Final Report

A Novel Hybrid Reformer-Electrolyzer-Purifier (REP) for Distributed Production of Low-Cost, Low Greenhouse Gas Hydrogen

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Recipient Organization: FuelCell Energy, Inc. (FCE)

Project Title: A Novel Hybrid Reformer-Electrolyzer-Purifier (REP) for Distributed Production of Low-Cost, Low Greenhouse Gas Hydrogen

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UCI: Jack Brouwer, Li Zhao, Derek McVay

DOE-EERE: Eric Miller, David Peterson

FuelCell Energy Management provided the test site and additional support and funding for the project.

1. Executive Summary

FuelCell Energy with support from the Department Of Energy's Office of Energy Efficiency and Renewable Energy (EERE) has investigated the production of low-cost, low CO_2 hydrogen using a molten carbonate fuel cell operating as an electrolyzer. We confirmed the feasibility of the technology by testing a large-scale short stack. Economic analysis was done with the assistance of the National Fuel Cell Center at the University of California, Irvine and we found the technology to be attractive, especially for distributed hydrogen. We explored the performance under various operating parameters and developed an accurate model for further analysis and development calculations. The next step towards commercialization of this technology would to do a longer-term demonstration test of the large scale stack, preferably at a site which could benefit from the hydrogen produced.

Research results

We successfully validated the operation of the system and achieved the expected results, meeting all program goals. We identified additional uses of the technology such as for CO_2 capture, power storage, and power load leveling. We successfully tested the hydrogen produced from a single cell in a small PEM fuel-cell and EHC (electrochemical hydrogen compressor).

Technical and economic effectiveness

The system performance was not impacted by scale up and an economic analysis met the DOE cost targets. Although near-term costs will be slightly higher, they are expected to be close enough to DOE's targets to provide a viable source of distributed hydrogen. The system benefits from external waste heat sources and can enhance the economics of sites with excess waste heat available. It is a good fit for combining with heat from CHP sites

Benefits to Public

After completion of a successful demonstration, we expect this technology to provide lower-cost, lower CO_2 distributed hydrogen for cars, manufacturing, and load following power. The system also has the potential to provide low-cost electrical energy storage and support grid stability. Longer-term, we believe the system can be used to coproduce a CO_2/O_2 byproduct which can be used for low-cost CO_2 capture.

2. Project Description / Background

Brief Description of FuelCell Energy Operations and Mission:

FuelCell Energy, Inc. (FCE) is a global leader in the design, manufacture, operation and service of ultra-clean, efficient and reliable fuel cell power plants. FCE's high temperature molten carbonate fuel cell-based power plants, sold under the trade name Direct FuelCell® (DFC), are generating ultra-clean, efficient and reliable power at more than 50 locations worldwide. With over 300 megawatts of power generation capacity installed or in backlog, DFC® power plants

have generated more than 4.0 billion kilowatt hours of ultra-clean power for utilities, industrial operations, universities, municipal water treatment facilities, government installations and other customers around the world. FCE's corporate mission is to meet the world's energy needs today with non-polluting and efficiently-generated power.

FCE has a long history of success for advancing fuel cell technologies starting from basic R&D to demonstration projects onto commercial products. **Figure 1** shows recent examples of FCE's power plants, including the 59 MW combined heat and power fuel cell park in South Korea.

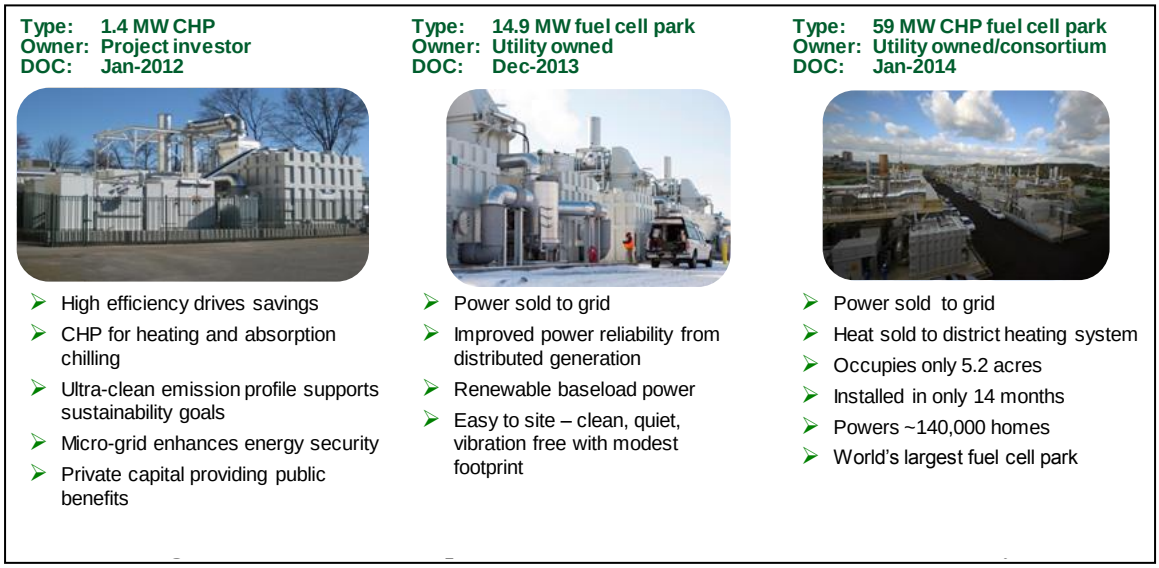


Figure 1- Recent Examples of FCE's Power Plants Installed Globally

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 new REP technology incorporates a high temperature electrochemical purification system to remove CO_2 from the reformed gas during the reforming process and drive the conversion of methane and CO to completion, producing hydrogen from natural gas in a manner which approaches the theoretical minimum of CO_2 emissions (not including CO_2 associated with waste heat or power used). See **Figures 2 - 4** below.

The basic REP operation is shown in **Figure 2**. Hydrocarbon fuels such as natural gas or biogas along with steam are fed into the system and the carbon in the gas is pumped out of the system electrochemically. A small amount of power is required for the CO_2 pumping, but the pumping also electrolyzes water to produce additional hydrogen which offsets much of the operating costs. Once the carbon is pumped out of the feed gas, only hydrogen and water exit the REP cell. Once the gas is cooled and the water condensed out, the system will produce hydrogen with a purity greater than 98%. For natural gas feeds, approximately 80% of the hydrogen produced is from reforming of NG and 20% from electrolysis/CO_2 pumping. Thus, only a small amount of power is required by the system, less than 8 kwh/kg H_2.

For power storage, the same system could be used with a CO_2 feed, such as exhaust gas from a DFC®, SOFC, or PSA. In this case, most of the H_2 comes from the highly efficient, high temperature electrolysis, storing the power consumed as H_2 or methane.

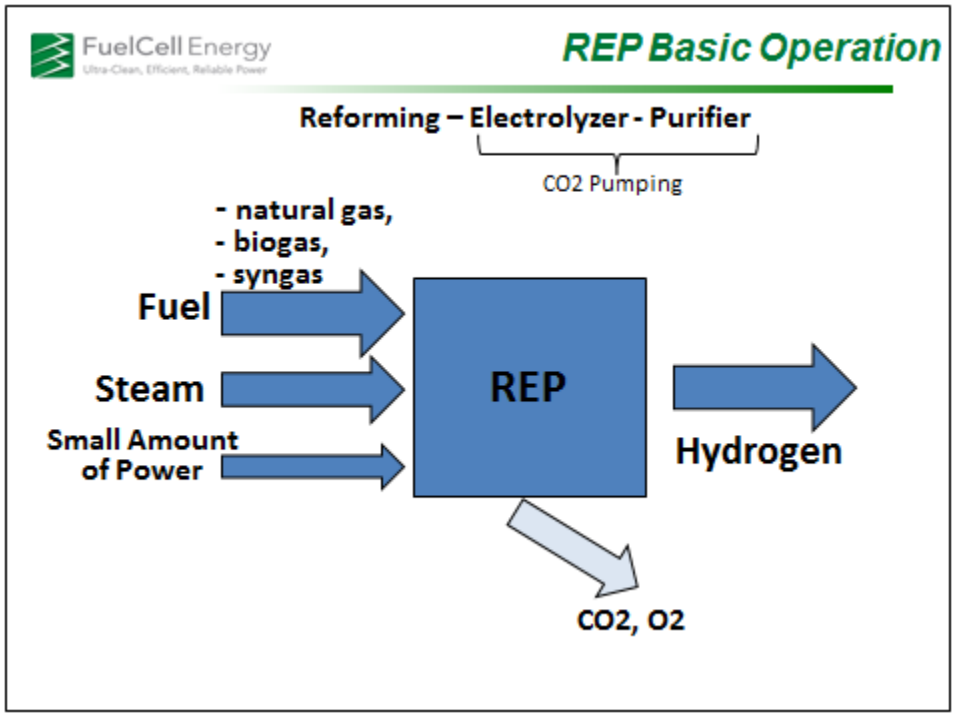
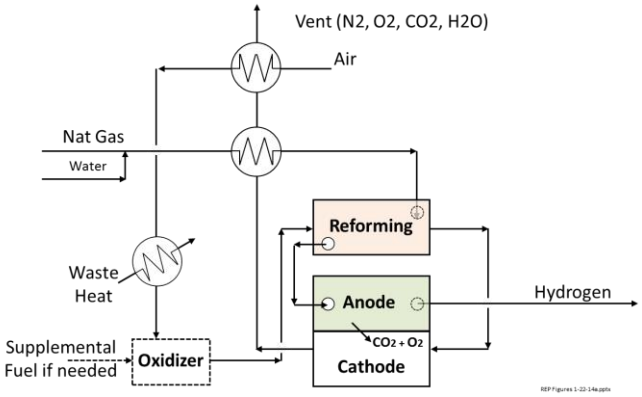


Figure 2 – Basic REP Operation.

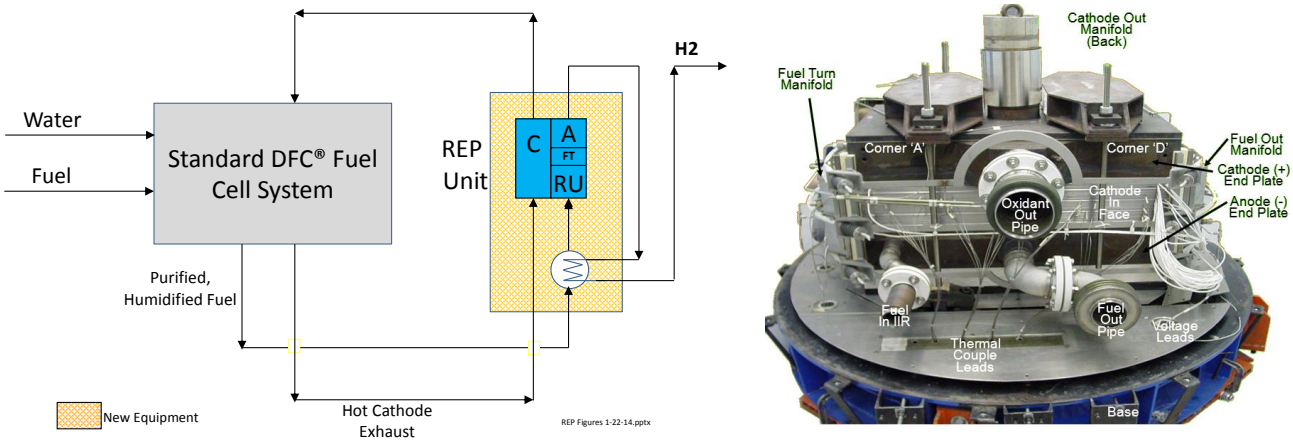


REP Unit will be built in manner similar to commercial DFC® stack shown, a new use for commercial technology

Figure 3 - Reformer-Electrolyzer-Purifier (REP) for H_2 production with Low CO_2 Emissions

As seen in **Figure 3**, natural gas and/or renewable fuel plus water are fed into the system. This feed is heated and then routed to reforming catalyst where the gas is partially reformed to hydrogen, CO and CO_2. Heat for this endothermic reaction is provided by waste heat. Extra fuel

could also be used as a backup or to raise the level of the waste heat, particularly when interruptible renewable waste heat such as wind power or solar heat is used. The partially reformed gas from the reforming unit is then fed to the anode side of an MCFC fuel cell operating in electrolyzer mode. In this cell, water is dissociated to hydrogen and oxygen, the oxygen combines with the carbon dioxide in the reformed gas, and the $CO_3^=$ is removed electrochemically across the molten carbonate membrane. This removes almost all of the carbon in the system and forces the equilibrium of the reforming and shift reactions to essentially completely convert the CH4 and CO to hydrogen. Thus the exiting gas stream is almost pure hydrogen (greater than 98%) with a small amount of CO_2 and CH_4. This small amount of CO_2 + CH_4 can easily be removed as the hydrogen is pressurized for systems requiring high purity hydrogen. Many systems are expected to use the low purity hydrogen directly. Traces of CO in the gas can easily be removed by methanation so that the H2 from the REP can be used in a PEM fuel cell without further purification (successfully tested at FuelCell Energy).



30 cell, 100 kg/d REP Unit will look like this

Figure 4 - REP System Integrated with DFC® Fuel Cell to Minimize Balance-of-Plant Equipment

The technology for the system has been developed by FuelCell Energy over the last 3 decades and is currently used in their commercial DFC® fuel cells. The REP system uses the same components it the REP unit. By using commercially available components, this new technology can be commercialized with competitive costs. In one potential configuration as shown in **Figure 4**, the system can be integrated with a high temperature power producing fuel-cell. In this configuration, the power producing fuel-cell can provide the waste heat, controls, feed gas and water treating, power, and auxiliary support equipment, minimizing the system capital cost.

We have analyzed the system for long-term hydrogen production costs using DOE's H2A model for 2 main cases. Case 1 would integrate the system with a DFC® fuel cell as shown in **Figure 4**.

Case 2 would be a standalone system as shown in **Figure 3**. The results of the analysis show a levelized cost of hydrogen at $1.47/gge and $2.07/gge respectively. Further purification to high pressure and 99.999% purity, could add ~$0.3 – $0.7/gge. In addition, the estimated CO_2 emissions (not including CO_2 associated with waste heat [~1500 g/gge] or power [~3200 g/gge] used) are less than 5000 g/gge, less than the 50% CO_2 emissions reduction target of 5500 g/gge.

FuelCell Energy has known for over 10 years the potential to use an MCFC cell in this mode. However, our focus has been on power production and developing a robust fuel-cell with a long life. Now that a robust MCFC cell is available, the REP system proposed is technically and economically feasible. We have operated full scale cells in a short (30 cell) stack as well as several MCFC single cells in this mode, confirming its technical feasibility as discussed further in the technical section below.

• Project Goal

The goal of this project, to demonstrate the REP technology on a scale of over 100 kg/d, was met. Because most of the hydrogen is generated directly from natural gas, only 7 to 8 kwh/kg H_2 is used. Testing has confirmed the scale up performance matches the results of the preliminary testing. Single cell testing of over 4000 hours also indicated a good durability of the system. Due to the successful completion of this project, we now have a unit ready for a follow-up long-term stack testing.

As part of this project, we have evaluated different sources of waste heat, different sites, and different hydrogen production rates. While the system is readily scalable to industrial hydrogen production rates, we also believe the technology has the potential to be scaled down to a home fueler size operation, particularly when coupled with a small EHC unit (electrochemical hydrogen compressor) which will pressurize and purify the hydrogen in one step.

• DOE Impact

To our knowledge, this REP type of technology is the 1st in the world and no one else is investigating it. This technology is outside of our core fuel-cell business and could not have been pursued independently by FuelCell Energy due to our limited resources and research funds without the DOE's assistance. FCE has worked with the DOE on other successful tri-generation projects to coproduce hydrogen from our fuel cells and we believe this system will reduce hydrogen production costs even further and help the DOE meet their H2@Scale goals.

• Technical Overview

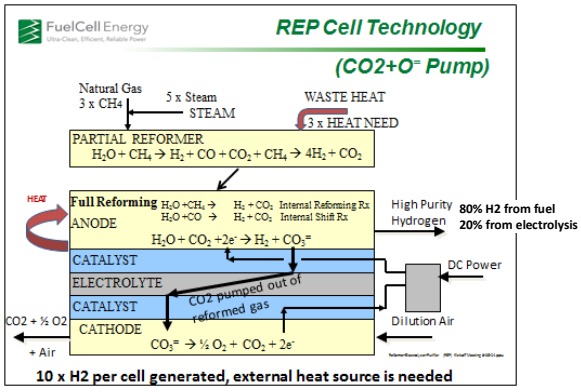
1. Scientific Principles

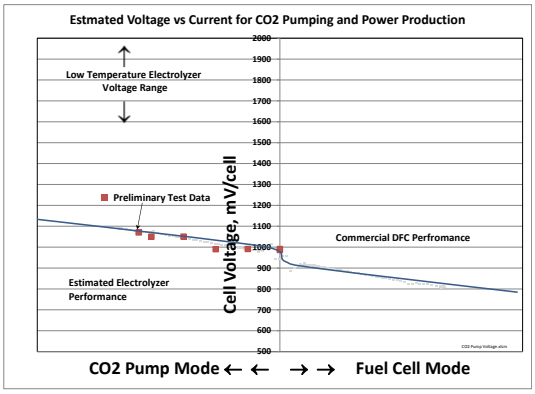
The proposed technology works on the same scientific principles as the molten carbonate fuel cell. In this case however a voltage is applied to the cell so that the current flow and ion reactions are in the reverse of the normal fuel-cell reactions. This requires CO_2 and water on the anode side and generates a mixture of CO_2 and oxygen on the cathode side as the $CO_3^{=}$ ion is pumped across the membrane. The oxygen needed to create $CO_3^{=}$ is generated by the dissociation of steam on the anode. This was initially demonstrated by applying a reverse voltage of roughly 1.2 V to a single MCFC cell and has been confirmed to work over long time periods, with good degradation rates, and for a large scale stack of cells. See **Figure 5**. The voltage required is a function of the Nernst equation. By configuring the system to dilute the cathode CO_2 concentration with air, a lower voltage and more efficient operation is realized. At the high

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

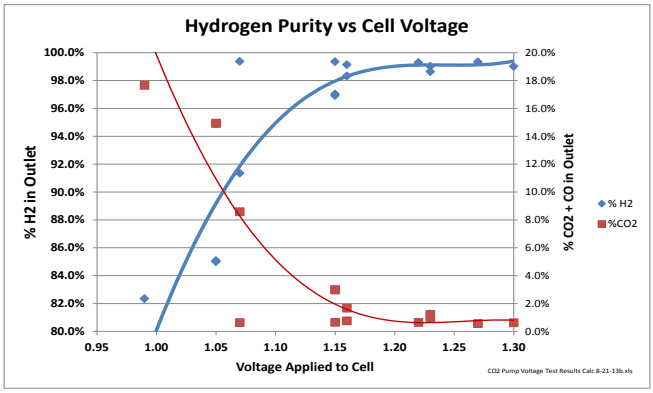
temperature, roughly 1100°F, methane is reformed by reacting with water to produce hydrogen and CO. The CO is then reacted with water to produce hydrogen and CO_2. All of these reactions are reversible, however, as the CO_2 is pumped out of the system, these reactions are driven towards complete conversion to hydrogen. We have operated the cells in this mode for over 4000 hrs (~6 months), without noticeable performance degradation.

Theoretically pure hydrogen can be produced from the anode, but complete CO_2 removal is not possible due to the vapor pressure of CO_2 from the molten carbonate membrane and the CO_2 on the cathode side of the cell. Testing has shown that the CO_2 can be reduced to around 1% on a dry basis which can easily be removed from the hydrogen using downstream purification systems if necessary. This level of CO_2 is sufficient to convert essentially all the methane to hydrogen. Note that the hydrogen and CO_2 rejected from a downstream purification step can easily be recycled to the REP (CO_2 pump) so that nearly100% conversion to hydrogen can be realized.





Reforming benefits from the waste heat added to the process



High temperature electrolysis is over 20% more efficient than typical electrolyzers

Electrolysis hydrogen also purifies the reformed gas, multiplying the benefits of the power consumed

Figure 5 - Preliminary Testing Indicates System Operates with Low Voltage and Power Consumption
At higher voltages ~99% H2 purity is achieved

2. Concept

The concept of the process is illustrated in **Figures 3 and 4**. **Figure 3** shows an independent process where waste heat is available from any site specific source, **Figure 4** shows a system integrated with FuelCell Energy's DFC® fuel-cell system with minimal changes to the DFC® system. Long-term, complete integration with a DFC® is planned. In the proposed system, the reforming of natural gas to hydrogen is driven to completion by removal of all carbon from the gas being reformed. This carbon removal in the form of $CO3^{=}$ is done at high temperature so that the reforming reaction continues to completion. The power used to remove the CO_2 provides a double benefit to the system in that it generates additional hydrogen while purifying the hydrogen from the reforming reaction. The hydrogen generated from the electrolysis reaction is highly efficient due to the high temperature and the fact that the reaction is based on steam electrolysis rather than water. We expect the electrolysis power (per kg of H_2 produced from electrolysis) to be less than 70% of the power used in typical low-temperature electrolysis systems.

The other key element in the process is the use of waste heat to drive the endothermic reforming reaction. For FuelCell Energy, the obvious source of waste heat is our DFC® fuel cell providing

power, however, many other sources of waste heat can be used. Some of the waste heat used is relatively low temperature (approximately 200° F) which is used to convert the feed water into steam and preheat the gases for the reforming reaction. The reforming reaction requires a higher level of heat, such as is available from a high temperature fuel cell, a gas turbine, solar heat, nuclear, gasification, or electrical heat.

Because the REP operation acts only on the carbon in the gas, when the REP cell is operated at a similar current level as our commercial units, three times the amount of hydrocarbon feed is fed to the REP cell and 10 times the amount of H_2 is produced. This high feed rate reduces the cost of hydrogen, but it means that the REP system needs an external heat source to provide much of the heat for the endothermic reforming reaction.

This is accomplished by a pre-reforming step in the REP system. This is similar to a standard steam methane reformer (SMR), however, it operates at significantly lower temperature (1150°) and pressure (1 psig) than a typical SMR/PSA (1500°, 300 psig), allowing the use of much lower cost materials (stainless steel rather than Inconnel).

Pre-reforming can also be done in FCE's high temperature DFC® fuel cell operating to produce power. By integration of an REP system with a DFC® power system, REP cost is minimized since much of the equipment may be shared. This includes feed clean-up, water treating, controls system, blowers, and steam generation as well as pre-reforming (including a heat of the pre-reforming). As discussed below, this is the lowest cost configuration.

3. State of art

Conventional H_2 production and separation systems such as a steam methane reformer (SMR) coupled with a pressure swing adsorption (PSA) suffer from the disadvantage of not converting all of the methane to hydrogen. Thus a substantial amount of the feed energy is converted to heat. This generation of heat makes it impractical for the system to use other waste heat to improve efficiency and reduce CO_2 emissions. These systems also suffer from efficiency losses and cost increases when scaled down from today's typical 500,000 kilograms per day systems. They typically produce a significant amount of NO_X in addition to high CO_2 emissions. This can make permitting of these units difficult, particularly in nonindustrial areas. For renewable feeds, such systems operate even less efficiently due to the dilution of the feed with CO_2 and required compression of the feed stream.

4. Impact

This technology could easily change the preferred method of hydrogen production. Because it is fully scalable it can be sized to provide the exact amount of hydrogen needed at a given site, eliminating the need for hydrogen transportation. Transportation costs can easily double or triple the cost of hydrogen at many sites and greatly increase CO_2 emissions due to emissions from trucks or other transportation means. A single DFC® stack of the size currently used for power generation can produce over 1,500 kg per day of hydrogen when operated in this mode. FuelCell Energy's standard large fuel-cell system incorporates 8 of these fuel-cell stacks which would

thus have the potential to produce over 12,000 kg per day of hydrogen. Thus large industrial scale hydrogen can be generated with this system.

On the other end of the scale, the system will maintain efficiency even as it is scaled down. FuelCell Energy is looking at a home refueling system concept which would scale this technology down to the 1 to 2 kg/d production level needed for typical fuel-cell vehicles. Such a system could potentially solve the hydrogen infrastructure problem which is a concern for these vehicles. FuelCell Energy is also developing an electrochemical hydrogen compression system which compresses and purifies the H_2 in one step. By combining these two technologies, the high pressure high purity hydrogen needed by the vehicles can be easily and cost-effectively generated at this small scale.

The REP system will produce a 33% oxygen / 67% CO_2 stream in the cathode. This gas could potentially be used as the oxidant in a gasifier or even in a standard boiler to produce a high purity CO_2 stream for capture. Even without CO_2 capture, the use of this gas as the oxidant in place of air would eliminate NOx formation. This project was focused on diluting this stream with air or cathode exhaust gas so that the composition of the gas on the cathode side was similar to the composition used in our commercial DFC® power generation cells. This dilution helps maintain the heat balance in the system and reduces the voltage requirement on the cell. In addition it reduces the risks by keeping the operation close to where we have long-term experience. Nevertheless, the system has the potential to significantly lower the cost of CO_2 capture.

The system also incorporates a high temperature electrolyzer which is much more efficient than current low temperature technology, using less than 70% of the conventional power per kg of H_2. This electrolyzer could be run without any fuel when integrated with a DFC® fuel-cell (for CO_2) and could efficiently store excess electrical power as hydrogen or methane.

5. Pathway to Commercialization

The proposed project has provided a major leap forward for the commercialization of this technology. The components used in this technology are already available commercially from FuelCell Energy's DFC® production line. Thus once the technology is sufficiently field tested, commercialization could be rapidly implemented.

The next step is the construction of a standalone 100kg/d system (including feed preparation) for longer term testing of a REP stack. This test will confirm the proper operation of the balance of plant, control strategy, and REP stack over a longer period. It will also allow evaluation of the system to load follow and determine the optimum pre-reforming level to minimize temperature variations within the stack. After a 3 -6 month shakedown of the unit at FCE, we would deploy the unit to a field demonstration site for long term operation.

6. H2A Evaluation

We worked with the UCIrvine National Fuel Cell Research Center to accurately assess the economics and commercial opportunities for the system. Based on data, heat and material balances, and cost estimates, they have analyzed the economics of the system using DOE's H2A model. The results are extremely encouraging. For a system integrated with a high temperature fuel cell, the projected hydrogen costs is $1.47/gge for 98% purity H_2 and $1.69/gge for high purity H_2. Even near term, we expect the technology will be competitive for the many smaller

hydrogen users which pay a premium for delivery of hydrogen to a site. For a standalone system, the costs are higher since processing equipment is not shared with another unit, but even in this case, the system should be able to produce hydrogen for $2.07/gge.

7. Technical Barriers

Based on our extensive work in developing the DFC® fuel cell, we do not expect any technical barriers that would prevent commercialization of the system. However, there are substantial risks that need to be addressed particularly the scaled up performance and the potential of a reduced stack life due to higher corrosion. Long-term stack testing will answer these questions.

8. Key Risks

The key risks associated with the technology prior to this work are listed below. The current program has addressed all of these risks so that the next research step of a demonstration unit can now be pursued. The demonstration unit will confirm the expectations for the stack life and performance over time which are currently based on single cell tests. It will also demonstrate the control system for the process.

1. Hydrogen purity

While single cell testing showed highly encouraging results, we needed to confirm these results on a commercial scale cell. Flow variations in the larger cell system could have potentially degraded the performance. The large scale testing showed the same performance as the single cell, producing a hydrogen purity over 98% as shown in **Figure 43** below.

2. Stack life

The life of the fuel-cell stack has been a key economic parameter in the development of our commercial DFC® fuel cell system. Over the last decade, FCE has increased our commercial stack life from less than 3 years to greater than 5 years and continue to develop technology to increase the life further. In our preliminary design of the system, we have tried to keep the atmospheres on both the anode and cathode side of the cell as close to those as used in commercial operation as feasible in order to insure a long stack life, however, some variation from our standard operation is unavoidable. The main difference is the voltage applied to the cell, changing from around 0.75 V/cell to 1.1-1.3 V/cell. We confirmed the stack life to be reasonable (2-5 years) by monitoring the cell resistance and testing a single cell over 4,000 hours of operation.

3. Voltage/power requirement

The voltage required to pump the CO_2 out of the reformed gas varies with the flow rate (current density) and the purity of the hydrogen (percent CO_2 in the hydrogen). The voltage determines the power required by the system and is thus a key parameter to be optimized. Preliminary results showed that we could expect to produce high purity hydrogen with less than 1.25 V across the cell. Long term and large scale tests confirmed this target was met.

4. Performance over time

The performance of all fuel cells will degrade over time. Long-term testing to determine the stack life indicates the degradation rate when the cell is operating as a CO_2 pump. Based on the 4000 hour operation of the single cell unit, we expect to the degradation rate to be less

than 2% per year. (Degradation rate of a single cell is higher than normal commercial fuel cells.)

3. Work Plan

• Project Objective

The objective of this project was to build and validate a commercial scale (> 100 kg/d) REP (Reformer-Electrolyzer-Purifier) stack and was successfully completed. This unit is suitable for use in a follow-up program for a field demonstration which is needed as the next step in commercialization. In addition, we generated the data needed to optimize the system, determine the performance of the system over time, and validate the economics of the system. We also looked at the economics of integrating the system with various waste heat sources and renewable fuel generators and found the economics attractive. We determined the performance not only with natural gas but also biogas (ADG) and feeds with even higher carbon content such as anode exhaust from a DFC® fuel cell.

The project started with the optimization of the design based on single cell performance. A commercial design was developed, including a detailed stack design, P&IDs, and a preliminary hazardous operation analysis (HAZOP). The REP stack was built and tested in FuelCell Energy's Danbury test facilities. Long-term testing of the single cell unit was carried out to determine the stack life and degradation rate.

In parallel, a commercialization plan was developed. This included reviewing the market for high and low purity hydrogen, reviewing potential sources of waste heat, potential waste fuels, and determining a site for a field demonstration of the unit. The economics of the system based on test results were developed based on the near-term and long-term expected capital cost.

• Task Summary

The tasks required to achieve the program objectives are shown listed in Appendix A, the program Statement of Project Objective (SOPO).

• Risk Mitigation Plan

We reviewed the risks associated with the project by identifying changes from previous experience, the potential impacts, and the potential mitigation steps. See **Figure 6** below.

In addition, we included a Go/No-Go decision point. This Go/No-Go point was early in the project just after the single cell parameter study when less than 25 % of the funding being spent. Once the results of the parameter study were incorporated into the economic models, the project risks were greatly reduced.

TECHNOLOGY RISK STATEMENT										
PROJECT:	Low Cost, Low CO2 H2 from NG			PROJECT No.:	FOA-0000826			DATE:	1/22/14	
CUSTOMER:	DOE / EERE			LOCATION:	FuelCell Energy			REV:	0	
STEP-OUTS AND NEW TECHNOLOGIES (SO/NT)	WHY IS IT A RISK?	WHY IS IT BEING TAKEN?	EXPERIENCE	CONSEQUENCE	SO/NT classification	Probability	Impact	Overall Risk Assessment	FALLBACKS	Tests to reduce risk
Econmics	**New technolgoy**	**Potential high benefits**	**Preliminary review looks attractive**	**Low return on investment would limit applications**	**3 - Med**	**30% Med-Low**	**4 –Med-High**	**2.5 - Med**	**look for cost reduction options**	**No specific test needed, detailed economic review is one of first tasks**
Reverse Voltage Operation of DFC fuel cell	Voltage required uncertain	Required of planned operation	Single cell tests indicate attractive voltage required	Economic impact	4 – Med to High	45% Med	4 - Med-High	**2.9 - Med**	Operate system at lower current density	Single cell tests planned early on will characterize voltage required
	Durability - Voltage could increase overtime too quickly	Required of planned operation	One month operation of single cell	Economic impact	4 – Med to High	45% Med	4 - Med-High	**2.9 - Med**	Operate system at lower current density	Durablity testing of single cell tests planned to start as soon as possible so that any severe change in voltage will be known early in program before larger expesive tests are performed
	Durability - Corrosion due to change in compositions could occurr	Required of planned operation	One month operation of single cell	Economic impact	4 – Med to High	45% Med	4 - Med-High	**2.9 - Med**	Operate system at lower current density	Durablity testing of single cell tests planned to start as soon as possible so that any severe corrosion impact will be known early in program before larger expesive tests are performed
H2 Purity	Desired puritity may not be reached	Required of planned operation	98 to 99% H2 purity reached in preliminary tests	Lower efficiency, lower value product if purity not met	3 - Med	45% Med	3 - Med	**2.2 - Med**	- Couple with EHC to remove impurities during compression of H2 - Optimize pressure differential between anod and cathode	Commercial scale test
Control of new technology	Control system must be developed and tested	Required of planned operation	Control in fuel cell mode, operation of PEM fuel cell in reverse mode	Low product quaility	1 - Low	15% Low	2 - Med-Low	**1.1 - Low-Med**	Develop new control algorithms if current systems insufficient	Commercial scale test CO2 Pump risk assessment 4-15-13.xls

Figure 6 - Risk Assessment indicates manageable risks for project

• Quality Assurance

The quality of the work done under this project was assured by the careful planning, the quick review of the data, and calibration of our instrumentation. We have found that material balances around the system can identify errors in flow rates and compositions and performed balances during the testing. We periodically calibrate our gas chromatographs with calibration gas compositions that are similar to those being produced.

The work was carried out at FuelCell Energy's Danbury test facilities using test methods developed for our commercial DFC® product development. **Figures 7 and 8** show our single cell and commercial scale test facilities.

Figure 7 - Single Cell Test Facility

Figure 8 - Commercial Scale Test Facility

4. Accomplishments

As summarized in **Figure 9** below, the advanced REP technology is highly relevant for a cost-effective future hydrogen-based infrastructure.

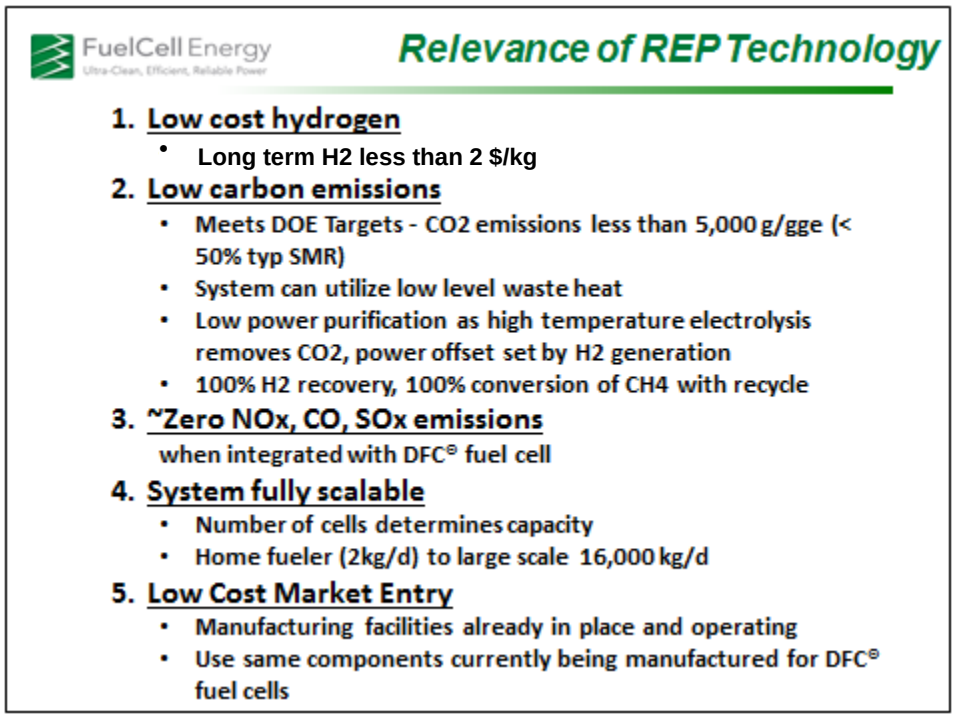


Figure 9 – Relevance of REP Technology

To develop this technology, the research was performed in a staged manner. Initially small scale single cell testing was done to confirm the expected performance and life. After successfully

testing the small-scale cell, a large-scale stack was constructed for testing. All of the test results met our initial performance expectations and goals. This approach is summarized in **Figure 10.**

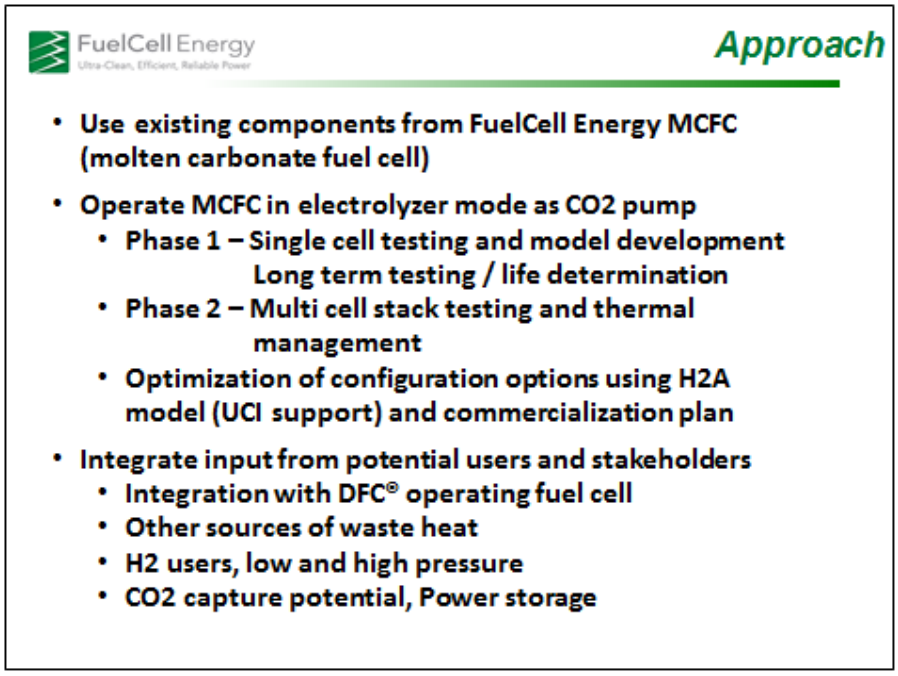


Figure 10 – Approach to Research Work

The significant accomplishments of this work are summarized in **Figure 11**. The details of this work are further discussed below.

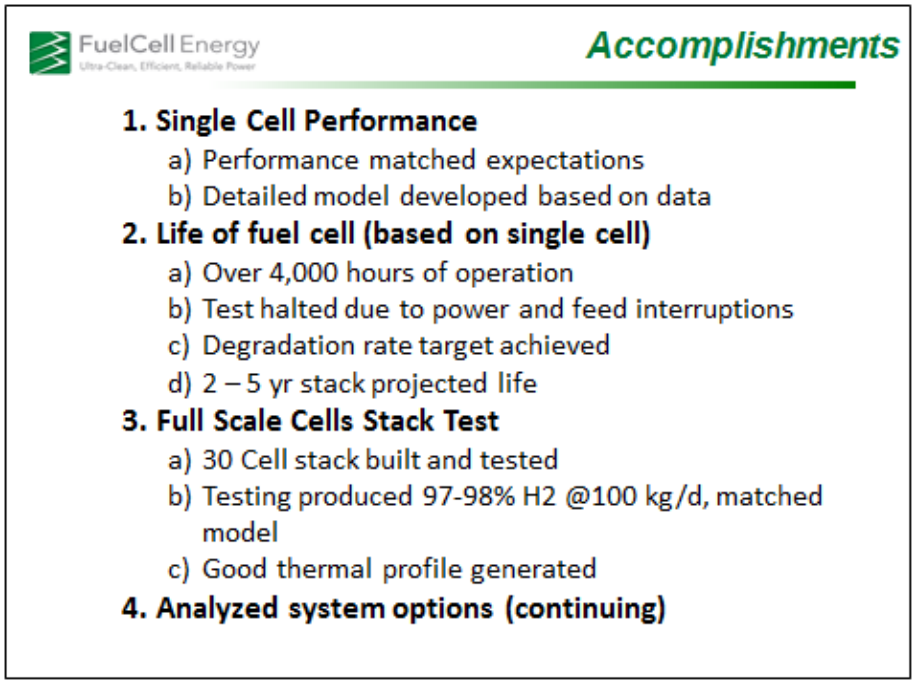


Figure 11 – Summary of Research Accomplishments

The operation and performance of the cell in REP mode was determined by testing of a small single cell using a test stand as shown in **Figure 12**. This is the same type of test used to validate improvements for our commercial fuel cells. The results of the tests were very positive, indicating that an REP unit can be operated with the cell voltage of around 1.2 V per cell and a very reasonable degradation rate so that a 2 to 5 year cell life is expected as shown in **Figure 13**.

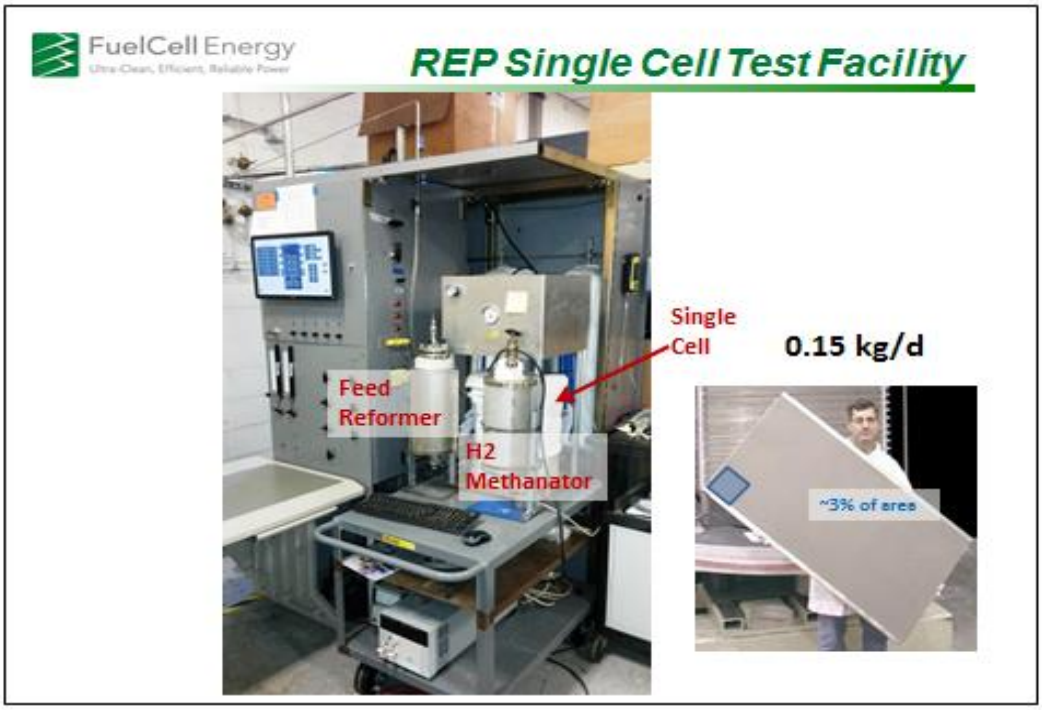


Figure 12 – Single Cell Test Stand and Size of Cell Compared to Commercial Cell

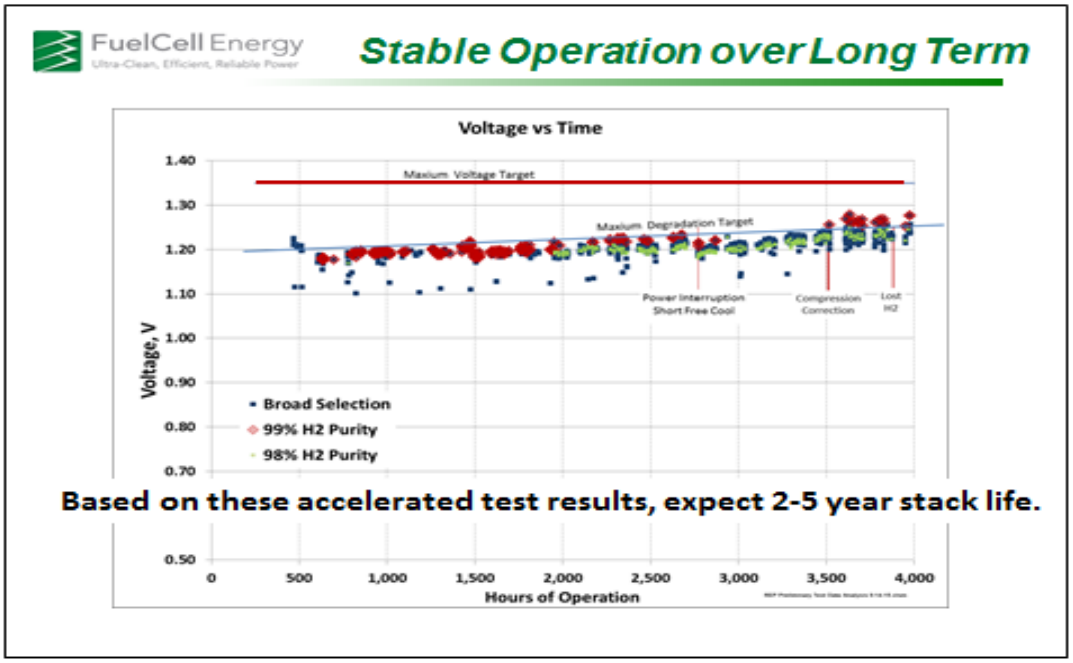


Figure 13 – Stable Operation of REP Unit Indicates 2 to 5 Years Life Can Be Expected

Based on the successful single cell test results, the REP research continued and a full scale 30 cell stack was built using cells from our commercial production line. After the cell was conditioned and prepared for operation, it was tested at low load in the conditioning facilities as shown in **Figure 14**. Even at low load (~10% normal) high purity H2 was produced. Unfortunately these facilities were unable to handle the 100 kg per day of hydrogen produced when the stack is operated at full load so the unit was relocated to our large test facilities as shown in **Figure 15**.

The full load tests were also highly successful, meeting all performance targets as shown in **Figure 16**. This test proved that high purity hydrogen could be generated from a full-scale stack as well as a single cell. It also showed that the temperature profile within the stack was excellent, with a maximum to minimum delta-T across the stack that was on the order ¼ the delta-T of our commercial fuel cell operating stacks.

The length of the full scale test was limited due to the limited availability of our large scale testing facility. The next step in the development of the technology is a longer-term testing (3-6 months), preferably in-house or at a site which can use the large amount of hydrogen produced.

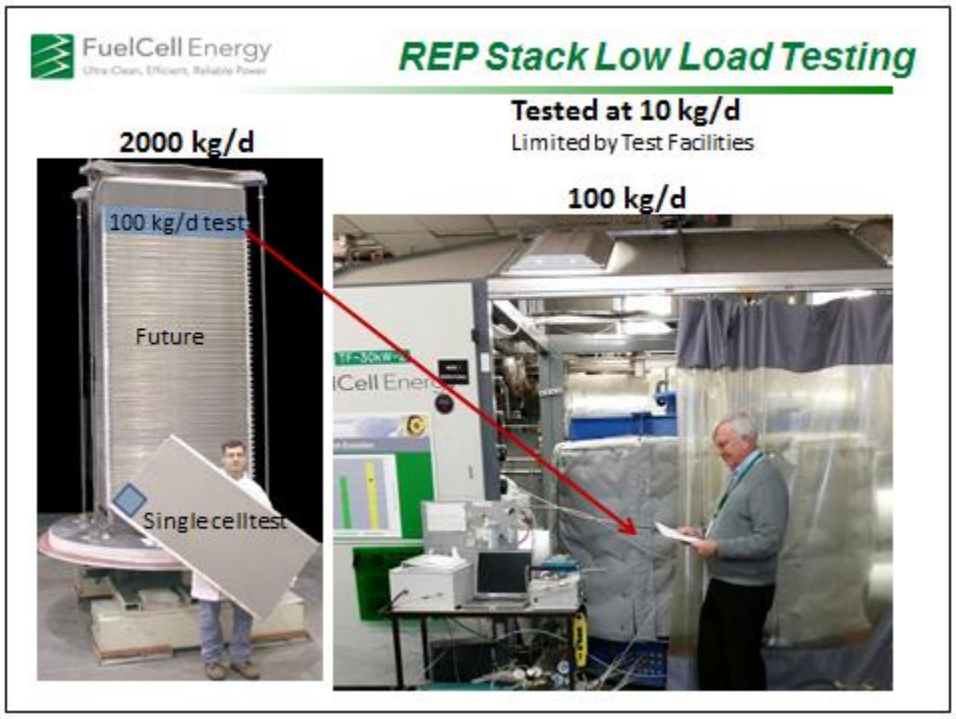


Figure 14 – 30 Cell Stack Conditioning and Low Load Testing

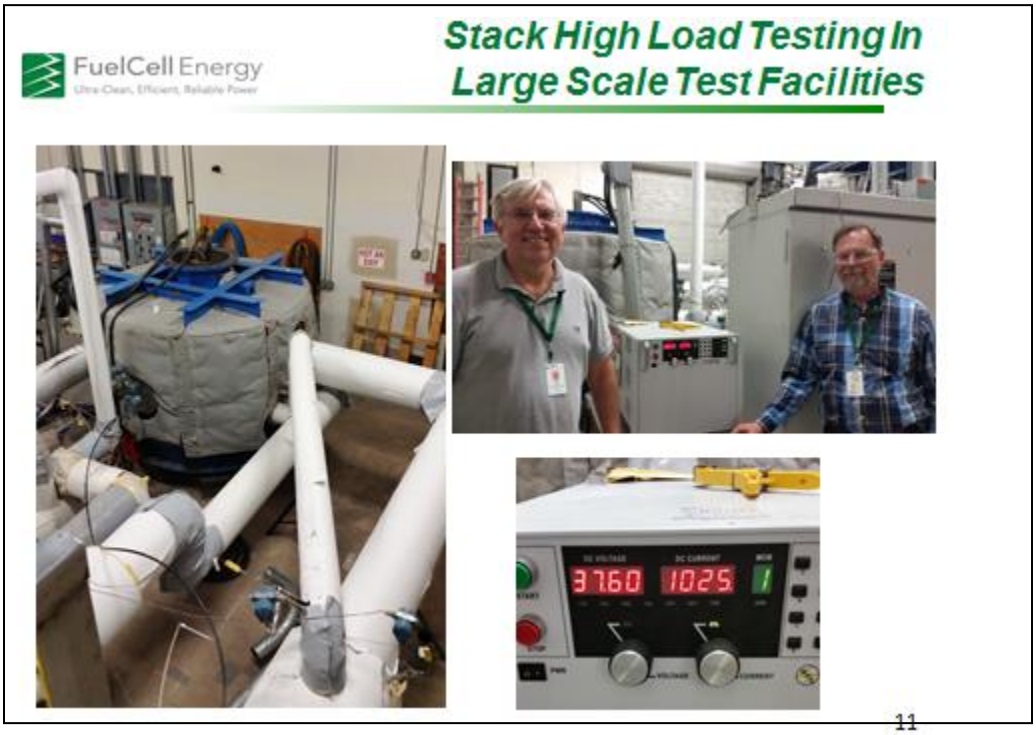
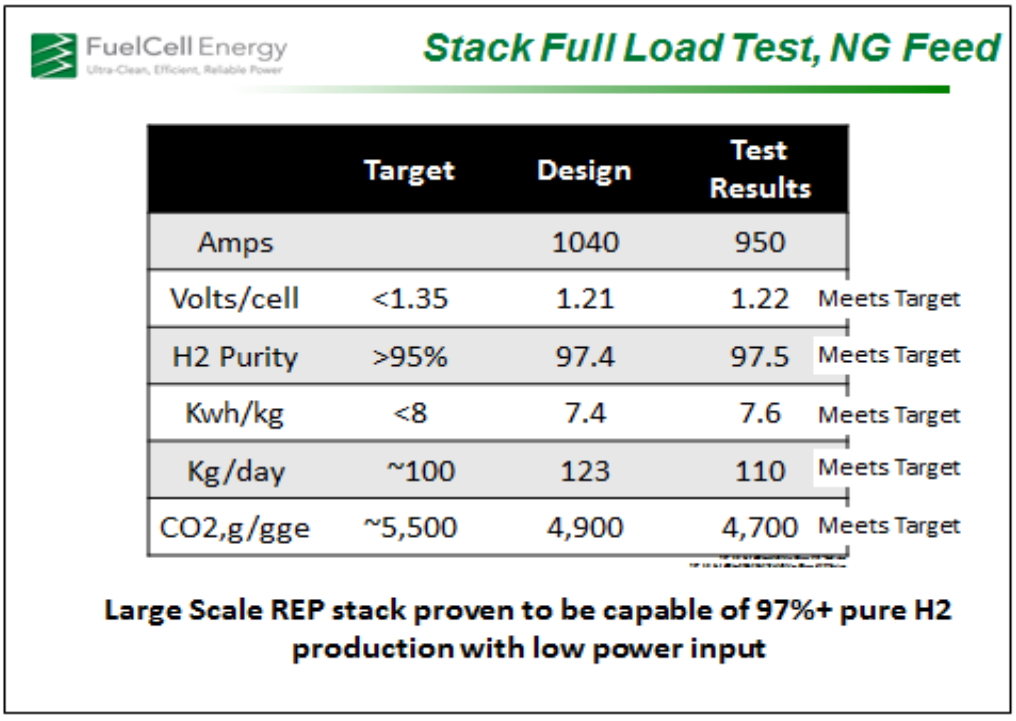


Figure 15 – Large Scale Testing at Over 1000 Amps to Produce Over 100 Kg/Day of H_2



	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

Figure 16 – All Performance Targets Were Met During the Full Scale Stack Test

To minimize the cost of hydrogen and the CO_2 emissions, waste heat from an external source, such as a combined heat and power unit (CHP), can be utilized. The temperature of the waste heat from the CHP system is important. **Figure 17** shows the heat needed by the REP and the waste heat temperature level available from various CHP systems. As can be seen in **Figure 17**, roughly 40% of the heat needed by the REP system is for the production of low pressure steam used in the process. Low-pressure steam has zero value in many locations. Higher level heat often has a value which must be included in the cost of hydrogen. When the higher level heat is unavailable, that heat can be generated by burning additional fuel. While burning fuel for the high level heat is not preferred, it can be combined with the low value, low level heat, to increase the efficiency and lower the hydrogen cost.

Figure 18 below shows the impact of free waste heat on the operating cost of an REP system. Note that the operating costs can be reduced up to 25% when free waste heat is available. The CO2 emissions show the impact on reducing the fuel required to heat-up and partially reform the feed to the REP (and assumes there are no CO2 emissions associated with using the waste heat).

Several different configurations and feedstocks for an REP system have been analyzed to see the impact of the different configurations on hydrogen cost. These results are shown in **Figure 19**. The DOE's H2A analysis spreadsheet was used to estimate the cost of the hydrogen produced from the system based on estimated capital costs, operating costs, and maintenance costs. The CO_2 emissions from the system are also well below the 11,000 g/gge emitted from a typical SMR. (g/gge = grams CO_2 per gasoline gallon equivalent of H_2, 1 gge = 1.003 kg H_2)

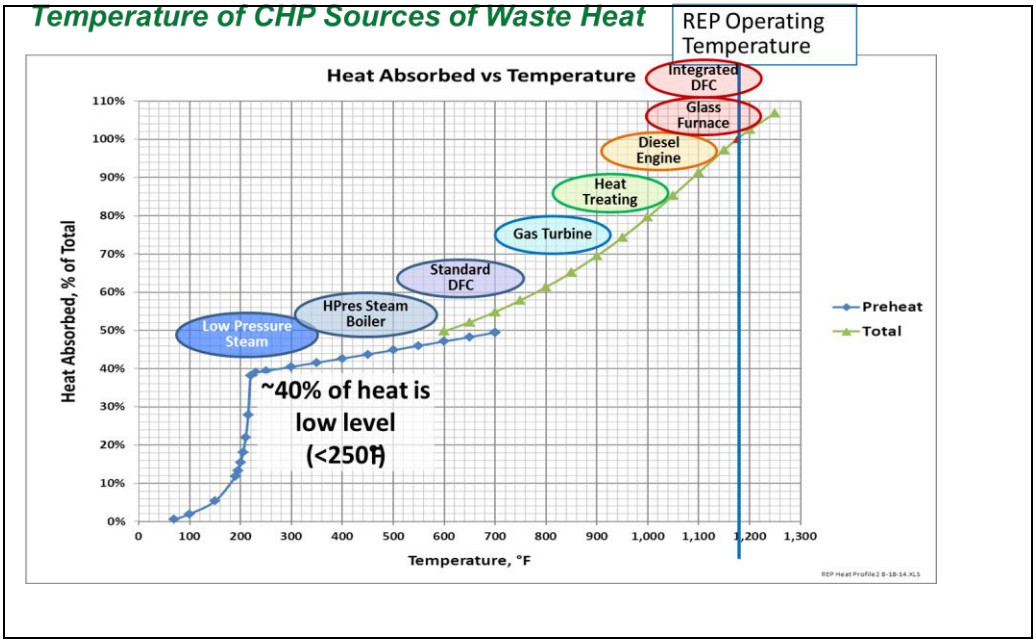


Figure 17 – Level of CHP Heat Available

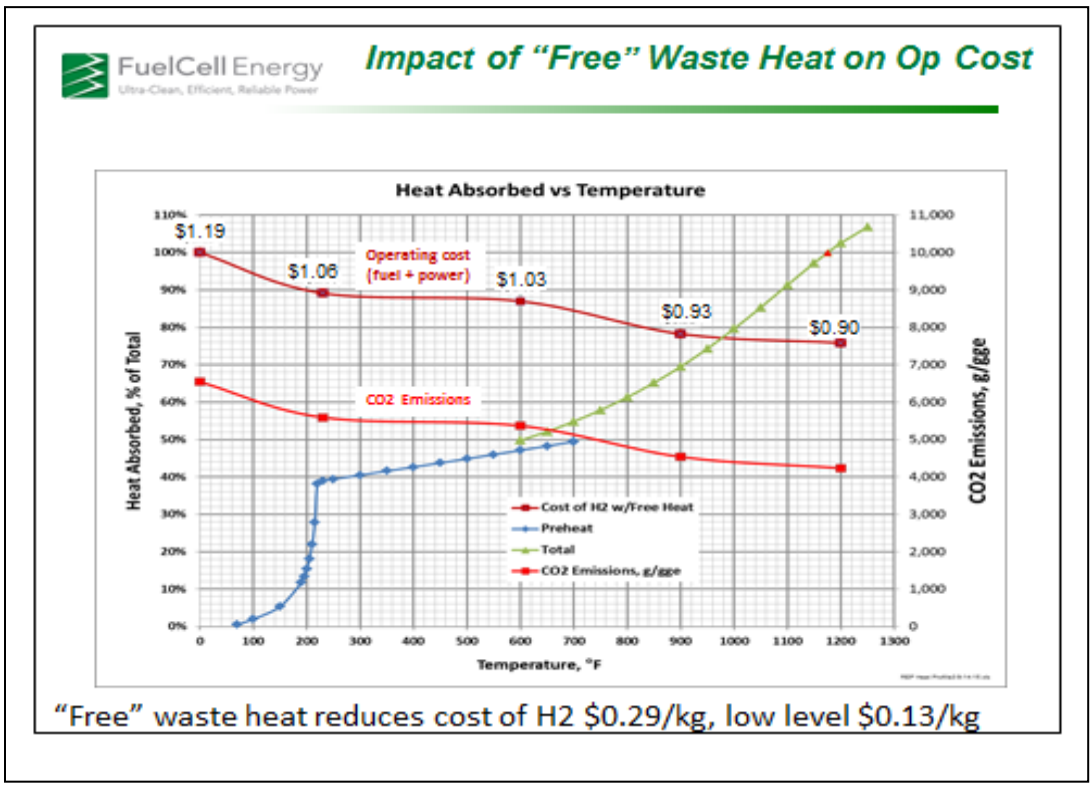


Figure 18 – Impact of Free Waste Heat on Production Costs

FuelCell Energy
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H2A System Analysis

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

REP Cases HMB Summary R7a.xlsm

[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 19 – Analysis of Configuration and Feedstock Impact

A detailed description of the case assumptions is as follows:

Case 1. Base Case - REP unit is integrated with a DFC fuel cell which shares the balance of plant equipment, provides the pre-reforming needed, and provides the heat required for pre-reforming the feed to the REP.

Case 2. Standalone Case - Heat needed for pre-reforming the feed gas and REP is provided by a burning additional natural gas. Full cost of the balance of plant equipment included in capital.

Case 2a. Standalone with CO_2/O_2 Coproduction - Same as Case 2, but elimination of air sweep provides CO_2/O_2 byproduct. This increases the voltage and power required slightly.

Case 3. Standalone with External Low-Pressure Steam - Same as Case 2 except that free low-pressure steam is assumed available at the site, reducing NG needed for heat generation.

Case 4. Standalone Self Powered - Power needed by the REP is supplied by DFC fuel cells in the same stack as the REP cells. No external power, but has higher capital / fuel costs. Lower output is due to many of the REP cells in the stack being used for power production.

Case 5. Standalone ADG Feed - Same as Case 2, but anaerobic digester gas (ADG) feed which has a higher C content relative to NG, and thus requires more power.

Case 6. Standalone with Syngas Feedstock – Same as Case 2, but with syngas generated from biomass gasification as the fuel source at same $/mmbtu.

Case 7. DFC Anode Exhaust - Feed is anode exhaust from a DFC fuel cell. Economically feasible with low cost peak power. Good for energy storage since feed very low value and most of H_2 comes from electrolysis.

Case 8. SOFC Anode Exhaust - Feed is anode exhaust from a SOFC fuel cell. . Economically feasible with low cost peak power or for CO_2 capture.

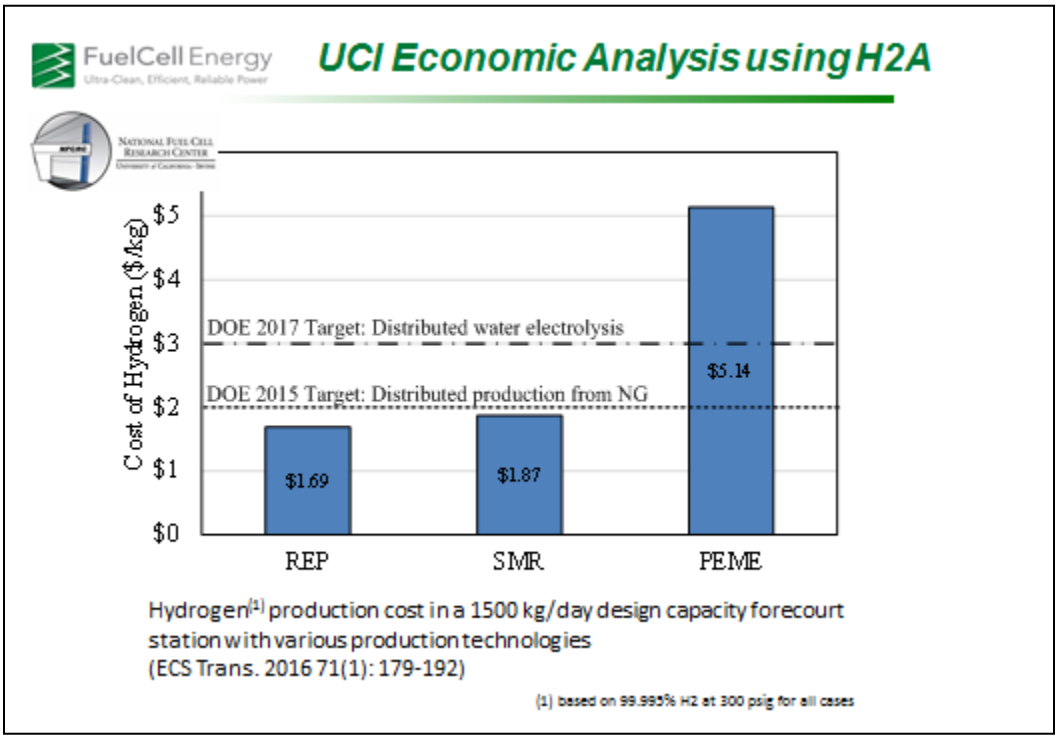

Figure 20 – Impact of Pressurization and Purification on Cost

The analysis shown in **Figure 19** is based on a low-pressure, 98% pure hydrogen product. UCI (University of California, Irvine) included the purification and pressurization costs in their

analysis. As shown in **Figure 20**, this adds about $.30 per kilogram to the costs. A similar analysis was done by a Strategic Analysis Inc and they estimated the cost of purification and pressurization at around $.70 per kilogram. Although pressurization and purification are required for automotive and some other applications, many hydrogen applications, including energy storage, can use the 98% pure hydrogen. Many applications can also use low-pressure hydrogen.

The system also compares well with standalone electrolysis. Because it is a high temperature electrolysis system, the voltage and power requirement for the electrolysis hydrogen is already low, on the order of 33 kwh/kg H_2. However, since only 20% of the hydrogen generated comes from electrolysis the overall power requirement is only 20% of this value or around 7 to 8 kwh/kg H_2, well below the 35 to 60 kwh/kg H_2 required for water electrolysis. For feedstocks with higher carbon content, such as anaerobic digester gas, slightly higher power consumptions are required as shown in **Figure 24** since a larger fraction of H_2 produced is from electrolysis.

"CO_2 free"hydrogen can be generated from a new renewable feeds and/or renewable power. We believe anode exhaust qualifies as a renewable feeds since no additional increase in CO_2 emissions result from this feed (with renewable power).

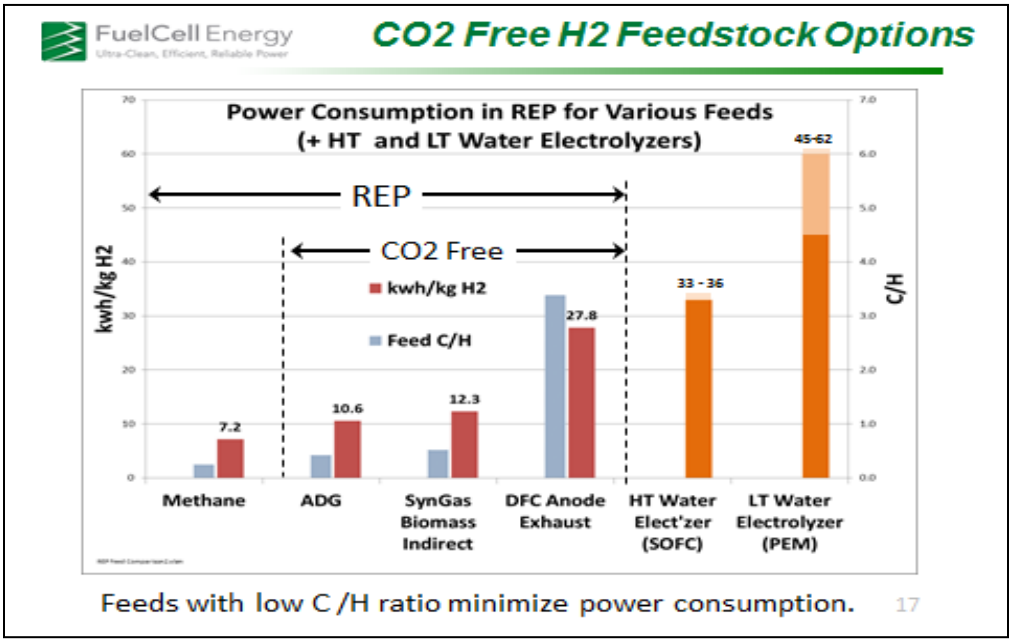

Figure 21 – Comparison of Power Consumption Required for Different Feedstocks and Technologies

Traces of carbon monoxide found in the hydrogen from the REP could be a problem for some downstream equipment, but can be easily eliminated by passing the hydrogen across methanation catalyst as it is cooled down. With the CO eliminated, the hydrogen from the REP can be used directly in a PEM fuel-cell for peak power generation. Such a configuration would allow very efficient energy storage in the form of hydrogen. It also allows the use of a PEM-based electrochemical hydrogen compressor (EHC) system which will produce high pressure, high purity hydrogen in one step. This operation was demonstrated using the hydrogen from the single

cell testing (see **Figures 22, 23 and 24**) when a small methanator was incorporated in the process. (We also demonstrated the system does not work without methanation.)

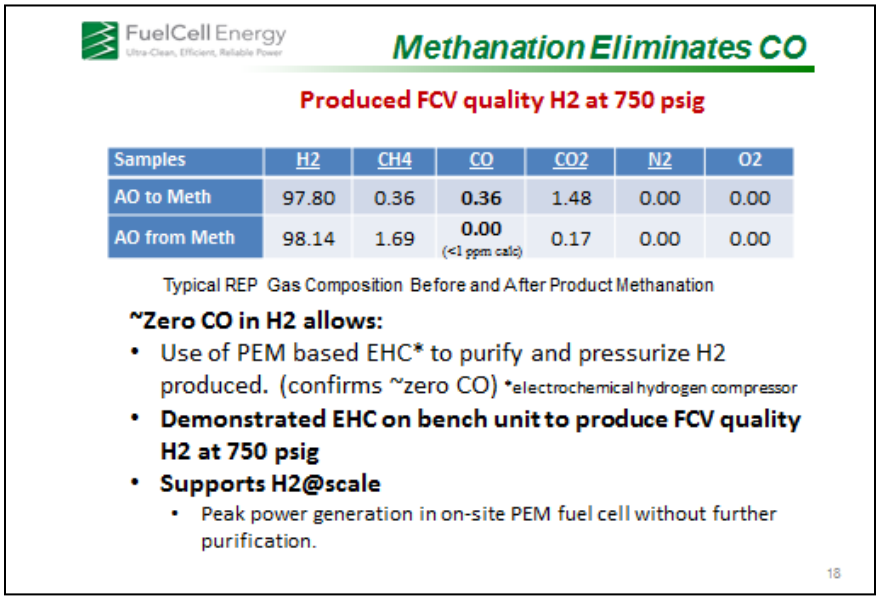

Figure 22 – Removal of CO Allows Electrochemical H_2 Compression

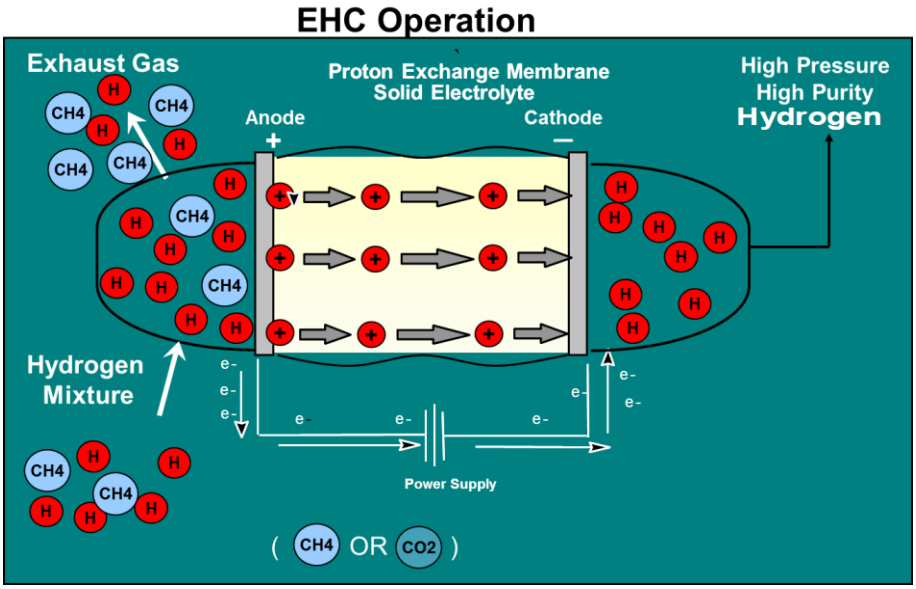

Figure 23 – Electrochemical H_2 Compression Operating Principles

The EHC exhaust gas would be recycled to the REP to achieve 100% conversion of feed methane to H2.

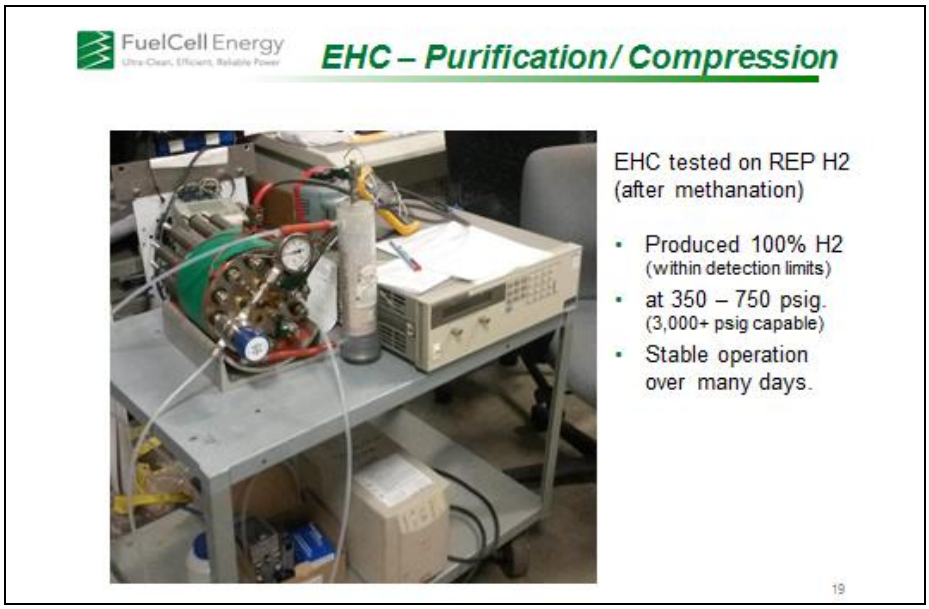

Figure 24 – EHC Test Facilities to Producing High Purity, High-Pressure H_2

Although not included in the original research program, a small EHC unit from another research program became available during our testing. We used that equipment to prove an REP/EHC operation is feasible. We believe this combination could be used in a cost effective home H2 generation system.

• Test Data – Single Cell

Initial test results showed the production of 98% hydrogen with the cell voltage of 1.2 V, matching the performance expectations of our proposal. As shown in **Figure 25** below, there is the potential to reduce the voltage slightly when the purity of the hydrogen produced is also reduced. At 94% purity, the voltage drops and power consumption decreases about 8%.

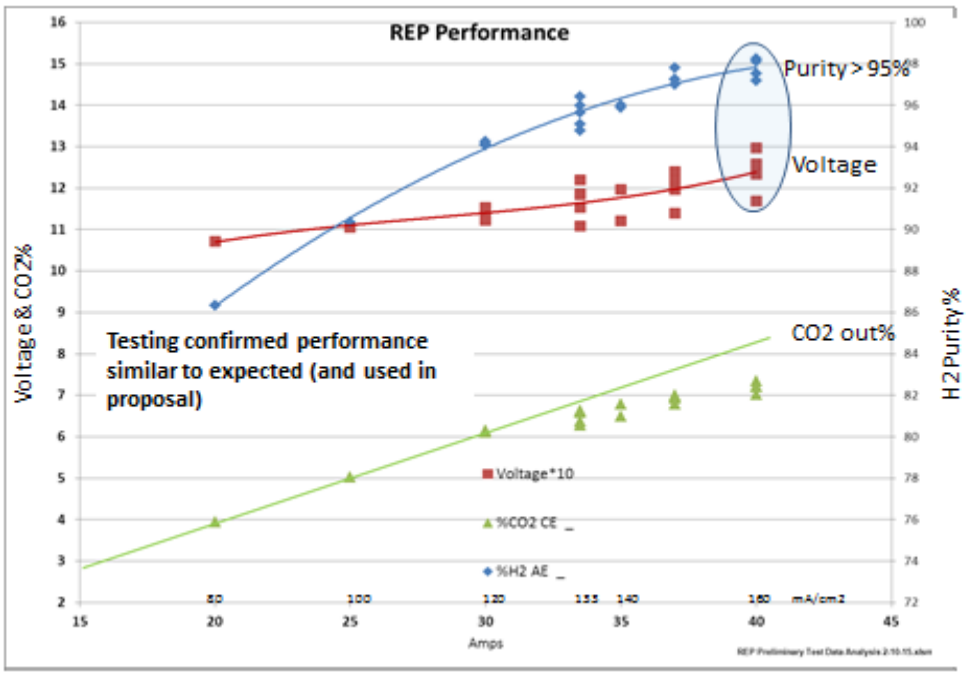

Figure 25 – REP Performance as a Function of Hydrogen Purity

Note that the CO_2 concentration on the cathode side matches the expected theoretical concentration for hydrogen purities of 94% and below. Above 94%, the amount of CO_2 in the cathode gas is slightly below the expected levels of CO_2. This implies that either some of the CO_2 diffuses back across the cell during operation or some of the charge is transferred as an OH^- ion rather than as $CO_3^=$ ion. Based on other research data, we believe that part of the current is being transferred with OH^- ions which increases slightly the power consumption of the REP cell. Fortunately the power consumption of the REP is quite low so that a slight increase has little impact on the cost of hydrogen production. In fact we estimate that with the 10% back diffusion, or OH^- ion transfer, less than 5% kwh/kg H_2 is added to the cost. In part this is due to the fact that only 20% of the hydrogen is generated from the electrolysis reaction. It is also helped by the fact that even with OH^- current transfer, electrolysis hydrogen is still produced.

We correlated the amount of CO2 back diffusion or OH^- current transfer as a function of hydrogen purity as shown in **Figure 26**. While there is significant scatter in that data, it appears

that only 15 to 20% of the current is transferred without CO_2, even with the production of high purity hydrogen

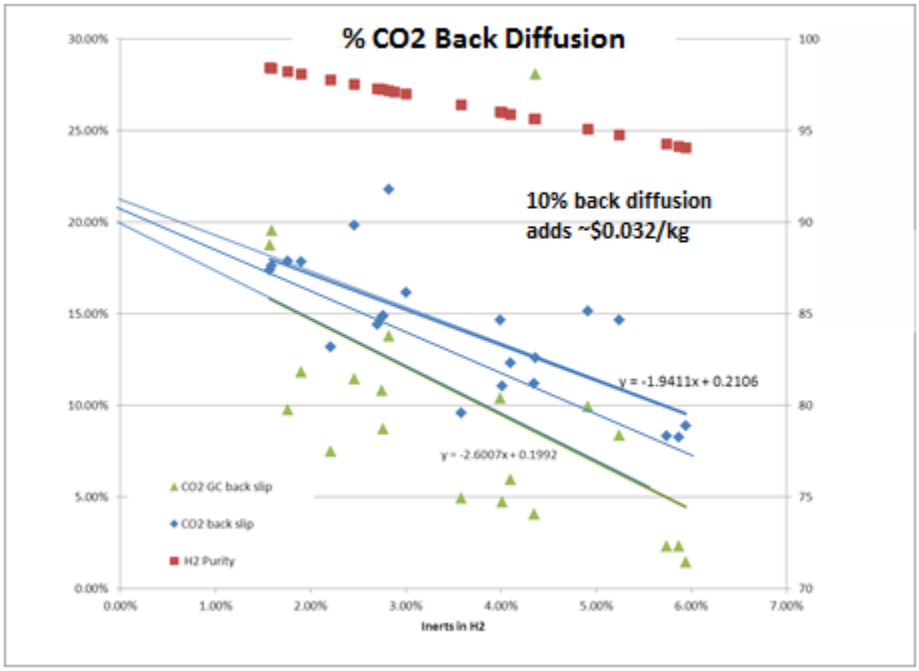

Figure 26 – Estimation of Back Diffusion as a Function of Hydrogen Purity

Another variable of interest is the operating temperature of the stack. As can be seen in **Figure 27** below, a higher temperature will reduce the voltage and improve the efficiency of the REP operation. This is also true for molten carbonate cells operating for power production, however, we have observed that as the temperature of the cell is increased, the life of the cell will be reduced. We used the middle temperature for our economic analysis. This temperature is similar to the temperature which we have found optimal for our fuel-cell operations.

A third variable is the current density of the operation. As with cells in fuel cell mode, better performance occurs at lower current densities. However, the lower the current density is, the lower the capacity of a cell is. Thus to minimize capital cost, a high current density is desired. **Figure 28** below shows the impact of current density on cell voltage. The power requirement and efficiency is a function of the cell voltage and is similarly impacted. For most of our testing, we assumed a current density equivalent to what we use in our commercial fuel cells.

The figure shows that a 10% reduction in capacity would provide about 2% increase in efficiency. Thus if the hydrogen demand is below the unit design, a more efficient operation will be realized. For energy storage systems using an REP, one could expect a significant amount of operation at part load with the current set by the amount of excess power on the grid.

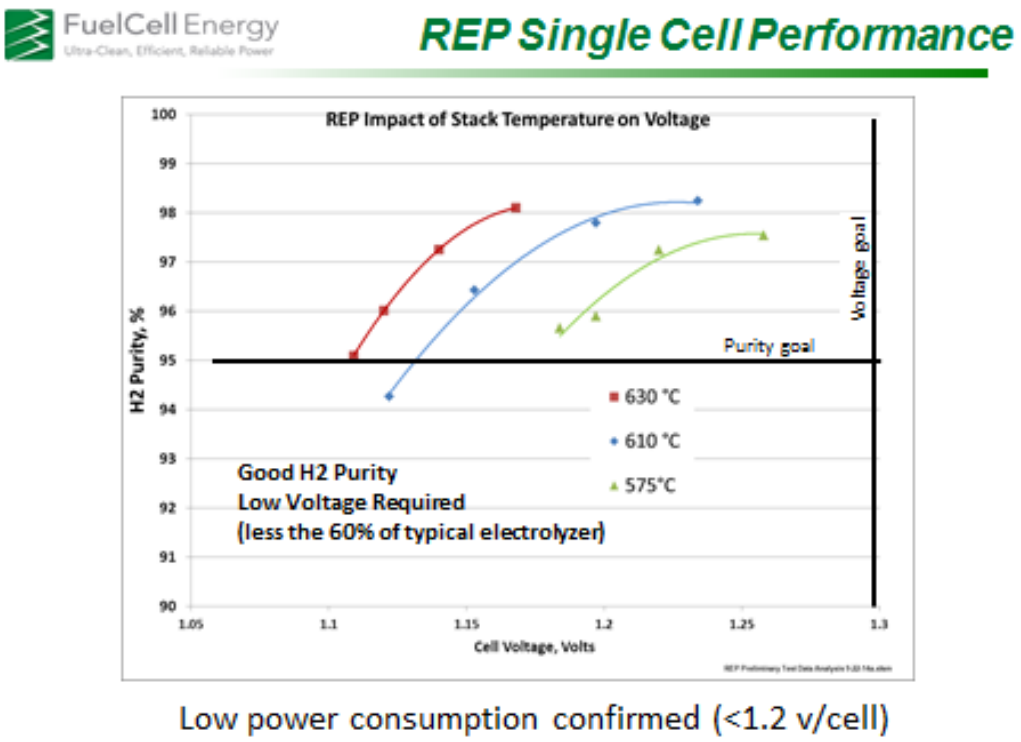

Figure 27 – Impact of REP Temperature on Performance

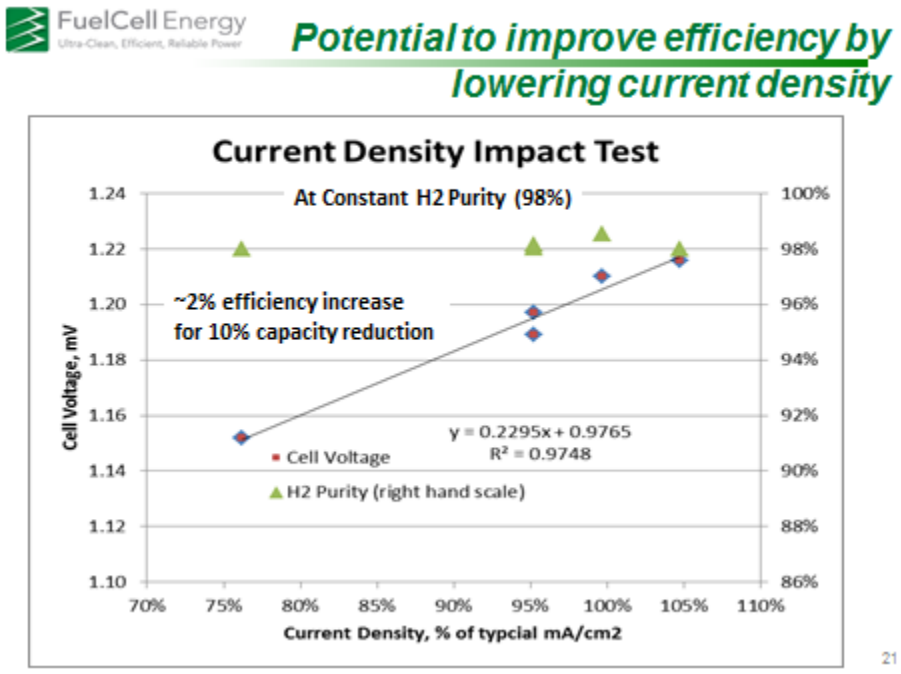

Figure 28 – Impact of Current Density on Cell Voltage and Efficiency

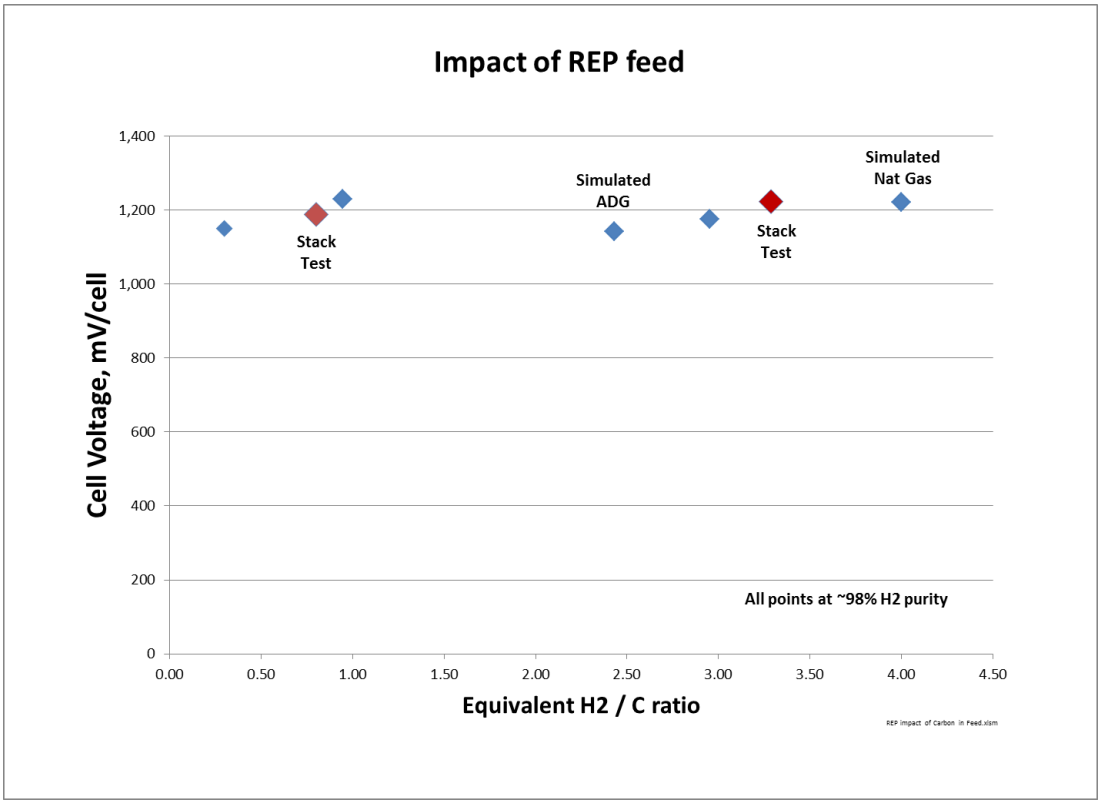

Figure 29 – Impact of Carbon (CO2) in REP Feed

Impact of carbon in the REP feed is shown in **Figure 29**. Higher carbon feeds, such as ADG and anode exhaust gas, appear to have little if any impact on the voltage (and power) required. However, a higher carbon to hydrogen ratio will increase the required kwh/kg of H2 since it will increase the amount of hydrogen from electrolysis relative to the H2 from reforming. This ratio impact is illustrated in **Figure 21** above. For methane, the ratio of H2 reforming / H2 electrolysis is approximately 80/20, for ADG, 71/29, for anode exhaust, 28/72. A lower H2/C in the feed will increase the required stack kwh/kg from approximately 7.2 (NG) to 10.6 (ADG) to 26.0 (AE).

We also looked at the impact of water in the feed to the REP. We have noted that when we have too little water in the REP feed and all of the water is consumed, the voltage on the stack becomes unstable and can spike to higher levels. As the water in the REP feed is increased, the voltage required to pump out all of the CO_2 is reduced slightly as shown in **Figure 30**. Note that a small step size was chosen for the plot which exaggerates the voltage impact. Increasing the water in the feed often requires more heat as more water must be vaporized and heated to the feed temperature. When we looked to optimize the amount of water in the feed, assuming that any additional water requires burning of natural gas to provide the heat, we found only a minimal impact of water on the overall performance efficiency. The additional fuel required for higher water content was essentially offset by the reduced power consumption due to the lower voltage resulting from the higher water. These optimization results are shown in **Figure 31** below.

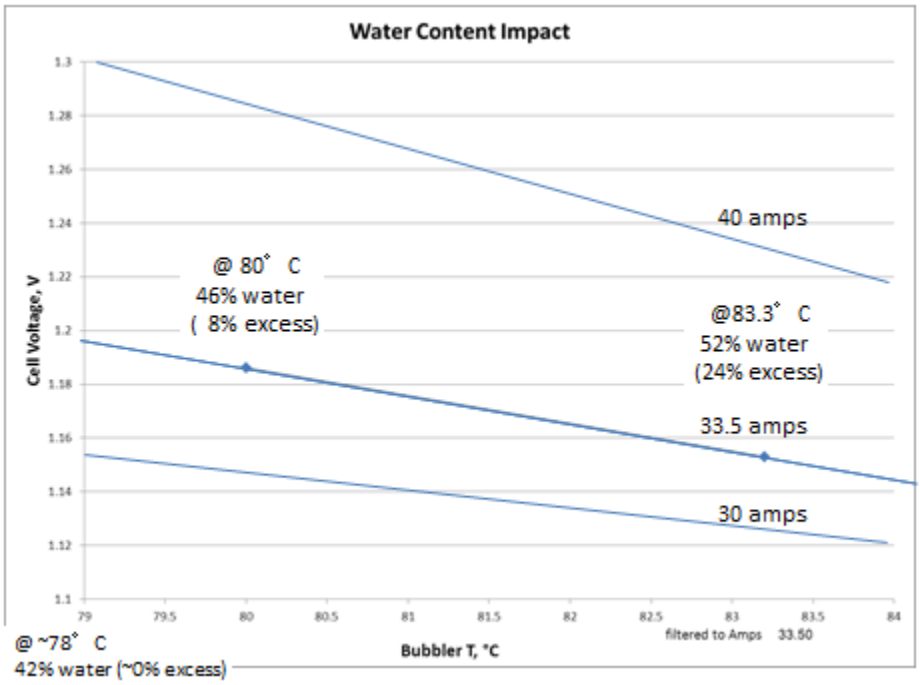

Figure 30 – Impact of Water Content on Cell Voltage

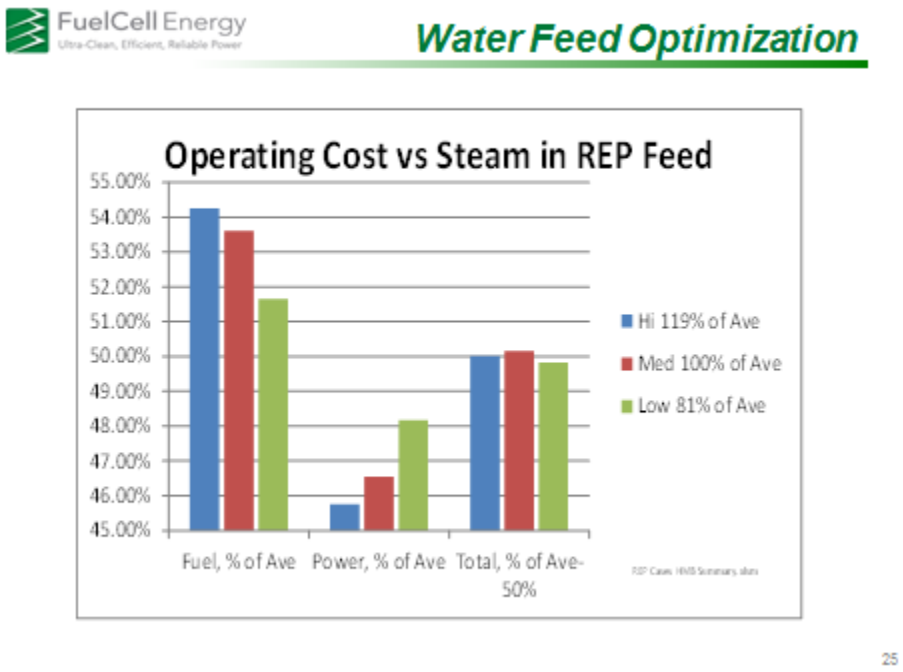

Figure 31 – Water in the REP Feed Has Minimal Impact on Overall Operating Cost
(when natural gas must be consumed to provide the heat to vaporize and heat up the additional water)

In normal fuel cell operation, hot air is fed to the cathode of the fuel-cell. This provides the CO_2 and oxygen transferred by the fuel-cell as well as removing some of the heat generated by the cells. For the current REP design, we have also assumed the use of an air sweep on the cathode side. The air sweep helps even out the temperature profile within the stack and dilutes the CO_2 and oxygen produced by the REP. As shown in **Figure 32** below, dilution of the CO_2 and oxygen reduces the cell voltage of the REP. More importantly, it creates an atmosphere on the cathode which is very similar to the atmosphere used in our commercial fuel cell operation, minimizing the likelihood of higher corrosion rates or other negative impacts which could occur with high CO_2 and O_2 concentrations. At the same time, we see a 10% reduction in voltage and power requirements when dilution air is used. Even a small amount of sweep gas will have a significant impact on the voltage. The biggest impact occurs when nitrogen is used instead of air as this reduces both the oxygen and CO_2 concentrations on the cathode, further reducing the voltage required.

In the long-term, operation without sweep gas may become desirable as this provides the potential to produce a pure CO2/O2 mixture as a byproduct. If this mixture is used in place of air in a boiler, the boiler exhaust will be almost pure CO_2 and water which would make CO_2 capture very easy. It would also allow the operation of the REP at higher pressure without the penalty of pressurizing the sweep gas.

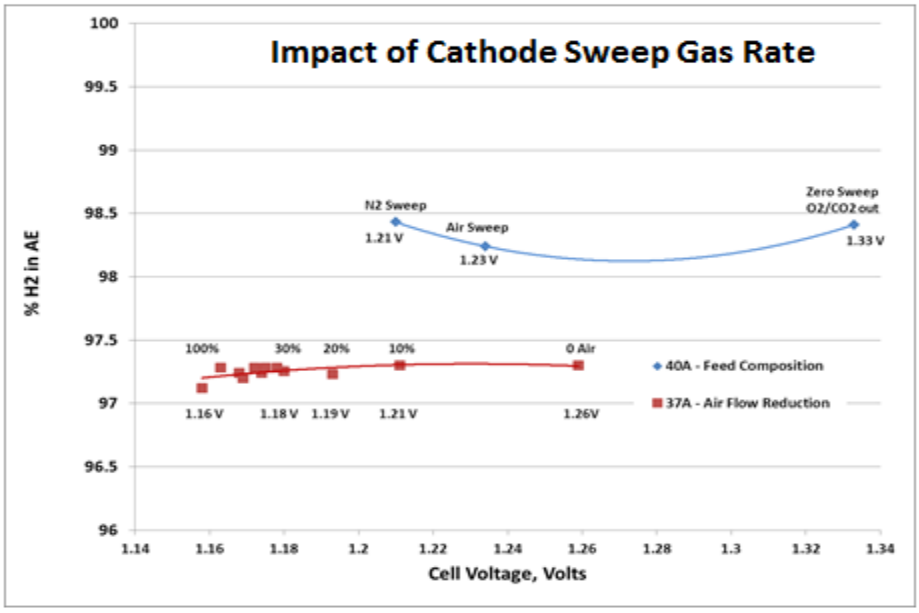

Figure 32 – Impact of Sweep Gas on Cell Voltage

Using the data developed in the above figures, we modeled the REP voltage performance. Fortunately the model developed for our normal fuel cells worked extremely well for the REP voltage is well as shown in **Figure 33**. By inputting a negative current into the model, a voltage

is predicted which closely matches the observed voltage even when the current density, cell temperature, sweep gas, and hydrogen purity were varied.

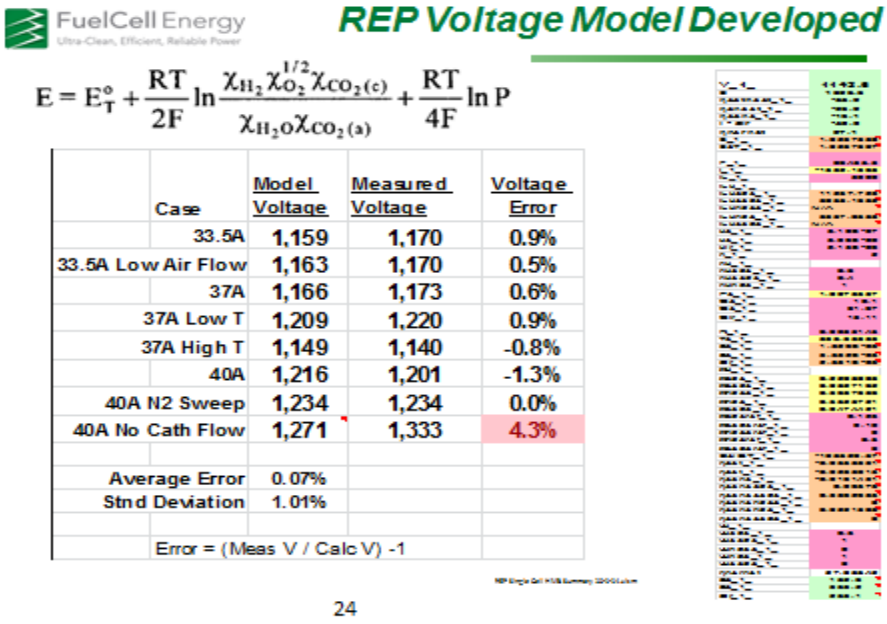

Figure 33 – Accurate Model for REP Performance was Developed

- **Test Data – Stack**

With the successful results from the single cell testing, we proceeded to build a short REP stack using full scale cells from our Torrington production facility. In the past, we have found that these short 30 cell stacks perform essentially the same as the large stacks with 300 to 400 cells. The short stacks also have the same temperature profile within the cells. Nevertheless, significant challenges were encountered for this testing as summarized in **Figure 34**.

These challenges were not fully appreciated in the proposal. The biggest challenge was the higher flow rates needed for the feed and produced in the outlet of the REP. For the REP, the natural gas feed rate is approximately 3 times the normal feed rate since only the CO_2 is acted upon and the hydrogen produced is more of a pass-through. Perhaps more importantly, the REP stack produces roughly 10 times the hydrogen at the outlet and our normal test facilities were unable to handle this high hydrogen flow. While we could test the REP unit at low load, we were unable to produce the hundred kilograms per day of hydrogen in these standard tests facilities which was the goal of our research.

When this was discovered we initially considered integrating the REP with a 300 kW mechanical balance of plant. Since one short stack had less than 10% of the cells associated with a standard fuel cell, the 10 times hydrogen flow was within the normal operating parameters of the balance of plant. We also purchased a pre-reformer which included a fired heater to provide the sweep gas and partially reform the feed gas required by the REP. Because of the high feed rate to the REP, some pre-reforming of the feed gas is required to maintain a proper heat balance within the REP system. Unfortunately due to schedule changes, the MBOP we were planning to use became unavailable and also the pre-reformer delivery was significantly delayed. At the same time a window opened up on our large-scale test facility and we decided to do the full load testing using that facility.

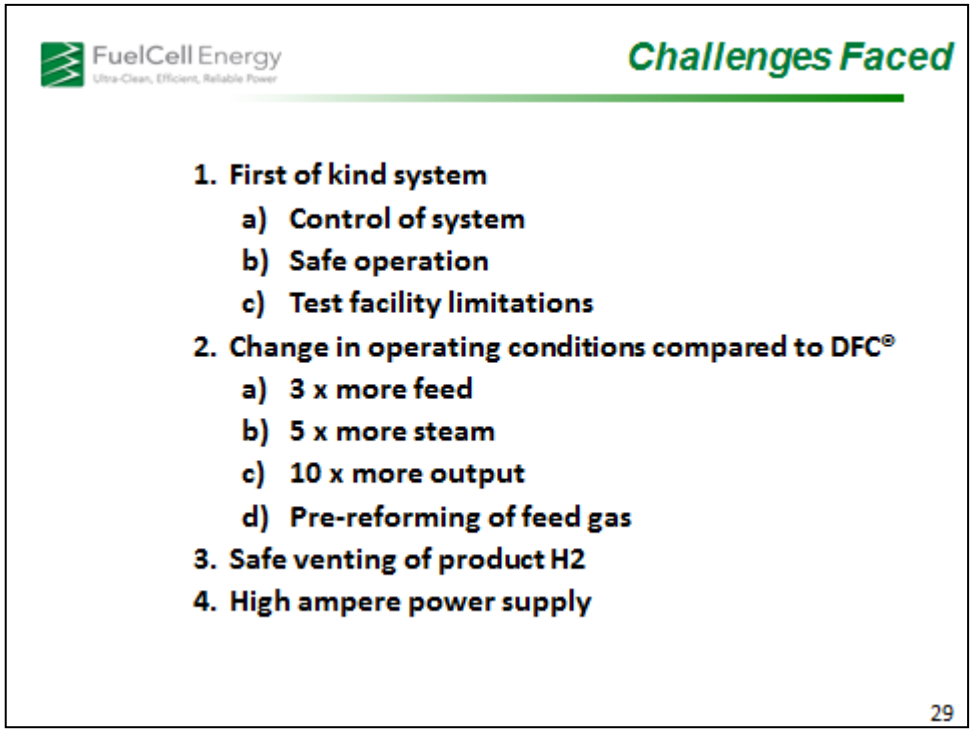

Figure 34 – Summary of Challenges Faced for 100 kg/d Testing

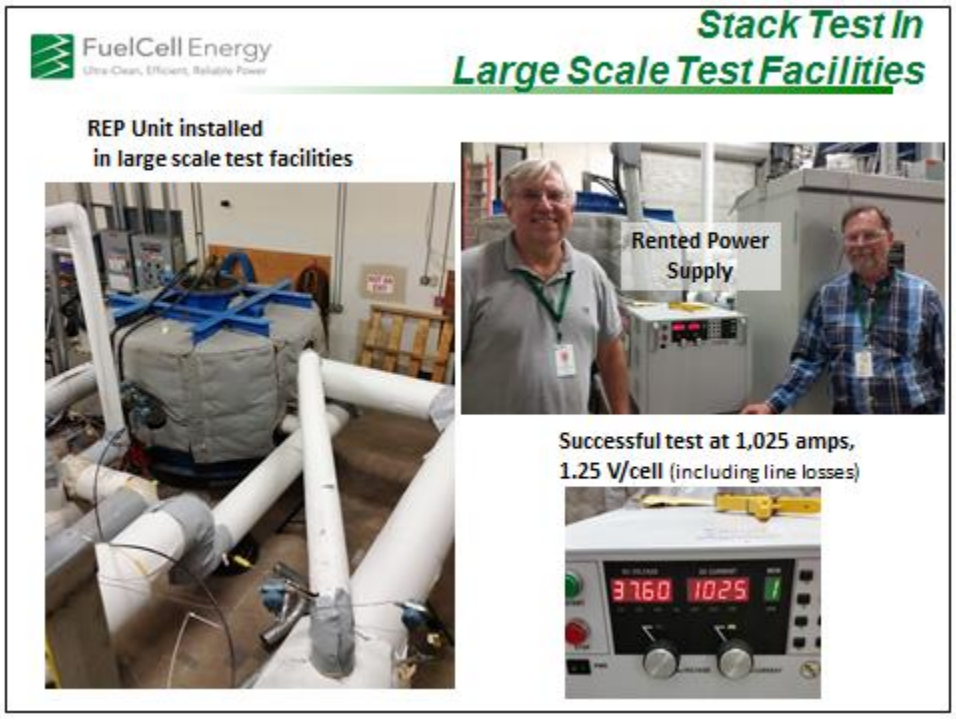

Figure 35 – Installation in Large Scale Test Facilities

With the REP stack installed in the large-scale test facilities along with a rented 1200 amp power supply, we were ready for testing. Unfortunately while we were heating the stack up to operating

temperature, we found a crack in one of the pipe joints that was leaking combustible gas into the facility. Thus we were forced to shut down, repair the crack and restart. This delayed the startup of the REP unit and limited the time available for testing.

The operation of the REP is shown in **Figures 36 and 37** below. After heating the stack up to temperature, initial power was applied to the system on Thursday around 3 PM and we continued operation at half load overnight. In the morning, we started ramping up the unit to full load but were delayed somewhat by the safety settings on the power supply which was interrupting the power. Once we were able to reset the allowable maximum voltage, we were able to ramp to full load and produce 98% hydrogen. As seen in the figures, these power interruptions had no observable impact on the REP performance (i.e. the voltage was unchanged after each cycle). The ramp to full load was gradual since this was the first time to operate a large stack in this configuration. No problems occurred with the operation and the performance goals were all met as discussed previously. (See **Figure 16**.)

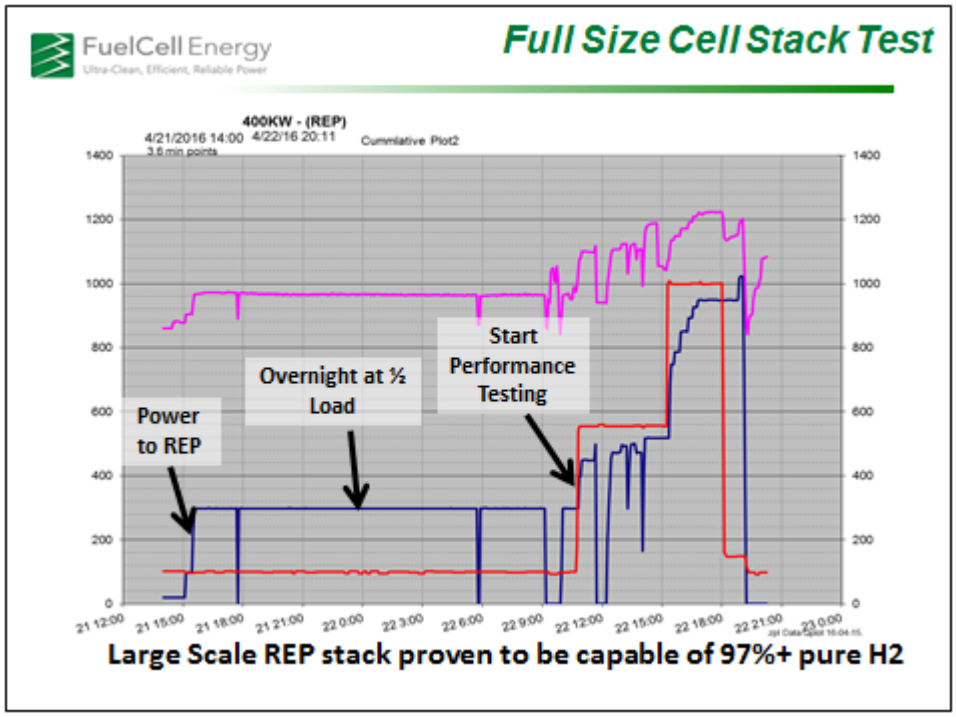

Figure 36 – Testing of Full Scale REP

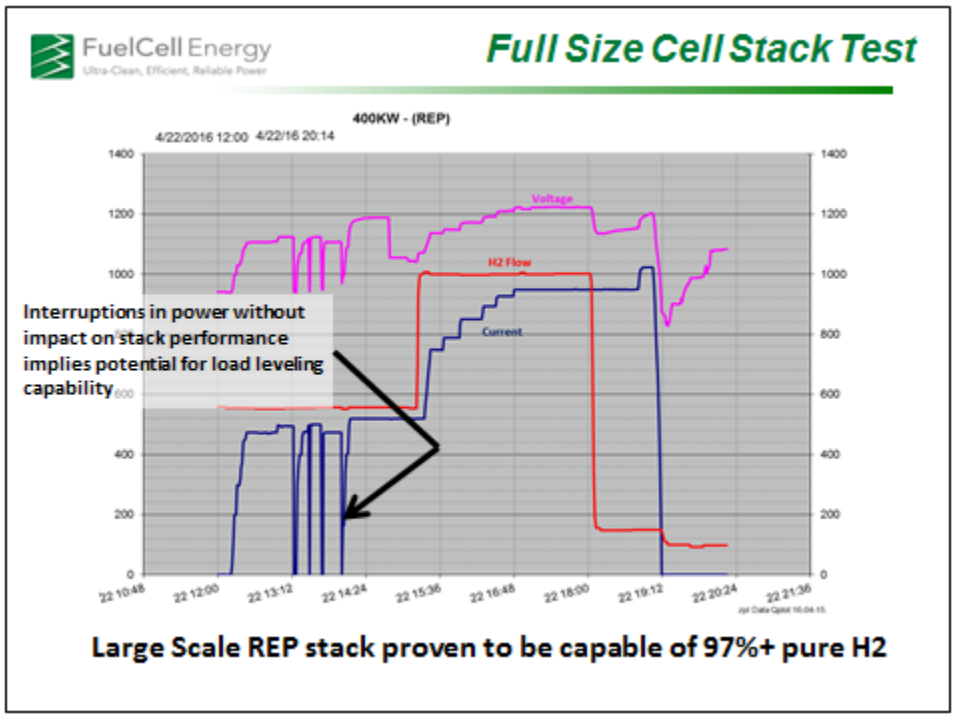

Figure 37 – Testing of Full Scale Cells in REP Short Stack

In addition to the performance measurements, the cell temperature profile, which is critical to the viability of the system, was measured. As can be seen in **Figure 38**, 57 thermocouples were located within the stack to accurately measure the temperatures across the cell. It is important that the cell temperatures are fairly uniform and critical that relatively smooth temperature gradients occur to ensure a long stack life. It is also critical that no hotspots appear within the cell.

The temperature profile at steady state operation is shown in **Figures 39-41** for various operating conditions**. Figure 39** shows the temperature profile at one half load. **Figure 40** shows the profile for steady state operation at full load with a natural gas based feed composition. **Figure 41** shows the profile for steady state at full load with DFC® anode exhaust gas feed composition. As can be seen in **Figure 40**, for the base case, the temperature profile is very flat and the temperature difference between the maximum and minimum points is less than 60 ° F. This is substantially less than the maximum delta T for our fuel cells operating in power production mode and we were very pleased with these results. In addition, an excellent temperature profile was maintained during the transition from half load to full load.

						Cath In				Ave In-Cell T				
						deg.F				Max -min				
						In T								
		U		P				K		F		A		
		7		22		15				7		1		
		15				19				9		15		In T
				25								24		
	Out T	V		Q				L		G		B		
				16						11				
										3				
		W		R		1		M		H		C		Anode
				10		10		4		10				In
	Anode	13		13						12		13		
	Out	15				15		16				15		In T
						17		18						
								22						
	Out T					30		28						
		X		S				N		I		D		
		11		14										
										20				
		Y		T				O		J		E		
		1		9		15				16		15		In T
	Out T	12		12										
		15				19				18		19		
			Out T		Out T		Out T				Out T		Out T	
							Cath Out							

Figure 38 – In-Cell Thermocouple Locations (57 Measurements)

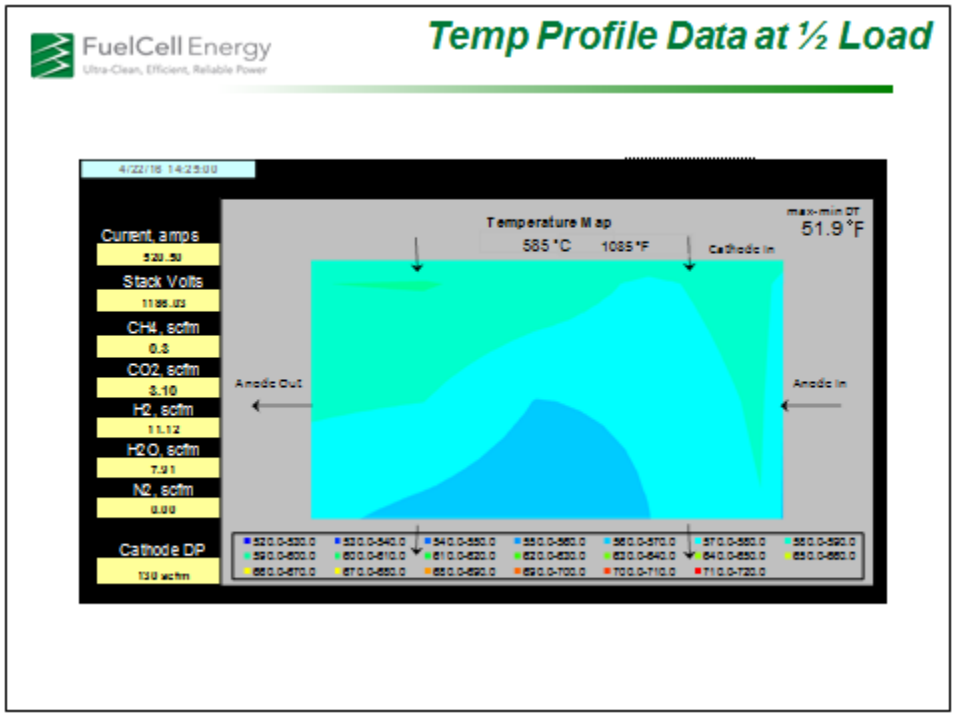

Figure 39 – Temperature Profile at Half Load

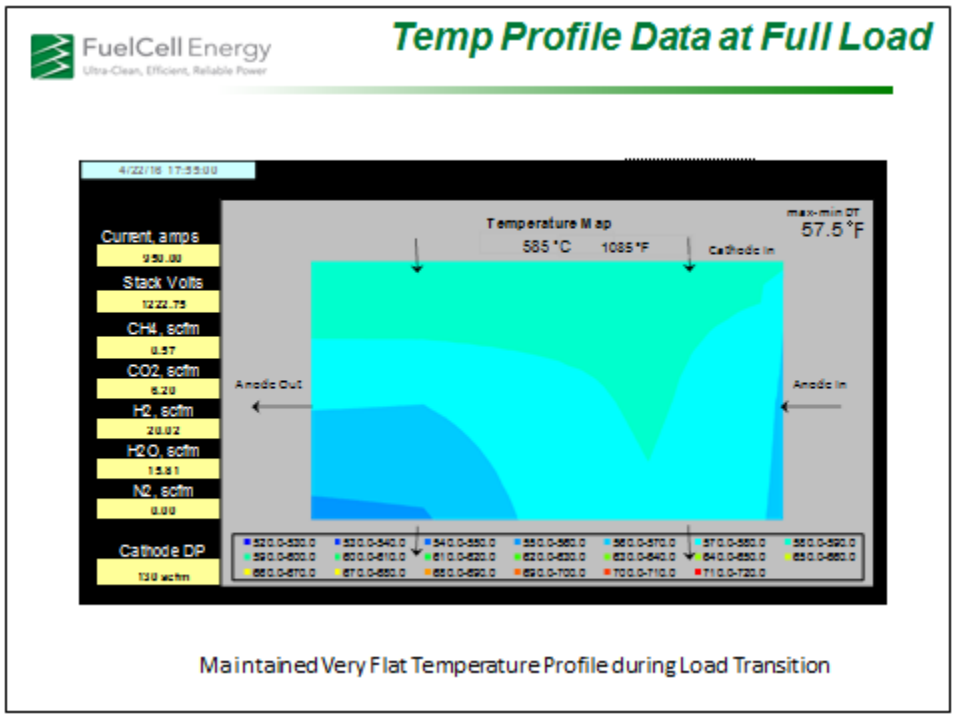

Figure 40 – In Cell Temperature Profile at Full Load (Base Case Operation)

We also simulated anode exhaust gas feed to the system for energy storage. When storing electrical power as hydrogen, the REP needs a source of CO_2 for the electrolysis reaction to store the energy. An excellent source of CO_2 is the anode exhaust gas from a high temperature fuel cell since this gas is already at temperature and contains steam as well as CO_2. It is available at essentially zero cost, only the heating value of the hydrogen and CO contained in the gas. The hydrogen and CO in the gas actually enhance the energy storage since they are converted to hydrogen and become part of the hydrogen generated by the REP but have no power associated with that fraction of hydrogen generated. As is shown in **Figure 21** earlier, the amount of power consumed per kilogram of hydrogen produced is substantially below the 33 kilowatt-hours per kilogram required by pure electrolysis generation.

To simulate the anode exhaust gas, we held the CO_2 feed constant and reduced the amount of hydrogen in the feed gas. The carbon fed to the REP was held constant since the same amount to carbon would be pumped out of the feed gas by the REP. This resulted in a slightly higher methane content in the feed which we believe cooled the inlet gas as it reformed when the CO_2 was pumped out of the gas. As can be seen in **Figure 41**, the simulated anode exhaust feed had a different temperature profile and higher maximum delta T. However even this profile is very smooth and within the normal operating conditions of molten carbonate cells.

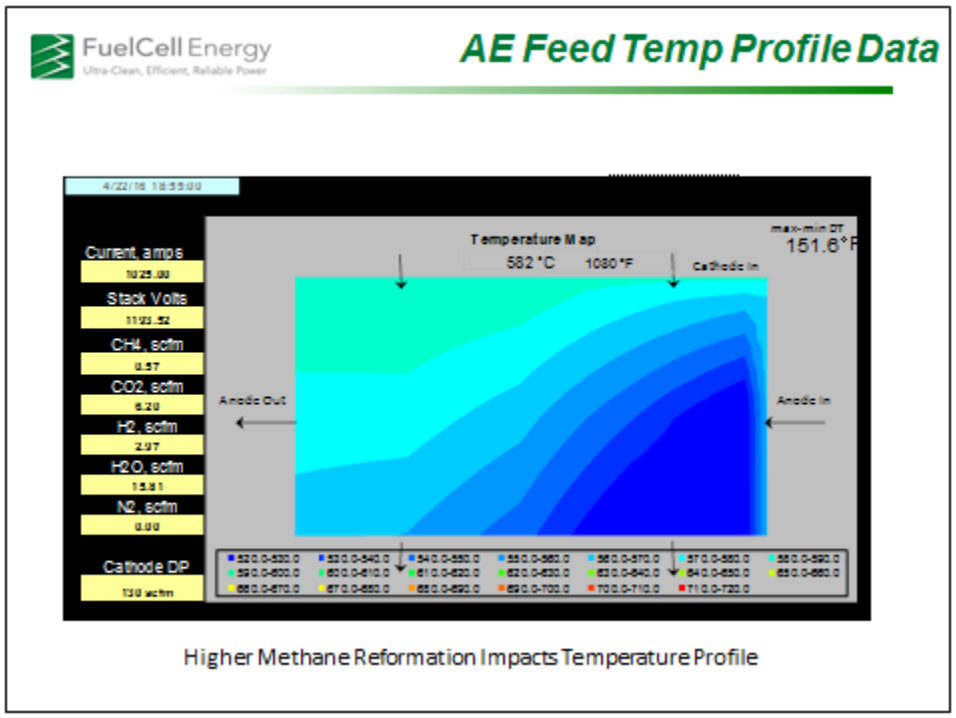

Figure 41 – In Cell Temperature Profile at Full Load for Simulated Anode Exhaust Feed

As can be seen in **Figure 42**, the performance of the REP unit with anode exhaust feed was essentially as expected, in fact marginally better than expected. This use of the REP for energy storage appears to be an excellent use of the system.

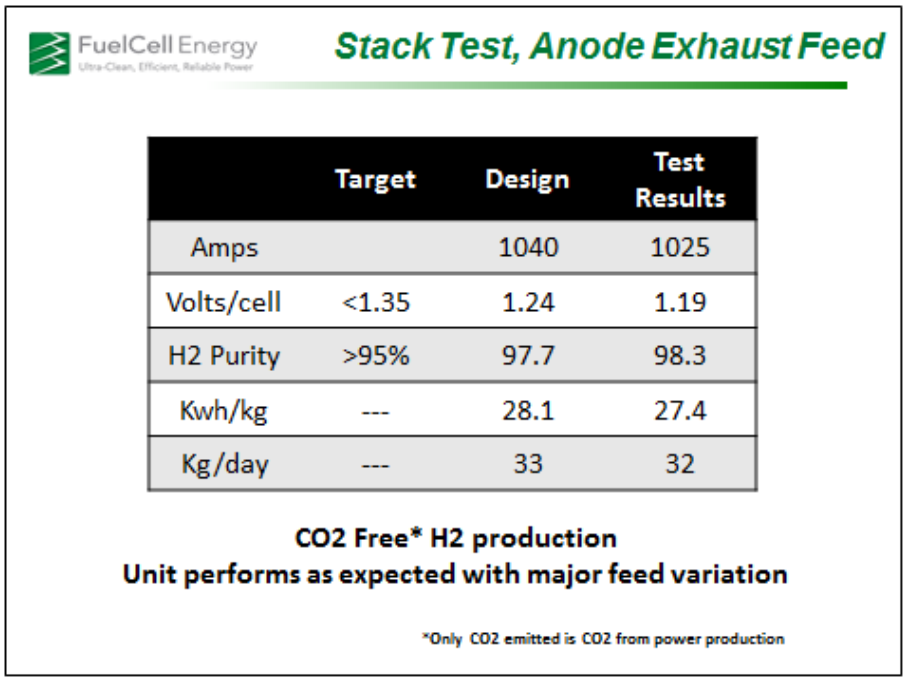

Figure 42 – Performance of REP Stack with Anode Exhaust Feed

Note in **Figure 42**, that the energy consumption for anode exhaust gas per kilogram of hydrogen is substantially higher, due to the fact that over 70% of the hydrogen is from electrolysis versus 20% in the base case.

A gas chromatograph was used to determine the performance of the REP during our testing. The data from the various samples are shown in **Figures 43 and 44** below. **Figure 43** shows how pre-reformed feed gas with basically 70% hydrogen on a dry basis was purified to over 97% hydrogen in the REP. During the samples, we also confirmed the accuracy of the GC by testing our calibration gas. The test of the calibration gas showed results within 0.25% of the hydrogen. The three cases circled in the figure show high hydrogen purity at half load, at full load, and at full load with anode exhaust gas feed.

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Raw Analysis Data

Date/Time	4/22 14:09	4/22 14:28	4/22 14:44	4/22 15:39	4/22 17:01	4/22 18:25	4/22 18:53
Sample	1/2 Load Feed Gas	1/2 Load REP H2	Calibration Gas	Full Load Feed Gas	Full LoadREP H2	Full Load, AE Feed Gas	Full Load AE REP H2
Amps	520	520		747.5	950	950	1025
Volts	1,159 mV	1,187 mV		1,136 mV	1,216 mV	1,142 mV	1,188 mV
Mid Stack Temperature	1,069°F	1,056°F		1,061°F	1,067°F	1,062°F	1,047°F
°C	576°C	569°C		571°C	575°C	572°C	564°C
AI T	1,057°F	1,058°F		1,053°F	1,054°F	1,052°F	1,044°F
CI T	1,084°F	1,085°F		1,086°F	1,085°F	1,084°F	1,081°F
Normalized							
Hydrogen	**70.80%**	**97.73%**	**96.73%** 97%	**69.34%**	**97.20%**	**20.72%**	**98.05%**
Oxygen	0.02%	0.01%	0.00%	0.01%	0.01%	0.03%	0.01%
Nitrogen	0.11%	0.52%	0.00%	0.07%	0.59%	0.16%	0.81%
Methane	**1.66%**	**1.45%**	**1.89%** 2%	**1.64%**	**1.67%**	**5.24%**	**0.33%**
Carbon Monoxide	0.71%	0.00%	0.57% .5%	0.16%	0.00%	0.00%	0.00%
CarbonDioxide	**26.68%**	**0.28%**	**0.82%** .5%	**28.74%**	**0.53%**	**73.75%**	**0.81%**

Figure 43 – Gas Chromatographic Results from Testing at Steady State Conditions

Figure 44 shows the gas chromatograph samples as the unit was ramped up in load and purity during the transition from half load to full load. This data is plotted in **Figure 45**. As can be seen in **Figure 45**, both the cell voltage and the hydrogen purity increase with increasing amps. The feed rate was held constant at full load rates during this period.

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Raw Data – Increasing Amps

Date/Time	4/22 15:39	4/22 15:48	4/22 16:09	4/22 16:21	4/22 16:42	4/22 17:01
Sample	Full Load Feed Gas					Full LoadREP H2
Amps	747.5	787.5	851	892.5	927	948.5
Volts	1,136 mV	1,148 mV	1,172 mV	1,189 mV	1,210 mV	1,216 mV
Cell 15 T	1,061°F	1,064°F	1,065°F	1,066°F	1,065°F	1,067°F
°C	571°C	573°C	574°C	574°C	574°C	575°C
AI T	1,053°F	1,053°F	1,054°F	1,054°F	1,054°F	1,054°F
CI T	1,086°F	1,086°F	1,085°F	1,085°F	1,085°F	1,085°F
Normalized						
Hydrogen	**69.34%**	**93.51%**	**94.82%**	**95.71%**	**96.89%**	**97.20%**
Oxygen	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%
Nitrogen	0.07%	0.61%	0.60%	0.57%	0.58%	0.59%
Methane	**1.64%**	**3.79%**	**3.06%**	**2.45%**	**1.95%**	**1.67%**
Carbon Monoxide	0.16%	1.24%	0.63%	0.37%	0.00%	0.00%
CarbonDioxide	**28.74%**	**0.84%**	**0.88%**	**0.90%**	**0.57%**	**0.53%**

Figure 44 – Gas Chromatograph Results During Load Ramping

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Data Analysis

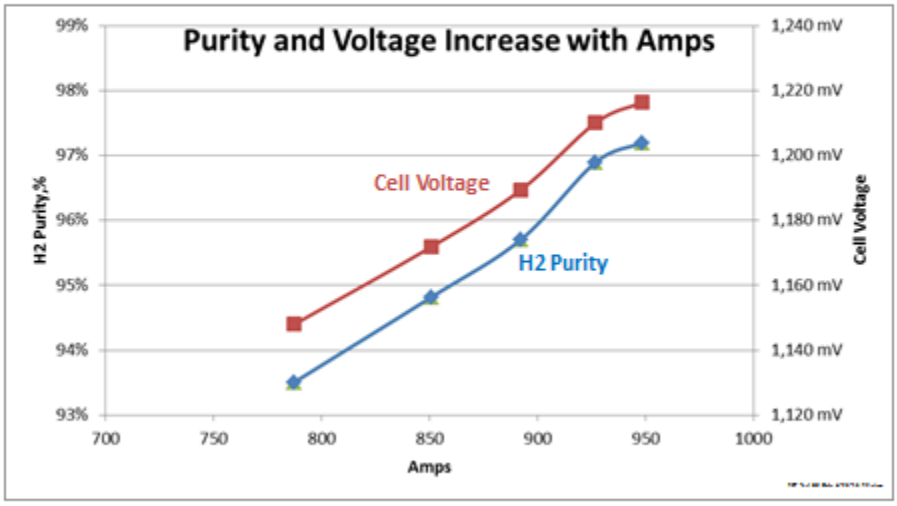

Figure 45 – Plot of Load Ramping Data

The data in **Figure 45** was replotted in **Figure 46** showing the hydrogen purity as a function of voltage. This shows that the hydrogen purity has an excellent correlation with cell voltage and

implies that controlling the cell voltage may be preferred to controlling the amps since fluctuations in the feed rate would not impact the hydrogen purity when controlled in this manner.

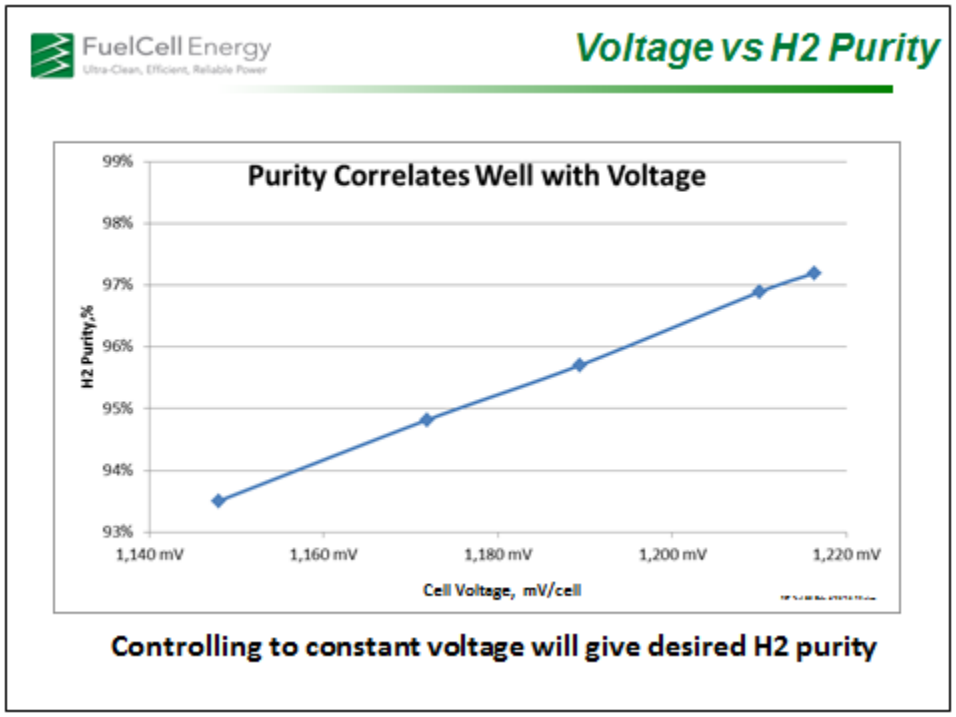

Figure 46 – Plot of Cell Voltage versus Hydrogen Purity During Load Ramping

We are also being supported in this work by the National Fuel Cell Research Center at the University of California, Irvine. They are currently working to develop a dynamic model of the system to simulate the performance during transitions and also to predict the temperature profile of the system. This model was adapted from a similar model for fuel cells, but was found to be much more difficult as the program had to be significantly modified to prevent the model from crashing. The current model is still being refined but is starting to show a reasonable approximation of the experimental data available from our testing. UCI plans to continue developing this model even though the current research program has been closed,

The perturbation response characteristics of this dynamic model to power, current, fuel flow, fuel composition, and sweep gas flow will provide insights into the operation and load following capabilities of the REP. UCI intends to publish the results in separate reports and articles along with presentations at various conferences in the future. Excerpts from the current model results are shown in **Figure 47** as an illustration of the work being done.

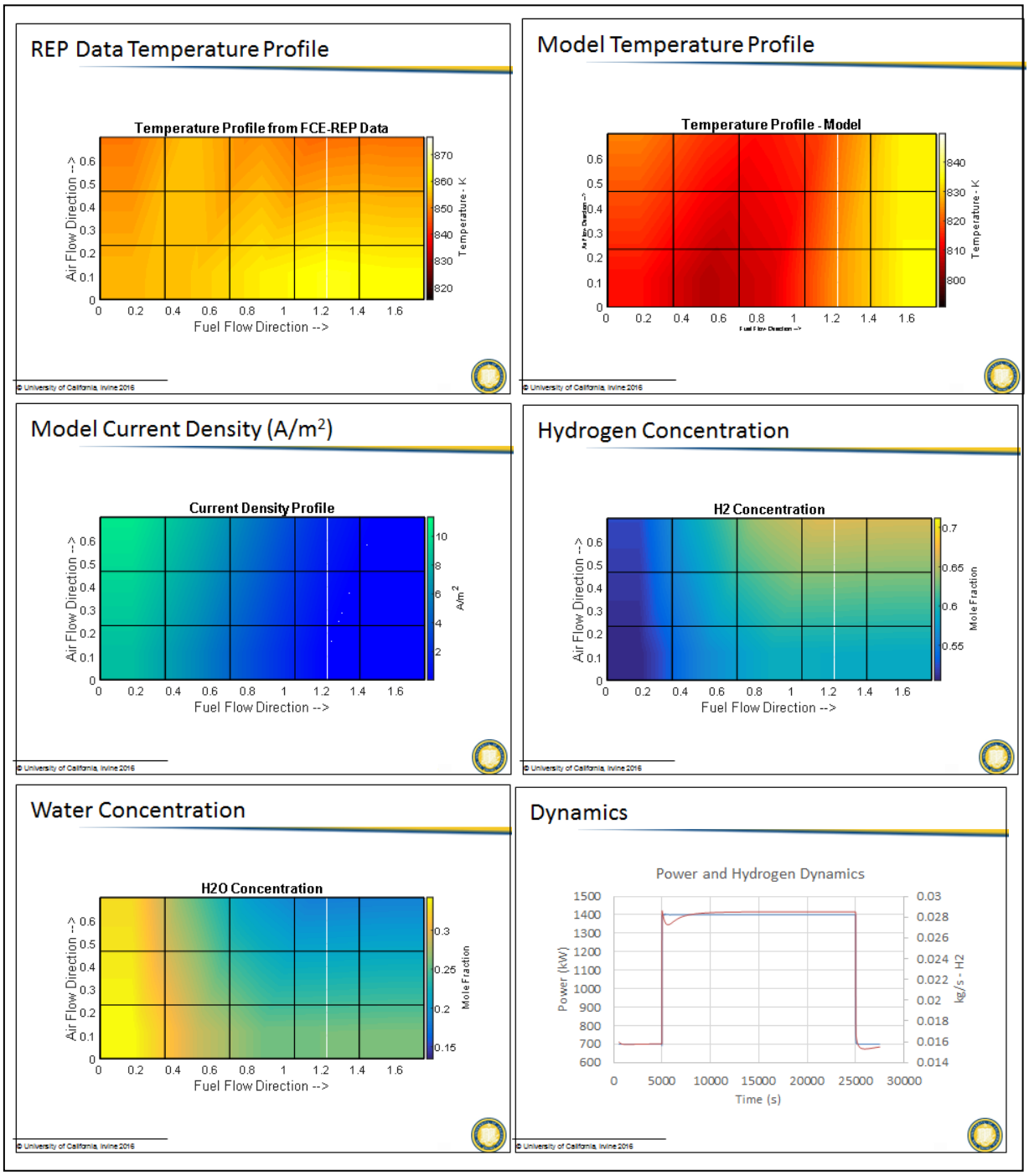

Figure 47 – Preliminary Simulation Results from UCI Dynamic Modeling

• Conclusions

The main goal of this research was to confirm that the REP process was feasible when operating with full size molten carbonate cells in a stack. Previously, only short term, single cell testing had been done.

Key parameters for success were:

1. High purity H2 produced (greater than 95%)

   > 98% H2 produced

2. Low power consumption (less than 1.35 volts/cell)

   1.22 volts/cell required

3. Good stack life (less than 10%/yr single cell performance degradation)

   Less than 10%/yr degradation rate (2-5 year life)

4. Production of 100 kg/day

   Produced 110 kg/d from stack

As can be seen from the data presented earlier, all of these goals were met.

In addition, analysis was performed which confirmed that the process is economically attractive with excellent potential for commercialization.

In conclusion, a highly successful research program has been completed. Major results include:

- Single cell REP and REP stack testing and successful operation
- Life and performance of the REP is good and met all targets
- Economics of REP is highly attractive, especially for distrubuted H_2 production
- CO_2 emissions are low and with waste heat, very low
- REP can also be used for energy storage and CO_2 capture
- New scalable low cost H_2 production technology for 1 to 150,000 kg/d of H_2 is feasible

5. Follow-up and Future Work

In order to commercialize the technology, a longer term large scale test is needed. Much of the equipment for the longer term stack testing and demonstration needed is available from the current research work. Both the 100 kg/d REP stack and a natural gas fired pre-reformer are available. In addition, a used mechanical balance of plant (MBOP) could be available at reduced cost. Thus the unit could be provided to a demonstration site at relatively low cost after testing the system at FuelCell Energy's Danbury research facilities. **Figure 48** shows a conceptual layout of the system. (P&ID's were also developed for this system.)

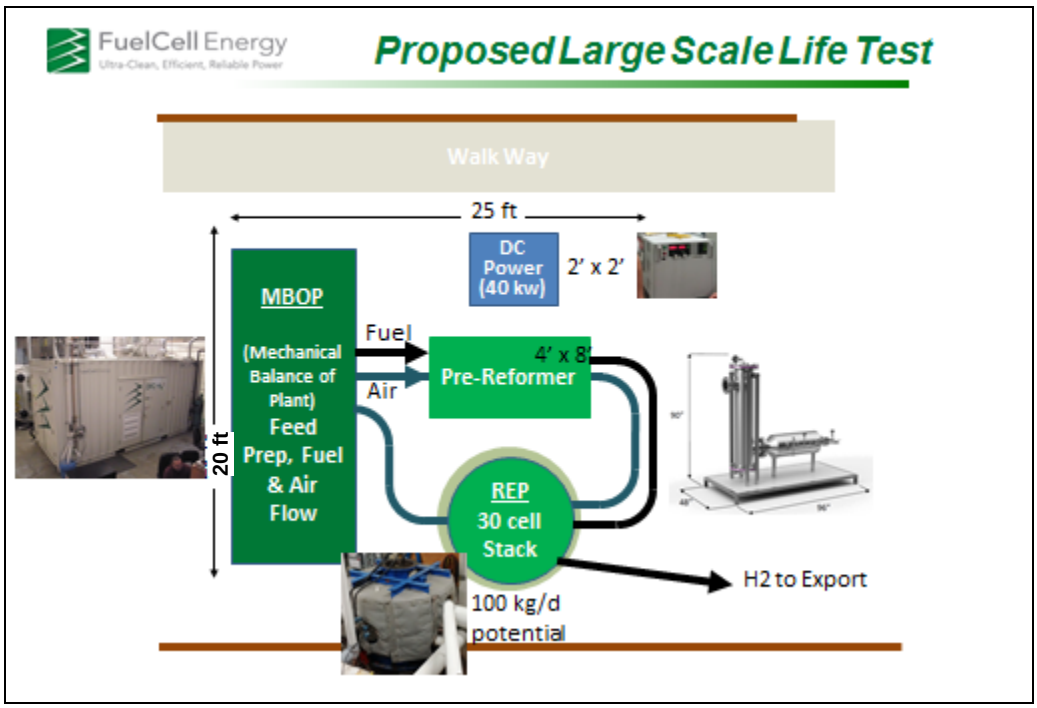

Figure 48 – Conceptual Layout 100 kg/d Demonstration Facility

Although the system is planned to operate with an air sweep gas on the cathode side to maximize life and minimize power requirements, the system has the potential to coproduce a CO_2/O_2 (66%/33%) gas mixture from the cathode with a modest performance penalty (~10%) and probably a reduced life (50-75% of swept life). However, when operated in this mode, the system has the potential to easily capture all of the CO_2 emissions from the system. This is done by using the CO_2/O_2 mixture in place of air to provide the heat needed in the pre-reformer. When this is done, the pre-reformer exhaust gas is essentially CO_2 and water. By cooling and compressing this gas, a pure CO_2 liquid stream can be exported. A conceptual figure for this type of operation is shown in **Figure 49**.

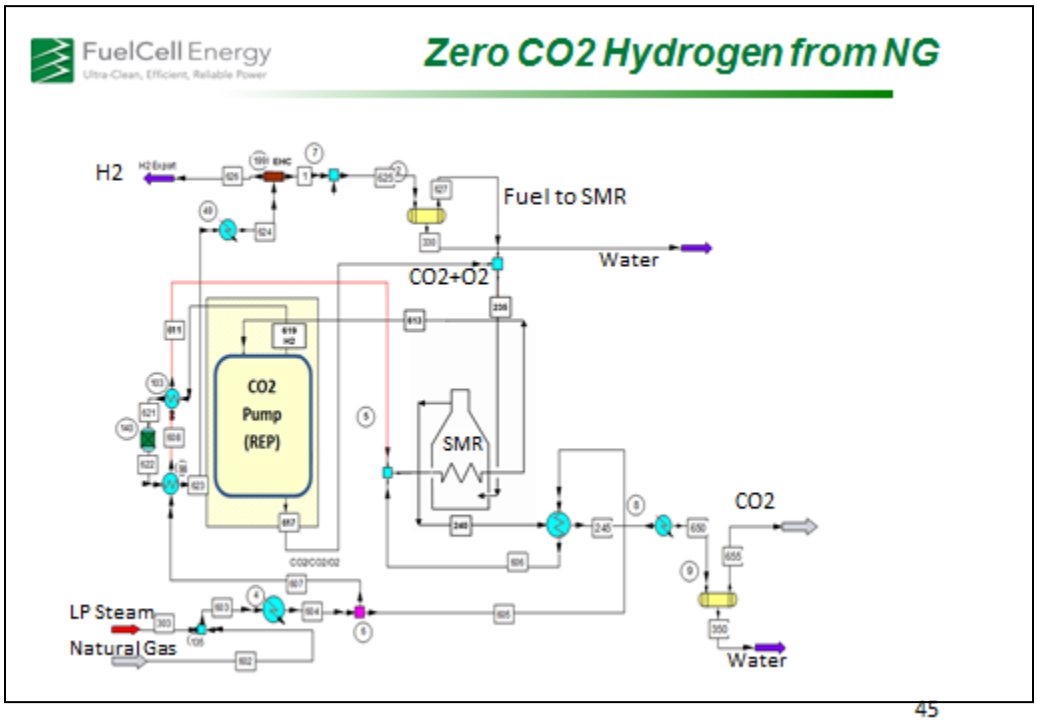

Figure 49 – Conceptual Design for Hydrogen Generation with CO_2 Capture

Other potential high-value applications, in addition to providing low-cost hydrogen for automotive purposes, are listed in **Figure 50**.

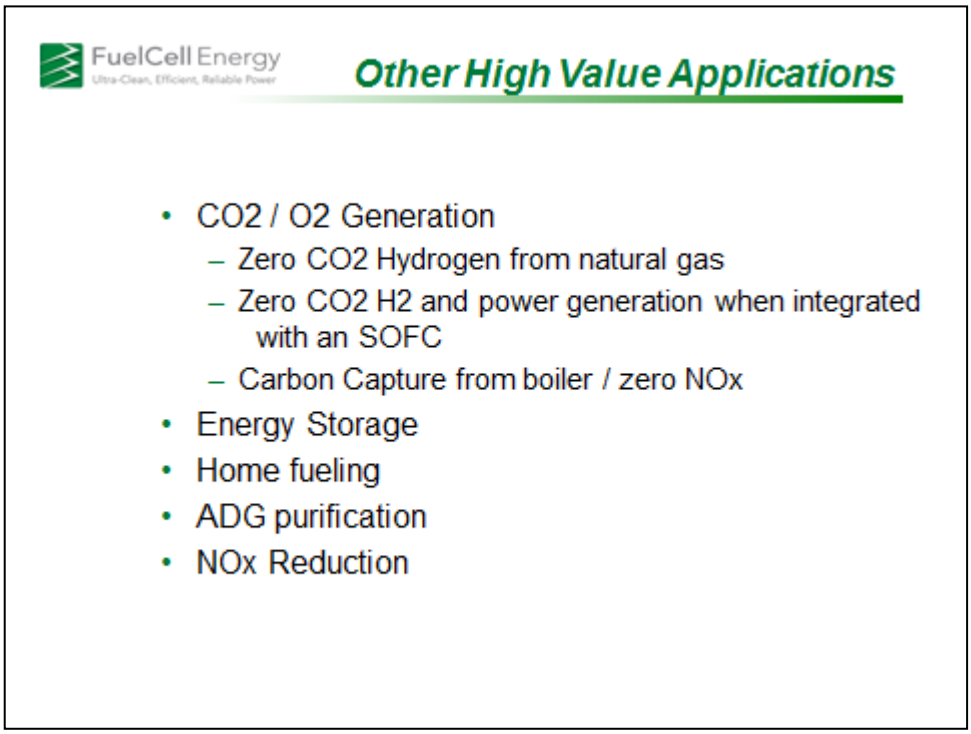

Figure 50 – Potential High-Value Applications for an REP System

6. Publications

Several presentations and publications were made during the course of this work as listed below.

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

"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

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

"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 http://www.hydrogen.energy.gov/pdfs/review15/pd112_jahnke_2015_o.pdf

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

"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

Appendix A - Statement of Project Objectives

STATEMENT OF PROJECT OBJECTIVES

A Novel Hybrid Reformer-Electrolyzer-Purifier (REP) for Distributed Production of Low-Cost, Low Greenhouse Gas Hydrogen

A. PROJECT OBJECTIVES

The objective of this project is to build and demonstrate the performance of a commercial scale REP (reformer electrolyzer purifier) unit. This unit could be suitable for use in a follow-up program for a field demonstration following the successful completion of this project.

In addition, we plan to generate the data needed to optimize the system, determine the performance of the system over time, and validate the economics of the system. We will also look at the economics of integrating the system with various waste heat sources and renewable fuel generators. We will determine the performance not only with natural gas but also simulated biogas (Anaerobic Digester Gas / ADG).

In parallel, a commercialization plan will be developed. This will include reviewing the market for high and low purity hydrogen, reviewing potential sources of waste heat, and determining a site for a field demonstration of the unit. The economics of the system based on test results will be developed based on the near-term and long-term expected capital cost.

B. PROJECT SCOPE

The project will demonstrate a system for central and distributed production of low-cost low carbon hydrogen from natural gas. The demonstration unit will produce between 20 and 130 kg per day of hydrogen. The commercial scale REP unit built for this demonstration is expected to be suitable for a follow-up field demonstration.

In addition to the commercial scale REP unit, a small scale (single cell) unit will be constructed for broad parameter testing and operated for up to 6000 hours to determine the expected life of the system.

Based on the data from the system, heat and material balances will be completed and economic studies will determine if the system will meet the $2/gge hydrogen costs goal. These studies will include alternate feedstocks such as biogas, alternate waste heat sources, and impact of scale.

C. TASKS TO BE PERFORMED

Budget Period 1 Parameter Optimization

Task 1. Parameter optimization on single cell

Initial work will reconfirm preliminary testing results and broaden the range of testing to allow optimization of the system parameters. A dedicated test stand will be constructed so that it will be available later for long-term testing needed for stack life determination. Impact of various parameters on cell performance will be calculated to allow optimization from an energy and economic standpoint.

Subtask 1.1 Single Cell Test Unit Construction

A single cell test stand will be built including all of the instrumentation and controls needed to operate the cell. The single cell will be approximately 300 cm2 in size, the same as FCE normally uses for testing the performance of new cell formulations.

Subtask 1.2 Parametric study

The parametric study will begin by confirming the performance used in the preliminary heat and material balances and duplicating some of the preliminary work. The system will then be used to determine the performance impact of variables within the operating envelope of the system such as applied voltage, amps, % water, % methane, % CO2, CO2 utilization, H2O utilization, and H2 purity. In addition, simulated alternate feeds such as ADG will be tested. Some additional parameter tests could be done in Budget Period 2 also.

Subtask 1.3 Cell resistance

The cell resistance will be measured at the start and during the parameter study. Changes in cell resistance are a good indication of changes in the fuel-cell and life of the cell.

Subtask 1.4 Begin long term testing

Assuming the parameter testing is satisfactory, we will then begin long-term testing to determine the life of the stack. The operating point for this test will be at the preliminary optimum point determined by the parameters from the single cell testing. This operating point may be adjusted as further analysis and additional data from the full scale unit becomes available. Work in this Subtask will take place in Budget Period 1 and Budget Period 2

Task 2. Process Optimization

Based on the data from Task 1, the system will be optimized to minimize energy consumption and CO2 emissions, cost of hydrogen produced, and maximize return on investment. The optimization review will be broadened to determine the economic impact of various feedstocks, waste heat sources, and costs scenarios. Understanding the impact of these parameters will help determine the test plan for the commercial scale REP stack.

Subtask 2.1 Update Heat and Mass Balances (HMB)

The base case heat and material balances will be updated based on the parametric study data. At the same time, alternate balances for alternate feeds such as anaerobic digester gas (ADG) pyrolysis gas, or coke oven gas will be developed.

Subtask 2.2 Update Economics

Based on the heat and material balances, an economic study will be performed to confirm that the process continues to meet the target cost of hydrogen and CO2 emissions. The economics will help us optimize the design for near-term and long-term systems. For example, operating costs can be reduced by reducing the current density of the stack, but this requires a larger stack with greater capital costs. During this optimization, we also plan to review potential sources of waste heat, including a DFC® fuel cell, solar heating with electric backup, a gas turbine, and flare gas. We will also look at potential fuel sources including natural gas, anaerobic digester gas, pyrolysis gas, syngas from a gasifier, and coke oven gas. The H2A model will be used in this task.

At the end of this task, the heat and material balances will be chosen for use in developing the design basis for the commercial scale unit.

Subtask 2.3 Go/No-Go Decision

A Go/No-Go decision will be made at the end of the first year based on key technical parameters resulting from testing of 300 cm2 REP single cell: H2 purity greater than 95%, cell operating voltage of less than 1.35 volts (for natural gas, this corresponds to power consumption of <8 kWh/kg of H2), and performance degradation rate over period tested of less than 10%/yr. Updated economics will need to confirm continued attractiveness for distributed H2 production.

Budget Period 2 Commercial Scale Unit Construction and Demonstration

Task 3. Commercial Scale Stack Construction

We plan to construct a REP unit with commercial scale hardware which is expected to be able to produce approximately 20-130 kg per day of hydrogen. This is similar in size to units that we use for testing new designs for our DFC® cells just prior to field testing. Although the gas supply and heating required for the testing will be controlled through FCE's Danbury test facilities, the REP unit built is expected to be usable in a future follow-up field testing program at a site which will use the hydrogen produced.

Subtask 3.1 Design

The design of the unit will be fairly straightforward as our standard commercial cells (nominal 10,000 cm2 area) will be used. Only the reforming cells (if used) and manifolds will be modified

as needed for this application. Standard end plates and piping connections will be used, modified only if needed.

Subtask 3.2 Test plan

The testing will be similar to the parameter testing done for the single cell test but refined based on those test results. Also for the commercial scale test we have to be more careful with the variation in operation across the cells. Cell resistance will again be used to determine if any degradation occurs.

Once the test plan is drafted, we will review the planned instrumentation to be sure all the test data desired can be obtained.

Subtask 3.3 Piping and Instrument Diagrams (P&ID's)

Prior to building the unit, we will also look at the facility piping and instrument diagrams (P&ID's) to confirm that the gas rates desired can be handled by the system. We will also perform a small HAZOP on the system to be sure that the planned instrumentation and flows do not result in any hazardous operating conditions. Modifications to the facility will be made as needed.

Subtask 3.4 Build REP Unit

Components from FuelCell Energy's commercial manufacturing facilities will be acquired and assembled into the REP unit. We plan to use standard commercial components for the system with the possible exception of the reforming cells.

In parallel with the REP unit construction, the test facilities will be checked and confirmed ready for testing. The system will be assembled and the commercial scale testing will begin.

Task 4. Commercial scale testing

The commercial scale testing will follow the test plan developed after the parameter study. The data from the test will be analyzed as soon as it is available and compared with expected performance. The test plan will be modified if needed based on these interim test results.

At the end of the tests, we will refine our planned operation to optimize hydrogen production costs and minimize CO2 emissions.

Subtask 4.1 Carry out tests

Subtask 4.2 Refine HMB's and economics based on results

Task 5. Documentation

Upon completion of the testing, a full report on the system cost and performance will be assembled and issued, including updating the H2A model. In addition, we will develop a commercialization plan to focus on the potential customer market for the system, long-term expectations, and near-term steps to achieve commercialization. We will summarize the various industries which can benefit from this technology.

The plan will identify potential field demonstration sites and look at site-specific benefits and infrastructure needed to demonstrate the technology at those sites. This final report will complete the project, however, we would hope to demonstrate this technology at a commercial site using the REP unit from this project.

Subtask 5.1 System cost and performance

Subtask 5.2 Commercialization plan / potential future field demonstration sites

Subtask 5.3 Final Report

Task 6. Project Management

We will implement the existing project management plan after reviewing all tasks, modifying the plan as needed and reviewing updated plan with all key participants. Plan will be updated to meet DOE reporting requirements and deliverables. Project manager will ensure results meet the desired techno-economic feasibility, including the strategy for commercialization and Go/No-Go decisions.

Subtask 6.1 Schedule tasks/manpower

When the project starts, reconfirm planned manpower is available and adjust preliminary schedule to appropriate start date. Get a commitment from all manpower planned. Confirm updated schedule with DOE manager.

Subtask 6.2 Track Progress

Track completion of all tasks until project is completed. Take appropriate action if there is any significant slippage in schedule.

Subtask 6.3 Reports

Issue quarterly and other reports as required by program. Reports and other deliverables will be provided in accordance with the Federal Assistance Reporting Checklist. Also, FuelCell Energy will participate in the DOE Hydrogen Program Annual Merit Review and prepare and present detailed briefings of plans, progress, and results of the technical effort to DOE personnel, as requested by DOE. FCE will also participate in Hydrogen Production Tech Team meetings as requested by DOE.