II.F.2 Reformer-Electrolyzer-Purifier (REP) for Production of Hydrogen [CO_2 Pump]

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Subcontractor:
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Project End Date: September 30, 2016

Overall Objectives

FuelCell Energy's overall objectives are based on the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration (MYRDD) Plan of 2015 to reduce the cost of hydrogen production to <$2.00/gge (<$4.00/gge delivered and dispensed). In addition, the technology used should minimize CO_2 emissions. To achieve this, FuelCell Energy has the following key objectives, all of which were successfully completed:

- Build and test the performance of a large scale REP stack (reformer-electrolyzer-purifier) using commercial cell components from our production line.
- Optimize parameters based on single cell testing and parametric studies.
- Test single cell long-term to establish expected life.
- Optimize process configuration and economics.
- Analyze the economics and cost of hydrogen using performance data from the tests.
- Support consultant (SAI) who is working to confirm the economics.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Production section (3.1) of the Fuel Cell Technologies Office MYRDD Plan (from 2007 plan).

(A) Reformer Capital Costs
(B) Reformer Manufacturing
(C) Operation and Maintenance
(D) Feedstock Issues
(E) Greenhouse Gas Emissions
(F) Control and Safety

Technical Targets

The REP combines reforming and electrolysis into one unit. Therefore, the technical targets for hydrogen production from natural gas and from water electrolysis are both addressed by this program.

As shown in Tables 3.1.2 and 3.1.4 of the MYRDD Plan (Table 1 and 2 below), where the expected REP performance has been added to MYRDD targets below, the efficiency of the system is substantially higher than the target efficiencies. These higher efficiencies reduce operating costs sufficiently to offset the higher capital so that the total hydrogen cost target of $2.00/kg is still achieved. The higher efficiencies also have the advantage of reducing CO_2 and other emissions associated with typical hydrogen production from natural gas and electrolysis.

TABLE 1. Technical Targets for Natural Gas (2007 MYRDD Plan)

Table 3.1.2. Technical Targets: Distributed Production of Hydrogen from Natural Gas

Characteristics	Units	2015 Target	REP Technology
Production Unit Energy Efficiency	% (LHV)	75.0%	96.2%* (up to 130% eff with waste heat)
Production Unit Capital Cost (Uninstalled)	$ (1,500 kg/d unit)	580K	947K
Total Hydrogen Cost	$/gge H_2	2.00	1.66

* efficiency for 80% of hydrogen generated from natural gas
LHV – Lower heating value

TABLE 2. Technical Targets for Electrolysis (2007 MYRDD Plan)

Table 3.1.4. Technical Targets: Distributed Water Electrolysis Hydrogen Production a, b, c

Characteristics	Units	2017 Target	REP Technology
Hydrogen Cost	$/gge	<3.00	1.66
Electrolyzer Capital Cost	$/gge $/kW	0.30 125	Included above
Electrolyzer Energy Efficiency	% (LHV)	74%	83.4%**

** efficiency for 20% of hydrogen generated from steam electrolysis

FY 2016 Accomplishments

Accomplishments during FY 2016 include:

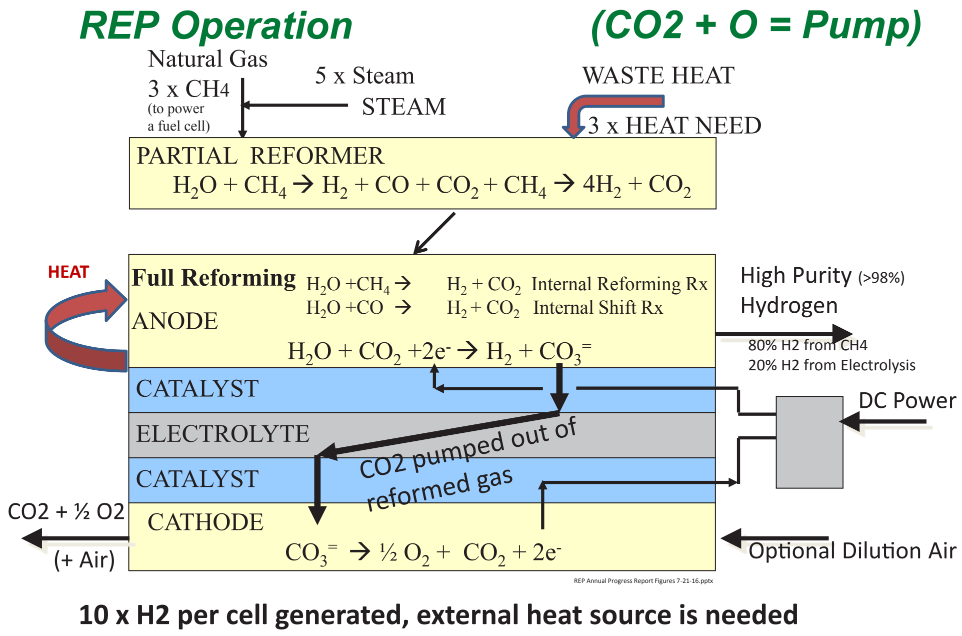
- Constructed 30-cell test stack using full scale cells from FuelCell Energy's commercial manufacturing facility.
- Tested 30-cell stack and met all performance targets including:
  - Greater than 100 kg per day of hydrogen production
  - Greater than 95% hydrogen purity (97% to 98% achieved)
  - Less than 8 kWh/kg of hydrogen power consumption
  - Excellent thermal profile across stack, even during load changes
- Confirmed REP hydrogen after methanation can be used without further purification to power a polymer electrolyte membrane fuel cell and/or be used as feed to an electrochemical hydrogen compressor. The electrochemical hydrogen compressor produces high purity, high pressure hydrogen suitable for fuel cell vehicles in one step.
- Developed accurate performance model and completed configuration analysis.

* * * * *

INTRODUCTION

The current conventional technology for production of hydrogen from natural gas suffers from excess CO_2 production due to incomplete conversion of methane and CO to hydrogen. The proposed technology would incorporate a high temperature electrochemical purification system to remove CO_2 from the reformed gas during the reforming process and drive the conversion of methane to H_2 and CO_2 to near completion, producing hydrogen from natural gas in a manner which approaches the theoretical minimum of CO_2 emissions.

The REP system (Figure 1) incorporates components developed for FuelCell Energy's commercial molten carbonate direct fuel cell (DFC®) technology. When this technology is operated in purification mode as an electrolyzer, it will pump out almost all of the carbon from the feed gas as $CO_3^=$ leaving pure hydrogen from the reformed methane. In addition, the system efficiently produces additional hydrogen by dissociation of steam (electrolysis) in the formation of $CO_3^=$ during the pumping step. Thus natural gas would provide about 80% of the hydrogen produced with the other 20% provided by the electrolysis reaction. The system appears to be highly attractive economically based on H2A modeling, and testing the system confirmed the performance is as expected when using full scale components from our commercial DFC® production line. When operated without cathode sweep gas, byproduct CO_2/O_2 (67%/33%) can also be produced with only a minor (~10%) power penalty.



Rx - Reaction; DC - Direct current

FIGURE 1. Operation of Reforming-Electrolyzer-Purifier (REP)

APPROACH

Because the system will be based on our commercial DFC® add registered trademark symbol fuel-cell components, the emphasis of our work was to make sure that the system works as expected. Based on FuelCell Energy's long history of research and development, initial testing was done on a single 300 cm² cell. Experience has shown that this size cell provides a good reflection of the performance of our larger commercial scale cells. Testing of the large cells was done in Phase 2 of the program and confirmed there are no unexpected results from the flow distribution or the thermal distribution within the cells. The large cell testing was done on a short stack of approximately 30 cells which we have found accurately reflects the performance and temperature profile of a commercial unit. We tested a single cell under various operating conditions to determine their impact on the cell performance. The same performance was shown by the large-scale test.

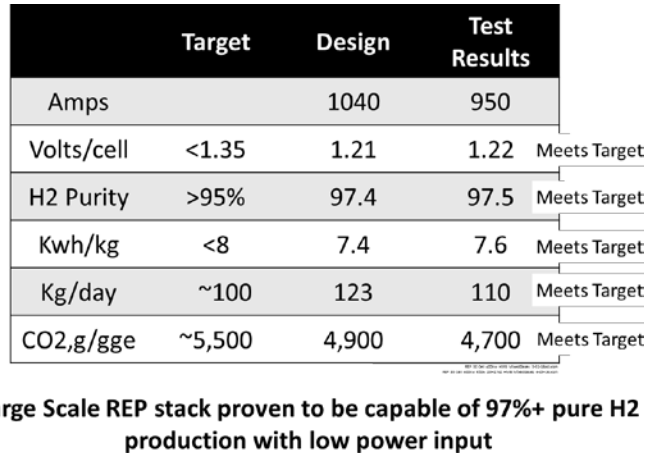
Long-term single cell tests, including microscopic scanning electron microscopy examination of the cell during posttest analysis, indicated that a commercial stack should have a good operating life and a reasonable performance degradation (2–5 years life). See Figure 2.

Based on the results of the testing, detailed system configurations and performances have been simulated using ChemCAD. The results of the simulation were then used in the H2A model to confirm the economic attractiveness of the system as shown in Table 4. After the brief successful short stack testing, we now would like to follow that with a longer test of the 30-cell stack (~6 mo), but that test was not included in the current program.

RESULTS

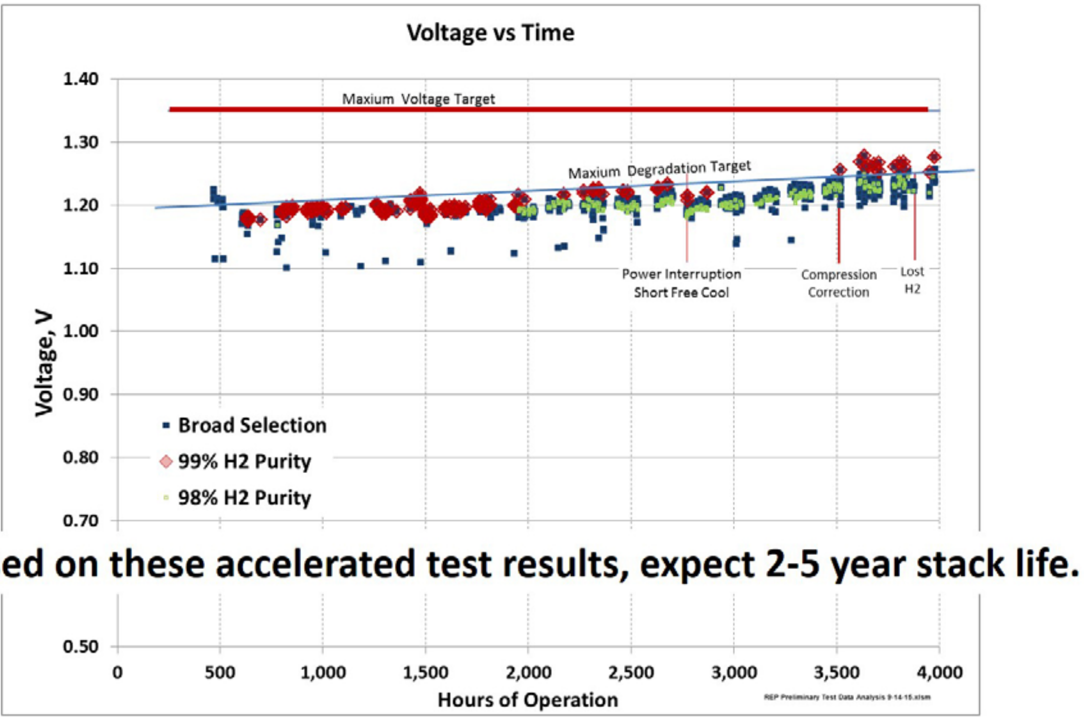
The results were excellent and the performance of the REP system is slightly better than the performance estimated in the initial proposal (Table 3). Using the data from the single cell and large scale tests, a detailed model was developed which allows us to accurately predict the

TABLE 3. Successful Test Results from Stack Using Commercial Cells



	Target	Design	Test Results	
Amps		1040	950	
Volts/cell	<1.35	1.21	1.22	Meets Target
H2 Purity	>95%	97.4	97.5	Meets Target
Kwh/kg	<8	7.4	7.6	Meets Target
Kg/day	~100	123	110	Meets Target
CO2,g/gge	~5,500	4,900	4,700	Meets Target

Large Scale REP stack proven to be capable of 97%+ pure H2 production with low power input



Based on these accelerated test results, expect 2-5 year stack life.

FIGURE 2. Single cell tests indicate stable operation and good cell life

TABLE 4. Configuration Analysis Based on Heat and Meaterial Balances and H2A Model

Case	mmbtu NG /kg	REP Power, kwh/kg	Operating Costs, $/kg(1)	CO2, g/gge(2)	Prod Rate, kg/d (8)	Capital Cost, $/(kg/d)	H2A Total H2 Cost, $/kg(9)
1. Base Case - Integrated with DFC®	0.069	7.915	0.925	4,529	1,622	$610	$1.47
2. Standalone - Grid Power, NG heat	0.114	7.216	1.188	6,619	1,622	$1,076	$2.07
Est Standalone - CO2 Capture	0.114	7.817	1.223	0(7)	1,622	$1,076	$2.11
3. Standalone - External LP Steam	0.095	7.211	1.058	5,590	1,622	$871	$1.78
4. Standalone - Self Powered	0.138	0.000	0.936	8,082	582	$2,112	$2.71
5. Standalone - ADG Feed	0.104	10.277	1.296	0(6)	1,192	$1,135	$2.11
6. Standalone - Renewable Syngas	0.066	12.181	1.529	0(6)	985	$1,294	$2.25
7. DFC® AE feed for Power Storage	0.010	29.518	1.886	0(4)	437	$2,012	$3.60
8. SOFC AE feed, Power Storage	0.000	23.768	1.529	0(4,5)	561	$1,352	$2.63

(1) Assumes $6.77/mmbtu NG (LHV), $0.057/kwh power.
(2) Does not include CO2 from power used, ~3,200 g/gge @ 7.5 kwh/kg
(3) All water needed is already in SOFC anode exhaust
(4) No additional CO2 emitted other than CO2 from power production
(5) Potential CO2 capture for zero CO2 power from NG as well as H2
(6) Renewable Hydrocarbon Feed
(7) Assumes CO2 Capture
(8) Production rate based on one DFC® stack
(9) 98+% H2 purity

NG – Natural gas; SOFC – Solid oxide fuel cell; LP – Low pressure; AE – Anode exhaust; ADG – Anaerobic digester gas; gge – Gasoline gallon equivalent

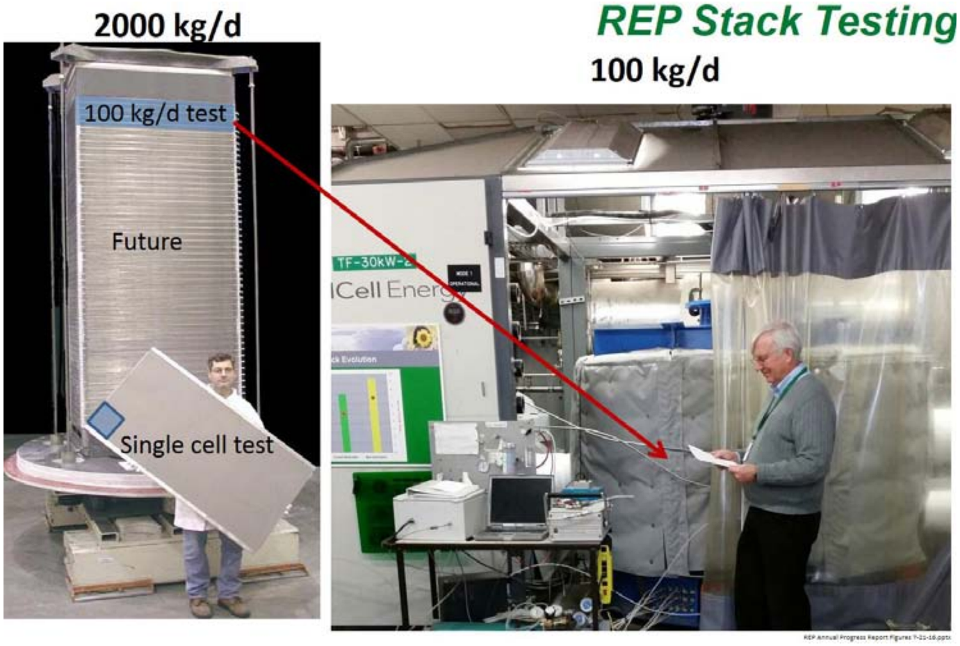


FIGURE 3. Testing of commercial cells in short stack

REP performance for various configurations and feedstocks. Based on this model and detailed process flow diagrams, heat and material balances were performed, and equipment costs were estimated. The results were then analyzed using the DOE H2A model. As can be seen in Table 4, the cost of hydrogen meets the DOE target of $2/kg for two cases and is close to the target for most of the cases.

In addition to the performance of the system, we were also concerned about the life of the cell. To address this concern, a long-term test of a single cell was performed. As shown in Figure 2, 4,000 hr of operation have been achieved with the voltage remaining well below the maximum target voltage. We are currently testing a second single cell operating to produce both H_2 and CO_2/O_2. By eliminating the optional air sweep of the cathode, a slight power increase is incurred (~10%), but the cell now generates a second valuable CO_2/O_2 (67%/33%) stream. This stream can be used for CO_2 capture, low-cost oxygen, and other applications. We are also looking at additional cases, including cases involving CO_2 capture as well as power storage.

The system can use waste heat at various temperature levels to reduce fuel consumption and cost as can be seen in Case 3 which assumes low pressure steam at no cost is available to the process. Approximately 40% of the heat required by the system is for the production of low pressure steam.

CONCLUSIONS AND FUTURE DIRECTIONS

Conclusions derived from the work are:

- The REP system performs well in a stack of commercial cells as well as in a single test cell.
- The economics of the REP system are highly attractive based on detailed configurations and material balances for distributed hydrogen and could provide competitive distributed hydrogen for many applications in the near-term.
- Testing of commercial cells showed excellent performance and temperature profiles within the stack.
- Not only does the REP system provide low-cost hydrogen but it has the potential to be a good technology for excess electricity storage and CO_2 capture. These alternate uses should be explored further.

Future work required to commercialize the process will comprise:

- Longer testing (minimum 3–6 mo) of the 30 commercial cell short stack (not included in current program).
- Integration with larger scale pre-reformer.

SPECIAL RECOGNITIONS & AWARDS/ PATENTS ISSUED

1. A patent application for the process, including multiple configuration arrangements, was filed January 31, 2015, prior to start of program.

FY 2016 PUBLICATIONS/PRESENTATIONS

1. "Reformer-Electrolyzer-Purifier (REP) for Production of Hydrogen," 2016 AMR (Annual Merit Review), Washington D.C., Fred Jahnke, FuelCell Energy, Inc. June 8, 2016, Project ID #:PD112.

2. "Reformer-Electrolyzer-Purifier (REP) for Production of Low Cost Hydrogen," 2015 Fuel Cell Seminar, Los Angeles, CA, Fred Jahnke, FuelCell Energy, Inc. November 19, 2015.

3. Zhao L., Brouwer J., Jahnke F., Lambrech M., and Patel P., "A Novel Hybrid Reformer-Electrolyzer-Purifier (REP) for Distributed Production of Low-Cost, Low Greenhouse Gas Hydrogen," The Electrochemical Society, 2015 Fuel Cell Seminar & Energy Expo proceedings.

4. 2015 Annual Progress Report, "II.F.2 Reformer-Electrolyzer-Purifier (REP) for Production of Hydrogen," https://hydrogendoedev.nrel.gov/pdfs/progress15/ii_f_2_jahnke_2015.pdf.