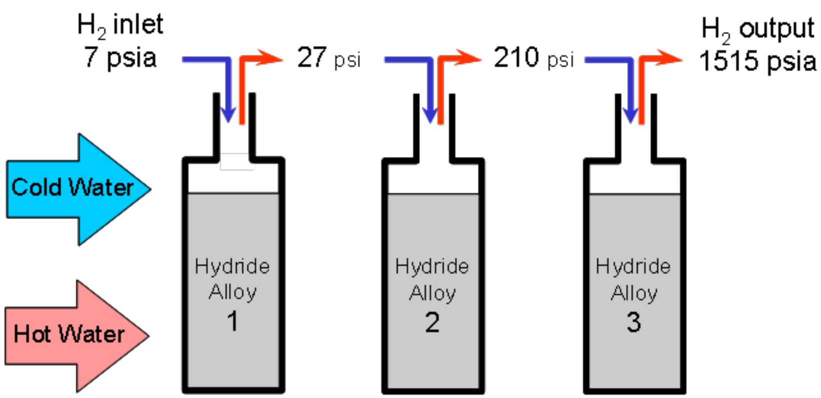
The metal hydride compressor uses thermal rather than electrical energy

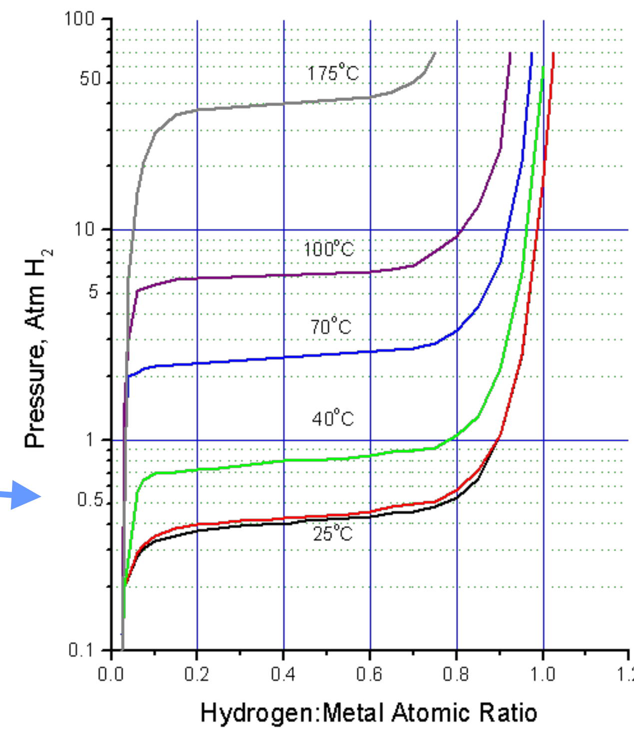
- Multi-stage metal hydride hydrogen compressor creates work (pressurized gas) from heat.
- Ergenics engineers the composition of hydride alloys to operate at different pressures.
- Staging progressively higher pressure alloys lets the hydride compressor achieve very high pressures, using only the energy in hot water.



Step 2: Hot fluid heats the alloy causing the hydrogen to be released with an exponential increase in pressure.

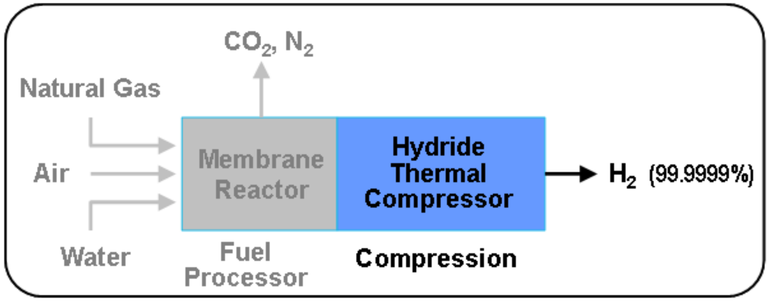
Step 1: Low pressure hydrogen is absorbed by an alloy at ambient temperature.

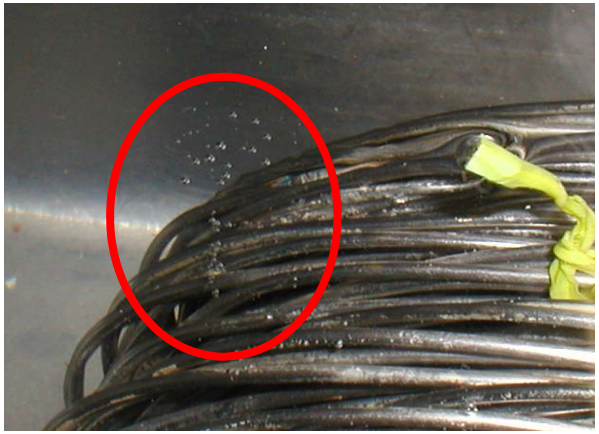




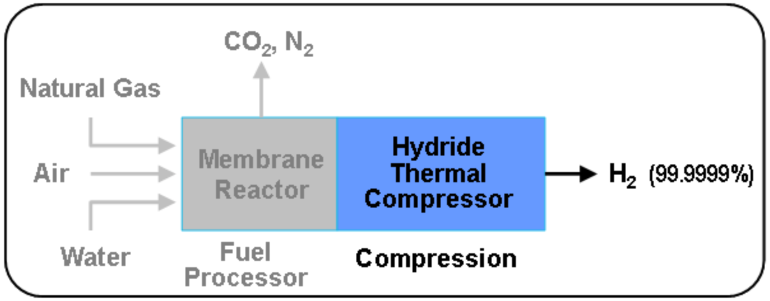
MHC performance - ring manifold hydride heat exchangers developed leaks

- Miniature hydride heat exchangers retain hydride alloy within 1/16” dia. tubes.
- After initial operation, leakage was observed in tube joints and tube walls.
- Repairs restored 5 of the 6 hydride heat exchangers; the MHC was shipped without one of its stage 3 beds.
- Leak issue is being resolved
  - Material compatibility and joining procedures for tube joints have been significantly improved
  - Improved annealing shows promise for tube walls
- With the stage 3 bed removed, the MHC achieved:
  - >250 L/m (the design flow rate) with two stages of compression (7 psia in, 200 psia out)
  - 70% of the design flow rate at the design outlet pressure of 1515 psia (CR=216)





MHC skid assembly completed, installed at test site and started up in March 2009



Less than 0.5 bara (7 psia) suction pressure

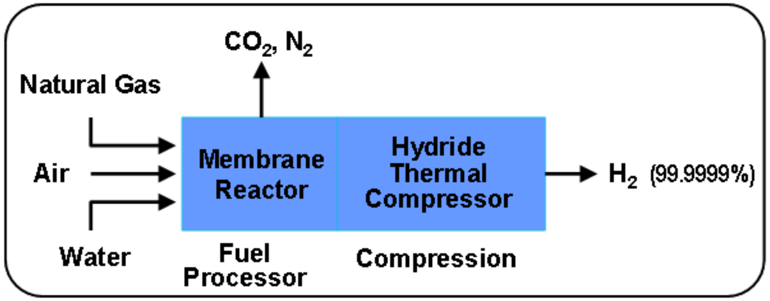
>105 bara (1,515 psia) discharge pressure

Above Left: The two MHC hydride beds are small and compact

Above Right: The MHC (foreground) is adjacent to the FMBR skid

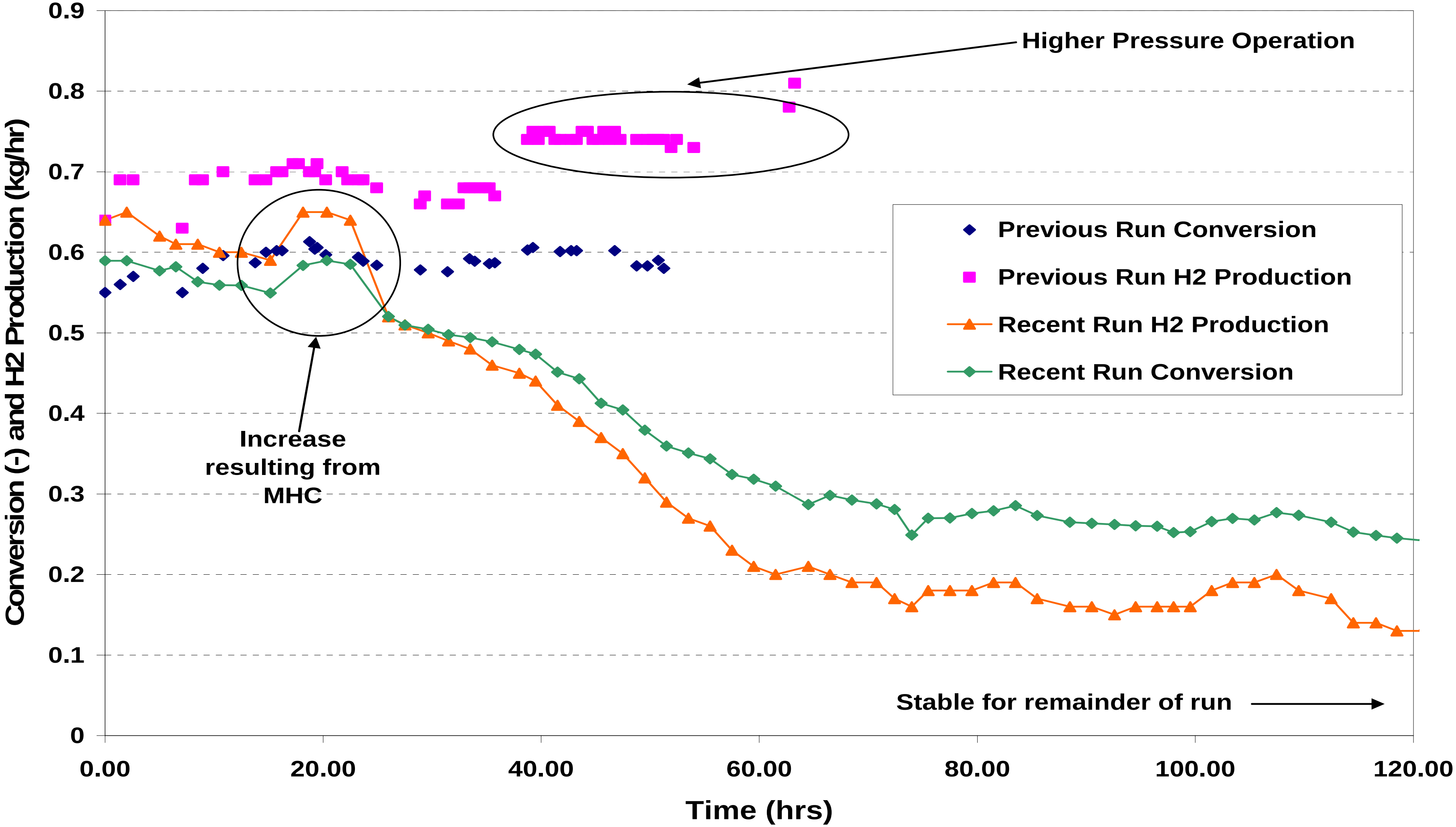
The next generation system will have a higher level of integration, eliminating the MHC balance-of-plant water heater, fan cooler and control panel.

System performance
Results of integrated system tests



- **First round of tests completed**
  - Lower production rate expected due to the reduced membrane area (resulting from narrower modules)
  - System was continuously operated for >425 hours, including one week of unattended operation
- **Initial FBMR results agreed with model predictions**
  - > 7 Nm3/hr production (without boost from MHC operation)
  - Methane conversions of > 60%
- **Performance decreased, possibly due to partial catalyst deactivation**
  - Behavior not seen in previous runs and is under investigation
- **FBMR conditions stable during integrated system operation**
  - MHC cyclic operation has minimal impact on FBMR temperature and pressure.

System performance - Reduced activity, not observed in previous runs



System Performance – MHC thermal cycles do not impact FBMR operation

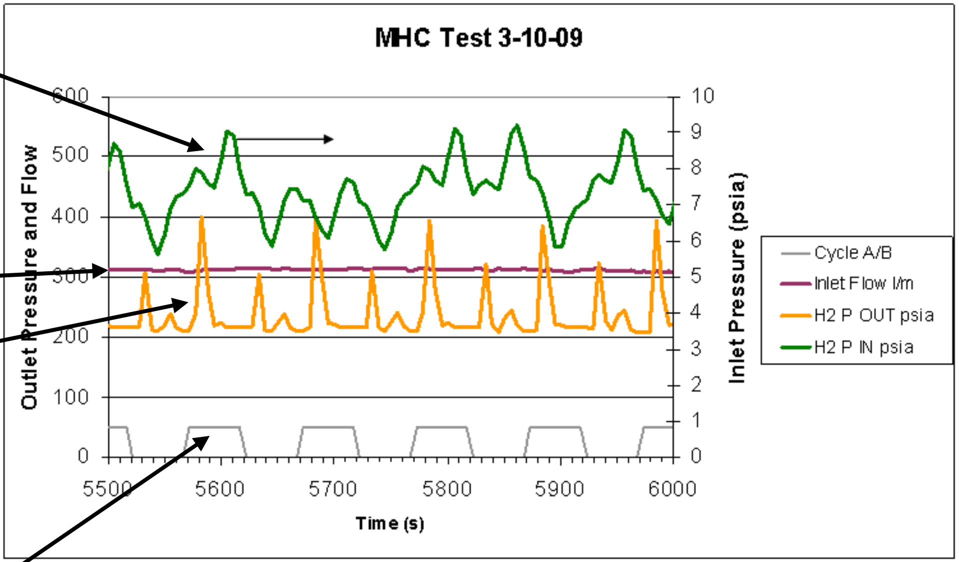
On regulated cylinder H2, suction pressure (2Y axis) varies from 6 psia to 9 psia with each half-cycle.

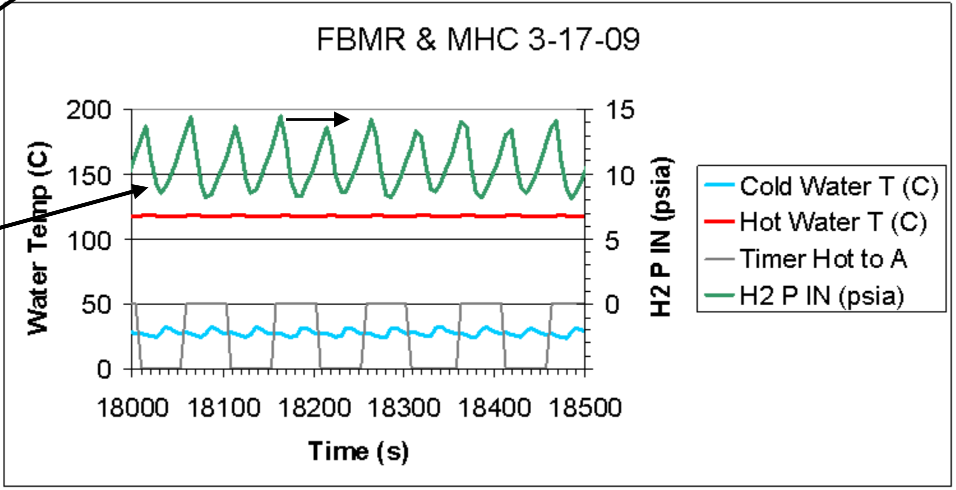
H2 suction flow rate is nearly constant at 310 L/m.

Outlet H2 is released through a back-pressure regulator, in this case set at the 2nd stage pressure of 210 psia.

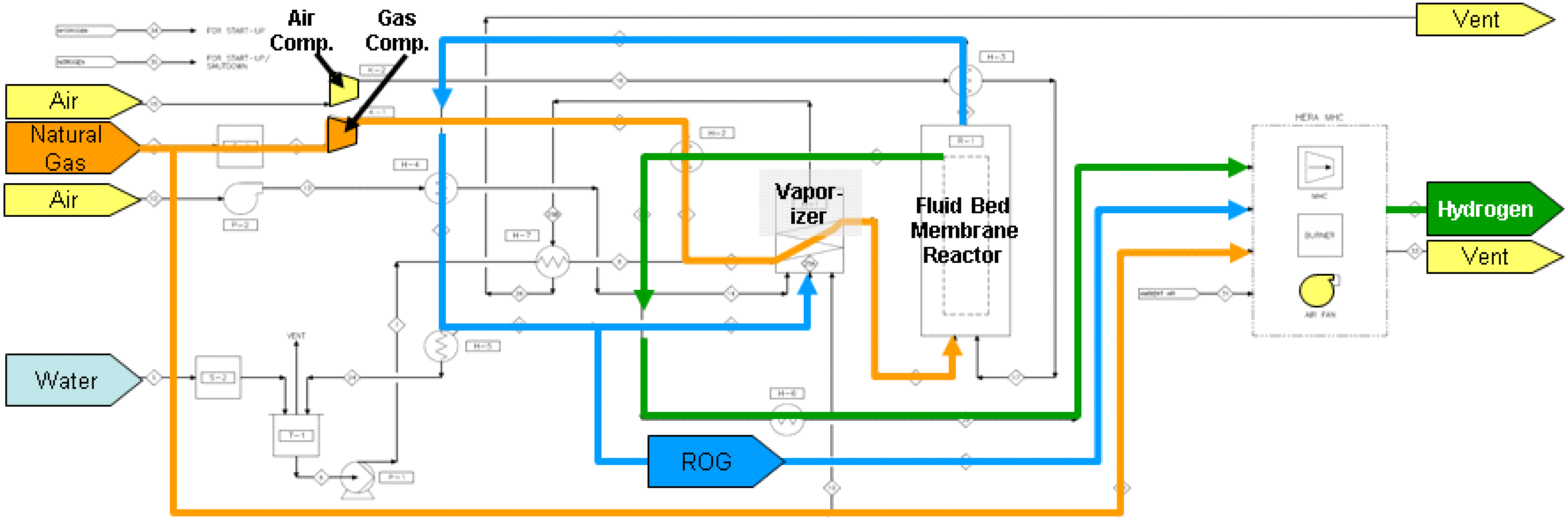
Hydride beds are alternately heated or cooled every 50 seconds by a timer.

During integrated FBMR-MHC operation, H2 suction pressure was sub-atmospheric and varied between 8 and 14 psia.





H2A Analysis - System Definition



Key Features

— High purity H2 is produced using Pd membranes within the reactor

— MHC maintains 7 psia suction pressure and discharges at 6250 psia; CR=900

— Natural Gas is primary feed and energy source for compressor

H2A Assumptions

— Capacity: 100 kg/day

— Capital Costs:

—H2 Production: $169,879

—MHC: $66,023

— Natural Gas: $5.24/MMBTU; 983 BTU/$ft^3$

— Electricity: $0.08/kWh

H2A Analysis - Preliminary Results

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	Integrated System	H2A Current	Comments
H2 Production Unit Cost	138,486	175,000	
Compressor Cost	66,023*	26,250	MHC CR=900 vs H2A CR=21
Storage/Dispensing Cost	106,068	106,068	
Replacement Costs	15,258/y*	26,250 (in year 6)	Adds $0.46/kg to H2 Cost
Hydrogen Cost	$6.82/kg	$6.38/kg	
H2A Efficiency:			
Production Efficiency	71.1	63.5	LHV Basis
Compression Efficiency**	74.7	93.8	MHC CR=900 vs. H2A CR=21
Total Efficiency	58.6	62.2	
Primary Energy Efficiency:	Electricity consumption adjusted to primary energy (35%)		
Production Efficiency	63	56.5	
Compression Efficiency**	70.4	84.1	
Total Efficiency	51.9	53.7	

** Originally estimated in 2005. Recent experience indicates further reduction is possible.*
*** 50% increase may be possible resulting in H_2 cost reduction of $0.20/kg.*

H2A Analysis
Critical assumptions and potential issues

- The robustness and life of critical items, such as membranes and high temperature hydrides, need to be validated – these factors will impact plant reliability and O&M costs
  - Ongoing R&D and rigorous test plans to address these issues
- It is assumed that the Balance Of Plant (BOP) costs can be reduced
  - Staged development approach (POC and AP) to commercialization
  - Process optimization, design modifications and value engineering at each stage to continuously improve performance and reduce costs
- Scale up of membrane reactor as well as MHC and cost implications for the final commercial system
  - Progressive system scale up proposed through Laboratory, POC and Advanced Prototype stages to obtain real life performance data
  - Stage Gate approach for decision to proceed at each stage
- Cost estimates for the final commercial product rely on volume discounts associated with mass production
  - Rigorous analysis is planned in the final phase of the project to validate volume discount factors assumed in the preliminary cost estimation

Summary of status and future plans

- Current status
  - MHC installed and integrated with the reformer
  - Stand-alone testing of MHC and reformer completed
  - MHC and reformer operated together for limited time; testing curtailed due to low catalyst activity
  - H2A Analysis completed
- FY2009 Plans
  - Address open issues (reduced catalyst activity, H2 purity, MHC performance)
  - Continue tests with the integrated POC unit to determine its ability to meet the defined performance targets
  - Reach a GO / NO GO / Redirect decision regarding the next phase in June 2009 based on the test results and revised economics
- FY2009 - 10 Plans *(dependent on decision)*
  - If GO, complete design, construction and testing of the advanced prototype unit to validate design improvements, and demonstrate that the next phase cost and efficiency targets can be met in commercial production of the units
  - If REDIRECT, consider alternate paths for additional R&D based on Task 2 results to improve on the POC performance

More info? Contact us:

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