II.F.2 Reformer-Electrolyzer-Purifier (REP) for Production of Hydrogen

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Contract Number: DE-EE 0006669

Subcontractor
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Project Start Date: September 30, 2014
Project End Date: September 30, 2016

Overall Objectives

FCE's overall objectives are based on the Fuel Cell Technologies Office (FCTO) 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, FCE has the following key objectives.

- Construction and performance testing of a commercial scale reformer-electrolyzer-purifier (REP) unit
- Parameter optimization based on single cell testing and parametric study
- Long-term single cell testing to establish acceptable expected life
- Process and economics optimization
- Economic analysis to confirm cost of hydrogen

Fiscal Year (FY) 2015 Objectives

- Construction of single cell and test unit
- Parameter optimization on single cell based on single cell testing and parametric study
- Long-term single cell testing
- Process and economics optimization

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Production section (3.1-23) of the FCTO MYRDD Plan.

(A) Reformer Capital Costs and Efficiency

(B) Operation and Maintenance (O&M)

(E) Control and Safety

(G) System Efficiency and Electricity Costs

(I) Grid Electricity Emissions (for Distribution)

Technical Targets

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 you can see from Tables 1 and 2 where the expected REP performance has been added to MYRDD Plan targets below, the efficiency of the reformer and electrolyzer components 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. Comparison to FCTO Technical Targets for Distributed Production of Hydrogen from Natural Gas (MYRDD Plan Table 3.1.2)

Characteristics	Units	2015 Target	REP Technology
Production Unit Energy Efficiency	% (LHV)	75.0	96.2
Production Unit Capital Cost (Uninstalled)	$ ($1,500 kg/day unit)	580,000	947,000
Total Hydrogen Cost	$/gge H_2	2.00	1.66

LHV – lower heating value; gge – gallon gas equivalent

TABLE 2. Comparison to FCTO Technical Targets for Distributed Water Electrolysis Hydrogen Production (MYRDD Plan Table 3.1.4)

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

FY 2015 Accomplishments

Accomplishments during FY 2015 include the following.

- *Installed test unit.* Specified and purchased unit, installed unit on-site, shook down unit, reviewed safety of system, corrected flaws, started up the unit
- *Characterized cell performance based on single cell testing.* Varied operating conditions of the cell to determine the impact of all key operating parameters
- *Developed REP performance model.* Model very similar to one used for our commercial fuel cells; performed heat and material balances on single cell test operation to check accuracy of the model
- *Long-term testing of single cell.* Achieved 4,000 h of excellent operation
- Met all milestones
- Developed detailed configuration (process flow diagram [PFD]) which was used for estimating the cost of the system
- Rechecked the economics of the system using the updated costs developed based on the PFD
- Met go/no go requirements needed for approval to proceed to Phase 2
- Estimated performance for alternate feedstocks including syngas from biomass

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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 incorporates components developed for FuelCell Energy's commercial molten carbonate fuel cell (MCFC) technology/Direct Fuel Cell (DFC®). When this technology is operated in purification mode as an electrolyzer, it will pump out almost all of the carbon from the system as CO_3^{2-}, leaving pure hydrogen from the reformed methane. In addition, the system efficiently produces additional hydrogen by dissociation of steam (electrolysis) in 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, and we are currently testing the system to confirm the performance is as expected.

APPROACH

Because the system will be based on our commercial DFC fuel-cell components, the emphasis of our work is 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 cm^2 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 is included in Phase 2 of the program to insure there are no unexpected results from the flow distribution or the thermal distribution within the cells. The large cell testing will be based on a short stack of approximately 30 cells which we have found accurately reflects the performance of a commercial unit. In Phase 1, we are testing a single cell under various operating conditions to determine the impact on the cell performance. We are also doing long term testing to make sure that the cell has an adequate life and a reasonable performance degradation.

Based on the results of the testing, a detailed system configuration and performance has been simulated using CHEMCAD. The results of the simulation were then used in the Hydrogen Analysis (H2A) model to confirm the economic attractiveness of the system. Assuming the short stack testing is successful, we hope to follow that test with an additional program for a field demonstration of the technology.

RESULTS

The results to date have been excellent and the performance of the REP system is slightly better than the performance estimated for the proposal. Figure 1, which shows the voltage required to obtain various hydrogen purities, shows the data confirming the REP performance. Using the data from these tests and others, a detailed model was developed which allows us to accurately predict the REP performance for various configurations and feedstocks. Figure 2 shows how the model closely matches the observed data. This model has been used in our heat and material balance simulations to check the economics of the technology. Based on the detailed PFD developed, a heat and material balance was performed, equipment costs were estimated, and the results were analyzed using the DOE H2A model. As can be seen in Table 3, the cost of hydrogen meets the DOE target of $2/kg.

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 cell was performed. As shown

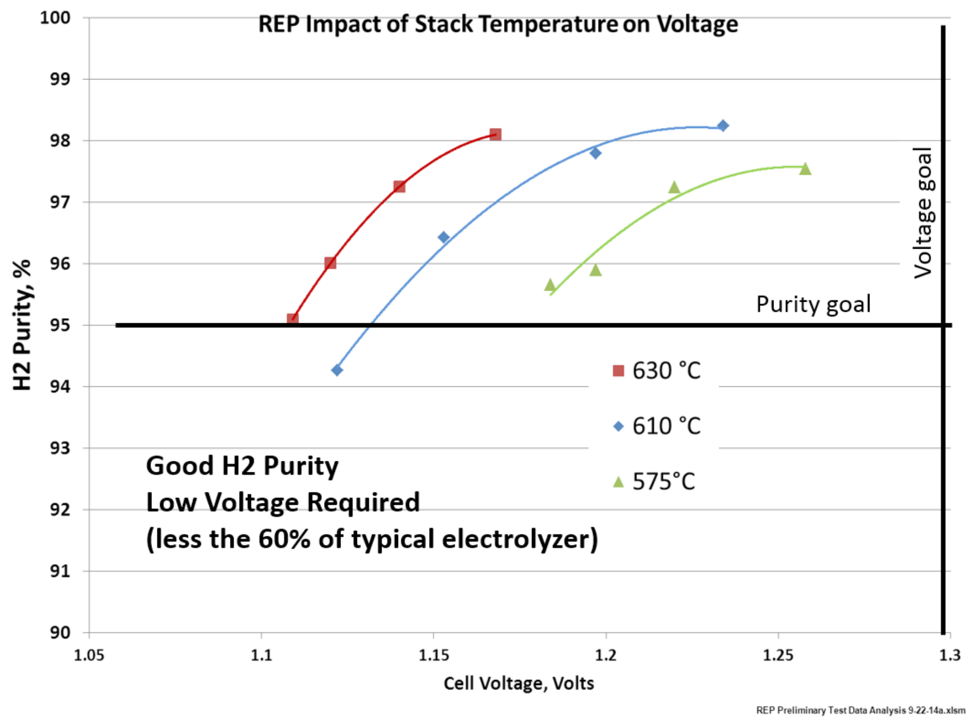

FIGURE 1. Performance of REP is attractive

$$E = E_T^\circ + \frac{RT}{2F}\ln\frac{\chi_{H_2}\chi_{O_2}^{1/2}\chi_{CO_2(c)}}{\chi_{H_2O}\chi_{CO_2(a)}} + \frac{RT}{4F}\ln P$$

Case	Model Voltage	Measured Voltage	Voltage Error
33.5A	1,159	1,170	0.9%
33.5A Low Air Flow	1,163	1,170	0.5%
37A	1,166	1,173	0.6%
37A Low T	1,209	1,220	0.9%
37A High T	1,149	1,140	-0.8%
40A	1,216	1,201	-1.3%
40A N2 Sweep	1,234	1,234	0.0%
40A No Cath Flow	1,271	1,333	4.3%
Average Error	0.07%		
Stnd Deviation	1.01%		

Error = (Meas V / Calc V) -1

- Sophisticated Model developed for REP (adapted from MCFC fuel cell model with minor adjustments).
- Model closely matches test data.
- Model allows optimization of system operation and accurate heat and material balances.

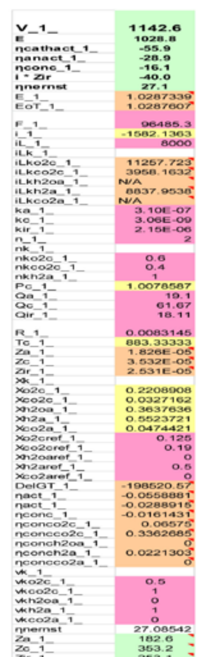

FIGURE 2. Accurate model of REP was developed and validated

TABLE 3. H2A REP Economic Analysis for REP Integrated with a DFC® Fuel Cell System

Specific Item Cost Calculation		
Cost Component	**Cost Contribution ($/kg)**	**Percentage of H_2 Cost**
Capital Costs	$0.49	29.5%
Decommissioning Costs	$0.02	1.1%
Fixed O&M	$0.13	7.9%
Feedstock Costs	$1.01	60.7%
Other Raw Material Costs	$0.00	0.0%
Byproduct Credits	$0.00	0.0%
Other Variable Costs (including utilities)	$0.01	0.7%
Total	**$1.66**	

in Figure 3, 4,000 h of operation have been achieved with the voltage remaining well below the maximum target voltage.

We are currently looking at various configurations and feedstocks, performing heat and material balances for these cases and estimating the operating cost of hydrogen production for each case. The initial results from these studies are shown in Table 4. All of these cases show an attractive hydrogen production cost.

Note that the lowest marginal cost of hydrogen production is estimated for Case 4, a standalone REP system that incorporates an advanced configuration. We are currently preparing a patent application on this system. Although this is a good long-term case, the advanced system is more complicated and will require additional research funding before it can be demonstrated. 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. Figure 4 shows the temperature level of heat that can be used and potential sources of that heat.

CONCLUSIONS AND FUTURE DIRECTIONS

The following conclusions were derived from the work in FY 2015.

- The REP system performs well.
- The economics of the REP system remain attractive after a detailed configuration and material balance were completed.
- The Phase 1 go/no go criteria have been met and we should proceed to Phase 2, construction of a commercial scale unit for testing.
- 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

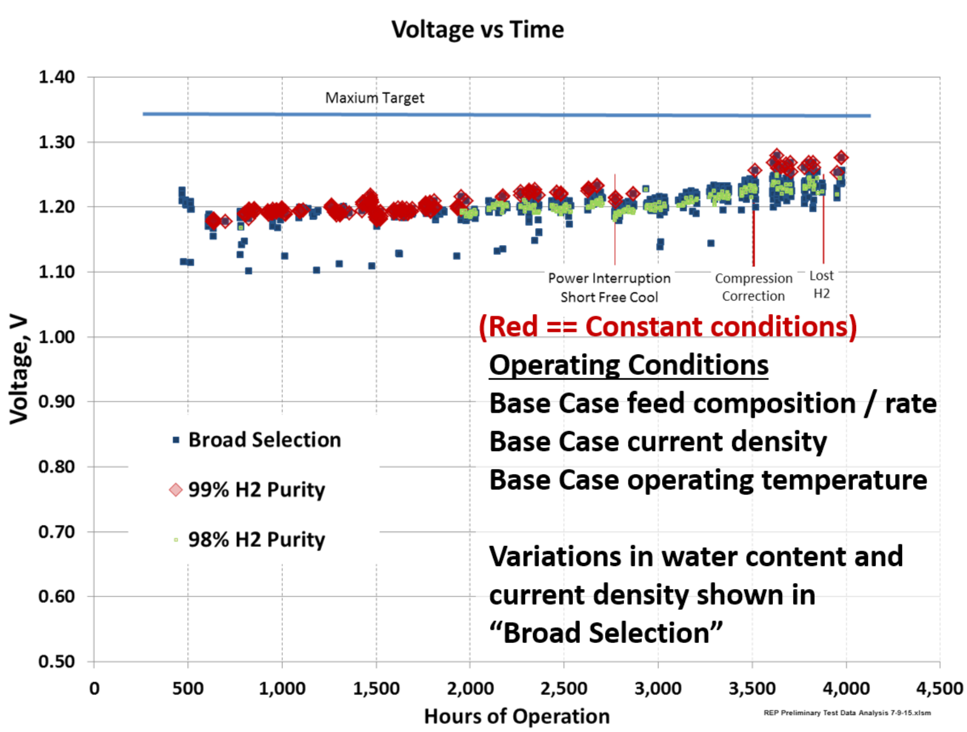

FIGURE 3. Long-term testing confirms acceptable cell life

TABLE 4. Configuration Analysis Based on Heat and Material Balances

Case	MMBtu NG /kg	kW NG /kW H_2	REP Power, kWh/kg	H2 Purity, %	Water, kg/kg	Operating Costs, $/kg*
1. Base Case– NG Feed Integrated with DFC®	0.069	0.62	7.915	97.0%	9.3	0.925
2. Standalone – NG for All Heat	0.114	1.02	7.216	98.1%	9.3	1.188
3. Standalone - External LP Steam	0.095	0.84	7.211	96.9%	9.3	1.058
4. Standalone - Advanced Cycle	-	-	-	-	-	0.488
5. Standalone - Syngas Feed	0.066	0.59	12.181	97.7%	8.7	1.529
6. Int with DFC - AE Pwr Storage	Future	-	-	-	-	-

* Assumes $6.77/MMBtu NG (LHV), $0.057/kWh power. Does not include capital and maintenance costs.
NG – natural gas; LP – low pressure; AE – anode exhaust (from DFC®); DFC® – FuelCell Energy commercial fuel cell

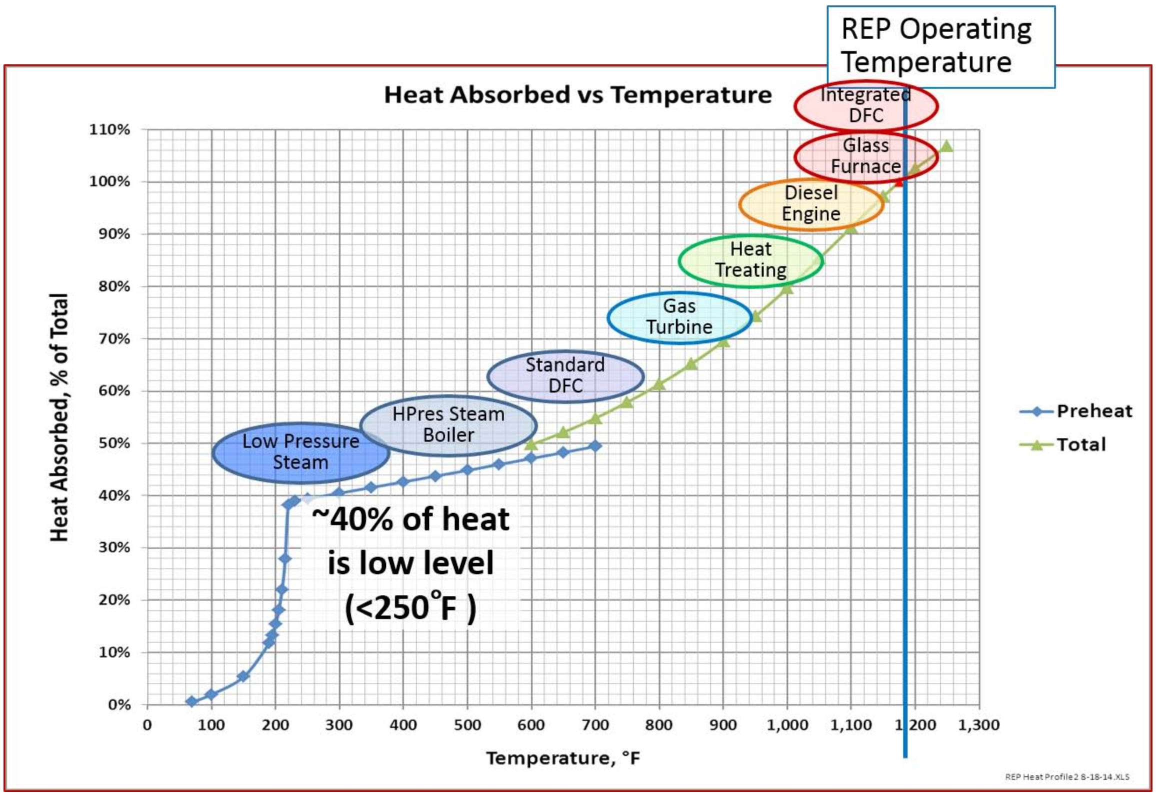

FIGURE 4. Multiple waste heat sources can improve efficiency and cost

uses should be explored further, and if found attractive, testing should be carried out to simulate the operating conditions for these applications also.

Future work in Phase 2 will comprise the following.

- Construction and testing of a commercial scale REP unit capable of around 100 kg/d of hydrogen production
- Continue long-term testing of single cell unit
- Test single cell under operating conditions for alternate configurations

SPECIAL RECOGNITIONS & AWARDS/ PATENTS ISSUED

1. A patent application for the process, including multiple configuration arrangements, was filed January 31, 2014, prior to start of program.

FY 2015 PUBLICATIONS/PRESENTATIONS

1. "Reformer-Electrolyzer-Purifier (REP) for Production of Hydrogen," 2015 AMR (Annual Merit Review), Washington,

DC, Fred Jahnke, FuelCell Energy, Inc. June 11, 2015, Project ID #:PD112.

2. "A Novel Hybrid Reformer-Electrolyzer-Purifier (REP) for Distributed Production of Low-Cost, Low Greenhouse Gas Hydrogen," review of project was given at the kick-off review meeting in Denver, August 26, 2014, for Hydrogen Production Technology Team Meeting.