Integrated Hydrogen Production, Purification and Compression System

Satish Tamhankar and Rustam Sethna, The BOC Group, Inc. (A Member of The Linde Group)

Tony Boyd and Ali Gulamhusein, Membrane Reactor Technologies

Mark Golben and David DaCosta, Ergenics Corp.

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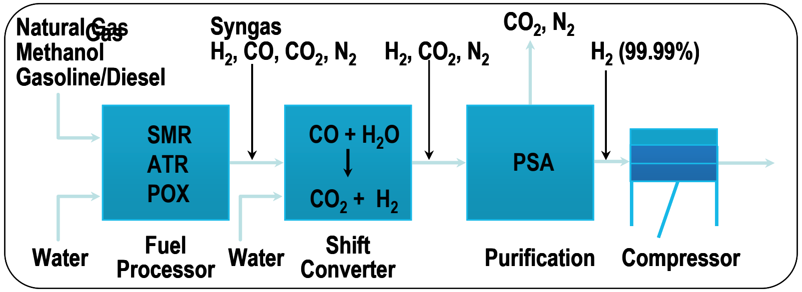
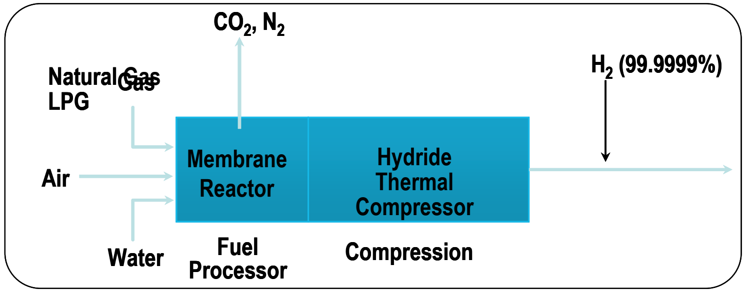
Approach

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



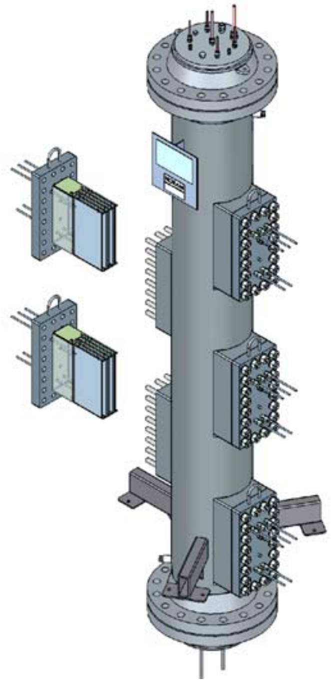
Conventional

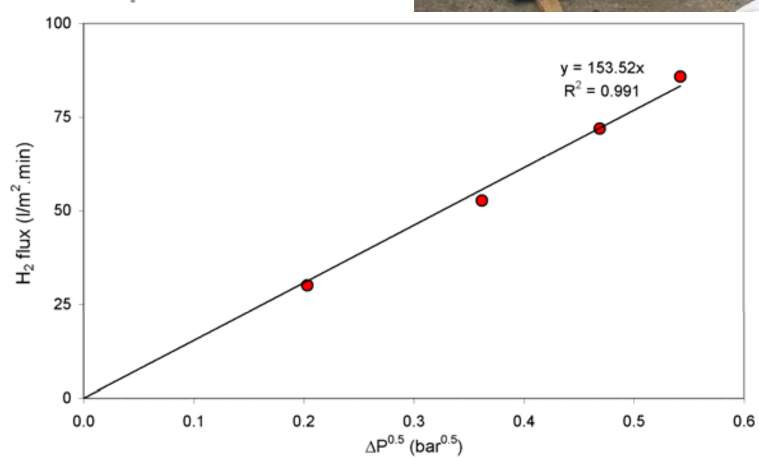


Proposed System

- 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, H2 selective membranes
  - 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

Fluid Bed Membrane Reactor



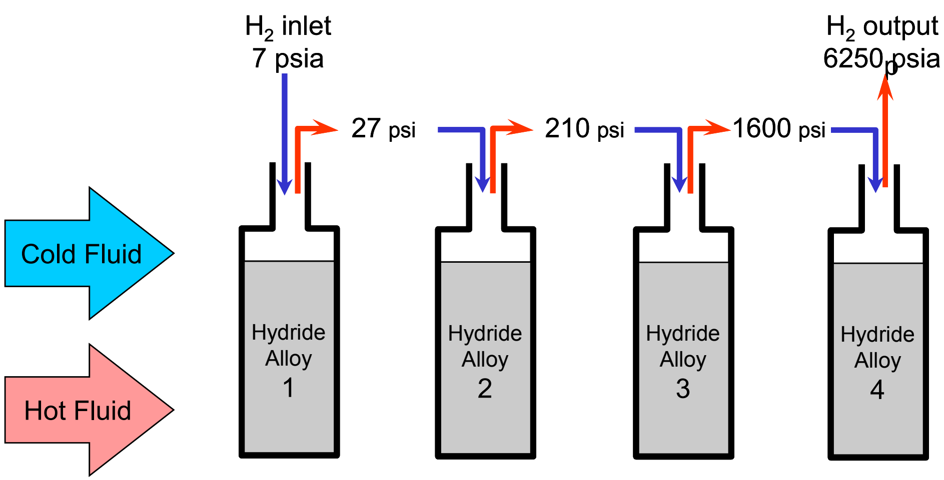


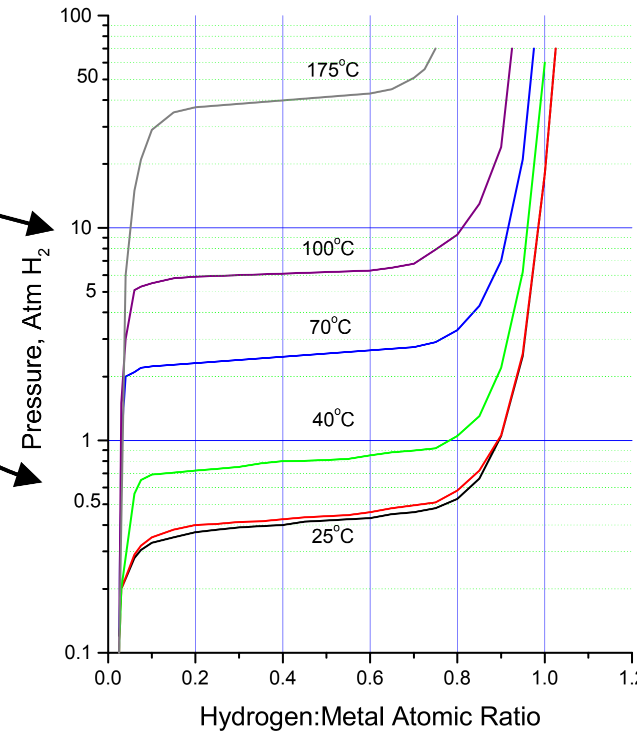
Metal Hydride Hydrogen Compressor

- 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 or hot air.

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.





System Definition

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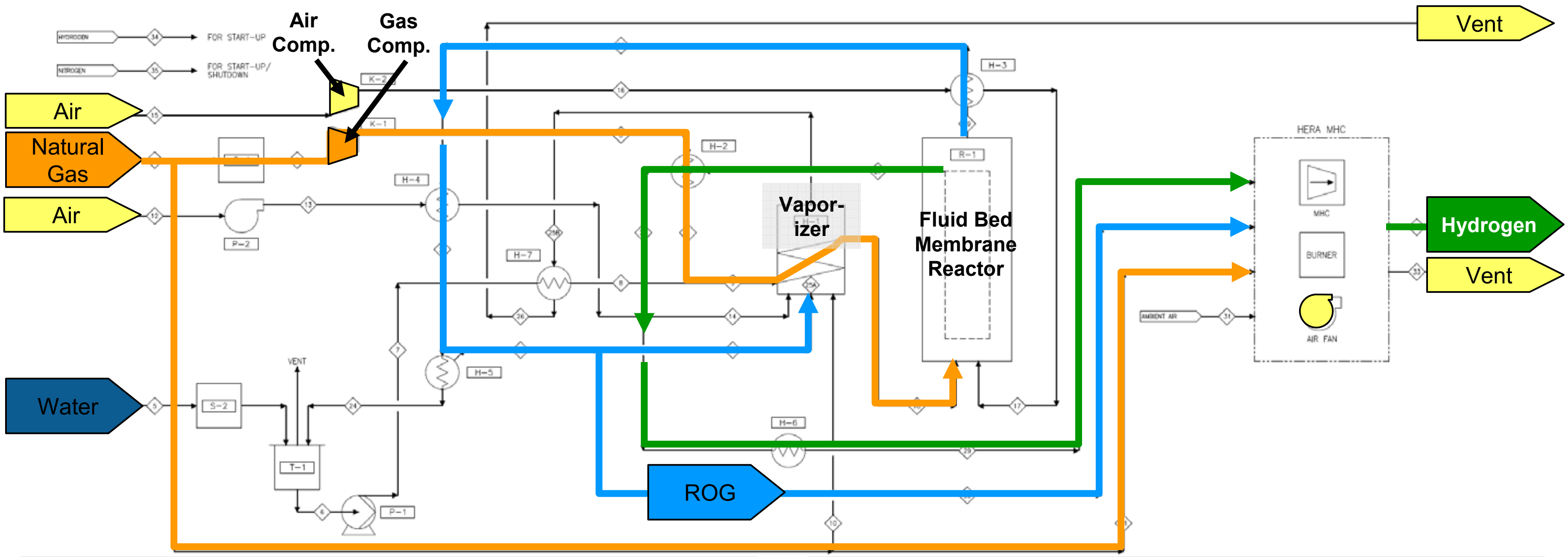

Key Features

- *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/ft³*
- *Electricity: $0.08/kWh*

Feed, Energy and Replacement Costs

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Primary Feed – Natural Gas

- *LHV: 48.7 MJ/kg (= 983 BTU/ft^3)*
- *Usage: 3.29 kg NG/kg H2; mol ratio = 2.6*
- *Cost: $0.24/kg*

Energy

- *Natural Gas to MHC: 0.735 kg NG/kg H2*
- *Electricity to Reformer: 2.5 kWh/kg H2*
- *Electricity to MHC: 1.5 kWh/kg H2*

Other Materials

- *Membranes $10,948/y*
- *Catalyst $4,335/y*
- *Desulfurization adsorbent $320/y*
- *Other (including labor) $3869/y*
- *Material recovery credit $4214/y*

H2A Preliminary Results

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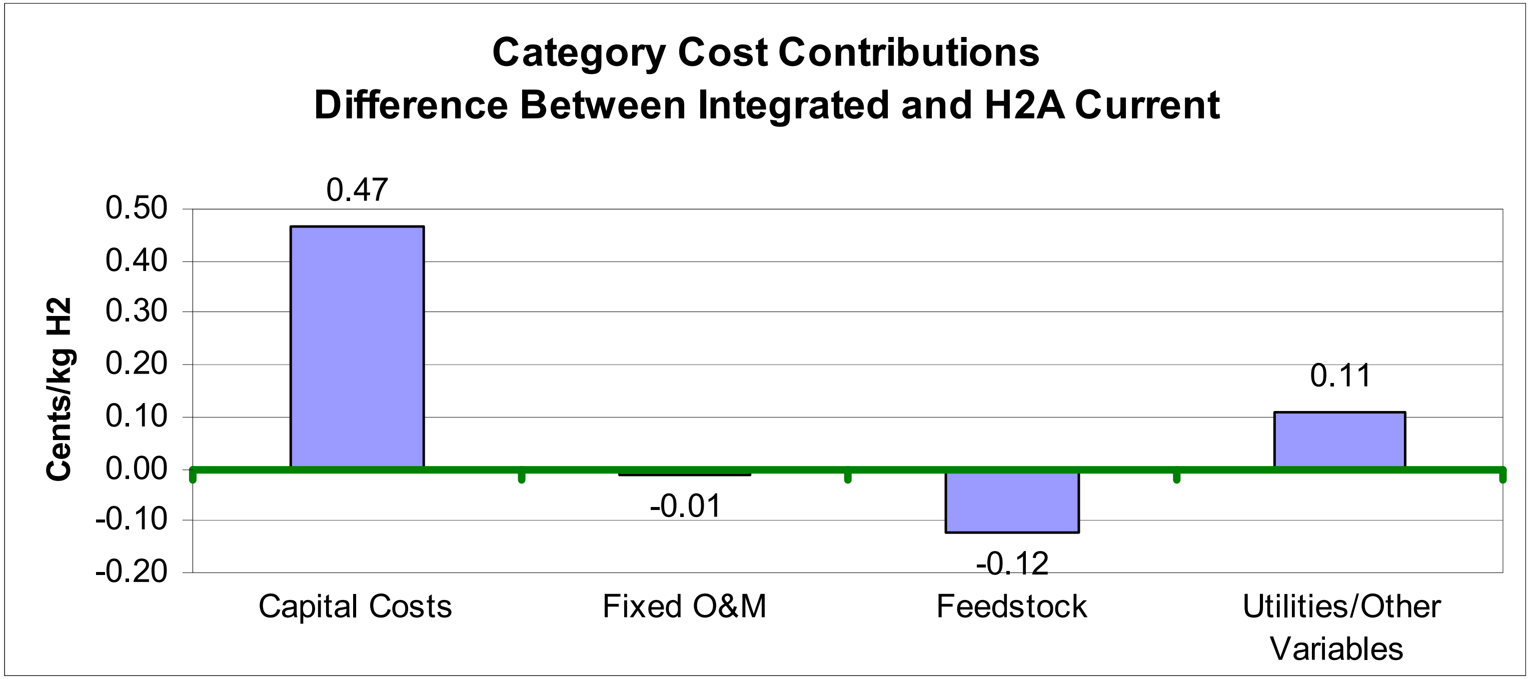
	Integrated System	H2A Current	Comments
H2 Production Unit Cost	138,486	175,000	
Compressor Cost	66,023*	26,250	MHC CR=900 vs H2A CR=21
Storage/Dispensing Cost	106,068	106,068	
Replacement Costs	15,258/y*	26,250 (in year 6)	Adds $0.46/kg to H2 Cost
Hydrogen Cost	$6.82/kg	$6.38/kg	
H2A Efficiency:			
Production 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 significant reduction is possible.**
**** 50% increase may be possible resulting in H2 cost reduction of $0.20/kg.**

H2A Preliminary Results - continued



Need to Reduce Costs

- More robust membranes to reduce replacement costs
- Extend life and substitute catalyst material to reduce capital and replacement costs
- Further integration of MHC with Reformer to reduce capital and utility costs
- Automate hydride heat exchanger assembly to reduce MHC capital cost
- Increase MHC isothermal efficiency to reduce utility cost

Assessment of Status

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Areas of Uncertainty

- Membrane and MHC interaction
  - Lab scale testing performed successfully
  - Proof of Concept Prototype tests to commence in December
  - Provision made for installation of buffer vessels / guard beds if deemed necessary
- Membrane performance and longevity
  - New methods to fabricate thinner, pinhole-free membranes
  - Ongoing independent R&D at MRT
- MHC Durability
  - Hot gas butterfly valves
  - To be tested in Advanced Prototype
- Testing timeline: Project to be completed September 2008

Reviewers Questions

Majority of reviewers' comments were positive. Answers to some of the important questions are summarized below.

How do the reforming, WGS and separation functions work together in the membrane reactor?

As H2 is produced, it is continuously and selectively removed through the dense Pd membrane as a function of the partial pressure difference across the membrane. As a result, both reforming and WGS equilibriums are pushed forward, increasing productivity and allowing lower temperature operation.

What is the basis and validity of assumptions about membrane life, production cost, etc. used in cost analysis?

Membranes have been tested at MRT for over 10,000 hr under simulated reformer conditions, which support assumption regarding membrane life. The substrate cost is a major cost component, and it is expected to be lower when mass produced.

Reviewers Questions

How are potential issues with catalyst attrition and membrane erosion addressed?

MRT has spent considerable time testing and selecting catalyst. The current catalyst has shown good attrition resistance over 3 years of testing. Lower bed velocities also reduce attrition rates. Longer term some attrition will result. Fluid bed allows easy catalyst replacement to makeup for any losses.

MRT is conducting testing of membranes. The configuration with gas flow parallel to membrane surface and mild fluidization greatly help in this respect. Over longer term, when necessary, the reactor design allows for easy replacement of membrane modules.

What are the benefits of a fluidized bed?

With a fluidized bed, heat and mass transfer are greatly enhanced compared to a conventional fixed bed system. Catalyst effectiveness is also much higher due to reduced particle size compared to conventional reforming. With enhanced heat transfer, direct air introduction can be utilized while minimizing reaction zone temperature gradients. The isothermality of the fluidized bed is an important characteristic to maximize performance in a membrane reactor.

Reviewers Questions

To prevent carbon formation in reactor, high steam to carbon ratio is required reducing system efficiency.

- *The reformer system operates at a conventional S:C of 3.0 while 65% of the process water is recycled through the system.*
- *Due to auto-thermal operation mode (direct air introduction to reformer) negative effects of carbon formation are minimized.*
- *Steam to Carbon ratio is a parameter to be optimized in the test plan*
- *Membrane reformer operates at 550oC (vs. 850oC in conventional) greatly reducing carbon formation potential*

Will the MHC still have a separate burner and blower for the integrated unit? Do you factor these into to your capital costs?

- *The MHC will have a separate burner and blower. They are included in the costs.*

Reviewers Questions

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MHC needs to be compared to conventional compressor (capital & operating costs).

MHC is performing two functions for an overall compression ratio of 900:

- *a vacuum pump to remove hydrogen from the membrane reactor at 7 psia and raise pressure to atmospheric and*
- *a compressor to boost pressure from atmospheric to 6,250 psia.*

100 kg/day	1 Unit – Quoted Prices			200 Units	
Type	MHC	Piston	Diaphragm	H2A Std. (300 to 6250)	H2A MHC (7 to 6250)
Vac Pump	included	18,250	18,250	-	-
Compressor	170,000	184,800	190,600	26,250	66,023
Total	170,000	203,050	208,850	26,250	66,023

Thank you

Contacts:

Satish Tamhankar at 908-771-6419; satish.tamhankar@boc.com

Tony Boyd at 604-822-4343; tboyd@membranereactor.com

David DaCosta at 973-728-8815; dacosta@ergenics.com