II.A.3 Integrated Hydrogen Production, Purification and Compression System

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Subcontractors:
[1] Membrane Reactor Technologies (MRT) Ltd., Vancouver, BC, Canada
[2] HERA USA, Inc., Ringwood, NJ

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Projected End Date: December 31, 2008

Objectives

- To demonstrate a low-cost option for producing fuel cell vehicle (FCV) quality hydrogen to meet DOE cost and efficiency targets for distributed hydrogen production.
- To develop a hydrocarbon fuel processor system that directly produces high pressure, high-purity hydrogen from a single integrated unit by combining a fluidized bed membrane reactor (FBMR) and a metal hydride-based compressor (MHC).

Technical Barriers

This project addresses the following technical barriers listed in the Hydrogen Production section (3.1.4) of the updated version (April 27, 2007) of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan.

(A) Reformer Capital Costs
(C) Operation and Maintenance (O&M)
(K) Durability
(L) Impurities
(M) Membrane Defects
(N) Hydrogen Selectivity
(O) Operating Temperature
(P) Flux
(R) Cost

In addition, the project addresses the following technical barrier from the Hydrogen Delivery section (3.2.4):

(B) Reliability and Costs of Hydrogen Compression

Technical Targets

Technical Targets and the current progress made towards achieving the 2010 milestones are presented in Table 1.

Accomplishments

- Detailed process flow diagram (PFD) and process and instrumentation drawings (P&ID), including control strategy, were developed for an integrated reformer/compressor system, designed to produce 1.35 kg/hr fuel cell grade hydrogen at 100 bar.
- Detailed hazard and operability (HAZOP) as well as risk assessment reviews were conducted. The PFD and P&ID were revised and finalized based on the recommendations developed during these reviews.
- Specifications were developed and equipment, instruments, parts and supplies were procured accordingly.
- Assembly of the natural gas and utility supply skid as well as the main reformer skid has been completed and these skids have been installed at the National Research Council's Institute for Fuel Cell Innovation (NRC-IFCI) site in Vancouver, Canada.
- The MHC skid design was completed and parts and supplies procured. The skid assembly is in progress.
- The reformer operations and testing began in June.

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Introduction

The DOE has determined that the delivered cost of hydrogen must be in the \$2 to \$3/gge range for hydrogen to be competitive with gasoline as a fuel for vehicles. For small, on-site hydrogen plants being evaluated for refueling stations (the "forecourt"), capital cost is the

TABLE 1. Progress Towards Technical Targets

Technical Targets: Distributed Production of Hydrogen from Natural Gas[1, 2]			
Characteristics	**Units**	**2010 Target[3]**	**Current FBMR-MHC Projection[4]**
Production Unit Energy Efficiency	%(LHV)	72.0	73.3
Production Unit Capital Cost (Uninstalled)	US$	900K	1,029K[5]
Forecourt Compressor Energy Efficiency	%	94[6] (CR=19.8)	72[7] (CR=895)
Compressor Installed Capital Cost (Basis:1,500 kg/day @6250 psi)	K$/(kg/hr)	4.0	4.43[8]
Total Hydrogen Cost	$/gge H_2	2.50	2.81

LHV – lower heating value
CR – compression ratio

[1] The H2A Production tool (http://www.hydrogen.energy.gov/systems_analysis.html) was used for the cost modeling. Economic parameters used were for a production design capacity of 1,500 kg/day of hydrogen: 20 year analysis period, 10% internal rate of return (IRR) after taxes, 100% equity financing, 1.9% inflation, 38.9% total tax rate, and Modified Accelerated Cost Recovery System (MACRS) 7-year depreciation for 2005, 2010, and 2015. A 70% capacity factor was used for 2005, and 2010. A 75% capacity factor was used for 2015. The results for 2005, 2010, and 2015 are in 2005 dollars.

[2] The natural gas cost and electricity cost used for 2005, 2010, and 2015 were $5.00/MMBTU (LHV) and $0.08/kWhr respectively based on the Energy Information Administration (EIA) 2005 Annual Energy Outlook High A case projection for 2015 in 2005$. The natural gas cost assumes industrial gas cost is available for distributed production of hydrogen.

[3] For the 2005, 2010, and 2015 analysis it was assumed that Design for Manufacture and Assembly (DFMA) would be employed and that on the order of 500 units per year would be produced.

[4] The FBMR-MHC cost projections are based on prior DOE targets and use somewhat different assumptions from those stated in footnotes 1 & 2. A direct comparison using identical assumptions to the April 27, 2007 RD&D plan will be prepared using actual performance measurements from the proof of concept (POC) unit. The figures presented in this table are based on the Advanced Prototype design, 1,500 kg/d, 6,515 psia H_2 pressure, 10% IRR after taxes, 2.5% inflation, 38% total tax rate, 83% capacity factor, $6.00/MSCF natural gas cost, $0.075/kWh electricity cost.

[5] Detailed estimates for an annual production quantity of 200 units yielded a capital cost of $1,285K. Increasing production quantities to 500 units per year is anticipated to reduce costs from 15 to 25%. A reduction of 20% results in the $1,029K figure.

[6] The 2010 target of 94% assumes a CR of 19.8 (300 psi inlet, 6,250 psi outlet) and does not include the efficiency losses from the production of electricity. If electricity efficiency of 35% is used, compressor primary energy efficiency for these conditions decreases to 65%.

[7] Compression efficiency of 72% is based upon a compression ratio of 895 and a primary energy source of natural gas, not electricity. This compares to the 2010 target forecourt compressor operating with a compression ratio of 895 at 89% (electric) and 47% if the electricity efficiency is factored in.

[8] Detailed estimates for an annual production quantity of 200 units yielded a capital cost of $5.54K/(kg/h). Increasing production quantities to 500 units per year is anticipated to reduce costs from 15 to 25%. A reduction of 20% results in the $4.43K/(kg/h) figure.

main contributor to delivered hydrogen cost. This project is based on achieving the target hydrogen cost by combining unit operations for the entire generation, purification, and compression system. It uses a membrane reformer developed by MRT which has H_2 selective, Pd-alloy membrane modules immersed in the reformer vessel, thereby directly producing high purity hydrogen in a single step. The continuous removal of pure hydrogen from the reformer pushes the equilibrium "forward" thereby maximizing reactor productivity with an associated reduction in the cost of product hydrogen. Additional gains are envisaged by the integration of the novel hydride compressor developed by HERA, whereby H_2 is compressed from 0.5 bar (7 psia) to 350 bar or higher in a single unit using thermal energy. Excess energy from the reformer provides over 25% of the power used for driving the hydride compressor so that system integration can improve efficiency. Hydrogen from the membrane reformer is of very high, FCV quality (purity over 99.99%), eliminating the need for a separate purification step. The hydride compressor maintains hydrogen purity because it does not have dynamic seals or lubricating oil.

Following the techno-economic analysis presented last year, the work this year was focused on designing and building the first proof-of-concept (POC) unit to demonstrate the technology and to verify the assumptions in our analysis. The POC unit is designed to produce 1.35 kg/hr high purity, high pressure (100 bar) hydrogen.

Approach

The project team will integrate the membrane reformer developed by MRT and the hydride compression system developed by HERA in a single package. This is expected to result in lower cost and higher efficiency compared to conventional hydrogen production technologies, as follows:

Lower cost compared to conventional fuel processors will be realized by:

- Reduced component count and sub-system complexity.
- Tight thermal integration of all reactions/processes in a single package.
- Thermal metal hydride compression without rotating machinery, which should result in high reliability, low maintenance and low electricity usage.

High efficiency will be achieved by:

- Using H_2 selective membranes within the reformer vessel to directly produce high-purity hydrogen, eliminating losses associated with a separate purifier.
- Using a fluidized catalyst bed to improve heat and mass transfer.
- Using the compressor suction to lower the partial pressure of hydrogen in the reaction zone, which shifts equilibrium to enhance hydrogen production.

- Thermally integrating the hydride compressor with the membrane reactor to reduce compression energy consumption.

Results

- POC prototype system designed, fabricated and installed:
  - Novel reformer mechanical design with good membrane access.
  - Prototype, large area membrane modules (6”x11”) with lower cost substrate successfully tested at operating temperature and pressure.
- Novel MHC powered by hot air designed and under construction.
- Appropriate safety reviews completed:
  - HAZOP completed in June 2006.
  - Updated safety plan submitted to DOE.
  - Technical risk assessment for POC installation and operation completed.
  - Pre-start safety inspection of the reformer skid completed.

Conclusions and Future Directions

- Cost and efficiency targets unchanged since last year, pending assessment and revision based on POC test results.
- Complete POC performance tests, and report results and economic assessment by September 2007.
- Review POC test results and the revised economic assessment with DOE for decision to proceed to the next step, which is an advanced prototype incorporating lessons learned and employing a higher degree of integration, with an associated reduction in the number of components to reduce capital cost.

FY 2007 Publications/Presentations

1. US DOE Annual Review, May 15, 2007.