Reversible Fuel Cells Workshop

Summary Report

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U.S. Department of Energy

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REVERSIBLE FUEL CELLS

Reversible fuel cells operate like batteries and may be one solution to the problem of storing electricity generated by variable resources.

This workshop will bring together subject matter experts and fuel cell developers to discuss the state-of-the-art and to draft a road map for future R&D.

You are invited to attend the
Reversible Fuel Cells Workshop
on
Tuesday, April 19, 2011
Renaissance Capitol View,
Crystal City, VA
9:00 AM to 4:00 PM

Organized by the National Renewable Energy Laboratory, and the U.S. Department of Energy.

Attendance at the April 19th meeting is by invitation only. Space is limited to 100 attendees.
For questions regarding this workshop, please contact Robert Remick (robert.remick@nrel.gov)

Presented by:

U.S. DEPARTMENT OF ENERGY

NREL NATIONAL RENEWABLE ENERGY LABORATORY

July 2011

Executive Summary

A workshop addressing the current state-of-the-art of reversible fuel cells that use hydrogen/air or hydrogen/oxygen was held on April 19, 2011, at the Renaissance Capital View Hotel in Arlington, Virginia. The genesis of this workshop was a report on the feasibility of using hydrogen to store renewable electricity produced from wind resources. The feasibility study looked at two technologies based on water electrolysis for producing the hydrogen, two methods for storing the hydrogen, and three technologies for using the stored hydrogen to produce electricity. The conclusions of the study suggested that various hydrogen-based systems might compete with battery systems for storing renewable electricity, but they could not compete with pumped hydro or compressed air energy storage (CAES) systems on the basis of cents per kilowatt-hour of electricity delivered to the electrical grid.

The study identified two important barriers that prohibited the various hydrogen systems from being cost competitive. They were the relatively low roundtrip efficiency of the hydrogen systems compared to batteries and pumped hydro, and the high capital costs for acquiring both the electrolyzer units needed to produce the hydrogen from renewable electricity and the fuel cell units needed to produce electricity from the hydrogen. The feasibility study also was limited to technologies for which there were useful data available on mature costs and for which products of a suitable scale were available commercially or were approaching commercialization. The study did not include high temperature steam electrolysis or high temperature fuel cells, nor did it evaluate the concept of a unitized stack that could serve as both fuel cell and electrolyzer, first and foremost, because mature costs for these technologies are not available.

The use of a unitized stack, a fuel cell stack that can be reversed and used as an electrolysis unit, herein called a reversible fuel cell, has the potential of substantially reducing the capital costs for the electrochemical equipment. Reversible fuel cells based on PEM technology have been under investigation for several decades by DOD and NASA for aerospace applications. High temperature steam electrolysis and high temperature fuel cells both show superior net electrical efficiency when compared to low temperature systems and thus hold the promise of substantially increasing the roundtrip efficiency of the storage system. Furthermore, since the publication of the feasibility study, work has been initiated by DOE and by DOD addressing the development and testing of reversible solid oxide fuel cells. It was the goal of this workshop to bring together the developers of these two technologies, reversible PEM fuel cells and reversible solid oxide fuel cells, to address three questions.

1. Are these technologies feasible for the cost-effective storage of renewable electricity?

2. What are the materials and systems barriers to developing these technologies for this application?

3. What are the manufacturing issues that need to be addressed to be cost effective?

Several important recommendations were developed during the workshop. It was recommended that a more in-depth techno-economic study be performed starting with the design of one or more complete systems for storing renewable electricity based on reversible fuel cells and that

the design be used to develop engineering flow sheets in sufficient detail to allow equipment to be sized and priced and roundtrip efficiencies to be projected on a consistent basis.

The air/oxygen electrode was identified as the element of the PEM base system that was most in need of further development. New or improved catalysts need to be developed to improve efficiency and reduce costs.

The additional R&D addressing the air/oxygen electrode also headed the list of recommendations for the SOFC/SOEC system. R&D addressing cell and stack design for a reversible system and heat management subsystems also were included in the recommendations.

It was generally assumed that, with the exception of quality control instrumentation, manufacturing was not a significant issue with PEM-based systems because systems in the 100 kW size class are already being manufactured for transportation applications. On the other hand, low-cost manufacturing of SOFC and SOEC components is an issue requiring further R&D. However, substantial manufacturing R&D is being conducted under the auspices of the DOE Solid State Energy Conversion Alliance (SECA) program and it was the consensus of the majority attending the workshop that a second manufacturing program specifically addressing a reversible SOFC/SOEC cell/stack is not needed at present, so long as the SECA program continues to address the development of manufacturing processes for large megawatt-scale stacks and systems.

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Background

In November 2009 NREL published a report titled “Lifecycle Cost Analysis of Hydrogen Versus Other Technologies for Electrical Energy Storage.”[1] A variety of approaches to energy storage were evaluated on the basis of cost-per-kilowatt-hour for electricity delivered in an electricity arbitrage scenario. For example, in one case study, alkaline electrolysis was used to produce hydrogen using off-peak electricity. The hydrogen was compressed into above-ground steel cylinders and then used during peak demand to produce electricity using PEM fuel cells. The results from this case study were compared to other approaches including geologic storage of the hydrogen, a gas turbine instead of a fuel cell for electricity generation, three types of batteries, pumped hydro, and compressed air energy storage (CAES). Consistent financial and operational assumptions were used. Cost and performance parameters for the technologies used in the case studies were taken from literature sources and manufacturers' specification sheets. Aspen Plus was used to model portions of the systems where information was lacking or where existing technologies did not match up due to size or maturity, for example, a hydrogen expansion combustion turbine.

The study was constrained by sizing all systems to deliver 300 megawatt-hours of electricity over a six-hour period and by fixing the cost of off-peak electricity at 3.8 cents per kilowatt-hour without regard to the method of generation. Figure 1 shows the results of the study in graphical form.

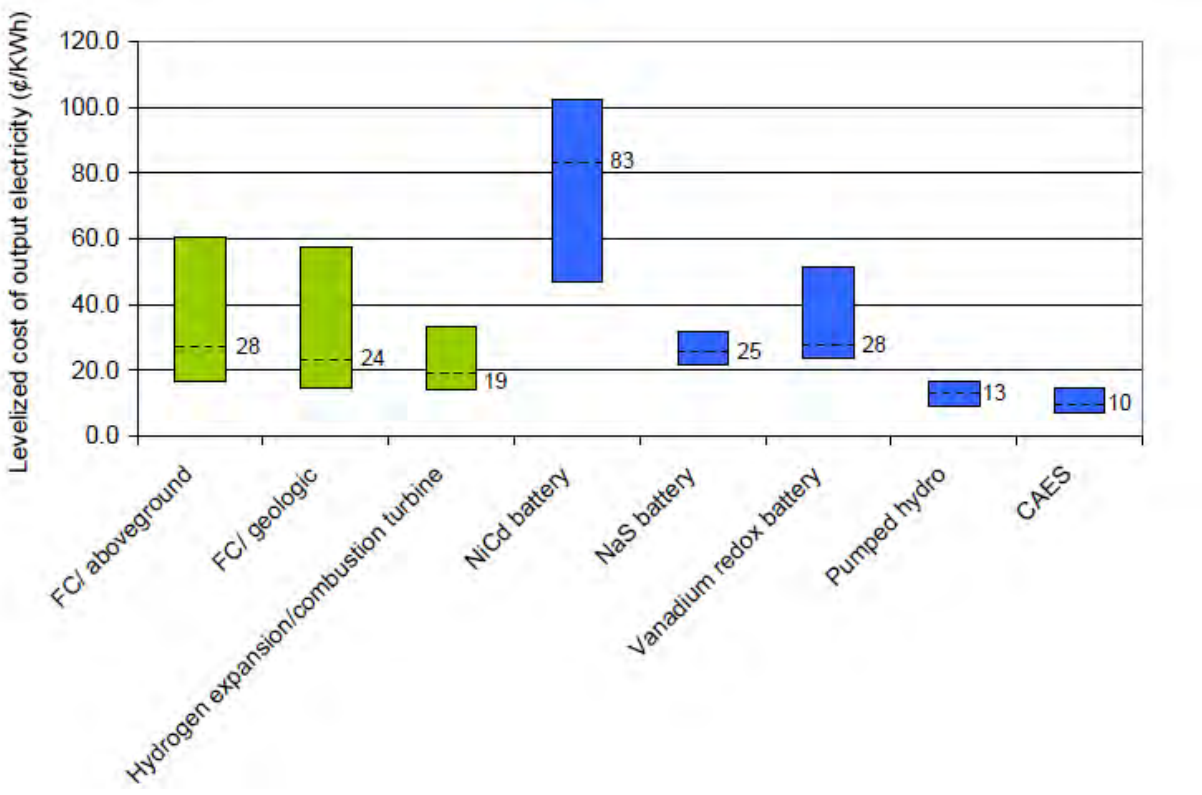


Figure 1. Ranges of levelized cost of electricity delivered by various electricity storage systems

The top of each bar represents a cost calculation based on the current off-the-shelf costs for the technology. The bottom of each bar represents the DOE goal for a mature commercialized (mass produced) technology, for example $30/kW with a 5000-hour life, which are the DOE goals for PEM fuel cells in transportation applications. The dashed line with the numeric value is based upon discussions with stakeholders regarding projected mature costs assuming wide-scale adoption of the technology. The full report can be found at http://www.nrel.gov/docs/fy10osti/46719.pdf.

Figure 1 illustrates that hydrogen-based electricity storage systems could compete with battery-based systems but not with pumped hydro or CAES. Two of the most important factors in determining the cost of electricity delivered by these hydrogen systems are the cost of the electricity used to produce the hydrogen and the roundtrip efficiency of the system. In the case study of aboveground storage in steel tanks combined with a fuel cell generator, the left-most bar, the roundtrip efficiency was about 30% and the cost of electricity input to the system was 3.8 cents/kWh. This means that about 12 cents of the 28 cents/kWh cost of delivered electricity shown for the mature system is generating costs. If the round trip efficiency of the system could be improved to 60%, substantial savings could be realized. High temperature steam electrolysis and high temperature fuel cell technologies based on solid oxide electrolytes hold the promise of achieving roundtrip efficiencies in this range.

Another factor that contributes to the high cost of delivered electricity is the high capital costs for the electrolyzer units and the fuel cells. Electrolyzer and fuel cell units are notorious for having small scaling factors. For example, alkaline electrolyzer units in size classes as large as 2 megawatts (electrical input) are available today from several sources. They cost on the order of $900/kW for a single unit. To build a 50 megawatt (electrical input) hydrogen production facility would require purchasing and joining 25 units. This has the potential of bringing the cost down to about $700/kW. Because alkaline electrolysis is a mature technology, no significant reduction in costs can be expected with volume production.

PEM fuel cells, on the other hand, are not commercially available in megawatt sizes at present and, because of their developmental nature, have costs in the thousands of dollars per kilowatt (electrical output). The transportation fuel cells currently under development for transit bus applications are the closest match to the fuel cells needed for an electricity arbitrage application. These units are being developed and tested in transit buses in sizes of about 100 to 200 kW output and are designed specifically to operate on hydrogen. Unlike grid-connected stationary fuel cells operating on natural gas that are designed to operate 24 hours a day, the transit bus fuel cells operate only about eight hours per day, which is a closer match to the operating time of a PEM fuel cell in an electricity arbitrage application. PEM fuel cells in transit bus applications have already demonstrated more than 9,000 hours of operational life. A 12,500-hour operational life in an electricity arbitrage application would be consistent with an 8-year replacement cycle. Here again, building a 50 megawatt (electrical output) fuel cell installation would require purchasing two hundred fifty 200-kilowatt fuel cells. Clearly there is not much in the way of cost savings, due to scaling factor, to be realized by building large electrolyzer and fuel cell installations. The question arises: can capital cost be reduced by developing a unit that combines the electrolyzer and fuel cell functions, in other words, a reversible fuel cell?

PEM Reversible Fuel Cell Session

Corky Mittelsteadt of Giner Electrochemical Systems and Everett Anderson II of PROTON ON SITE reviewed the status of their companies' PEM reversible fuel cell technology. These presentations established the background technology and established the state-of-the-art for PEM reversible fuel cell systems.

Reversible PEM Fuel Cell Design Concepts

Two approaches for the reversible PEM fuel cell have been developed: 1) the Unitized Regenerative Fuel Cell system (URFC) and 2) the Discrete Regenerative Fuel Cell system (DRFC). Both design concepts will vary based on application. For applications where air is readily available for the fuel cell (Air-URFC or Air-DRFC), the oxygen produced in the electrolysis mode is purged to the atmosphere. Applications that use sealed systems where air is unavailable will store the oxygen produced by electrolysis and use this oxygen for fuel cell operation (O_2-URFC or O_2-DRFC). The Balance-of-Plant—i.e., the pumps, compressors, storage vessels, and gas cleanup devices—will vary considerably depending on whether the reversible fuel cell design is an Air-device or an O_2-device.

Unitized Regenerative Fuel Cell System – PEM

The PEM URFC cell stack delivers power when operated as a fuel cell using hydrogen fuel and either air or stored oxygen as the oxidant and generates hydrogen and oxygen when operated as an electrolysis cell. Design of the individual cells and cell components for the URFC needs to address the distinctly different operating conditions occurring at the electrodes during each mode of operation. For example, the oxygen/air electrode may swing from 200 millivolts above to 200 millivolts below the reversible oxygen potential as the cell switches from electrolyzer to fuel cell mode. In the exothermic fuel cell mode, humidified, gas-phase reactants are required along with rapid removal of the heat and water produced, while in the electrolysis mode, liquid water is required as the reactant at the hydrogen producing electrode with rapid removal of the product hydrogen.

The Balance-of-Plant (BoP) supporting the PEM URFC is designed to collect product water in the fuel cell mode, maintain the thermal balance within the fuel cell, deliver clean reactants, and produce regulated power (either AC or DC depending on the application). URFC BoP issues include design of the thermal management system because operation in the electrolysis mode is slightly endothermic while operation in the fuel cell mode is exothermic and cooling plates are typically used to remove excess heat when the fuel cell is producing power.

The URFC system is best suited to those applications where operation in the fuel cell mode and the electrolysis mode are approximately balanced in terms of power density and operating times with the time operating as a fuel cell approximately matching the time operated as an electrolyzer. The URFC system has the advantage of reduced size, compared to the DRFC, and the URFC system is the preferred design for those applications where power density and energy density specifications are critical, for example, in unmanned aerial vehicles (UAV).

Discrete Regenerative Fuel Cell System

The DRFC uses two different PEM electrochemical devices: an electrolysis stack and a fuel cell stack that share connections to a common hydrogen storage system. While in strict terms the DRFC is not a reversible fuel cell, it is included here because its use of a common storage system allows DRFC systems to rival URFC systems in energy density. The electrolysis system has a cell stack specifically designed for operation at potentials above the reversible potential for water splitting and a design optimized for removal of the product hydrogen and oxygen. Carbon-based materials are not used in the electrolysis stack and the catalyst layer is designed to operate in the presence of liquid water. The bipolar plate materials are typically metals such as tantalum or niobium that are highly resistant to oxidation and corrosion. Tantalum- and niobium-coated stainless steels also could be acceptable. The fuel cell system is consistent in both design and materials with stationary and automotive PEM fuel cells. The stack can use carbon supported catalyst or the nano-structured thin film (NSTF) catalyst developed by 3M. Bipolar plate materials for the fuel cell systems include graphite and may include corrosion-protected stainless steel. Those bipolar plate materials acceptable for PEM automotive fuel cell systems will be acceptable for the fuel cell in the PEM DRFC.

The DRFC system may have greater durability requirements than the automotive PEM fuel cell. The durability requirements will be application dependent because the 5,000 hours durability target for a PEM automotive fuel cell represents approximately 5 years of operation in the vehicle while a reversible fuel cell operating in an electricity arbitrage application (20% capacity factor) or in a UAV application (60% capacity factor) could reach 5,000 hours in 7 months. "Hard" starts and stops (i.e., complete turndown with replacement of the hydrogen in the anode by air) are known to increase the rate of degradation of the PEM fuel cell. Continuous operation of the PEM fuel cell has a smaller effect on degradation.

In the DRFC system, separate plumbing is required for the electrolysis stack and for the fuel cell stack, although some of the remaining BoP can be common to both, for example hydrogen storage vessels, control systems, and power conditioning systems. The use of separate BoPs for reactant flow and cooling systems allows each stack to be optimized for its application and simplifies the requirements for individual BoP components and subsystems. However, this increases somewhat the overall size, part count, and complexity of the DRFC system compared to the URFC systems. Thermal management and reactant delivery systems for the fuel cell can be optimized for efficiency in the DRFC. Gas collection and product clean-up (e.g., water removal) are readily optimized for the PEM electrolysis unit without compromising the performance of the separate PEM fuel cell. The DRFC fuel cell system will benefit from automotive, material handling equipment (MHE), and backup power fuel cell development activities that will help drive down the cost of the fuel cell and BoP components for the DRFC.

The DRFC system can satisfy those applications where operation in the electrolysis mode may be extended in time and at lower power than when operating in the fuel cell mode. One application would be backup power where hydrogen production and storage can occur over several days at low power density while fuel cell operation may require minutes to hours of operation at high power density. This backup power application can utilize a much smaller electrolysis unit compared to the fuel cell unit. The DRFC system also can satisfy applications

where the fuel cell and the electrolysis systems are of equivalent ratings, for example, remote power or MHE applications. For both of these applications, separation of the electrolyzer system and the fuel cell system is acceptable. At an extreme case, the automotive fuel cell applications using hydrogen from a stationary, centralized, electrolysis source and a high power density fuel cell onboard the vehicle can be interpreted as a DRFC system.

PEM Presentations

PROTON ON SITE

Everett Anderson, Vice President of Electrochemical Technology for PROTON ON SITE (PROTON), reported that the specific energy of reversible fuel cells could reach 1,000 Wh/kg, which is an approximate 5-fold increase over lithium metal oxide battery technology. Several applications developed by PROTON were identified including the integration of a high pressure electrolyzer with a fuel cell as a DRFC system. Five demonstration systems were identified and all of the systems were rated at 10 kW or less; the systems are shown in Appendix A.

Charge/discharge cycle data for a DRFC system showed little to no degradation over 35 charge/discharge cycles in a 350 hour test. The fuel cell degradation was not evident while the electrolysis system may have improved over the life of the test; however within the error of reading the data in the presentation (see chart 16 of PROTON in Appendix A) no degradation was observed.

The URFC system reported on by PROTON exhibited some degradation of the fuel cell and the electrolysis system over a 1,300 hour test with 780 closed loop cycles operating at 200 ASF (amps per square foot) in the electrolysis mode and 300 ASF in the fuel cell mode. One ASF equals 1.076 milliamps per square centimeter. The roundtrip efficiency of the URFC test stack developed by PROTON was 37%.

PROTON compared the URFC and DRFC based on applications. The URFC systems are better suited for applications requiring storage of both oxidant and fuel for the fuel cell. For system applications where storage volume is critical (e.g., unmanned undersea vehicles or unmanned aerial vehicles) the URFC system affords a minimum stack volume with a beneficial increase in the volume for reactant storage. The URFC is also well matched with applications where the charge/discharge cycles are equivalent. The URFC systems have several drawbacks:

- The catalyst and electrode structures are not optimized for a single function (e.g., oxygen reduction) but must fulfill both fuel cell and electrolysis functions. Up to a 70% penalty in performance (efficiency) for the unitized approach was reported and was associated with the multifunctional requirements of the catalyst and electrode structures.
- The URFC BoP has increased complexity to function in both the fuel cell mode and the electrolysis mode. The exothermic fuel cell process requires cooling of the fuel cell stack with a cooling fluid. The endothermic electrolysis process using liquid water at the electrodes does not need a cooling system. Humidification of either or both fuel cell reactants is necessary while the electrolysis system must remove water vapor from the product gases prior to their pressurization.

- The DRFC system leverages mature technology and the large scale investment in automotive fuel cell technology along with established commercial electrolysis technology. On the other hand, the URFC system must develop novel catalyst, novel electrode structures, and new system concepts.

PROTON listed potential grid energy storage applications for reversible fuel cell systems and these are given in Table 1.

Table 1. Grid Energy Storage Applications for Reversible Fuel Cells
(from PROTON ON SITE presentation)

Application	Power Range	Duration	System Voltage
Distributed Energy Storage	25 to 200 kW	2 to 4 h	Secondary
Load Shifting	kW to MW	10 h	Various
Substation Grid Support	1 to 20 MW	2 to 6 h	Distribution
PV Voltage Transient Support	≈ MW	1 sec to 20 min	Distribution
Wind Smoothing	1 to 100 MW	2 to 15 min	Distribution

Distributed Energy Storage applies to peak load management, voltage regulation, and frequency regulation and can provide backup power. Load Shifting couples with a renewable resource to shift load at peak times (electricity arbitrage). In some configurations the Load Shifting may facilitate load balancing where renewable production is uncertain and variable. Substation Grid Support assists with peak load management, frequency regulation, and reactive support. PV Voltage Transient Support can eliminate rapid voltage and power swings. Wind Smoothing can ensure wind farm ramp rates are kept within design limits and provide frequency regulation.

Table 2 lists the development needs identified by PROTON in its presentation.

Table 2. Development Needs Identified by PROTON ON SITE

Development Need	URFC	DRFC
Materials Development	Bi-functional catalysts	High pressure materials compatibility for electrochemical pumping applications
	Oxygen compatibility	New catalyst with NSTF concepts
	Electrode structure	
	High pressure materials compatible with electrochemical pumping applications	
System Development	Integration of Balance-of Plant components (e.g., thermal and water management systems)	Compatible power conversion systems
	Compatible power conversion systems	
Manufacturing	Development of standard manufacturing procedures for URFC electrodes and cell components	Develop supply chain for electrolyzers and fuel cell manufacturing
		Automation of electrolyzer and fuel cell manufacturing

Giner Electrochemical Systems

Corky Mittelsteadt, Vice President of Electrochemical Technology for Giner Electrochemical Systems, reviewed the development of Regenerative (Reversible) Fuel Cells at Giner Electrochemical Systems (GES). Slides from the GES presentation are available in Appendix B. Water management for the URFC was identified as a critical issue that GES has resolved using a Water Management Membrane (WaMM), which is a porous component that provides water vapor for humidifying the fuel cell cathode and withdraws product water from the fuel cell cathode chamber. When the URFC is operated as an electrolyzer, the WaMM delivers water vapor to the anode of the electrolyzer (the oxygen evolving electrode). The performance of the WaMM-containing URFC was reported to be comparable to a standard electrolyzer operating at moderate current densities, <1,000 mA/cm^2. The WaMM benefits to the URFC are given in Table 3.

The GES presentation discussed the economics of hydrogen from PEM electrolysis. Using the U.S. Department of Energy's H2A model, they calculated the gallons of gasoline equivalent for

hydrogen ($/kg) to be $3.02/gallon comparing a hydrogen vehicle with 50 miles per kg of hydrogen to a gasoline vehicle with 30 miles per gallon of gasoline; they assumed for the analysis electric power cost at $0.039/kWh. The critical conclusion was that hydrogen vehicles would be $1.00 per equivalent gallon less expensive to operate than present internal combustion vehicles based on the above assumptions.

Table 3. Benefits of the WaMM URFC Design Identified by GES

Function	Benefit
Electrolyzer	>99.9% dry product gases with no liquid phase separation required for hydrogen storage
	Feed water is static with no liquid recirculation pumps
Fuel Cell	Gas feed can be static with no gas recirculation pumps
	In-situ humidification and no external humidifiers required
Combined System	Water permeable plate not susceptible to impurities in feed water and purity constraints can be relaxed; no deionization beds needed.
	Rapid turnaround time from fuel cell mode to electrolyzer mode; ~ 5 seconds

GES demonstrated the importance of efficiency for a regenerative system with a calculation of the profit or loss realized by a 100 MW wind farm that used a reversible fuel cell system and hydrogen storage in an electricity arbitrage scheme. A regenerative wind farm with a regenerative system operating at 50% roundtrip efficiency would have an annual profit of ~$1,200,000. On the other hand, if the regenerative system had only a 40% roundtrip efficiency it would realize an annual loss of ~$300,000. The swing from a profit to a loss for a 10% reduction in efficiency emphasizes the very critical need to optimize the technology and the importance of eliminating performance degradation. More details of this calculation are available on Slide 13 of the GES presentation in Appendix B.

GES identified three approaches for improving the performance of its electrolyzers: 1) lowering the gas permeability of the membrane, 2) increasing the ionic conductivity of the membrane, and 3) developing catalysts and membranes that operate at elevated temperatures. GES reported that a 5-fold improvement in conductivity/permeability would reduce the energy needed to produce hydrogen from 54 kWh/kg-H_2 to 45 kWh/kg-H_2 for an electrolyzer operating at 500 mA/cm^2 and from 50 kWh/kg-H_2 to 46 kWh/kg-H_2 for an electrolyzer operating at 1,000 mA/cm^2. Increasing the electrolysis operating temperature from 60°C to 80°C reduces the energy requirements for hydrogen production by 4% at 1,000 mA/cm^2.

GES's analysis of high pressure electrolyzer operation concludes that high pressure leads to system simplification but does not necessarily lower the cost of hydrogen due to the higher equipment costs for a pressurized electrolyzer. The calculated cost of generating H_2 for storage at 300, 2,000, and 5,000 psi is shown in Figure 2 as a function of electricity costs and current density. The minimum costs are projected for operation at 300 psi.

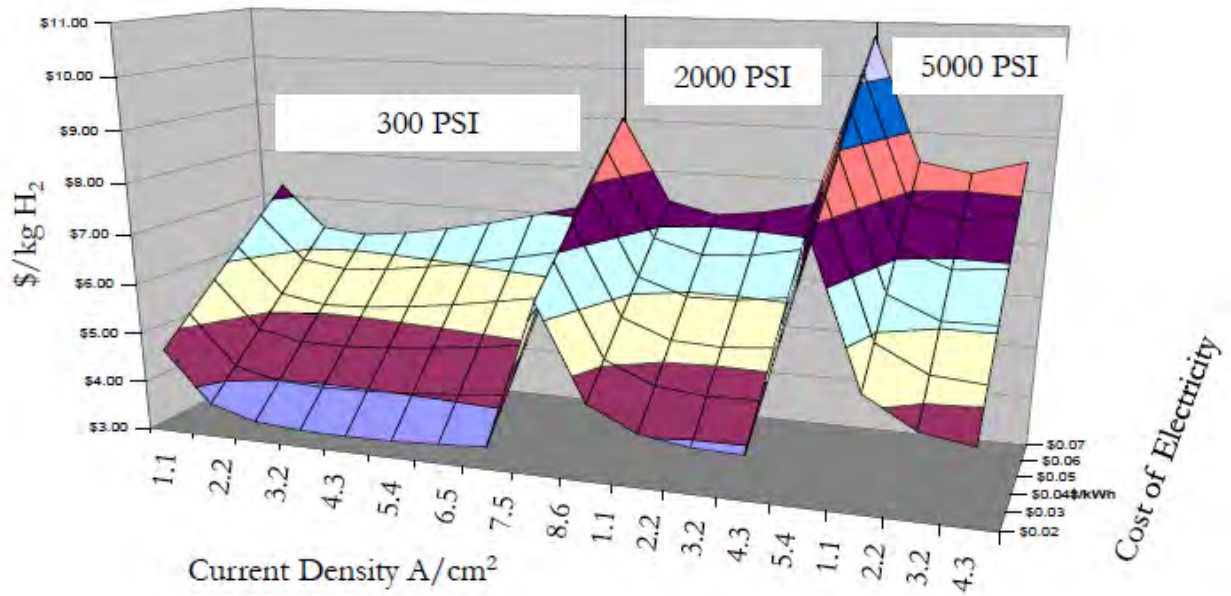


Figure 2. Costs of hydrogen as a function of electrolyzer operating pressure
(Slide 26 from GES presentation)

GES identified membranes and oxygen/air electrode catalysts as two important needs for reversible fuel cell development. Fuel cells benefit from thinner membranes that reduce conductivity losses and improve water transport properties, and fuel cells operating on air also benefit from thin membranes. On the other hand, electrolyzers benefit from thicker membranes that reduce product gas crossover. High pressure electrolysis is not possible with thin membranes that use the currently available perfluorinated sulfonic acid chemistry.

Operation of the fuel cell on oxygen using platinum black catalysts compared to operation on air using platinum catalyst supported on carbon yields a 17% improvement in fuel cell efficiency for the oxygen system. The high cost of platinum is a limitation that needs resolution. GES suggested that the new low-platinum load catalysts developed by 3M, which do not use carbon supports that corrode during electrolysis, may greatly decrease the catalyst cost. The cost sensitivity of the reversible fuel cell systems to efficiency makes it difficult to operate the fuel cell on air, and GES suggests both hydrogen and oxygen be stored and used in the fuel cell.

GES answered the three questions proposed at the beginning of the workshop in the following ways.

1. Is this (reversible fuel cell) technology feasible for cost effective storage of renewable electricity?
    - Depends on scale and duty cycle
        - Fuel cell and duty cycle need to be closely matched
        - For operating on air it is difficult to match fuel cell and electrolyzer membranes

2. What are the materials and systems barriers for developing this technology?
    - Membrane permeability
    - Catalyst cost
3. What are the manufacturing issues that need to be addressed to be cost effective?
    - Continuing to lower part count and component cost.

The GES answers apply primarily to URFC systems where compromises in materials and designs have to be found to allow both fuel cell and electrolyzer operation in the same unit. For DRFC systems, there is no requirement to match the duty cycles of the electrolyzer and the fuel cell or to find material compromises. However, lower part count and lower costs are needed with both systems.

PEM Reversible Fuel Cell Breakout Sessions

The participants were divided into two groups to discuss the information presented by PROTON and Giner Electrochemical Systems. The two breakout groups were challenged to recommend areas of research and development for the URFC and DRFC. No attempt was made to homogenize the groups and as a result the developers tended to congregate in one group and the academics in another. This proved to be beneficial in that both groups could delve deeper into their areas of expertise with less overlapping of recommendations between groups. The results of the discussions, as reported back by the two groups, are listed separately below.

Highlights of PEM Reversible Fuel Cell Breakout: Group 1	
Critical Issues	• Energy penalty to dry hydrogen: equals 1%–3% of the energy value of the hydrogen produced. • Cost of pressurization—at what point does the cost of pressurizing the electrolyzer negate the value of reducing the number of components in the BoP? • Can oxygen be used beneficially? • Are reversible fuel cells only valuable for specialty markets? • Is cost the only barrier to commercial applications? • Efficiency penalty favors development of DRFC.
Material & System Barriers	• Membrane permeability must be decreased. • Breakthrough for bi-functional catalyst for oxygen electrode needed (URFC). • Cycle time between electrolysis and fuel cell operation needs to be as short as possible for grid support. • PEM URFC should have a faster cycle time compared to SOFC/SOEC URFC. • Thermal management of URFC is complex and needs resolution. • Need to understand impact on materials of high pressure hydrogen storage. • Need to understand impact on materials of high pressure cycling. • Need to develop alternative, non-carbon catalyst supports for electrolysis applications. • Need to reduce membrane gas permeability and increase ionic conductivity. • Need stable, cost effective metal bipolar plates.

Manufacturing Issues	• Build on and exploit manufacturing technology under development for PEM FC applications. • Develop non-carbon supported electrode and catalyst manufacturing processes. • Develop seals for high pressure electrolysis systems. • URFC departs from automotive fuel cell production and will need new manufacturing methods. • Definitions of Low Rate Initial Production and Full Volume Production needed. • Cost analysis needed for high volume manufacturing of reversible fuel cell systems. • At what pressure are electrolyzers and fuel cells optimized based on cost drivers.
Miscellaneous	• Are there alternative chemistries such as hydrogen/bromine that make sense for regenerative fuel cells? Systems that eliminate the oxygen reduction reaction over potential should be considered.

Highlights of PEM Reversible Fuel Cell Breakout: Group 2	
Issues unique to URFC	• Hydrogen electrode structure/catalyst used for both hydrogen production and hydrogen oxidation. • Oxygen electrode structure/catalyst used for both oxygen production and oxygen reduction. • Oxygen electrode catalyst platinum black; NSTF potential future catalyst.
Issues unique to DRFC	• The DRFC approach enables optimization of MEAs for each mode in separate stacks. • Oxygen fuel cell catalyst: can benefit from automotive and other fuel cell applications. • Oxygen evolution catalyst IrO_2 and develop IrO_2 NSTF catalyst.
Power Range	• 10 kW to several MW acceptable for both URFC and DRFC. • Application dependent choice for URFC and DRFC. • Backup power uses a low rate electrolysis system with a high rate fuel cell system. The optimum system for backup power is the DRFC. • Distributed energy or load shifting can use either URFC or DRFC. • Applications requiring high energy density favor URFC.

Critical Issues	• Degradation in performance. • Alternating electrolyzer-fuel cell cycles degrades performance of URFC. • Efficiency is critical to URFC and DRFC system economics. • Applications with 1,000 cycles or less may find degradation acceptable.
	• Water management: URFC design must prevent flooding of electrodes in fuel cell mode. • Humidification of reactants for fuel cell applications is necessary. • URFC design must permit liquid water at the cathode interfaces for electrolysis. • DRFC separately resolves water management but with more complex Balance-of-Plant.
	• Thermal management: exothermic reaction of fuel cell requires cooling of fuel cell. • Endothermic reaction of electrolyzer does not require cooling plates except at high current densities. • DRFC separately resolves thermal management but with more complex Balance-of-Plant.
Materials Issues	• Carbon supported catalyst acceptable for fuel cell system but unacceptable for electrolyzer. • New catalyst supports needed for URFC—NSTF catalyst suggested. • Carbon supported catalyst acceptable for fuel cell in DRFC system.
	• High catalyst loadings for electrolysis is a cost issue. • NSTF for IrO_2 support may reduce catalyst loadings.
	• Bipolar plates: carbon/graphite bipolar plates unacceptable for URFC because of corrosion. • Carbon/graphite bipolar plates acceptable for DRFC fuel cell. • Low cost metal bipolar plates for URFC are needed. • Low cost metal bipolar plates used in DRFC are needed.
Balance-of-Plant Issues	• Power electronics is an expensive component that needs development for both URFC and DRFC. • Development of power electronics subsystem that would be common to both fuel cell and electrolyzer.
	• DRFC has potentially more complex Balance-of-Plant. • Two separate BoP subsystems: fuel cell BoP and electrolyzer BoP but with common hydrogen storage. • Bi-functional water management and thermal management systems need to be developed for URFC.

Competition	• Batteries. • Initial cost will be driver. • Application will be important driver.

Recommendations from PEM Session

The industry presenters and the breakout group participants recommended research and development to optimize the designs and reduce the cost of both URFCs and DRFCs. The recommendations are as follows:

1. Cost reduction of the catalyst with the development of lower precious metal contents was specified with research recommended on NSTF catalyst concepts for both URFC and DRFC systems.
2. Efficiency was recognized as an important driver for both URFC and DRFC. Catalyst and cell performance optimization was considered important to improve the efficiency of the reversible fuel cell systems.
3. Cost reduction by development of power electronics that would be common to both the electrolyzer and the fuel cell was considered an important development activity.
4. Minimization of parasitic losses in the BoP is essential to increasing the efficiency of the reversible fuel cell systems.
5. Water management systems that reduce the energy losses associated with drying the hydrogen prior to storage could provide a 5% improvement in total efficiency.
6. It was recommended that materials research and development programs be initiated to discover lower cost bipolar plate and catalyst support materials. Low cost metal bipolar plates for URFC systems were identified as a specific need.
7. System concepts that reduce the cycle time for transitioning between electrolyzer operation and fuel cell operation are needed for both the DRFC and the URFC.
8. Manufacturing research and development projects that build on the emerging fuel cell manufacturing processes should be supported including those that address quality control procedures and instrumentation.
9. Cost analyses should be conducted to establish a basis for manufacturing research and development direction.
10. Engineering analysis is needed to determine load profile and system requirements for the various renewable electricity storage applications.

Reversible SOFC/SOEC Session

Three presentations were made in the SOFC/SOEC session. Greg Tao from Materials and Systems Research in Salt Lake City, Utah, presented on "Lessons Learned from SOFC/SOEC Development." Casey Brown from Versa Power Systems in Littleton, Colorado, presented on "Progress on the Development of Reversible SOFC Stack Technology." Dr. S. Elangovan from CERAMATEC, also in Salt Lake City, Utah, presented on "Materials and Systems Issues with Reversible SOFC." These presentations established the background and state-of-the-art of the technology for the breakout sessions addressing reversible SOFC/SOEC development.

SOFC Development

Solid oxide fuel cells have been under development since the 1960s. Small scale SOFC systems are included in the R&D portfolio of the Fuel Cell Technologies Program in the DOE Office of Energy Efficiency and Renewable Energy (EERE). However, the largest SOFC development effort currently underway in the world today is the Solid State Energy Conversion Alliance (SECA) funded by the DOE Office of Fossil Energy.[2]

DOE funding for SECA has averaged about $50 million/year over the last 10 years. The SECA program was initiated in 2000 with the goal of developing technology for mass producing small 5 to 10 kW SOFC stack modules that could serve as a base for commercializing a wide variety of products from residential fuel cells to auxiliary power units (APU) for overland trucks and for recreational vehicles. More recently SECA has refocused its efforts on the development of megawatt-scale SOFC power modules for coal gasification-based power plants with carbon capture. The current focus on developing large SOFC power modules is very much in line with the needs for large SOFC modules that can operate on pure hydrogen.

Current SECA goals are for $175/kW stack costs and $700/kW power plant costs with an overall net electrical efficiency of 54% (HHV) including carbon capture. The current programmatic timeline calls for a 250 kW to 1 MW demonstration of a single SOFC power module by 2013 and a 5 MW multi-module demonstration by 2015.

SOEC Development

Solid oxide electrolysis cells have received less attention and funding than their fuel cell counterparts. In 2005 the DOE Office of Nuclear Energy initiated the Next Generation Nuclear Plant project. Among the R&D efforts associated with this project was the Nuclear Hydrogen Initiative having the goal of assessing various methods for producing hydrogen at high efficiency from a Generation IV nuclear reactor operating with a helium cooling loop able to deliver heat in the range of 750°C to 800°C. Among the approaches evaluated was steam electrolysis based on cells using solid oxide electrolytes that were similar in materials and construction to SOFC. Idaho National Laboratory (INL) leads the effort to develop and test the SOEC. CERAMATEC was the principal supplier of SOEC stacks to INL. This program culminated in a demonstration of three 5 kW SOEC stacks at INL in 2009.

One of the most important incentives for mating an SOEC to a high temperature nuclear reactor is based on the fact that the electrochemical water-splitting reaction (electrolysis) is endothermic. Both heat and electricity are required to split water by electrolysis. In addition, the amount of heat required increases with increasing temperature while the amount of electricity required decreases. For example, at 80°C, the maximum operating temperature of an atmospheric pressure PEM electrolysis cell, 93% of the energy required to split water vapor into hydrogen and oxygen must be supplied in the form of electricity and the other 7% as heat. However, at 800°C the breakdown is only 76% as electricity and 24% as heat—supplied at the operating temperature of the unit. Initially it was thought that this made steam electrolysis an excellent match for the high temperature Gen IV reactor.

However, all electrochemical devices use ion-conducting electrolytes that have an inherent internal resistance. When an ionic current flows through the electrolyte, heat is generated. In the industry this is called Ohmic heating or "I-squared R" (I^2R) heating and is proportional to the square of the ionic current, I, passing through the cell, multiplied by the ionic resistance, R. This is the analogue of resistive heating in an electrical circuit. The ionic resistance of state-of-the-art electrolyte membranes in PEM electrolysis cells is such that, at moderate to high current densities, far more heat is generated than is required to supply the endothermic needs of the water-splitting reaction. Therefore, at useful current densities, PEM electrolysis units must be cooled to remove the excess heat generated by the internal resistance.

This is not necessarily true of SOEC cells and stacks. Because of the higher heat requirement for these high temperature devices, it is possible to operate at a moderate to high current density such that the heat generated by the internal resistance exactly matches the endothermic demands of the water-splitting reaction. This is called the thermal neutral point. Operating below this current density means that both electricity and heat must be supplied to the cell stack. Operating above this current density means that excess heat must be removed from the cell stack.

There are several advantages to operating at the thermal neutral point including low thermal stresses on the ceramic parts and the elimination of the need for heat management. The disadvantage is that the cell stack must operate in a narrow range of current densities.

Reversible SOFC/SOEC Development

It has been known almost from the inception of work on SOFC that the cells could be reversed and used for steam electrolysis cells. However, until recently there has been no concerted effort to develop reversible SOFC/SOEC. For the last two years Versa Power Systems (Versa) has been performing work funded by DARPA, via a subcontract from Boeing, developing high specific power units for an autonomous aircraft, known generically as a UAV. Versa also has been performing work under a contract with the DOE Fuel Cell Technologies Program to demonstrate a kilowatt size-class reversible SOFC/SOEC.

SOFC Presentations

Materials and Systems Research, Inc.

Greg Tao, Principle Investigator at MSRI, reported on work performed separately on SOFC and SOEC and provided information on how each behaved when reversed. The slides from MSRI's presentation can be found in Appendix C. MSRI has performed work developing SOFC for the DOE Office of Fossil Energy and SOEC for the Office of Nuclear Energy under subcontract to INL. MSRI uses an anode-supported SOFC design with a thin solid oxide electrolyte averaging 8 microns in thickness. The cathode of their SOFC uses a mixed (electronic and ionic) conductor. MSRI has demonstrated multi-cell SOFC stacks up to 2 kW in power output. They reported on a 60-cell SOFC stack, shown in Figure 3, that operated for 2,500 hours with a degradation of only 0.85% per 1,000 hours operating on 50:50 H_2:N_2 fuel and with air as the oxidant.

Figure 3. MSRI's 60-cell stack
(Slide 10 from MSRI presentation)

In work begun in 2008, MSRI used their standard SOFC materials to investigate how the cells behaved when used as SOEC for steam electrolysis. Using identical 5-cell stacks having 100 cm^2 active area per cell, they operated one stack as an SOFC and one as an SOEC. The degradation rate of the 2008 vintage SOFC was less than 2% per 1,000 hours while the degradation of an identical stack operated as an SOEC was 30% per 1,000 hours. Post-test analysis indicated that the rapid decay of the SOEC was due to delamination of the oxygen electrode at the electrode/electrolyte interface, a problem that was not observed in the SOFC.

The conclusions reached at the time were that cell designs and materials optimized for SOFC were not optimized for SOEC operation. MSRI then began work to develop a set of materials optimized for SOEC operation. In January 2011 MSRI completed a successful 5-cell SOEC stack test that exhibited an average degradation rate of less than 2% per 1,000 hours over a 10,000 hour period of testing. In one particular 5-cell stack test MSRI operated the device as an SOEC

but periodically reversed current direction and operated it as an SOFC. The 5-cell stack exhibited good reversible behavior with the slope of the voltage-versus-current (VI) plot for the SOFC mode being the same as the VI plot for the SOEC mode of operation. This is the behavior desired for a good reversible SOFC/SOEC.

MSRI summarized their presentation with the following bullets.

- Reversible SOFC/SOEC shows logical promise for storing renewable electricity/energy.
- But for a near-term target, smaller units for distributed/decentralized storage may make more sense.
- Due to the different operation mechanisms between SOFC and SOEC, cell materials developed for SOFC may not be suitable for SOEC applications.
- SOECs typically show a higher degradation rate than SOFCs.
- MSRI has investigated and developed high-performance material sets for reversible SOFC/SOEC applications.
- With knowledge gained from the accumulated 10,000 stack-hours tests, MSRI has successfully reduced the SOEC stack degradation rate from initial 30%/1,000 h to <2%/1,000 h.
- Fundamental studies of cell materials are needed to further improve reversible SOFC/SOEC performance.

Versa Power Systems, Inc.

Casey Brown delivered the Versa presentation, slides from which can be found in Appendix D. As with all the presentations, Casey began his presentation speaking about the company and its history doing SOFC and SOEC work. Versa has a history of SOFC development reaching back to the mid-1990s and has been a subcontractor under the SECA program since 2001. Current activities at Versa include a broad portfolio of projects on SOFC, SOEC, and reversible SOFC/SOEC. The basic design of the Versa SOFC is similar to that used by MSRI; anode supported cells, thin yttria-stabilized zirconia electrolyte, and a mixed ionic/electronic conducting ceramic as the cathode. However, unlike MSRI, Versa has a manufacturing facility located in Calgary, Canada, capable of fabricating several megawatts of SOFC components per year. As with most SOFC developers, Versa has made great strides reducing stack degradation in the fuel cell mode. In 2009 Versa reported a 0.45% degradation rate for a 28-cell (about 1-kW) SOFC stack that had run continuously for more than 18,000 hours. However, as with other developers, when a 28-cell stack assembled from similar materials was tested as an SOEC, it had a degradation rate of about 3.8% per 1,000 hours.

Versa also shared the results of work on reversible SOFC/SOEC. Versa reported results for a single cell test in which the cell was cycled between SOFC mode and SOEC mode once per day for more than 100 days. The results, shown in Figure 4, are interesting in that a slightly higher rate of decay was shown for the cell when operating in SOFC mode. However, the degradation was a factor of 4 higher than observed for similar cells operated only as a fuel cell.

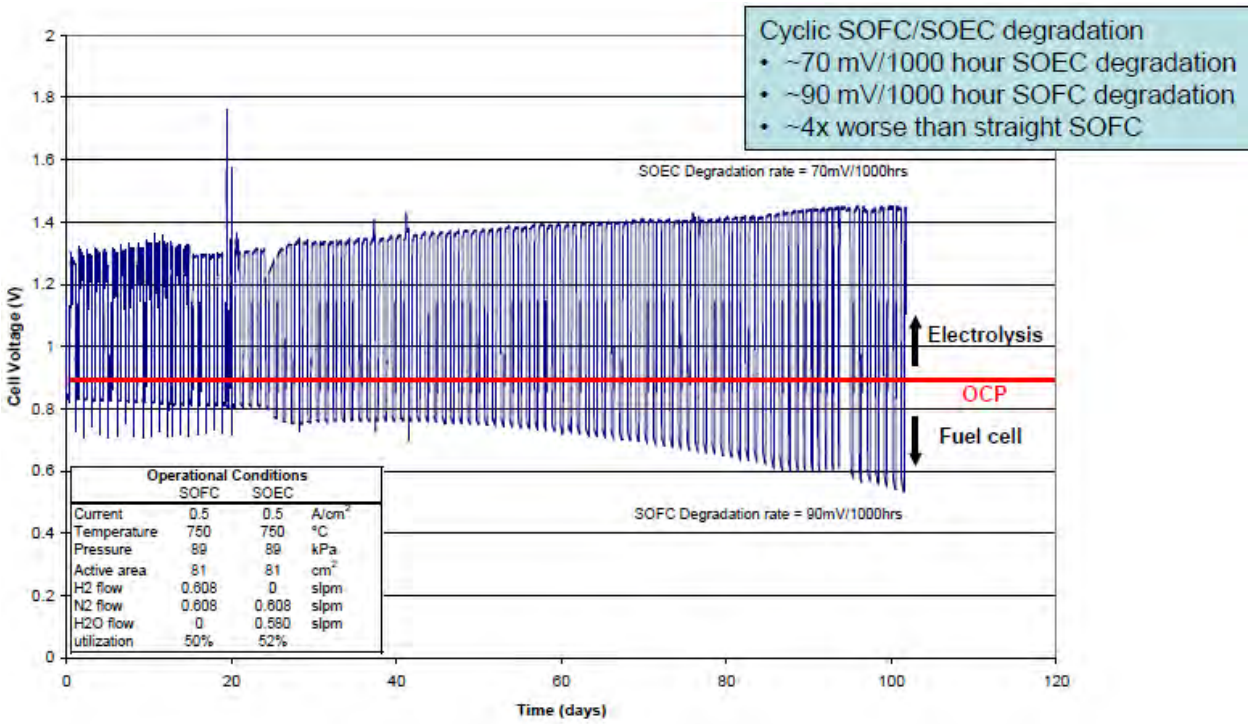


Figure 4. Degradation rate of reversible SOFC/SOEC cycling daily
(Slide 26 from Versa presentation)

Versa summarized their presentation with the following.

- Compared to its SOFC experience, Versa has very little SOEC experience.
- Despite significant improvements, degradation generally remains higher in electrolysis mode than in fuel cell mode.
- Energy storage efficiency is strongly influenced by system design.

Versa answered the three questions raised in the introduction in the following ways.

Q: Is this technology feasible of cost effective storage of renewable electricity?

A: A qualified yes.

Q: What are the materials and systems barriers to developing this technology?

A: Materials: Experience and confidence are lacking, but if demonstrated cell performance is stable and scalable, we already have 1+ year solutions. Degradation improvements always welcome.

System: Need to understand real requirements, things like power profiles of different applications, in order to answer this question. It would be nice to see demonstration systems running. Need low cost, high storage efficiency system designs that take advantage of SOFC potential.

Q: What are the manufacturing issues that need to be addressed to be cost effective?

A: Build on SECA work for volume production.

CERAMATEC

Incorporated in 1976, CERAMATEC has a long history developing solid oxide electrolyte devices including oxygen sensors and SOFC. Recently acquired by CoorsTek, CERAMATEC is continuing as an R&D wing of that organization. CERAMATEC supplied three 5-kW SOEC stacks that were demonstrated by INL as part of the Next Generation Nuclear Plant program. Slides from the CERAMATEC presentation can be found in Appendix E.

CERAMATEC uses a somewhat different materials arrangement for its cells than does Versa or MSRI. The CERAMATEC cells are electrolyte supported rather than anode supported. As part of the SOEC work performed for INL, CERAMATEC uncovered several key issues when using their baseline SOFC stack as an SOEC. They observed unacceptably high degradation rates due to oxygen electrode delamination. They also reported chromium transport from the stainless steel separator into the oxygen electrode and strontium migration from the strontium manganite oxygen electrode into the electrolyte. They then launched a project evaluating various alternative oxygen electrode compositions and settled on a cobalt-ferrite. They added a ceria layer between the oxygen electrode and a partially-stabilized scandium-doped zirconia electrolyte and achieved a significant reduction in the degradation rate. With regard to reversible SOFC/SOEC, CERAMATEC included information on a 25-cell stack test that was operated in both SOFC and SOEC mode. Results indicated a slightly higher Ohmic resistance when operating in the SOEC mode. Although no quantitative information was provided, CERAMATEC also identified seals as an issue needing further study.

CERAMATEC included important discussions in their presentation on the heat management issue. In one particularly useful slide, Figure 5 below, different temperature maps are shown for a cell operated in the SOFC mode and the SOEC mode at the same approximate current density. In the SOEC mode the cell was operating, by their calculation, approximately at the thermal neutral point of 1.29 V at 1,100 K. CERAMATEC also pointed out, in their discussion of heat management, that it will be necessary to operate the reversible system, when in the SOEC mode, at a voltage above the thermal neutral point so excess heat is generated that can support the thermal demands of the system, for example raising steam and heating it to the operating temperature of the stack.

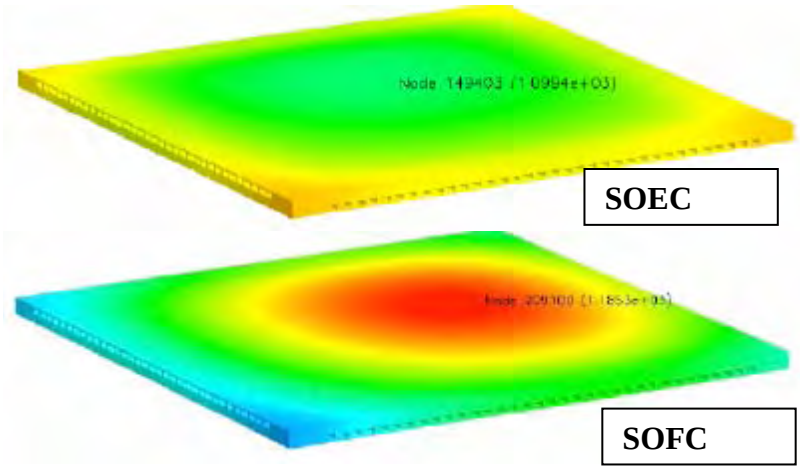


Figure 5. Temperature maps for cell in SOEC mode and SOFC mode of operation
(Slide 41 from CERAMATEC presentation)

As the last part of their presentation, CERAMATEC introduced the concept of CO_2 beneficiation. The proposed process is the production of liquid fuels by feeding carbon dioxide and steam into the hydrogen side of the SOEC. Hydrogen, produced by electrolysis of the steam, reacts with the carbon dioxide while still in the cathode chamber to produce syngas, which is dominated by hydrogen and carbon monoxide. The syngas is then passed to a Fischer-Tropsch (F-T) reactor where it is used to produce hydrocarbon fuels. This process was proposed as an alternative to hydrogen as a means of storing renewable energy.

Electrolysis Reaction:

Cathode: $H_2O + CO_2 + 4e^- \rightarrow H_2 + CO + 2\,O^{2-}$

Anode: $2\,O^{2-} \rightarrow O_2 + 4e^-$

Fischer-Tropsch Reaction: $(2n+1)H_2 + nCO \rightarrow H_{2n+2}C_n + nH_2O$

The F-T liquids can be substituted for petroleum-derived products. If the electricity supplied to the electrolyzer is from renewable sources, the hydrocarbon liquids would be considered a 100% renewable fuel.

CERAMATEC summarized their presentation with the following bullets.

- Single SOFC device capable of reversible operation expands applications potential
    - Allows greater use of renewable resources
    - Opportunity for CO_2 re-use to store renewable electricity as a liquid fuel
    - High efficiency hydrogen generation
- Significant differences in degradation mechanism between SOFC and SOEC
    - Promising composition identified for reversible cells
    - Good stability in SOFC mode with new materials
    - Requires additional research to study cyclic behavior between modes of operation
- Thermal issues more severe in SOFC mode

SOFC/SOEC Reversible Fuel Cell Breakout Sessions

The participants divided into two groups to discuss the information presented by MSRI, Versa, and CERAMATEC. The two breakout groups were challenged to identify critical issues, materials and systems barriers, and manufacturing issues that need to be addressed and to recommend areas of research and development for the reversible SOFC/SOEC.

No attempt was made to homogenize attendance by assigning people to the two groups. As a result the developers tended to congregate in one group and the academics in the other. This was beneficial in that there was less overlap of the discussions and a broader range of responses. There were many open questions raised for which there are no immediate answers. No attempt was made to prioritize issues either to importance or to the order in which they should be addressed.

Highlights of the Reversible SOFC/SOEC Breakout: Group 1	
Critical Issues	• Oxygen electrode degradation in SOEC mode. • Develop and optimize electrode materials that show good performance and durability working in both the SOFC and SOEC modes of operation. • Develop and assess designs for complete SOFC/SOEC systems and use to assess costs and efficiency. • Need to demonstrate a system at a size large enough to use to make reliable projections for full-scale facilities.
Material & System Barriers & Open Questions	• Seals – determine the impact of high steam content in the SOEC mode on perimeter and manifold seals. • Chromium volatilization from stainless steel hardware – little is known about this issue in the SOEC mode. • Little to no information is available on the impact of cycling on materials corrosion and electrode morphology. • Gas crossover through the thin electrolyte and leakage through the seals could be 5X more problematic in the SOEC mode than in the SOFC mode. • How fast can these systems be reversed? The answer will have a direct impact on the range of applications. • How can the SOEC be designed to follow the changing output from a wind farm? Can it respond to a rapid drop in wind speed? • Is combined cycle operation possible in SOFC mode? • What's the smallest size system for which a good business case can be made? • How is heat best supplied for endothermic reaction – Ohmic heating or sensible heating? • Is thermal storage of heat produced in SOFC mode an option for supplying heat required in SOEC mode? • Need to design and model a complete SOFC/SOEC system to answer some of these questions.
Manufacturing Issues	• SOFC manufacturing is still in its infancy. • Part count in stacks and processing steps for making components both need to be reduced. • Need to develop innovative processes for high speed, low-cost, high quality manufacturing of stack components along with methods for QC/QA. • SOFC heat management will drive stack footprint while SOEC heat management will drive system design.
Miscellaneous	• Can the SOFC/SOEC stack be operated under pressure?

Highlights of the Reversible SOFC/SOEC Breakout: Group 2	
Critical Issues	• Need a quick techno-economic analysis of using air in the SOFC versus the option of also storing oxygen. • Thermal management will be very difficult for a unitized SOFC/SOEC system. • Must find good compromises for cell and stack design and for materials selection for the unitized stack that does not significantly impact cycle efficiency, costs, or durability.
Material & System Barriers & Open Questions	• Hydrogen must be present in the steam entering the SOEC to prevent oxidation of the nickel electrode (electrolyzer cathode). • More R&D is needed on the oxygen electrode and its interface with the electrolyte. • Contaminants in the air and coming from the hydrogen compressor may be a problem. Can contaminant studies from SECA be leveraged? • Need materials for BOP that will survive in high hydrogen or high oxygen environments at high temperature for long periods of time. • Can a compressor/expander be used to capture energy from the compressed hydrogen as it expands through the fuel cell? • Need to capture latent heat from steam on SOEC and SOFC exhaust. • Need a more sophisticated engineering analysis to reliably determine the roundtrip efficiency. • What is the duty cycle for the SOFC and the SOEC and how does it vary? Are there different duty cycles for different applications and sizes? • Can these systems handle variable energy inputs and outputs? Is there a max and min to the variability? How fast can they respond? • How fast can the system switch between modes? • Can batteries be integrated with the system to give more flexibility? • Can one BoP be developed that serves both SOFC and SOEC modes of operation or are two BoPs more cost effective? • Will need new control systems and strategies.

Manufacturing Issues	• Are the SECA cost goals for the SOFC stack attainable? • Is it reasonable to use the SECA goals to cost a reversible system? • What is a reasonable scaling factor for a reversible SOFC/SOEC plant? • Need to develop the best compromise design for cell materials and geometry for manufacturing. • Need to develop high speed, low cost manufacturing methods for large area cells. • Need reproducible methods for component manufacture and cell stacking. • Need QC/QA methods and procedures for manufacture and assembly.
Miscellaneous	• Look for alternatives to zirconia for the electrolyte. • Is there a benefit to operating at lower temperatures? • Would other cell designs such as metal-supported or electrolyte-supported architecture work better for the reversible cell? • Demonstrations are needed to generate operational data and gain experience.

Recommendations from SOFC/SOEC Sessions

The industry presenters and the breakout group participants recommended research and development to identify and mitigate sources of degradation, to develop more robust materials, and to perform techno-economic studies of complete SOFC/SOEC systems in renewable electricity storage applications. The recommendations are as follows:

1. Perform fundamental material science and electrochemical studies of candidate air/oxygen electrodes and electrode/electrolyte interfaces to identify the best performers.

2. Perform applied science studies of SOFC/SOEC stack and BoP components to identify degradation mechanisms and develop solutions.

3. Perform material science and corrosion studies of seals and bipolar plate hardware in high temperature steam and oxygen environments to identify potential long term problems.

4. Demonstrate a SOFC/SOEC stack at a sufficient size to measure realistic roundtrip efficiencies and define an operating window for a full scale plant.

5. Develop flow sheets for a complete SOFC/SOEC energy storage system, possibly at both the 200 kW and 10 MW scales, and use it to conduct a techno-economic analysis and develop a business case.

References Cited

1. "Lifecycle Cost Analysis of Hydrogen Versus Other Technologies for Electrical Energy Storage," Steward, D., Saur, G., Penev, M., and Tamsden, T., Technical Report **NREL/TP-560-46719**, National Renewable Energy Laboratory, Golden, Colorado (November 2009).

2. www.netl.doe.gov/technologies/coalpower/fuelcells/seca/

Appendix A

Development of Reversible Fuel Cell Systems at Proton Energy

Mr. Everett Anderson, PROTON ON SITE

Proton ENERGY SYSTEMS | The Leader in On-site Hydrogen Generation

Development of Reversible Fuel Cell Systems at Proton Energy

Everett Anderson

NREL/DOE Reversible Fuel Cell Workshop

19 April 2011

PROTON
THE LEADER IN ON SITE GAS GENERATION.

Development of Reversible Fuel Cell Systems at Proton Energy

Everett Anderson

NREL/DOE Reversible Fuel Cell Workshop

19 April 2011

Proton Energy ⇨ Proton OnSite

- Reflects developing business model & expansion into other markets
- Leader in on-site generation of nitrogen, oxygen & zero air to compliment hydrogen
- Remains dedicated to the H_2 energy market

"We bring the gas solution to our client - be it hydrogen gas to a power plant, nitrogen gas to a laboratory or oxygen to a submarine. Proton OnSite is now the leader in on-site gas generation, everywhere."

- Rob Friedland, CEO and president of Proton OnSite

Outline

- Company Intro
- Regenerative Fuel Cell Configurations
- Technology Development/Demonstrations
- Unitized vs. Discrete Trade-off
- Renewable Energy Storage Application
- Development Needs
- Current Progress / Future Work

Proton OnSite

- Manufacturer of Proton Exchange Membrane (PEM) hydrogen generation products using electrolysis
- Founded in 1996
- Headquarters in Wallingford, Connecticut.
- ISO 9001:2008 registered
- Over 1,400 systems operating in 60 different countries.

ANAB ACCREDITED

Certified to ISO 9001:2008

TÜVRheinland®

Precisely Right.

Proton Capabilities

PEM Cell Stacks

Complete Systems

Storage Solutions

- Complete product manufacturing & testing
- Containerization and on-site gas storage solutions
- Integration of electrolysis into RFC systems
- Turnkey product installation
- World-wide sales and service

Power Plants

Heat Treating

Semiconductors

Laboratories

Government

Hydrogen Products

Commercial Products

HOGEN™ Hydrogen Generators

S Series

H Series

C Series

HPEM
High Pressure
Generators

Lab Gas Generators

StableFlow™

Hydrogen Control
Systems

GC

Future Products

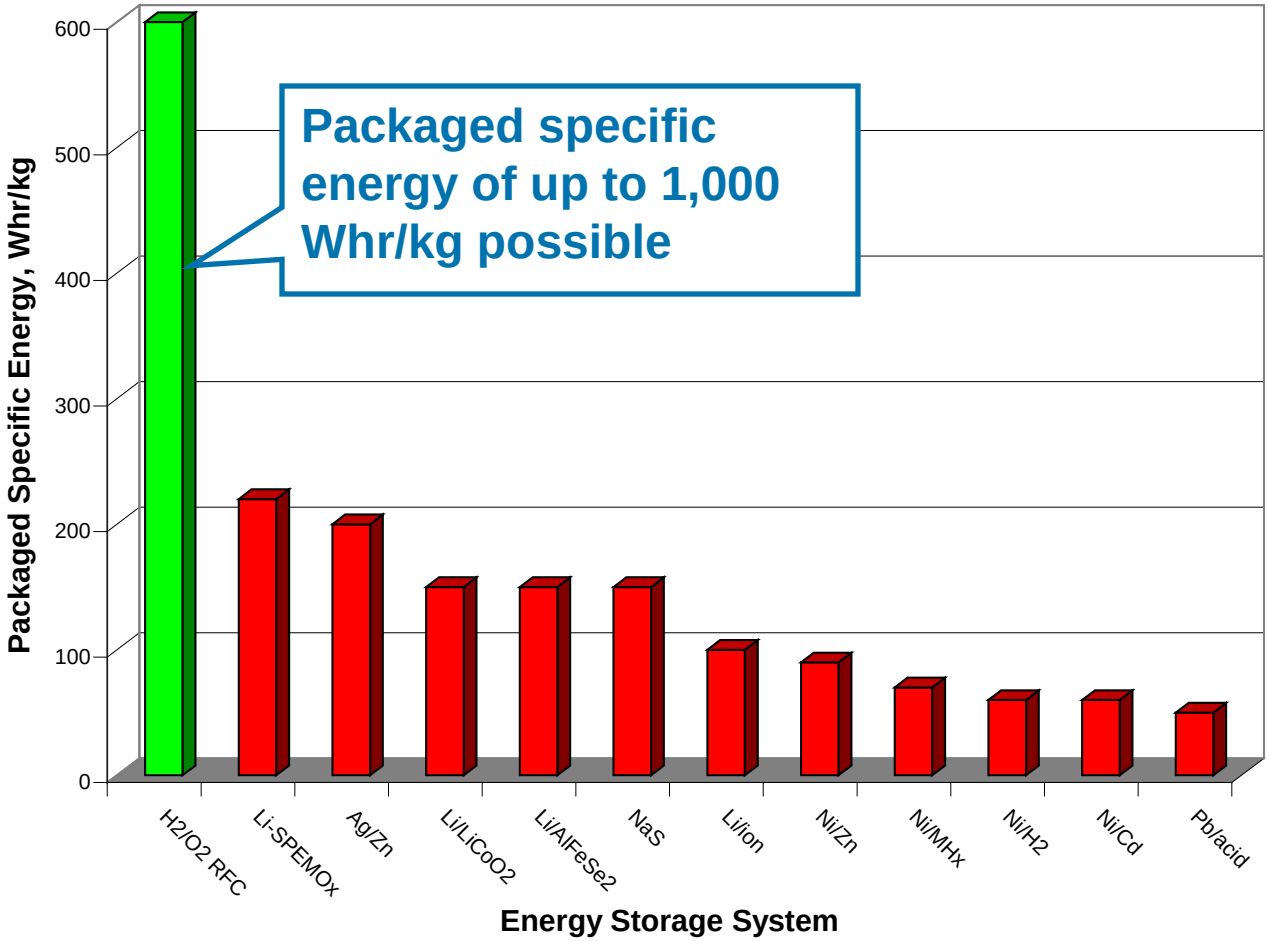
Fueling

Backup Power

Renewable Energy
Storage

Regenerative Fuel Cells

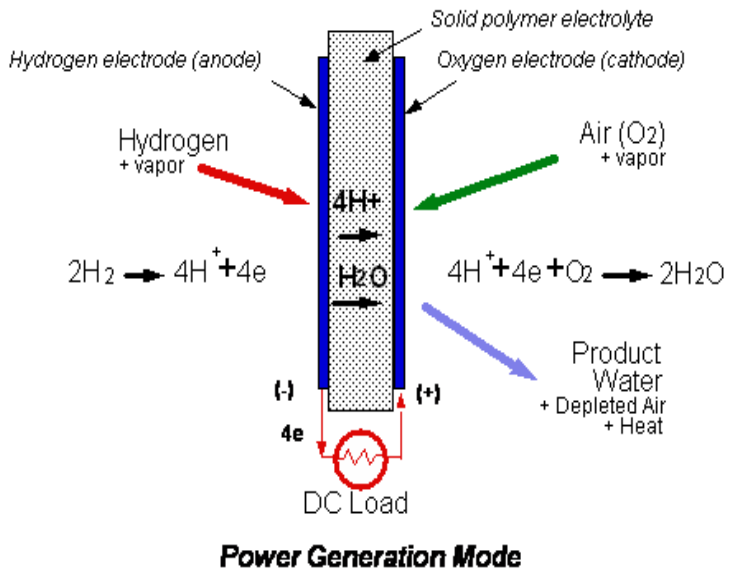
Comparison of specific energy to batteries



Source: Mitlitsky, et al, "Regenerative Fuel Cells", Energy and Fuels, 1998.

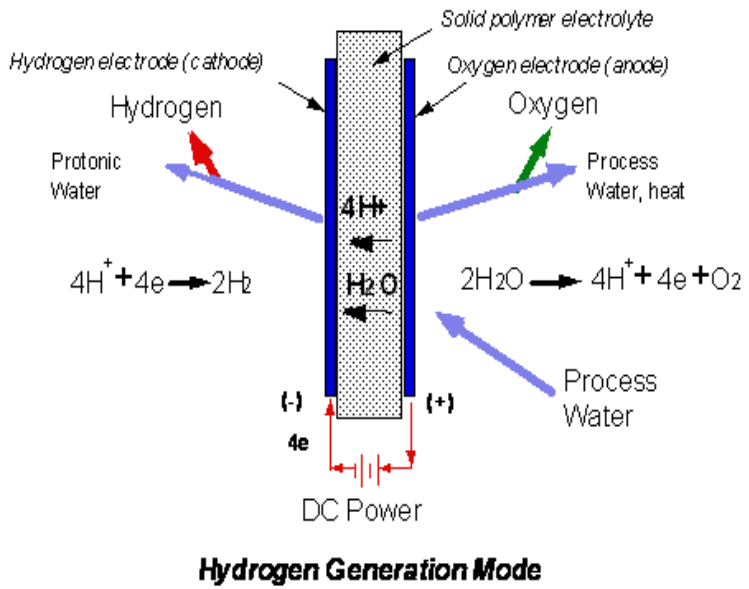
PEM Fuel Cell & Electrolysis

PEM Fuel Cell



Power Generation Mode

PEM Electrolysis

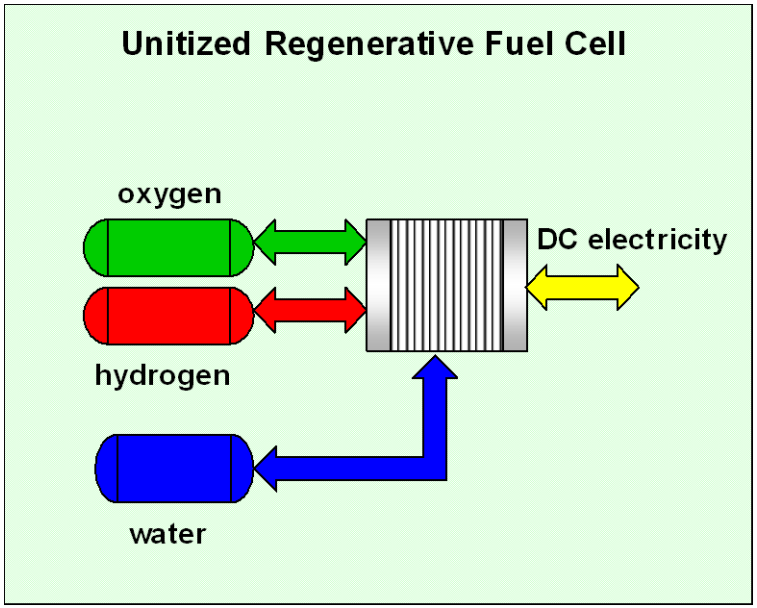


Hydrogen Generation Mode

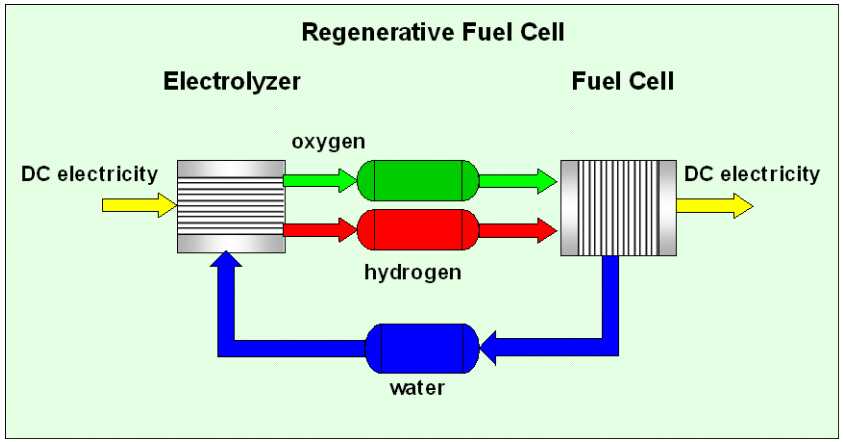
- Humidified gas streams vs. liquid water in contact with membrane
- Both need to consider 2-phase flow optimization in flow fields
- High potential material compatibility (~1V or less versus up to ~2V or more)
- Different pressure differentials (20 to >2400 psi) and high sealing loads
- Long lifetime expectations (5,000 vs. > 50,000 hours)

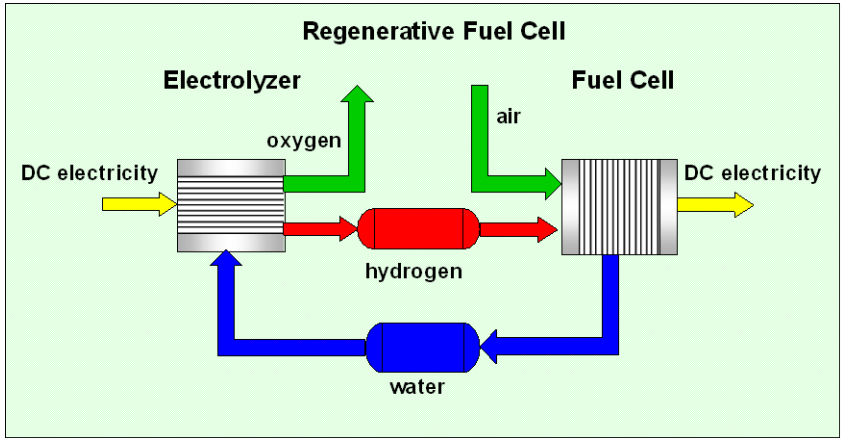
Regenerative Fuel Cells Options

- URFC – Unitized RFC
  - A cell stack that operates as both fuel cell and electrolyzer

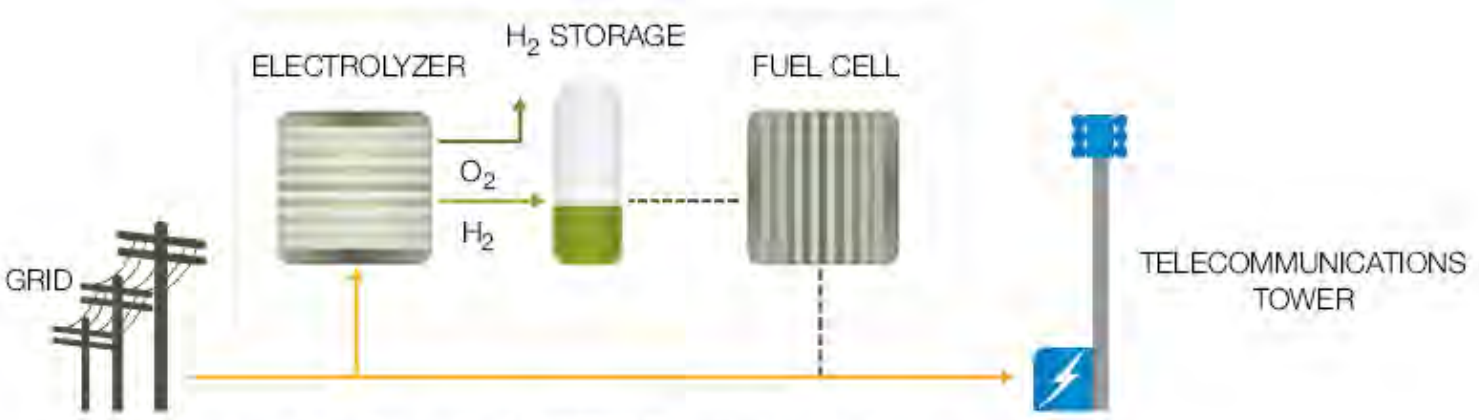


- DRFC – Discrete RFC
  - Separate fuel cell and electrolyzer stacks

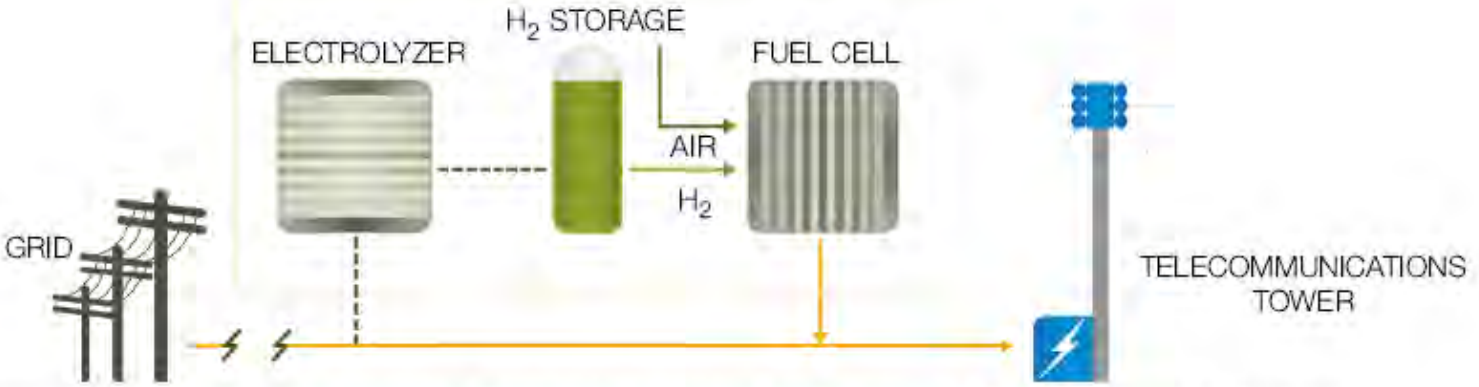




Backup Power System Concept
Using RFC & High Pressure Electrolyzer



When grid power is available, the HOGEN HP recharges the hydrogen storage.



When grid power is lost, the stored hydrogen is directed to a fuel cell, which provides backup power to the load.

Backup Power

Major Telecom Backup Power

- 3.5kW (net) of backup
- High-pressure hydrogen electrolyzer
- Enables function during a prolonged power outage

Wallingford Electric Substation

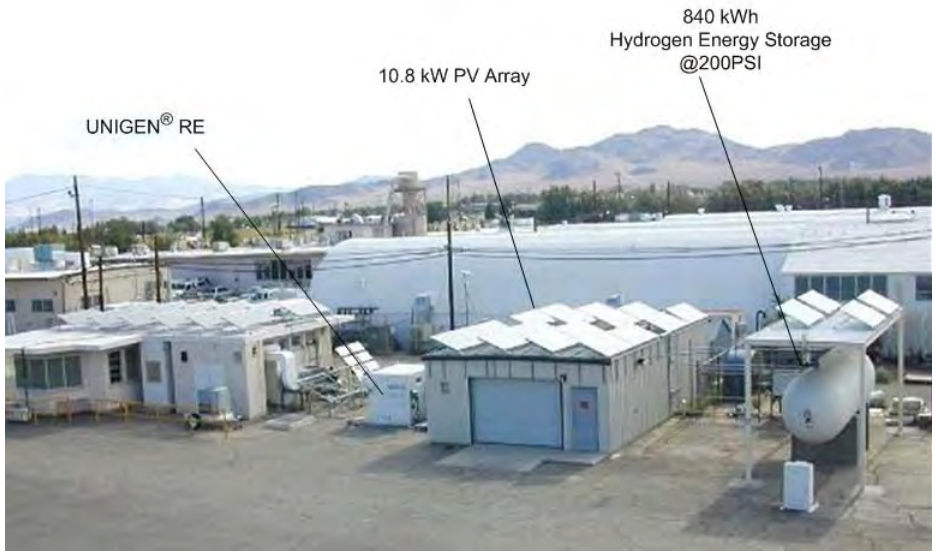
- 10kW (net) of backup
- Up to 8 hours of operation
- Outdoor high-pressure hydrogen electrolyzer
- 3 Plug Power GenCore® fuel-cell modules

Renewable Hydrogen Based Energy Storage

- China Lake Project
- Battery Replacement

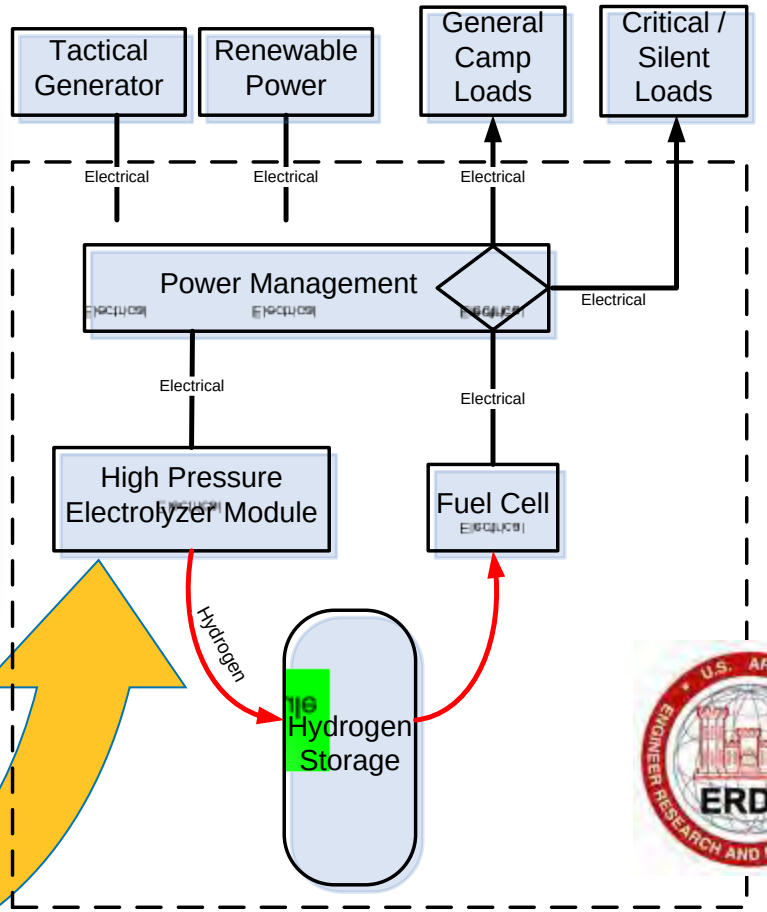
Project System Parameters:

- 24/7 Power from Photovoltaics
- 10.8 kW Photovoltaic Array
- 840 kWh stored as H_2 @ 200 psi
- Two 1.2 kW PEM Fuel Cells



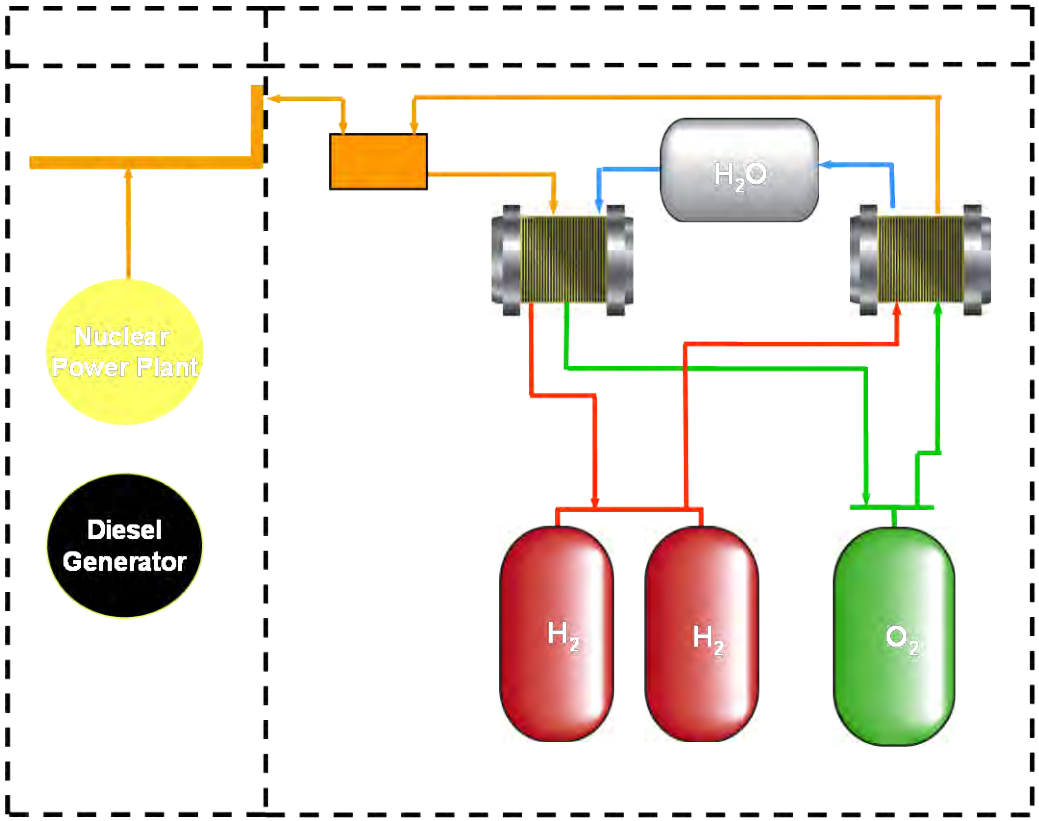
Army CERL Silent Camp® System Concept

Silent Camp high pressure electrolyzer in outdoor rated cabinet



"Regenerative Fuel Cell" integrated into CERL's Silent Camp system concept

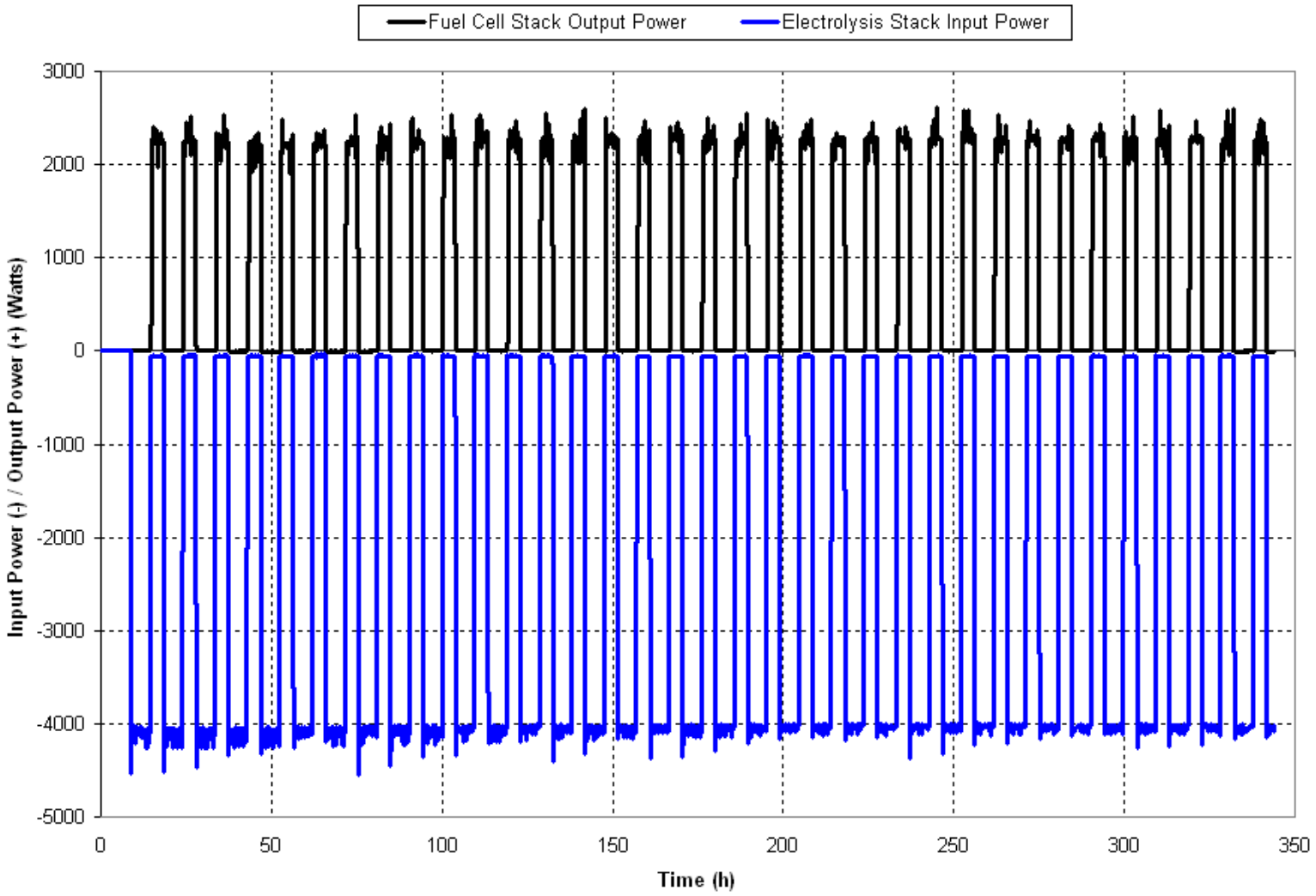
2 kW Closed Loop Regenerative Fuel Cell System



Proton's closed loop RFC system on test, demonstrating feasibility of UUV power concept

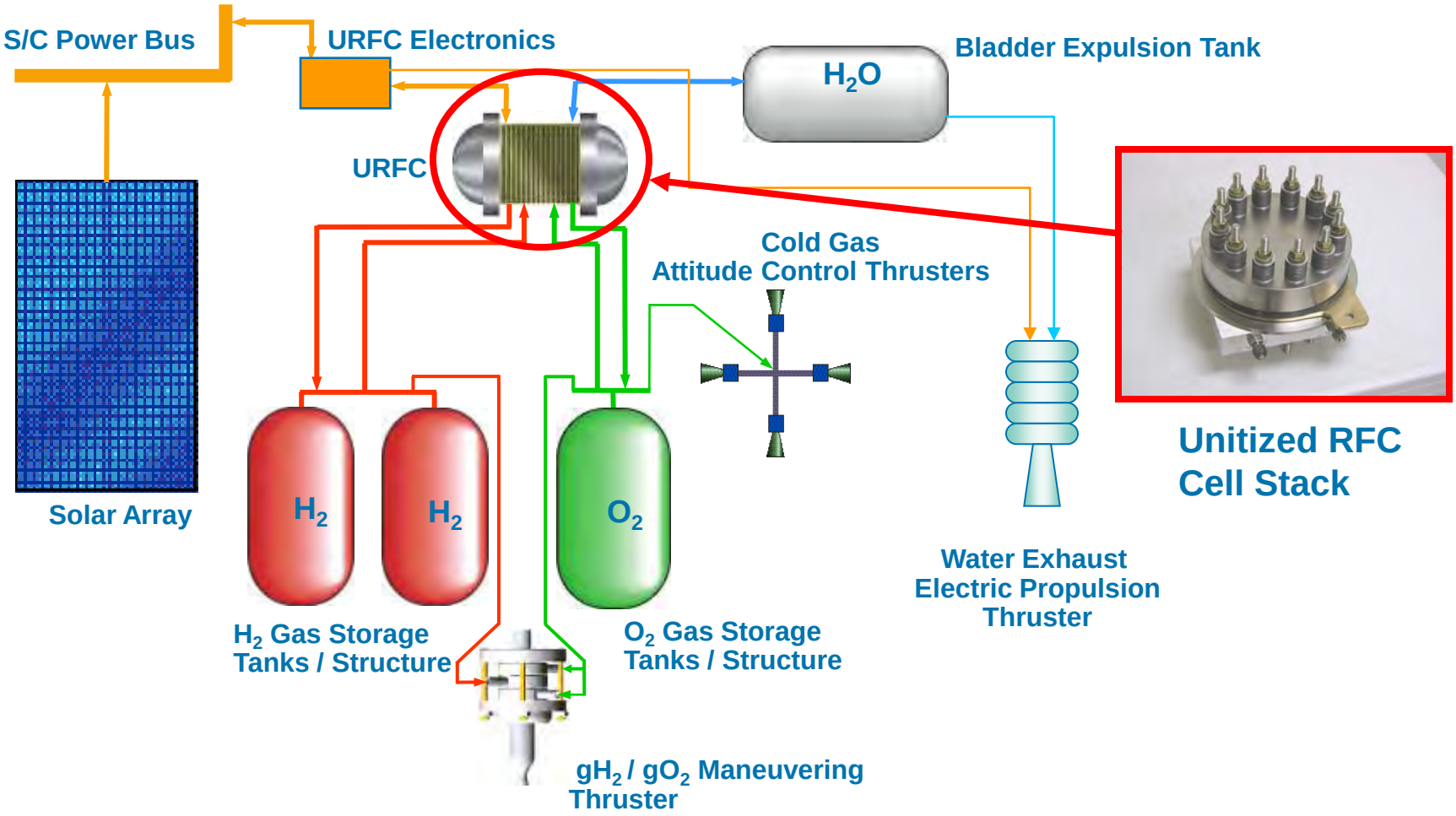
System Details:
Fuel Cell – 4.4 kW Commercial H_2/Air stack
Electrolyzer – HOGEN® S-series stack, modified for 400 psi balanced pressure

Charge / Discharge Cycle Data for RFC System

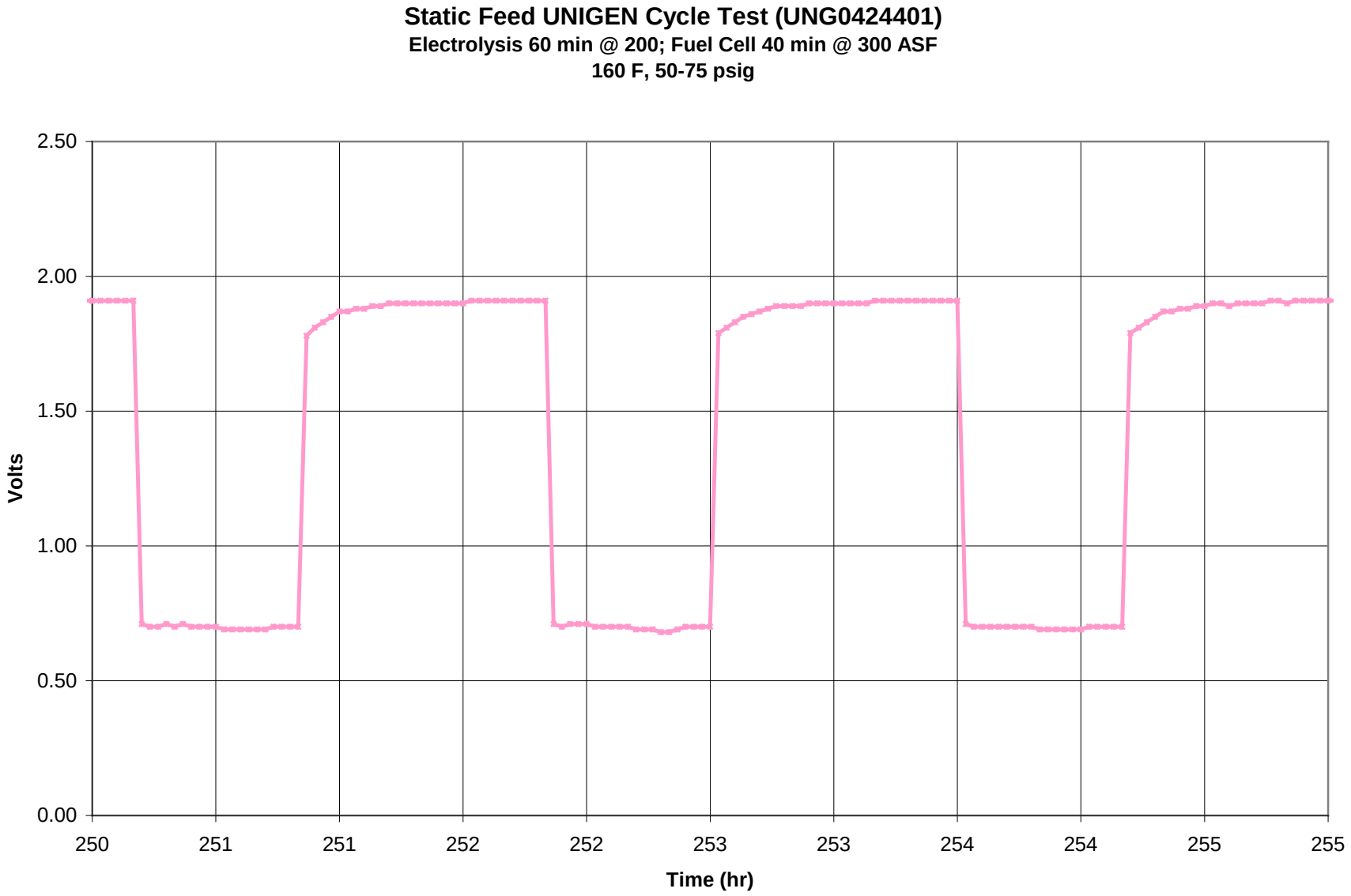


Energy Storage Plus On-Board Fuel Production

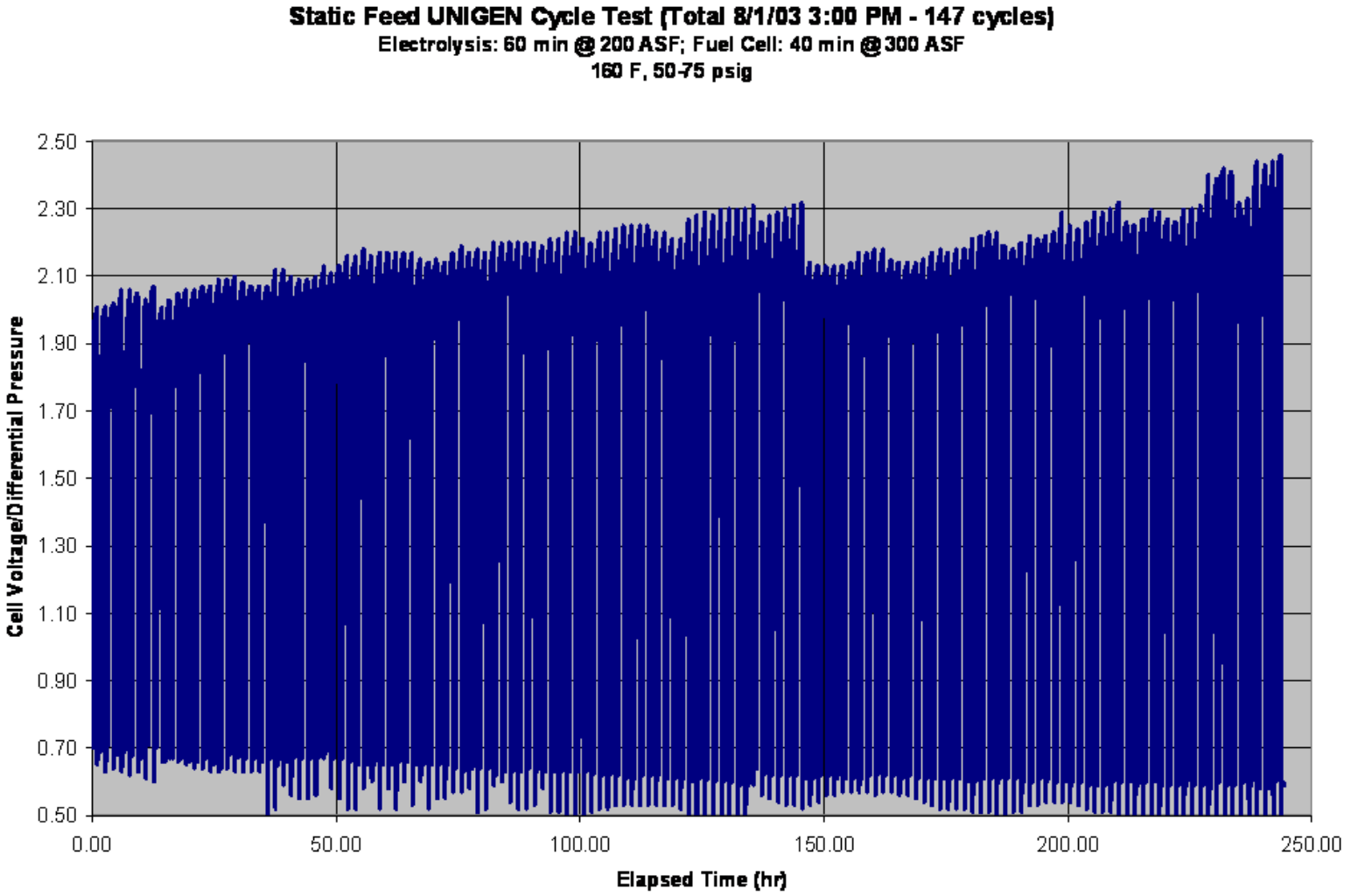
DARPA Water Rocket: Unitized, Zero-G RFC



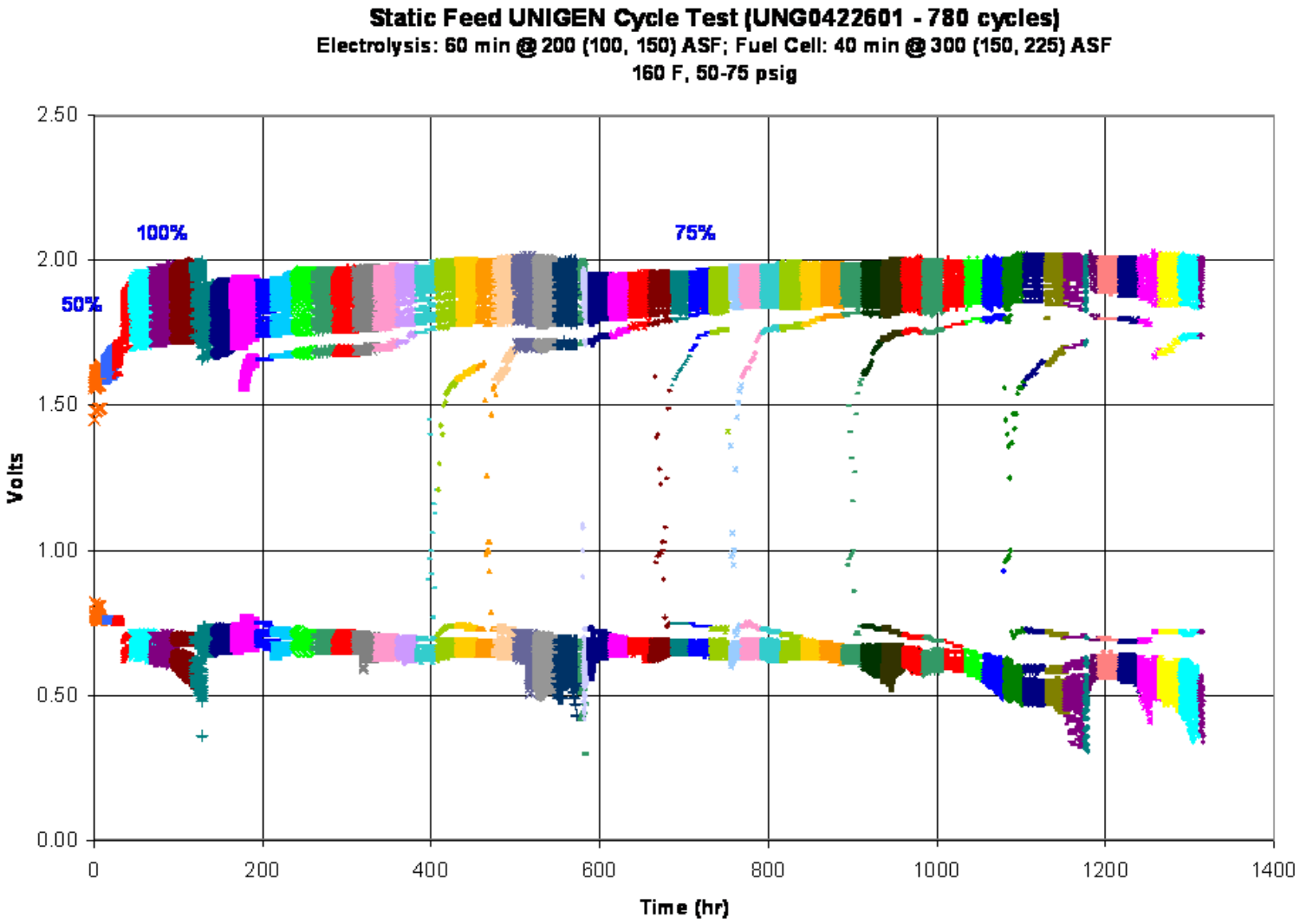
Closed-Loop Static URFC Cycles



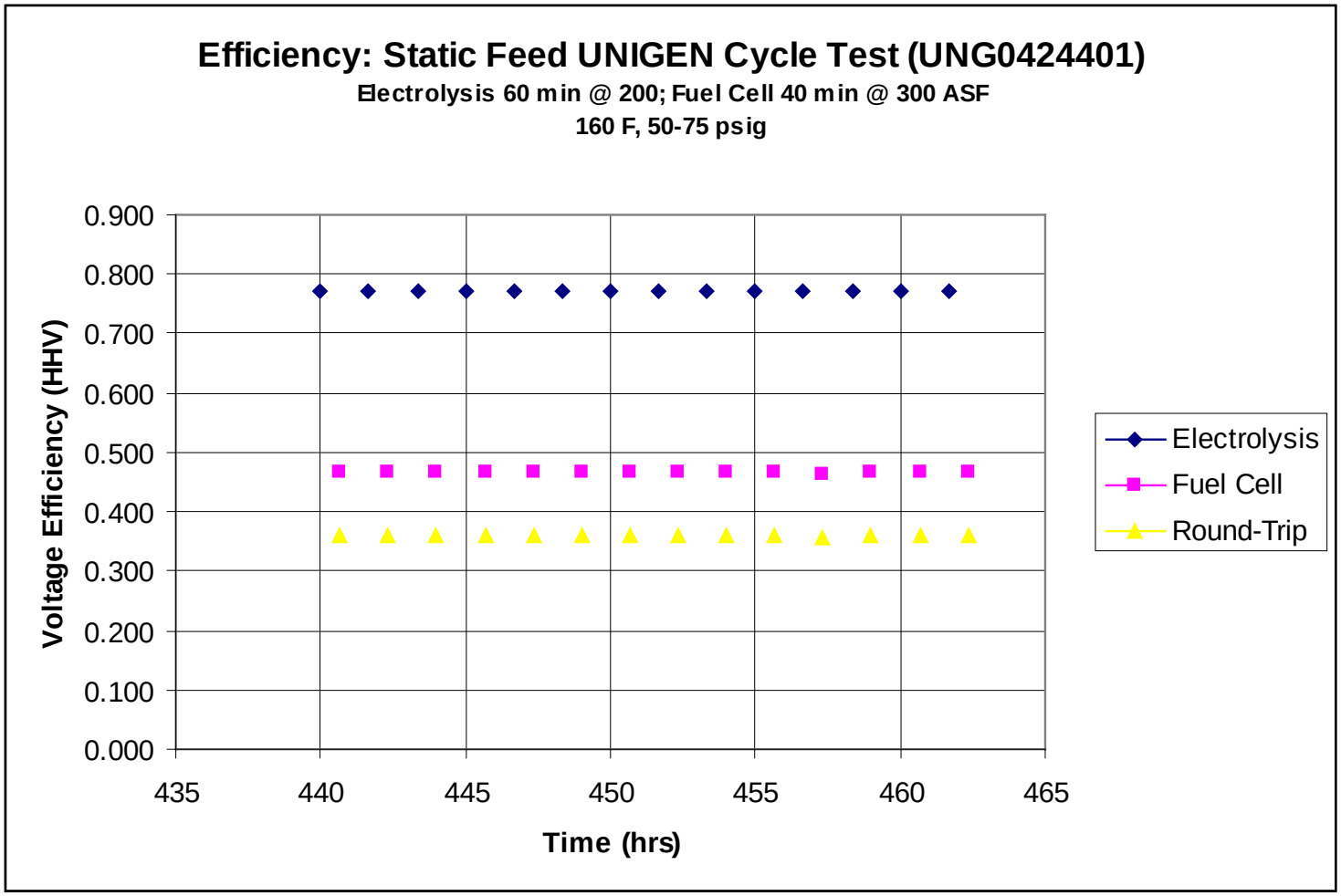
Static URFC ~150 Closed-Loop Cycles



Static URFC 1,300 h Closed-Loop Cycles



Roundtrip Efficiency of URFC Test Stack 37%



Cycle #264 ---------- #278

Unitized Versus Discrete RFC

- Grid Support Requirements
  - Size (kW to MW)
  - Operating mode (Charge – Discharge Cycle)
  - Time scale (ratio of stack as % of total system)
- Performance Compromise
  - Non-optimum catalysts, electrode structures
  - Up to 70% penalty for unitized approach vs. discrete
- BoP complexity
  - Water, thermal management
- Leveraging Mature Technology
  - Commercial readiness of PEM fuel cells & electrolysis

Grid Energy Storage Applications

- Distributed Energy Storage
  - 25-200 kW, 2-4 hrs, secondary (customer) voltage
- Load Shifting
  - kW's to MW's, up to 10 hrs, various voltages
- Substation Grid Support
  - 1-20 MW, 2-6 hrs, distribution voltage
- PV Voltage Transient Support
  - Up to MW's, 1 sec to 20 min, distribution voltage
- Wind Smoothing
  - 1-100 MW, 2-15 minutes, distribution voltage

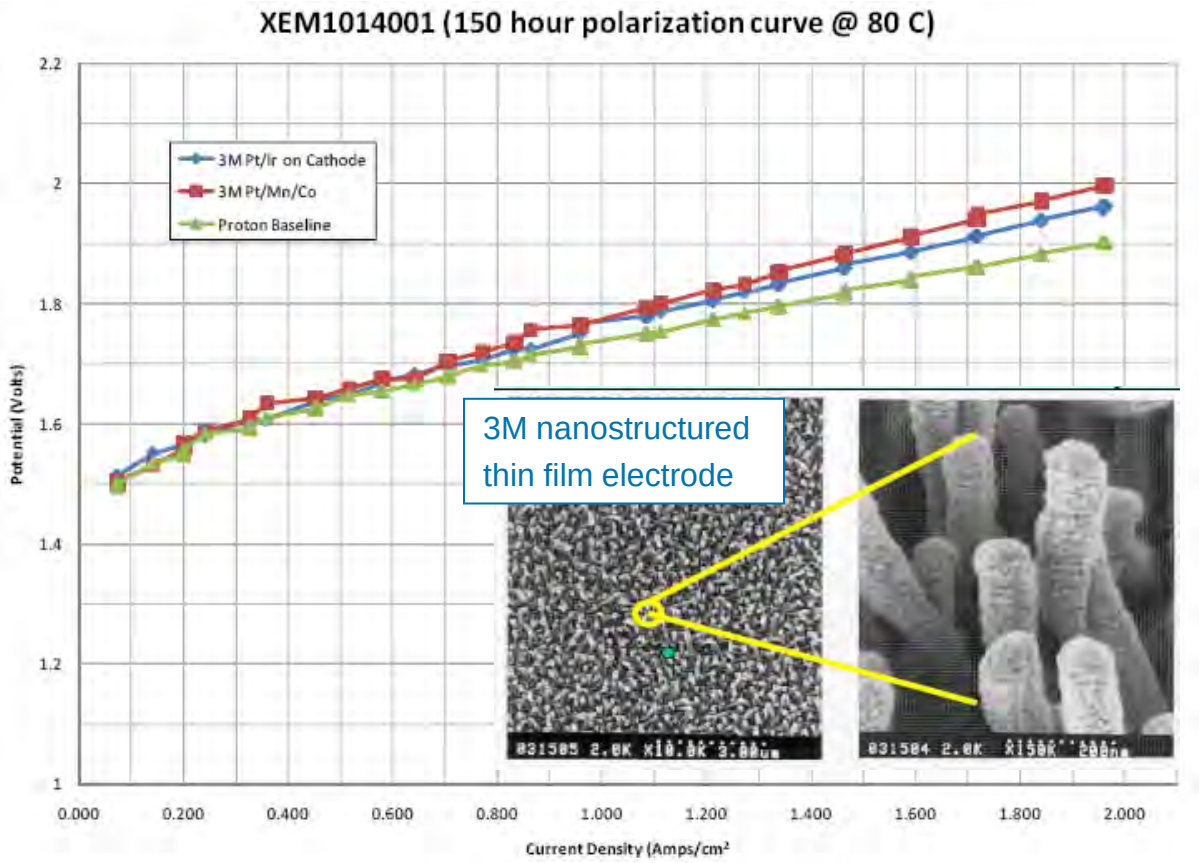
Ref: EPRI Energy Storage Systems Project, 2010, TTC

Development Needs

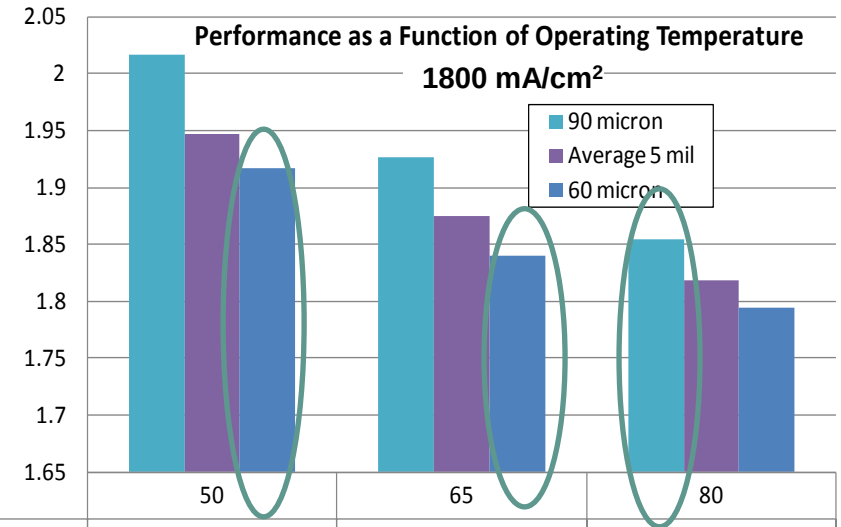
- Materials Development
  - Bifunctional catalysts, electrode structures, GDLs, membrane robustness for electrolysis
  - Oxygen compatibility
  - Complications of pressure generation
- System Development
  - Integration of separate BoP's, gas drying, power, thermal & water management
  - Benefit of pressurized oxygen?
- Manufacturing
  - Lack of supply chain for electrolysis, active area scale vs. pressure, need for automation to drive cost reductions

Catalyst Loading

- Alternate electrode structure shows near equivalent performance for 10x lower loading

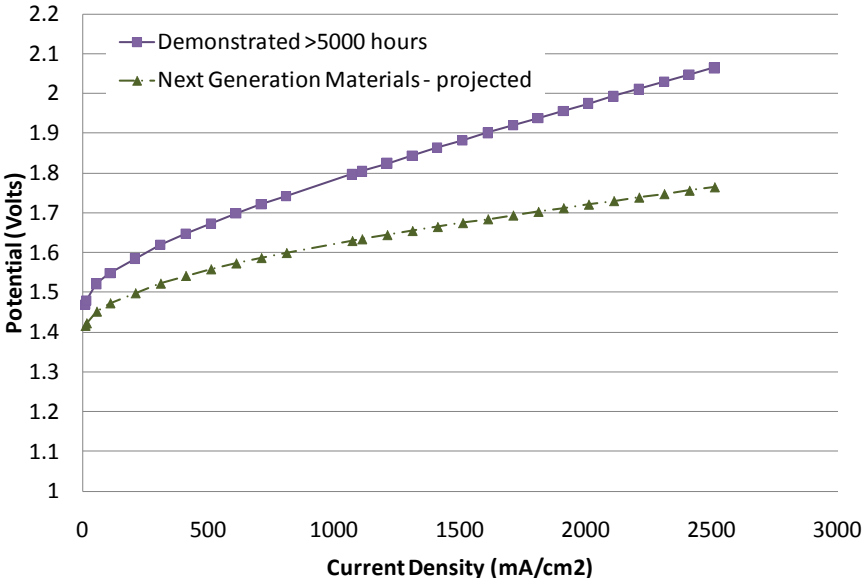


Performance Improvements



	50	65	80
90 micron	2.017	1.927	1.855
Average 5 mil	1.947	1.875	1.818
60 micron	1.917	1.840	1.794

Demonstrated >85% efficiency @ 80°C and 1.8 A/cm² at production-scale cell and 200 psi differential pressure



Production Scale

65 Kg/day (200 kW_{in})

1 MW BPS PEMFC

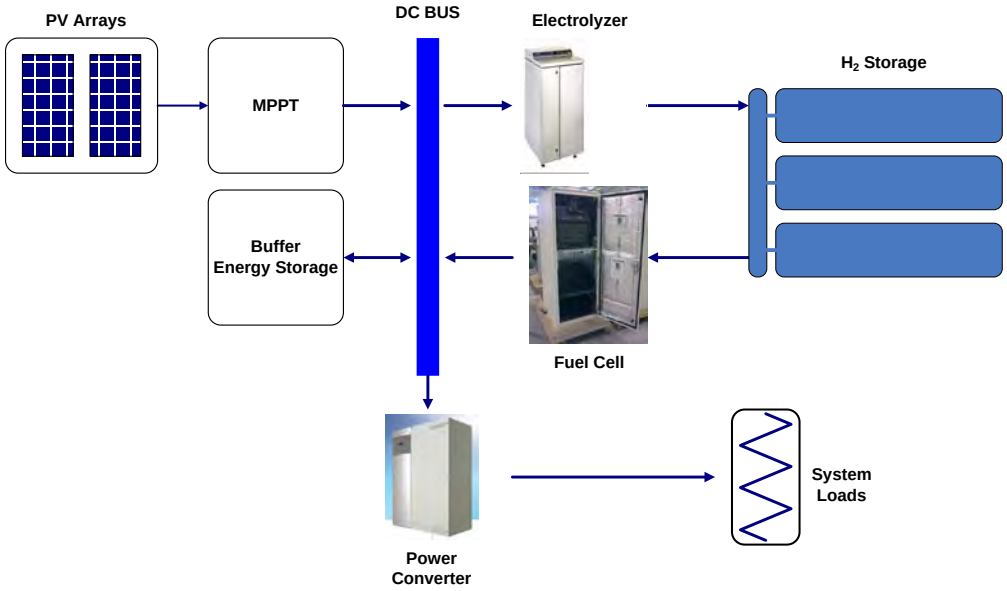
Fluids Side

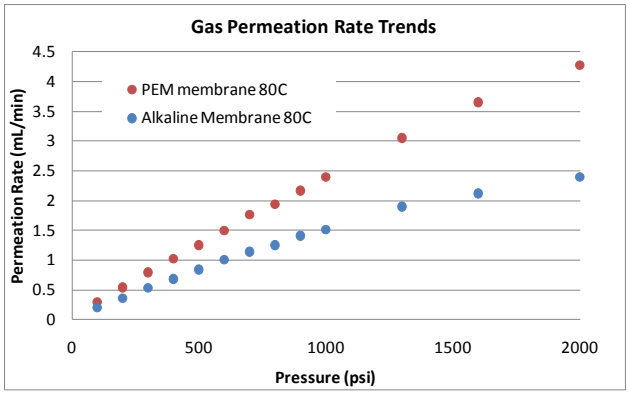
Electrical Side

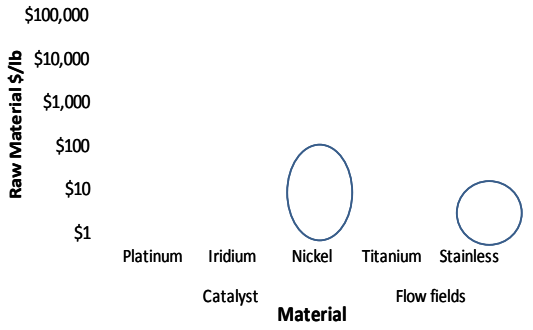
Future Work

AEM-based Regenerative Fuel Cell

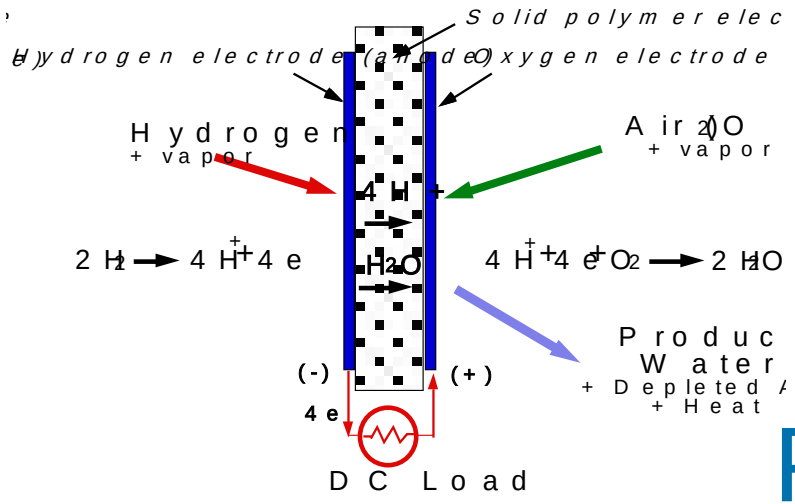
- Develop a low-cost, high efficiency
- Tightly integrated electrolyzer / fuel cell system
- Advanced rechargeable energy storage device for grid buffering.



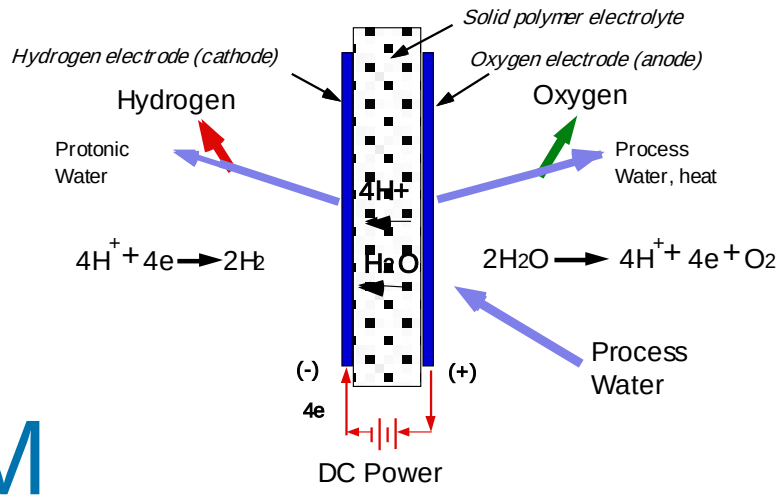




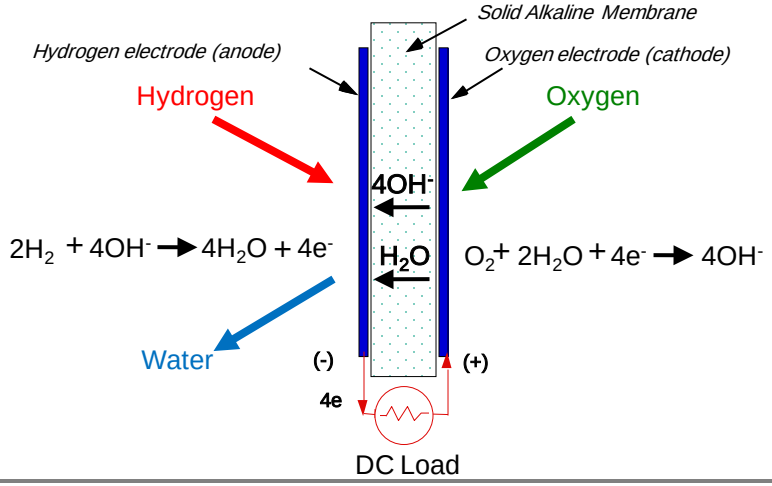
PEM / AEM Cell Comparison

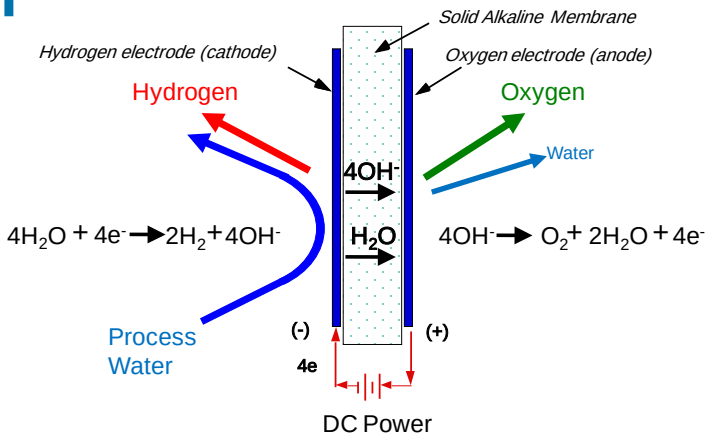


PEM



AEM





Summary

- Demonstrated history in development of regenerative fuel cell systems
- Single stack – dual stack debate depends on application
- Integration of existing technology can bridge gap
- Single stack is longer term approach
- Both options need materials & systems development and can benefit from manufacturing scale

Thank you!

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Appendix B

Regenerative Fuel Cells for Energy Storage

Mr. Corky Mittelsteadt, Giner Electrochemical Systems

Regenerative Fuel Cells for Energy Storage

April 2011

Corky Mittelsteadt

Outline

1. Regenerative Fuel Cells at Giner
2. Regenerative Systems for Energy Storage
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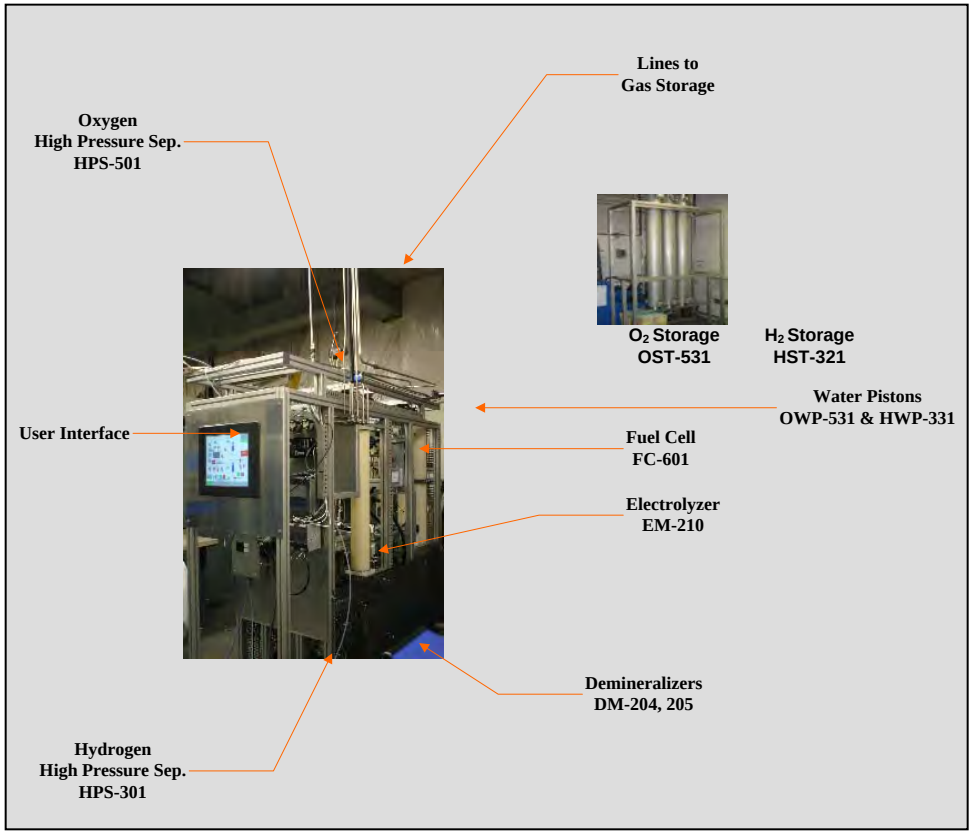
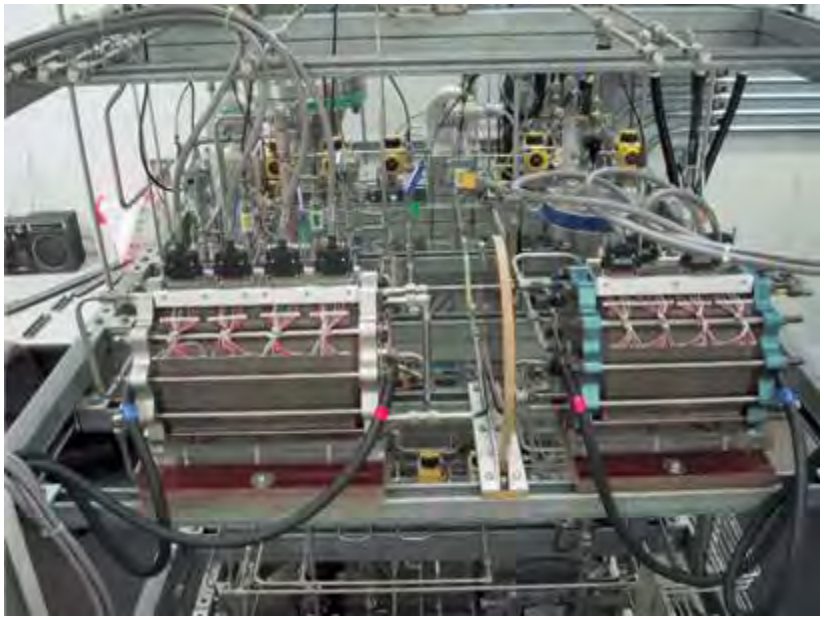
RFC System Challenges



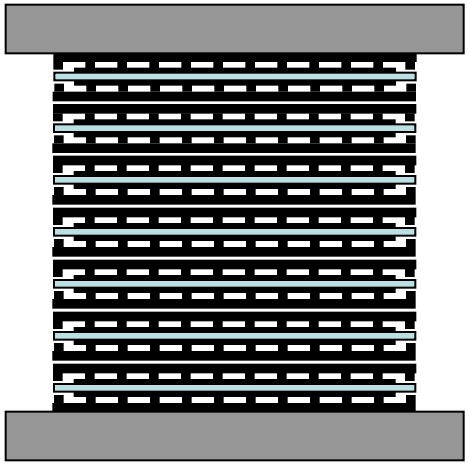


Regenerative Fuel Cell System at NASA Glenn Research Center (above)
Regenerative Fuel Cell System for High-Altitude Airships at Giner (left)

Existing state of the art regenerative fuel cell systems require two separate stacks and significant auxiliary support hardware

Fuel Cell vs. Electrolyzer: Stack Comparison

Fuel Cell Stack



Membrane

Catalyst

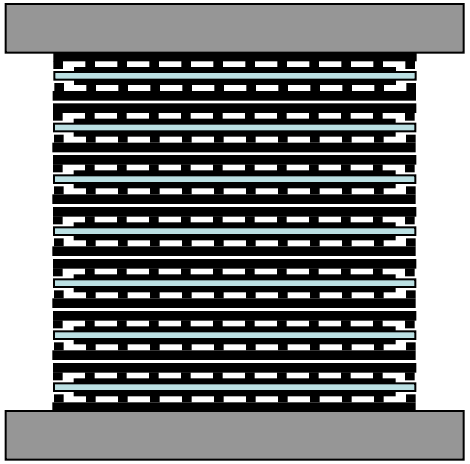
Bipolar Plates

End Plates

Never on at the Same Time

Combine Them

Electrolyzer Cell Stack



Membrane

Catalyst

Bipolar Plates

End Plates

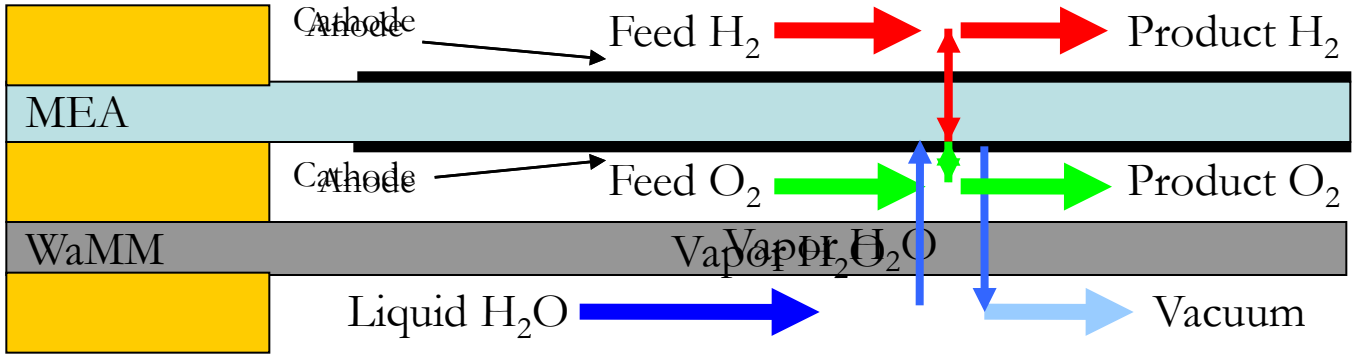
Issues Motivating WaMM Development

- Unitized Regenerative Fuel Cell:
  - Could save volume/weight of extra stack, however, water management becomes difficult.
- Fuel Cell Mode:
  - Almost impossible to avoid liquid water flooding the cathode in pressurized systems operating at low stoich.
  - Systems must operate at lower pressure/high recirculation rates to remove water.
    - Complicated in low gravity
    - Parasitic Efficiency Loss
- Electrolyzer Mode:
  - The same features required in a fuel cell to evacuate product water will also stop feed water from reaching the electrode during electrolysis
- Solution: keep water in the vapor phase

Single Cell Operation

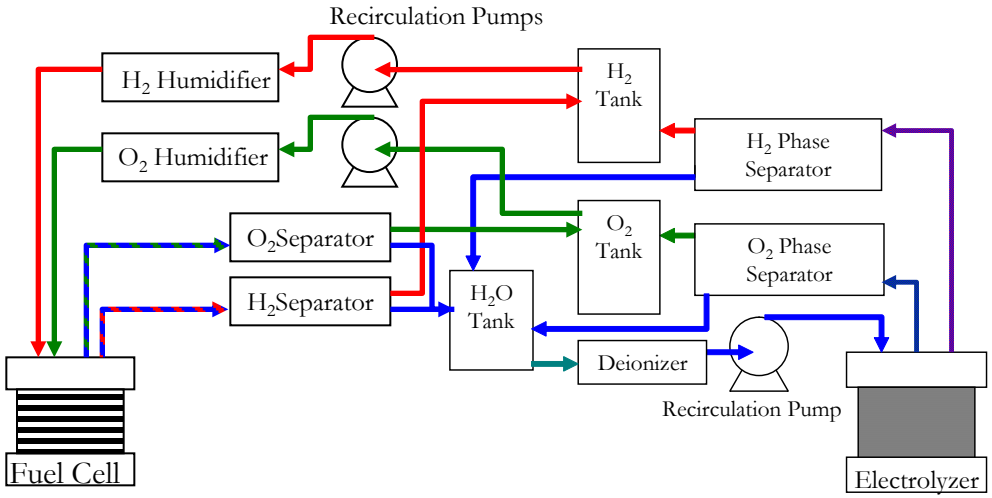
Fuel Cell:

Electrolyzer:

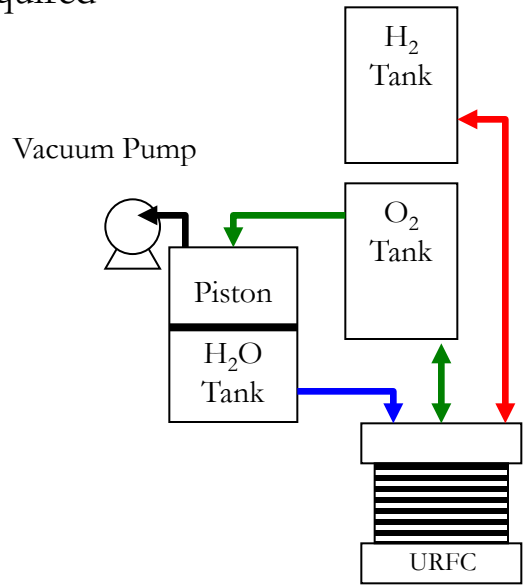


System Implications

- Vapor fed electrolyzer produces >99.9% dry product gases: no liquid gas phase separators required
- Electrolyzer feed water can be static feed for further system simplification: no liquid recirculation pumps required
- Fuel cell feed gases can be static feed: no gas recirculation pumps required
- Fuel cell is humidified *in situ* by product water: no external humidifiers required
- Because water permeable plate is relatively insusceptible to impurities in feed water, water purity constraints can be relaxed: no deionization beds required

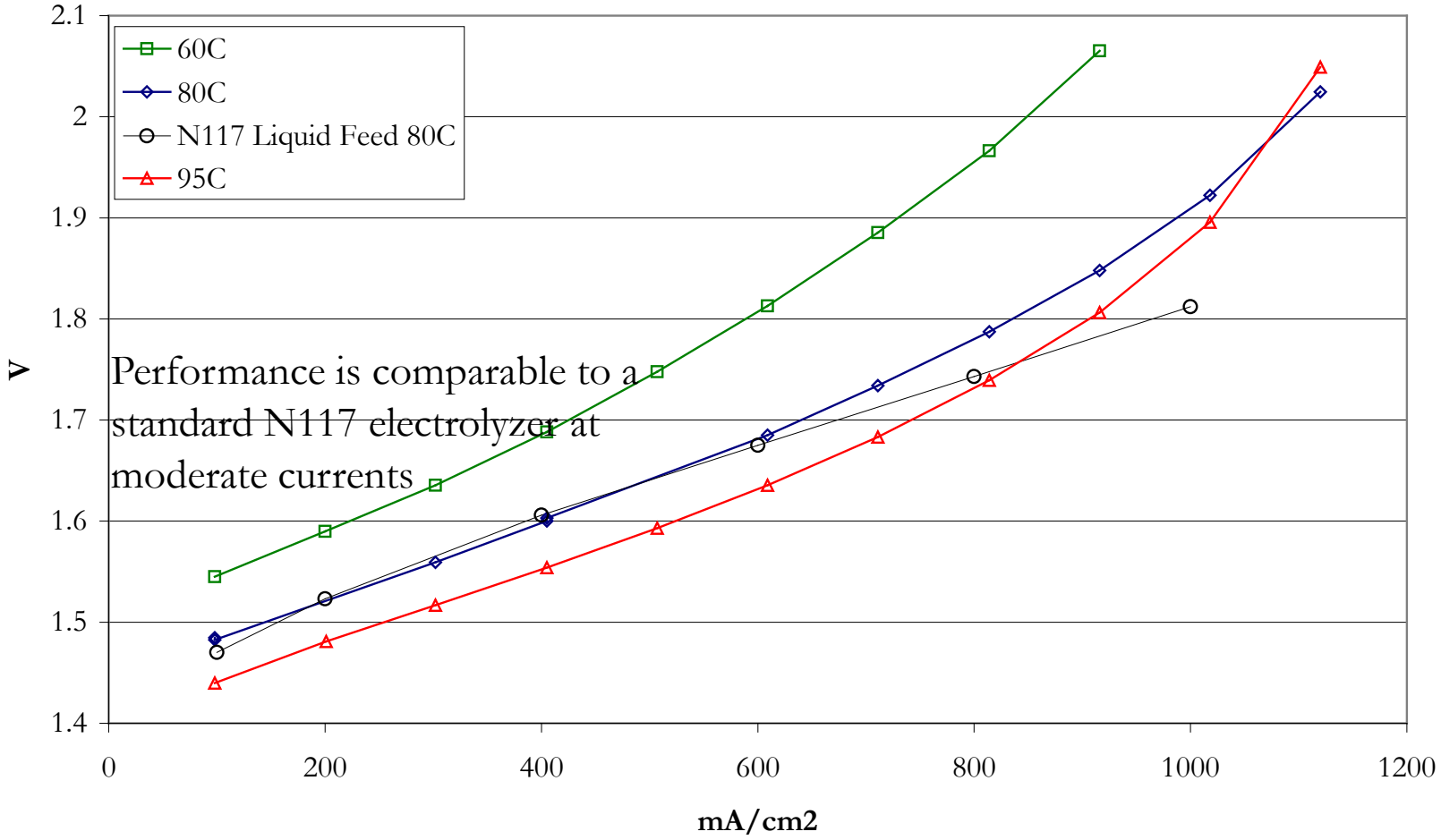


Traditional RFC System

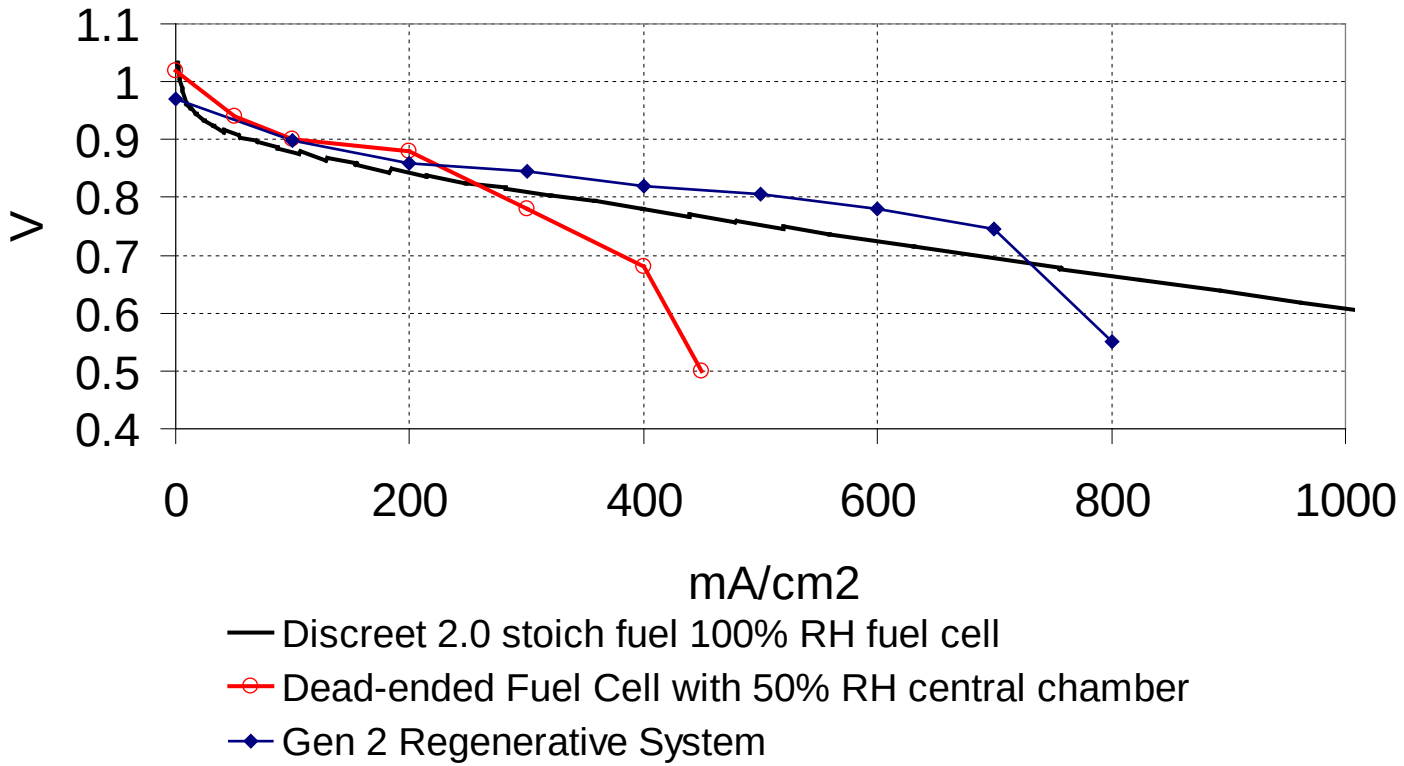


WaMM-Based URFC System

URFC: Electrolyzer Performance

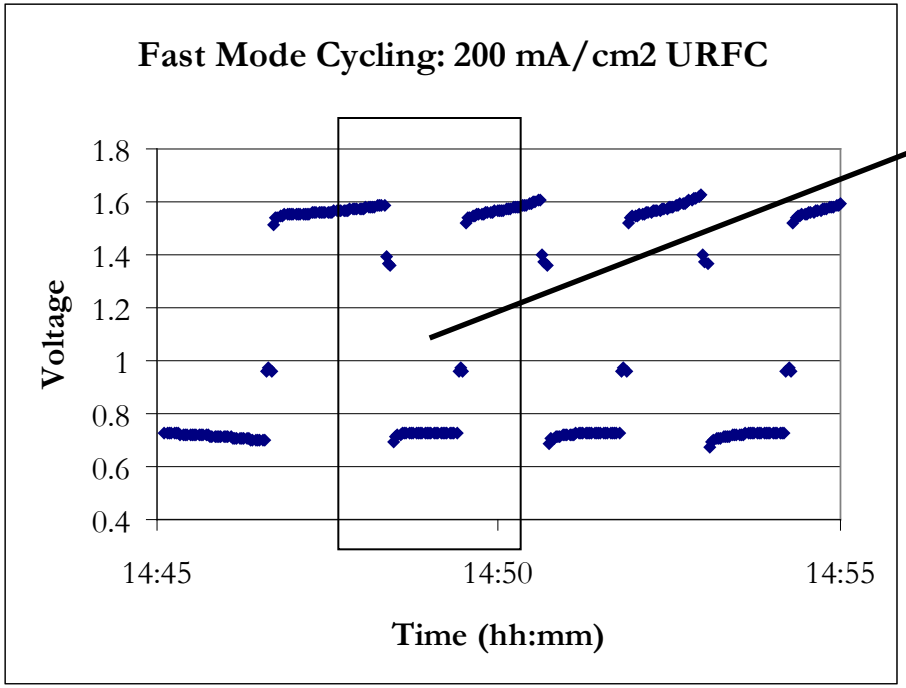


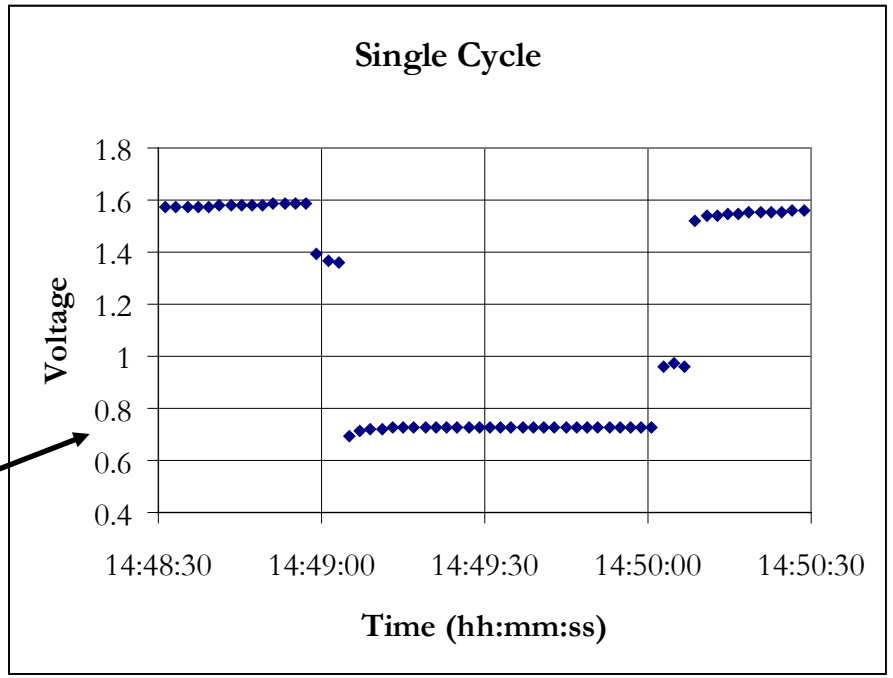
URFC: Fuel Cell Testing



URFC: Mode Cycling

- Because system is vapor based, it can change modes very quickly
- Turn around time around 5 seconds





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Cost of Electrolysis is Becoming Competitive

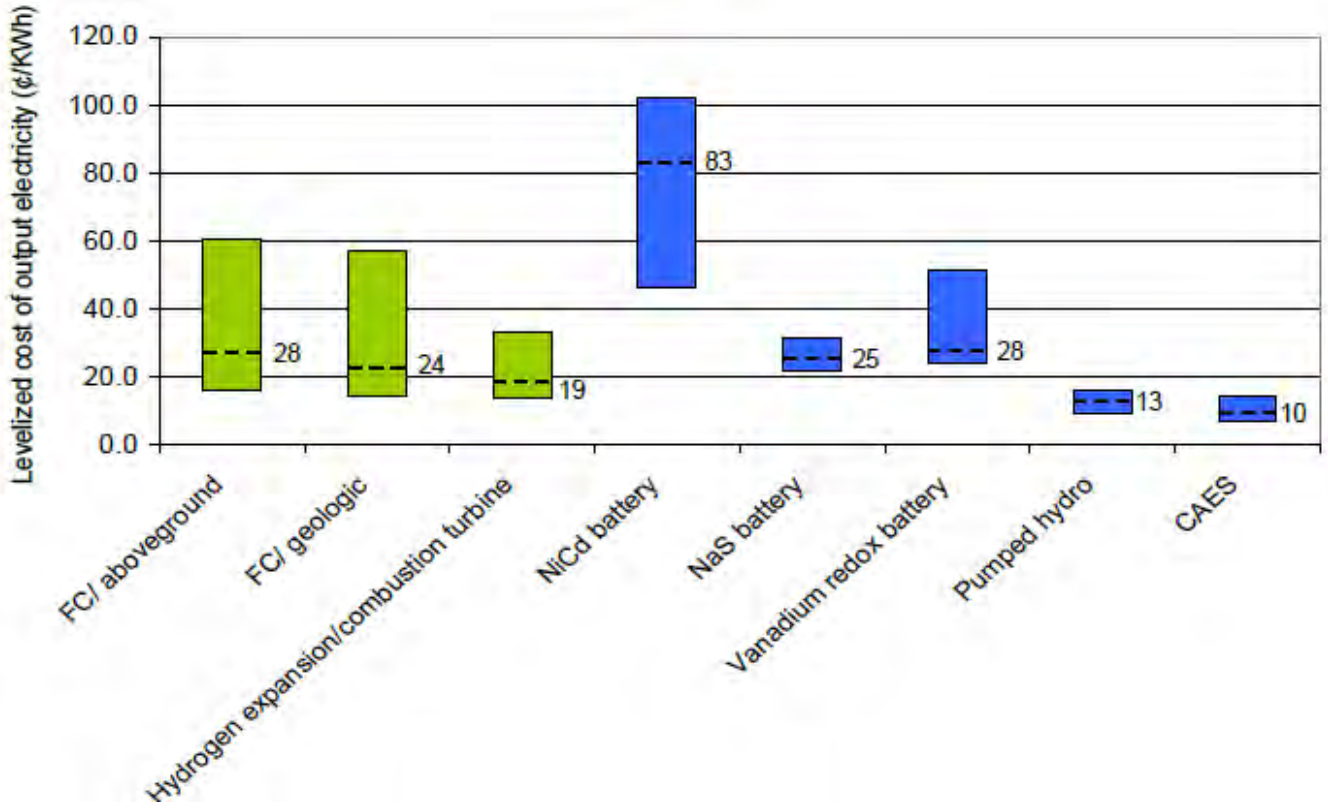
Table 1
COSTS OF HYDROGEN FROM PEM ELECTROLYSIS
Based on US Department of Energy's H2A Model

Item	Cost $/kg
Capital Cost	$0.79
Fixed O&M	$0.49
Power Cost ($0.039/kWh)	$1.95
Other Variable Costs (utilities etc.)	$0.01
High Pressure Storage (pumps and tanks)	$1.80
Total Cost	**$5.04**
Miles travelled kg H_2/gallon of gasoline	50/30
Total Cost in gallons of gasoline equivalent	**$3.02**

Regenerative Systems Can Make Renewables More Competitive …But Efficiency is Extremely Important

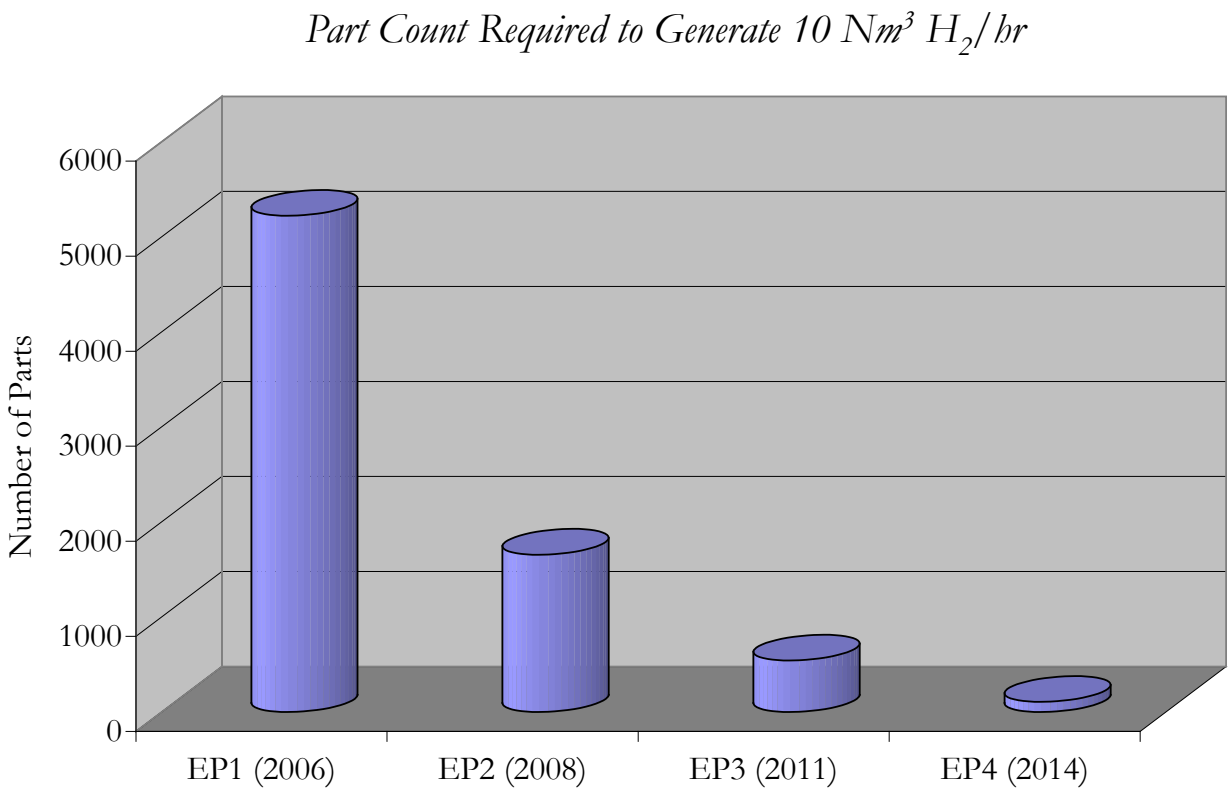
100 MW Installed Wind, 33 MW Electrolyzer, 22,500 kg Storage, 25 MW Fuel Cell	Windmill Only	Windmill with 50% Efficient Regenerative System	Windmill with 40% Efficient Regenerative System
Windmill Cost ($1000/kW 20 Year Amortization at 5%)	$ 8,024	$ 8,024	$ 8,024
Annual Storage H2 Cost (20 Year Amortization)	$ -	$ 181	$ 181
Annual Electrolyzer and Fuel Cell System Cost ($500 kW electrolyzer, $500/kW fuel cell) (20 Year Amortization)	$ -	$ 2,648	$ 2,648
Annual Operating, Maintenance, Refurbishment $1.5 MM	$ 2,000	$ 2,705	$ 2,705
Annual Off-Peak Power Yield (GW) -	307	205	205
Annual On-Demand Power Yield (50% Efficiency) -	0	50.6	40.5
Annual Value of “Off-Peak” Power @ 3.0¢/kWh	$ 10,731	$ 7,190	$ 7,190
Annual Value of “Peak” Power @ 15¢/kWh	$ -	$ 7,588	$ 6,071
Annual Profit	**$ 707**	**$ 1,220**	**$ (297)**

…Don't Just Take our Word for it…



Kevin Harrison 2010 DOE Merit Review,
http://www.hydrogen.energy.gov/pdfs/review10/pd031_harrison_2010_o_web.pdf

By Increasing Efficiency and Lowering Part Counts Electrolysis Cost has Been Dramatically Lowered



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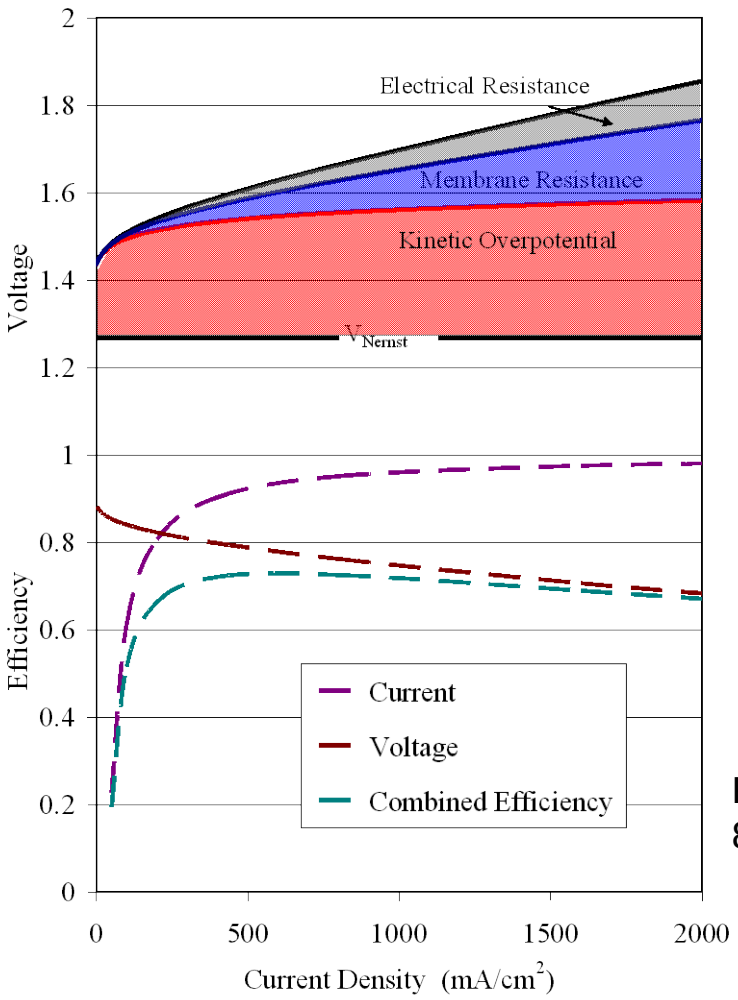
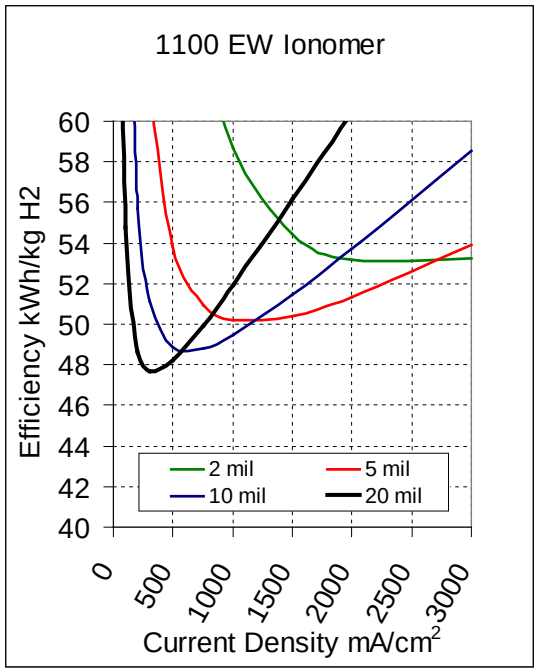
Optimizing Performance For Electrolyzers

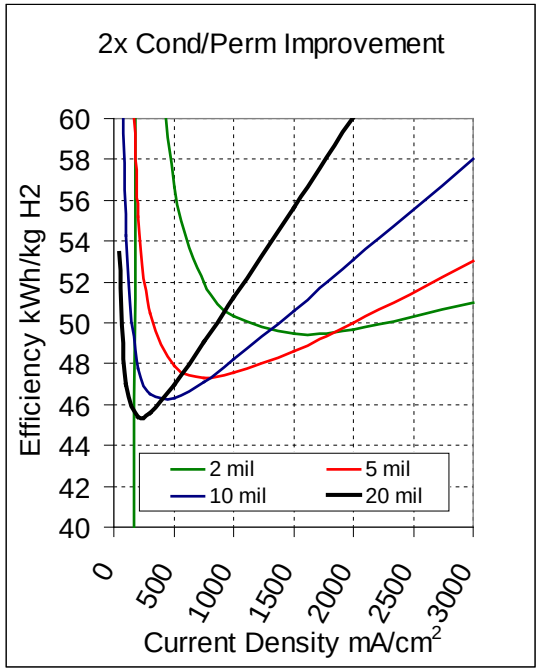


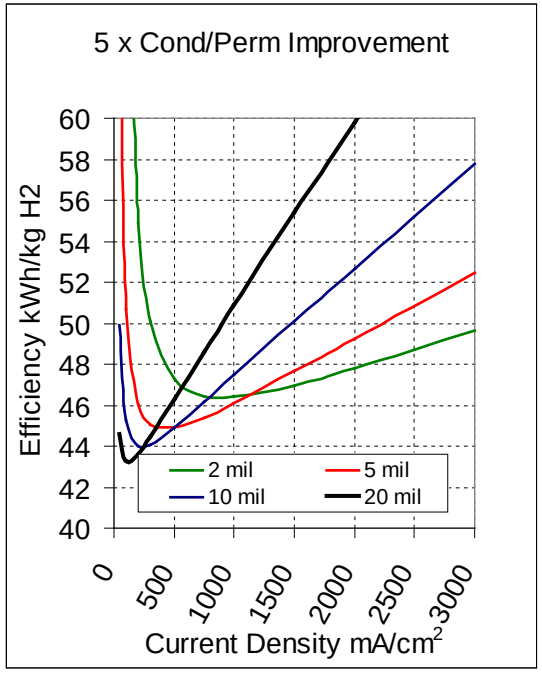
Similar to fuel cells, the majority of efficiency losses are due to slow oxygen kinetics and membrane resistance

For cell operating at 1000 psi and 80°C with Nafion 117

Improvements in Lowering Permeability can Greatly Improve Operating Efficiency



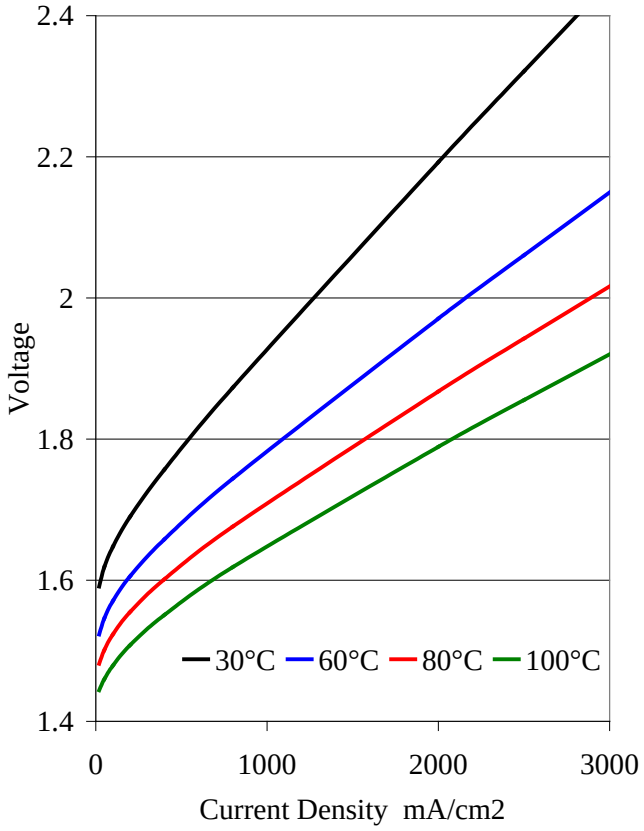


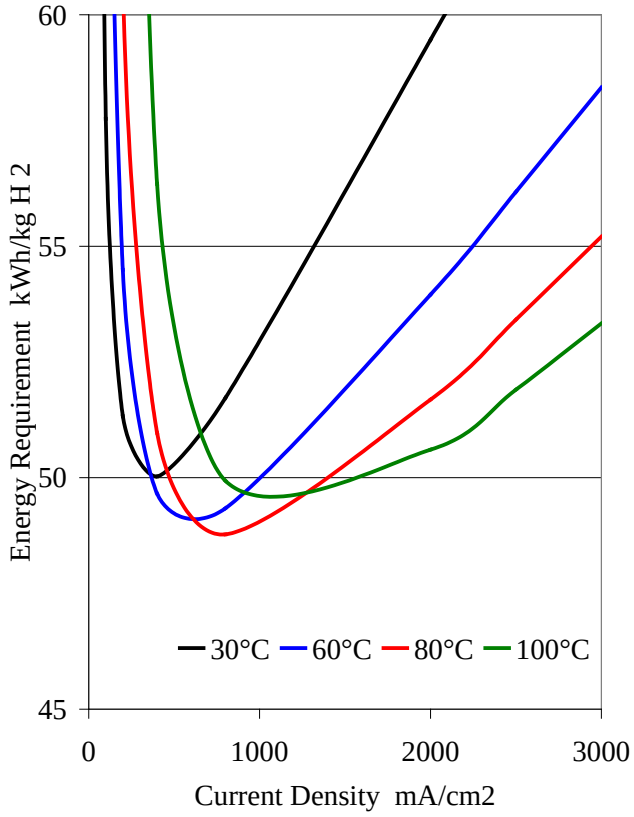


Operation at 80°C and 1000 psi

Using Current PFSA's Thick Membranes is Required for High Pressure Operation

Membranes and Catalysts that can Tolerate High Temperatures Can Greatly Improve Efficiency





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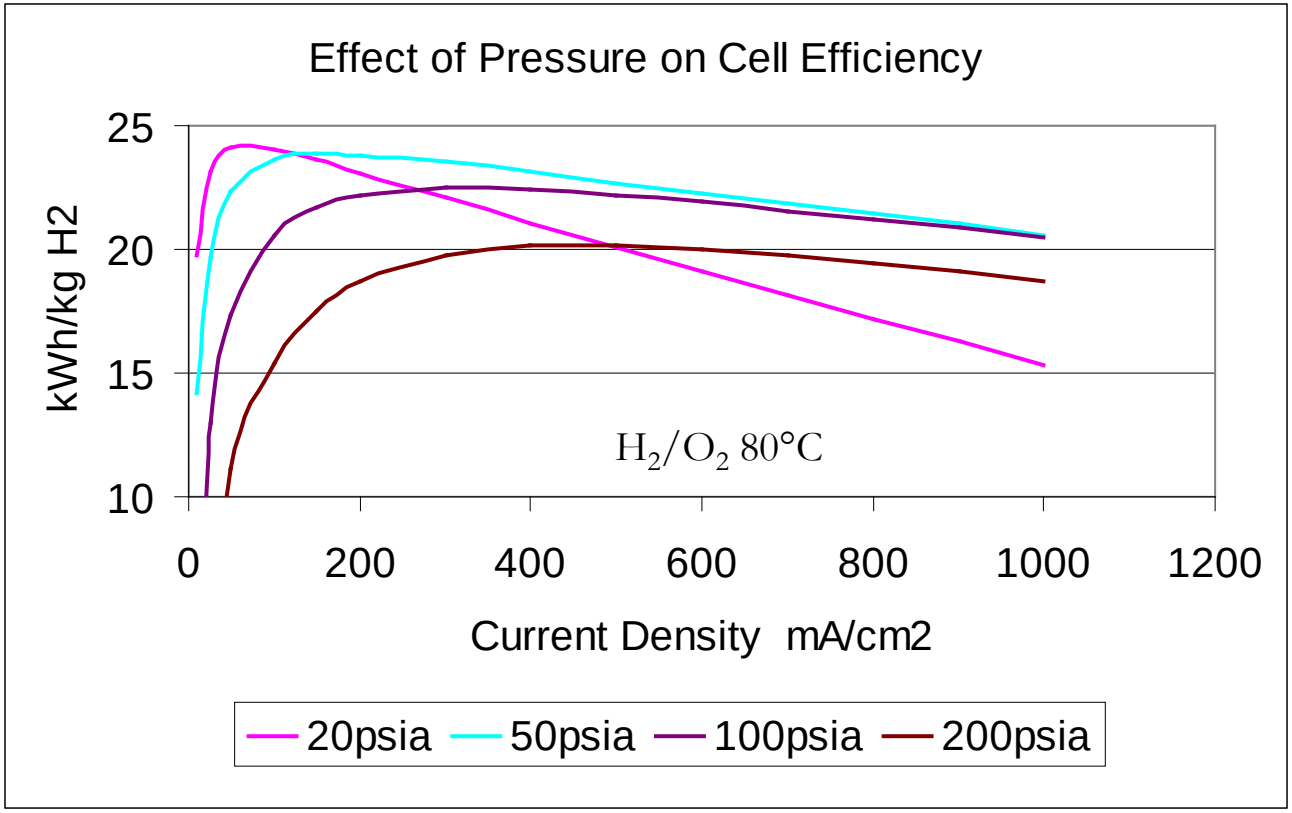
Due to Crossover, Fuel Cells Generally do not Benefit From "Nerstian Boost" of High Pressure



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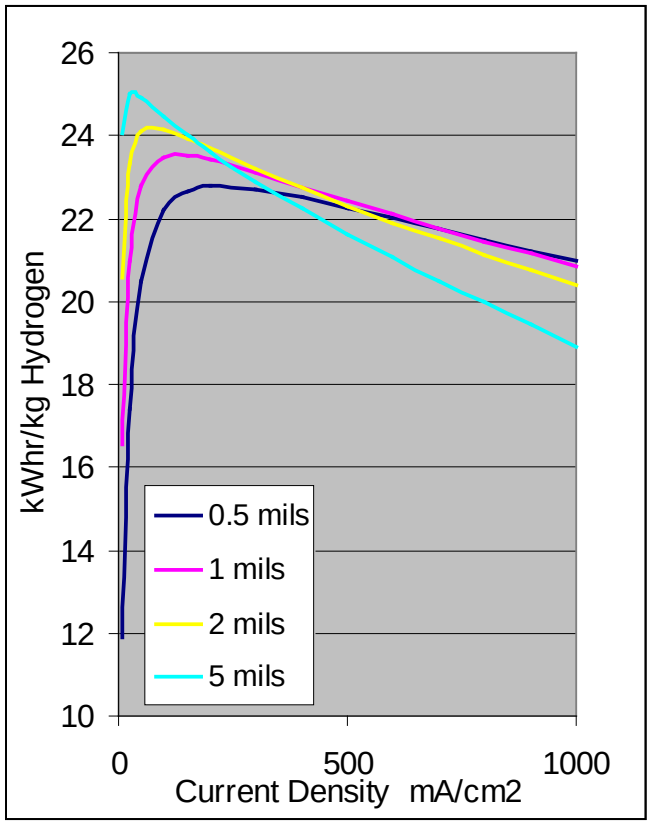
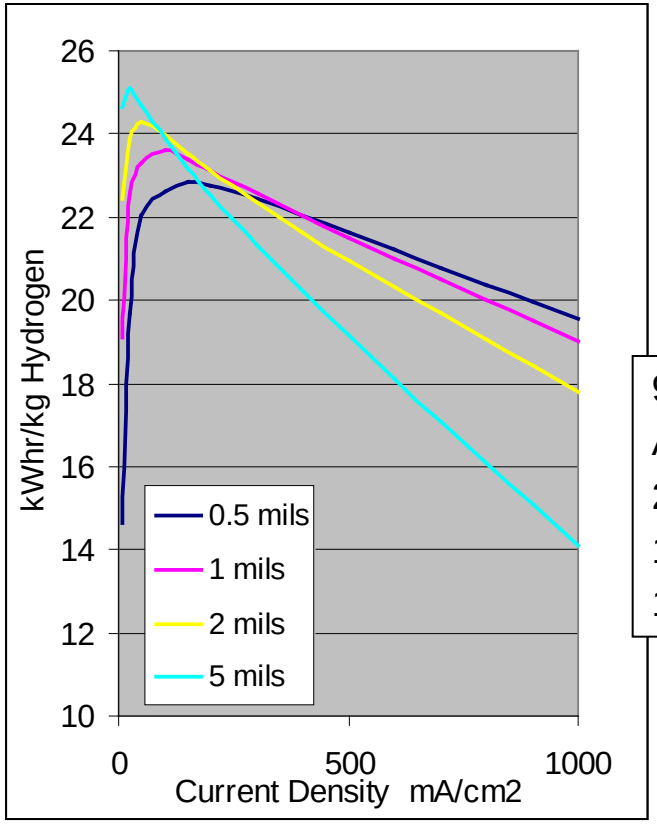
If Operating on Air, Fuel Cells Need a Thin Membrane

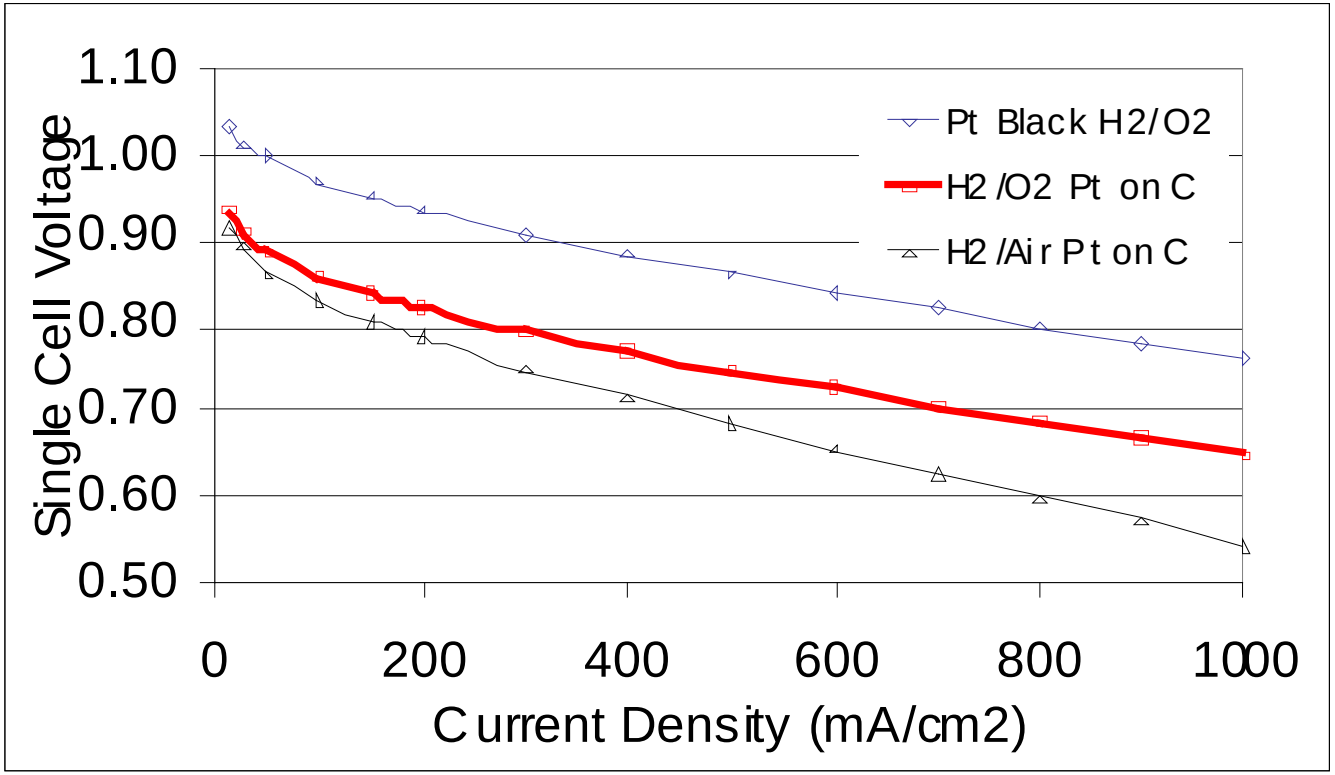




90°C
Anode/Cathode:
20/20 psia
1.1/2.0 Stoich
100/20% Inlet RH

With current PFSA membranes it is not possible to operate high pressure electrolysis with a thin membrane

With Focus on Efficiency it is Difficult to Operate with Air



Further improvements in catalysts still needed. 3M and Argonne catalysts look promising.

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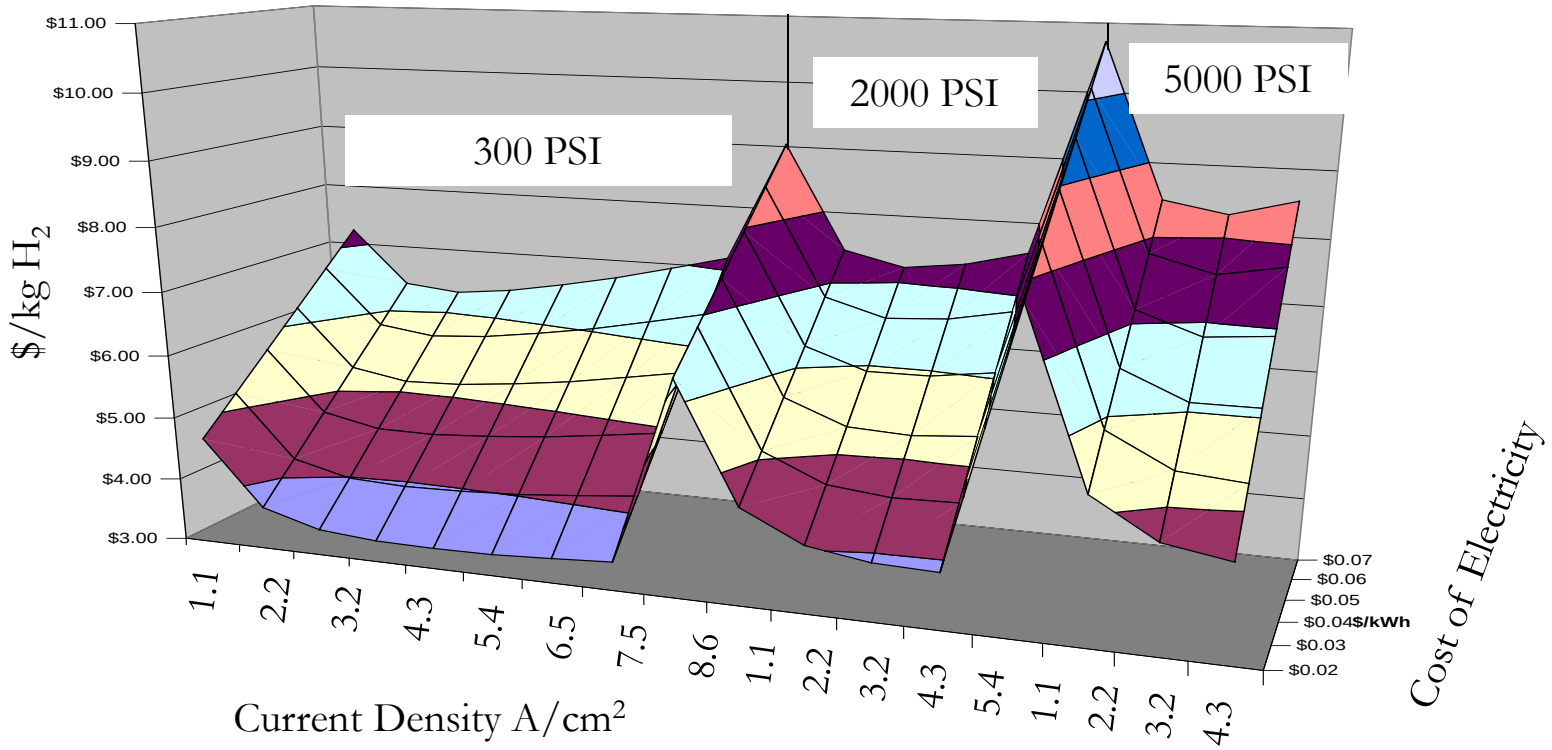
Increasing Electrolyzer Pressure Leads to System Simplification but not Necessarily Lower Cost

Complete Cost of Generating H_2 for Storage at 5000 psi as a Function of Electrolyzer Operating Parameters



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The Three Questions

1. *Is this technology feasible for cost effective storage of renewable electricity?*
   - *Dependent on scale and duty cycle.*
     - *Fuel cell and electrolyzer duty cycle need to be closely matched*
     - *For air operating it is difficult to match fuel cell and electrolyzer membranes*
2. *What are the materials and systems barriers to developing this technology?*
   - *Membranes with lower gas permeability*
   - *Lower Cost Catalysts*
3. *What are the manufacturing issues that need to be addressed to be cost effective?*
   - *Continuing to lower part count and component cost*

Efficiency is still key for cost competitiveness.

Appendix C

Lessons Learned from SOFC/SOEC Development

Mr. Greg Tao, Materials and Systems Research, Inc.

Lessons Learned from SOFC/SOEC Development

Greg Gege Tao and Anil V. Virkar

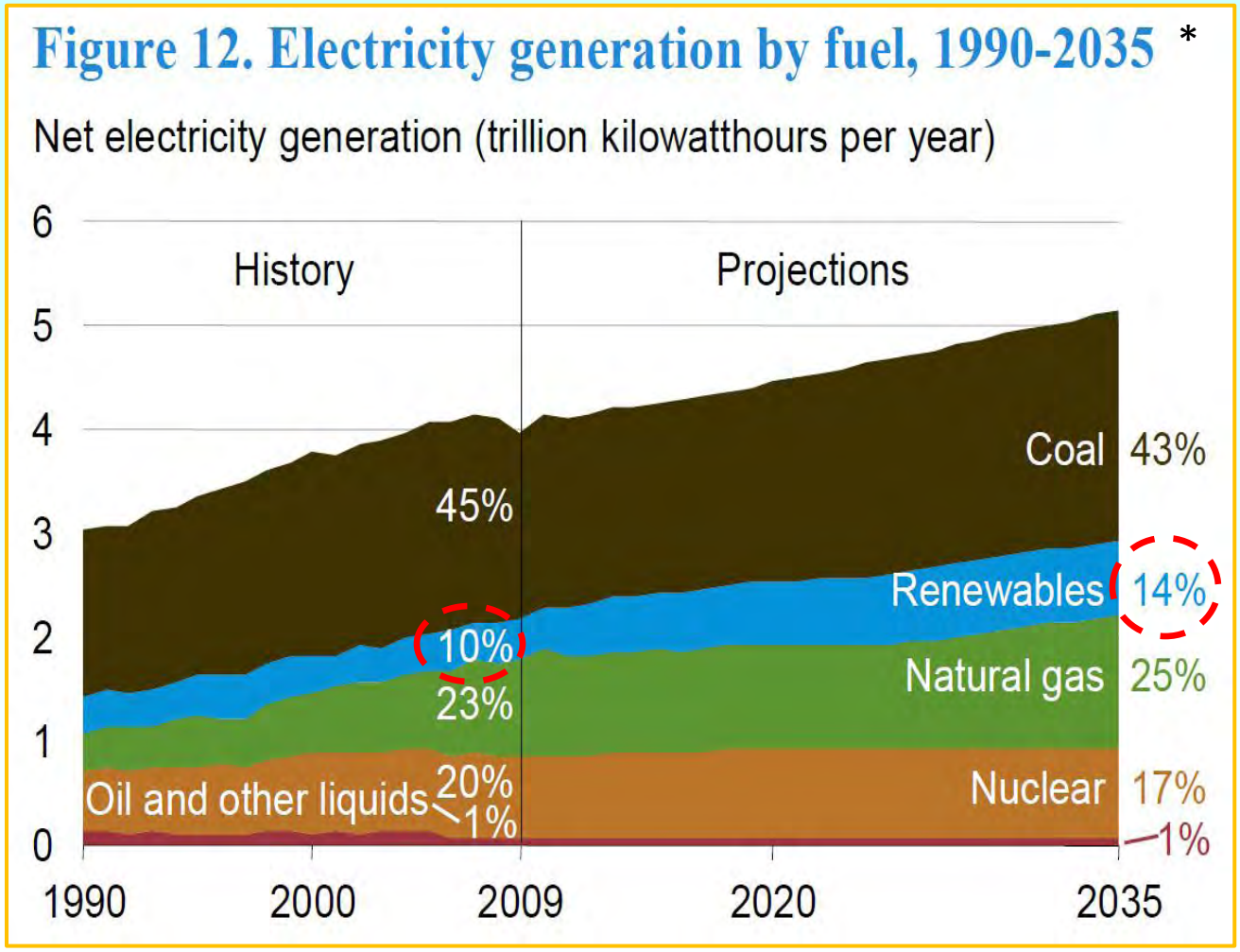
Materials and Systems Research Inc., Salt Lake City, Utah

Presented at NREL/DOE 2011 REVERSIBLE FUEL CELLS Workshop

Crystal City, Virginia

April 19, 2011

U.S. Electricity Generation – present & future

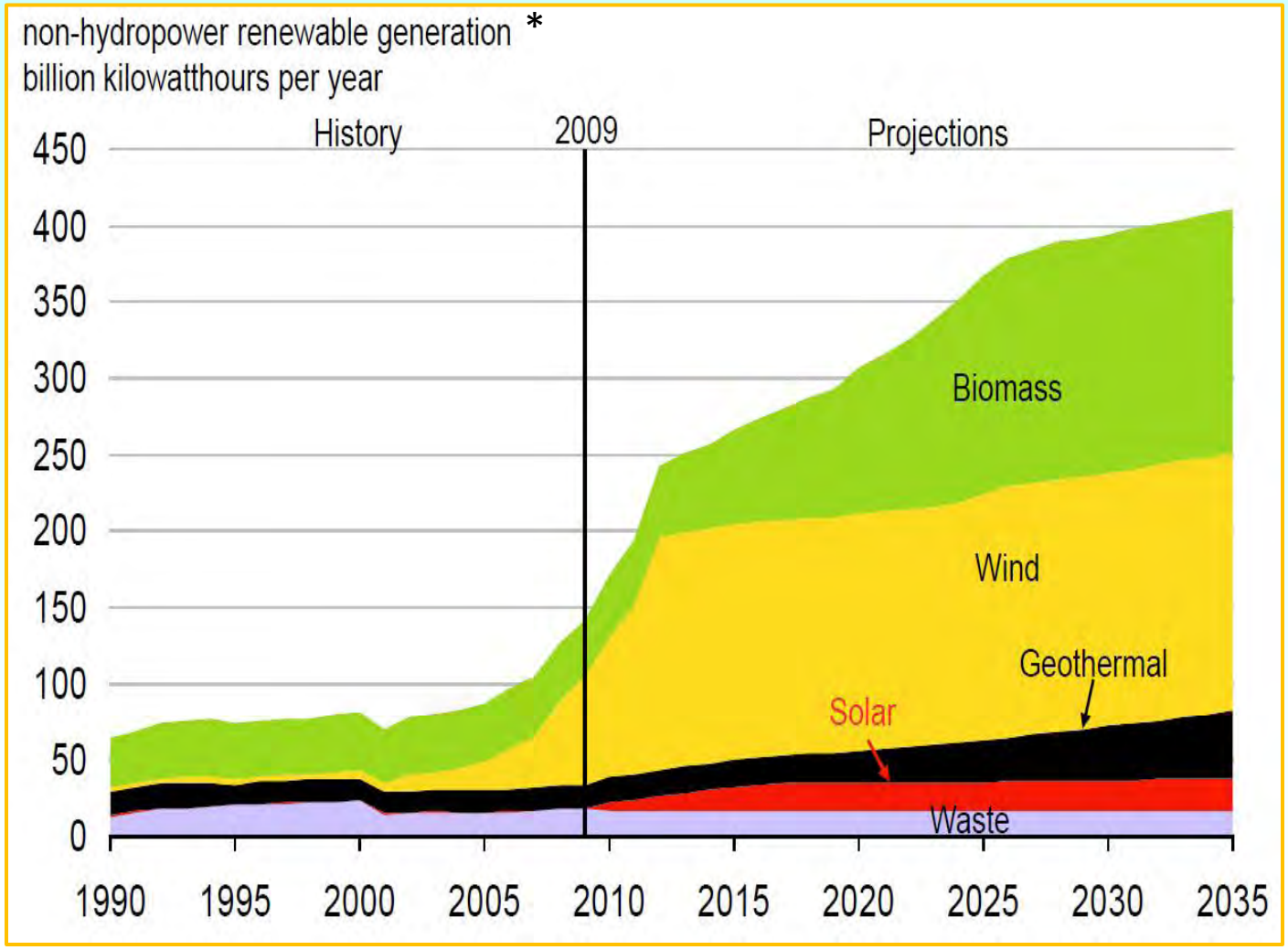


by year 2035:

- 80% of America's electricity from clean energy sources: wind, solar, clean coal, natural gas, nuclear, etc.
- Renewables represent the smallest share among the various sectors, but are significant
- Renewable generation increase from 10% to 14%: 415 billon kWh/yr to 725 billion kWh/yr (>75% increase)

** EIA Annual Energy Outlook AEO2011 Early Release, December 2010*

Renewable Generation Breakdown



	2010	2011
	billion kWh	
Solar	4.82	20.81
Geo	16.91	44.47
Wind	91.75	168.91

** R. Newell, Annual Energy Outlook 2011 Reference Case, December 16, 2010*

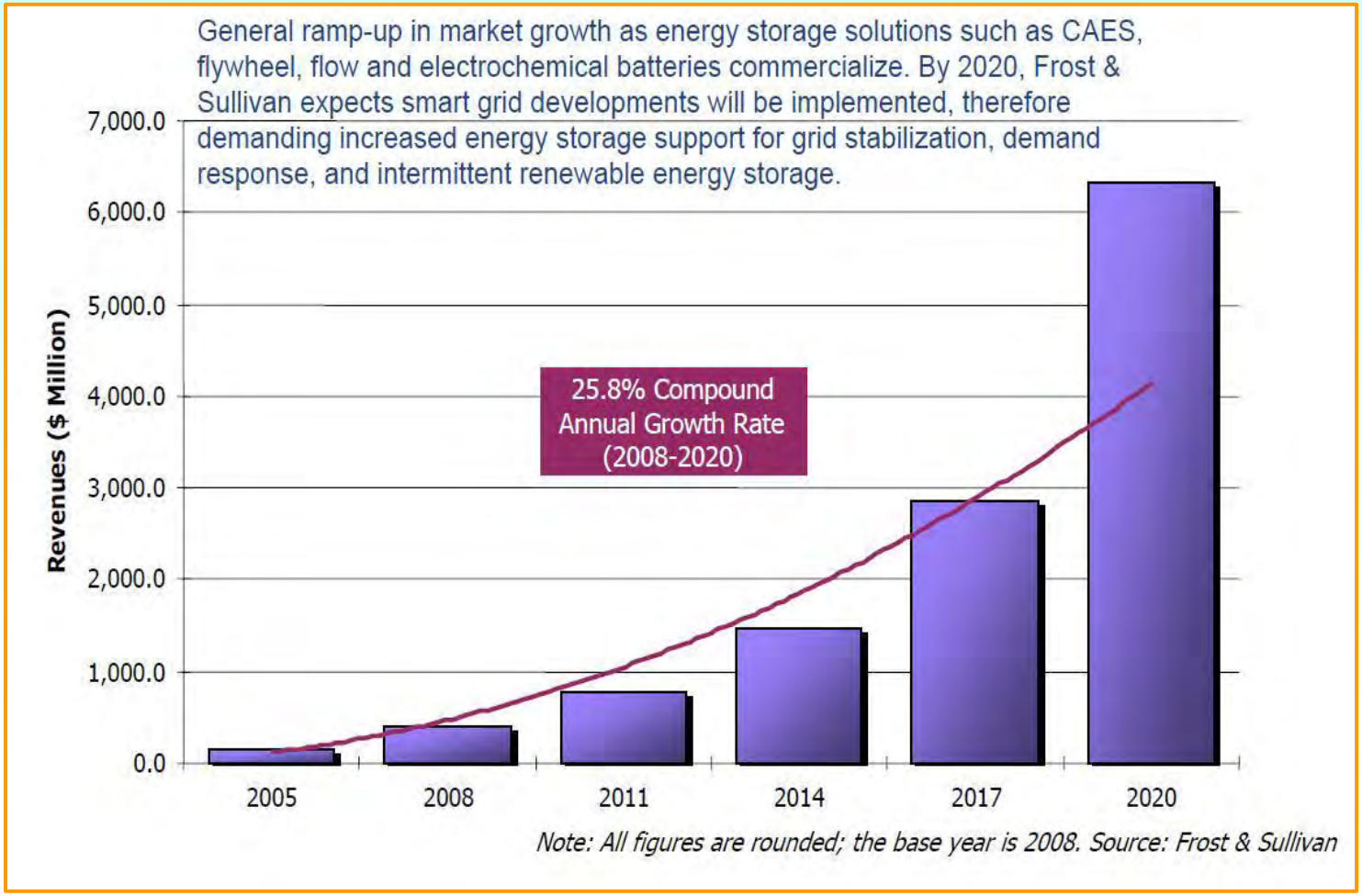
Renewable Energy Storage after Generation

Pros:
- Abundant
- Readily accessible

Cons:
- Resources are less controllable
- Intermittency
- Seasonal nature
- Lack of demand-based control (load following and regulation)
- Typically power plants are in remote areas

Solutions:
- Renewable energy storage and grid stabilization
  - electrical energy (e^-),
  - chemical energy (H_2 or synthetic fuels)
  - mechanical/potential energy (CAES, hydroelectric)

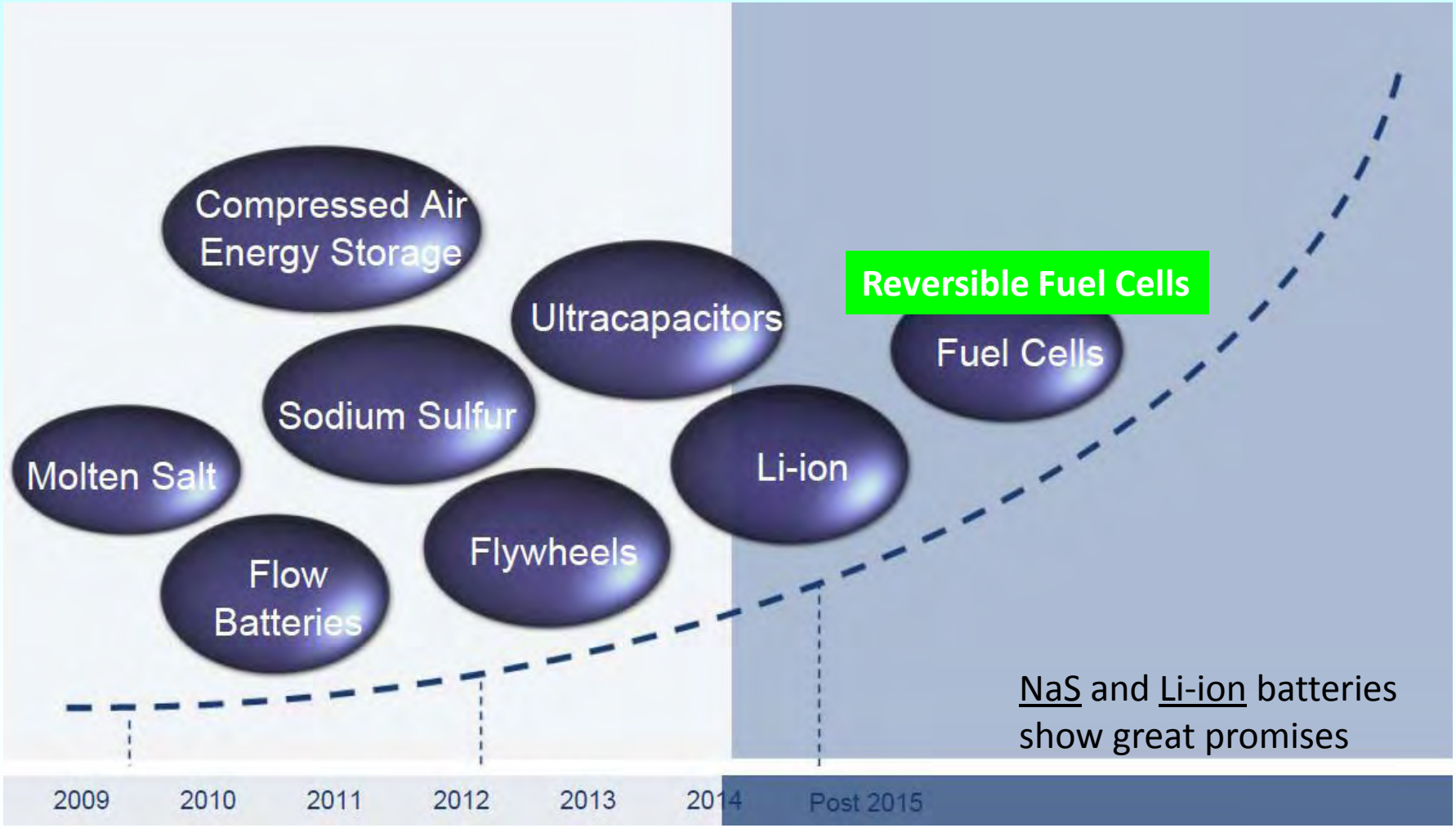
Grid Energy Storage Market in North America*



* "North American Grid Energy Storage Market", Frost & Sullivan Report, July 2009

Energy Storage Technologies

European Emerging Technology Roadmap 2009-2020*



* "Renewable Energy Storage – European Market Analysis", Frost & Sullivan Report, December 2009

What Can Reversible Fuel Cells Do?

To store excess electricity/energy and release it during times of heavy needs with its high quality power

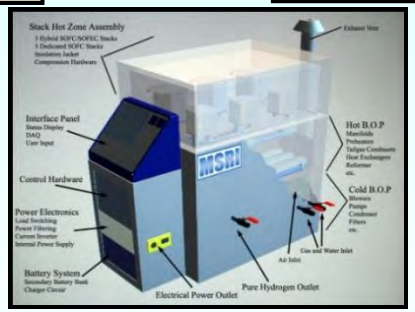
Pros compared to electrochemical batteries	Cons compared to electrochemical batteries
➢ Extensive R&D efforts on FC development, which can be leveraged to electrolyzers development	➢ Early commercialization technology
➢ Wider operating temperatures (80ºC for PEM to 800ºC for SOFC) than Li-ion batteries	➢ High cost per kWh
➢ Higher energy density than Li-ion (1000 Wh/kg vs. 160 Wh/kg)	➢ Low power density, ➢ Relatively low round-trip efficiency
➢ Modular-based technology, readily systems scale-up	➢ Lack of large scale (grid-scale) systems or field-test results, applicable to distributed/decentralized storage applications (near term)
➢ No moving parts, quiet operation, minimum maintenance	
➢ Good for power stabilization (improving power quality)	➢ Long response time
➢ Operation is independent of capacity (unlike batteries, capacities are limited by the amount of active electrode materials)	➢ Hydrogen fuel storage, or synthetic fuel production/storage
➢ No self-discharge issue, long shelf-life ➢ Charge (electrolyzer mode) /discharge (fuel cell mode) cycles degradation rate probably is less temperature dependent on operating temperatures than batteries	➢ Lack of supporting data on the charge/discharge cycle degradation rate ➢ **High long-term degradation rate**

MSRI's Fuel Cell / Electrolyzer R&D Activities

MSRI has expertise in materials and electrochemical technologies for power generation and energy storage applications, including fuel cells/electrolyzers, rechargeable batteries and thermoelectric converters.

Fuel Cells

- SOFC based-on oxygen ion conducting electrolyte membrane
- SOFC based-on high temperature proton conducting electrolyte membrane
- PEMFC
- SOFC cells from 1 to 400 cm^2 active area
- Planar SOFC stacks 75 W to 2 kW
- Tubular SOFC bundles up to 300 W



Hydrogen Production

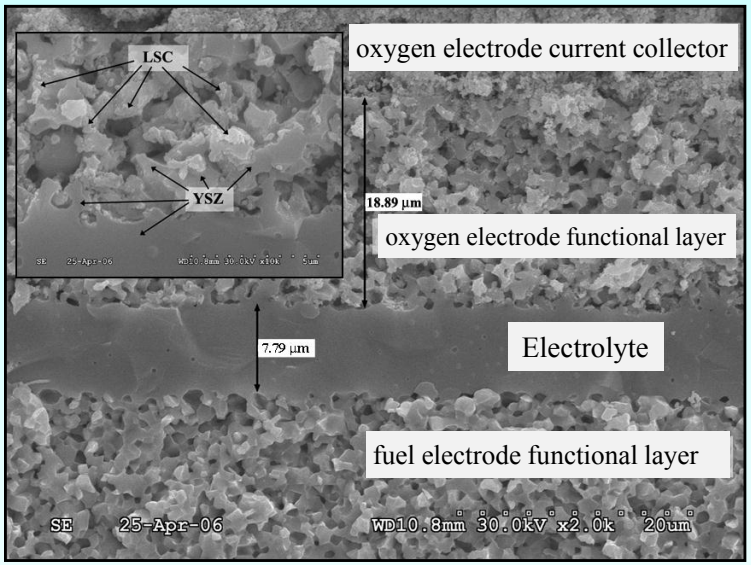
- High temperature steam electrolysis
- Advanced fuel-assisted electrolysis
- H_2 production direct from coal and petcoke

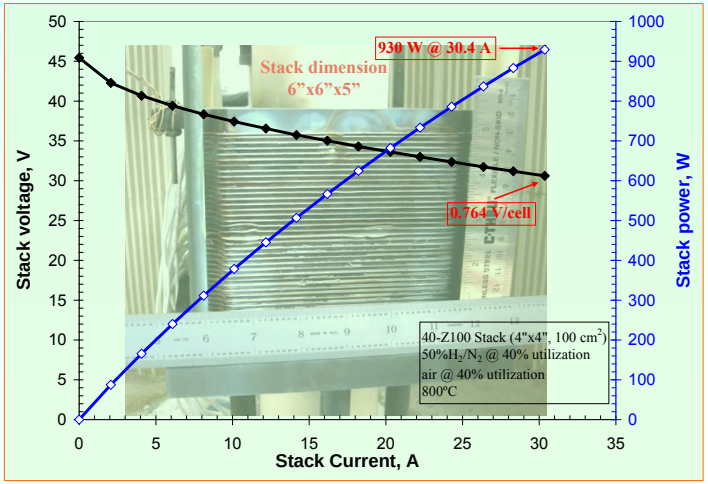
Solid Oxide Electrochemical Technologies

Fuel-electrode Supported Solid-Oxide Devices: SOFC & SOEC

specializing in cell/stack materials R&D

1. Nickel+zirconia-based fuel-electrode supports: ~700 µm
   - mechanical strength; redox-tolerance; low concentration polarization losses; costs
2. Graded, fuel-electrode functional layer: ~ 15 µm
   - sulfur-tolerance; redox-tolerance
3. Thin film electrolyte: ~ 8 µm
   - enhanced conductivity
4. Graded, O_2-electrode functional layers: ~ 20 µm
   - Low sheet resistance; extended three phase boundary length; improved bonding
5. O_2-electrode current collector layer: ~ 50 µm
   - low ohmic/contact resistance
6. Metallic interconnect
   - low oxidation rate; low cost
7. Sealing gasket
   - Compliant/rigid seals; thermal expansion match; easy fabrication/assembly

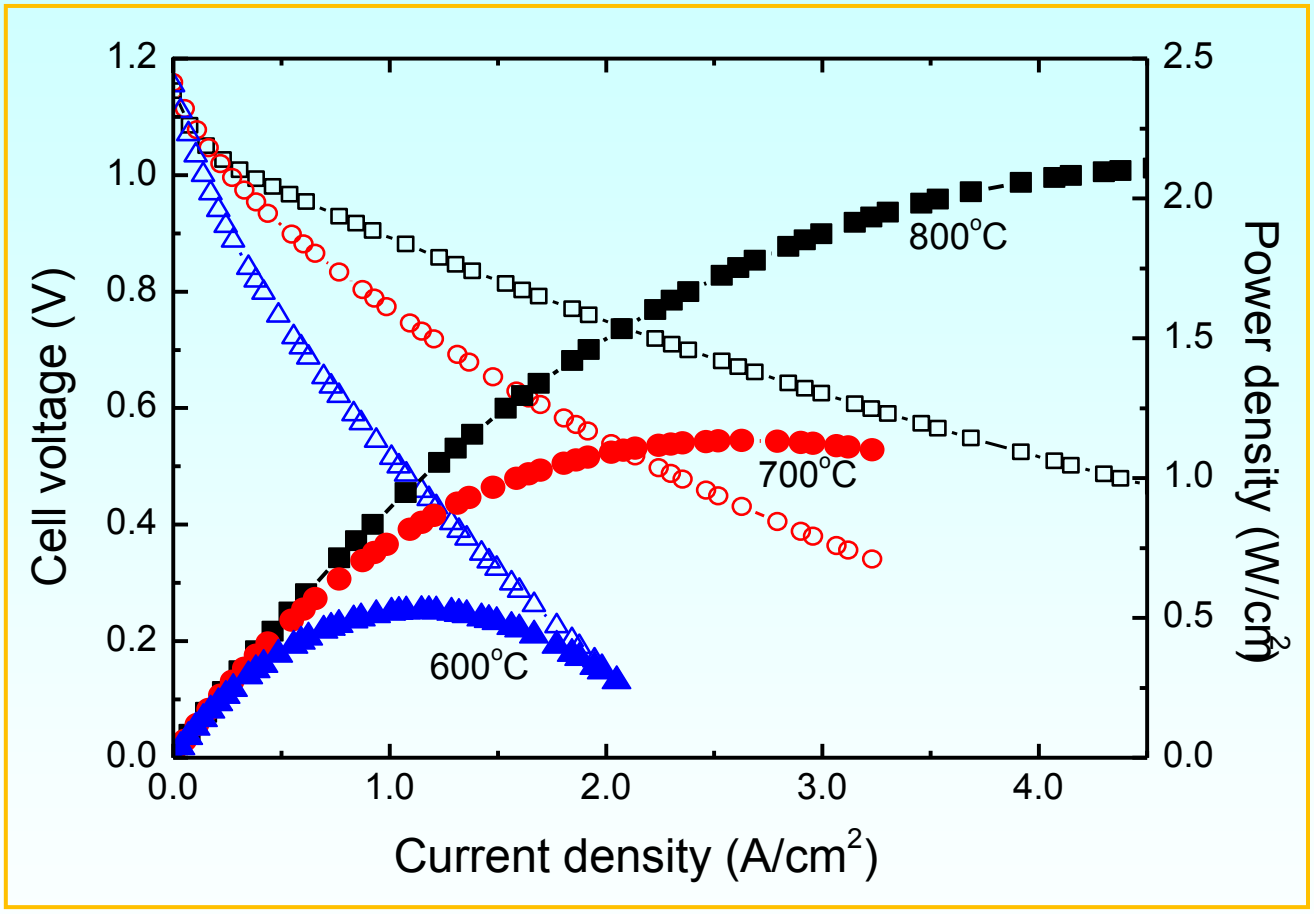




SOFC Electrode Materials Development

Single Button-sized Cell Performance

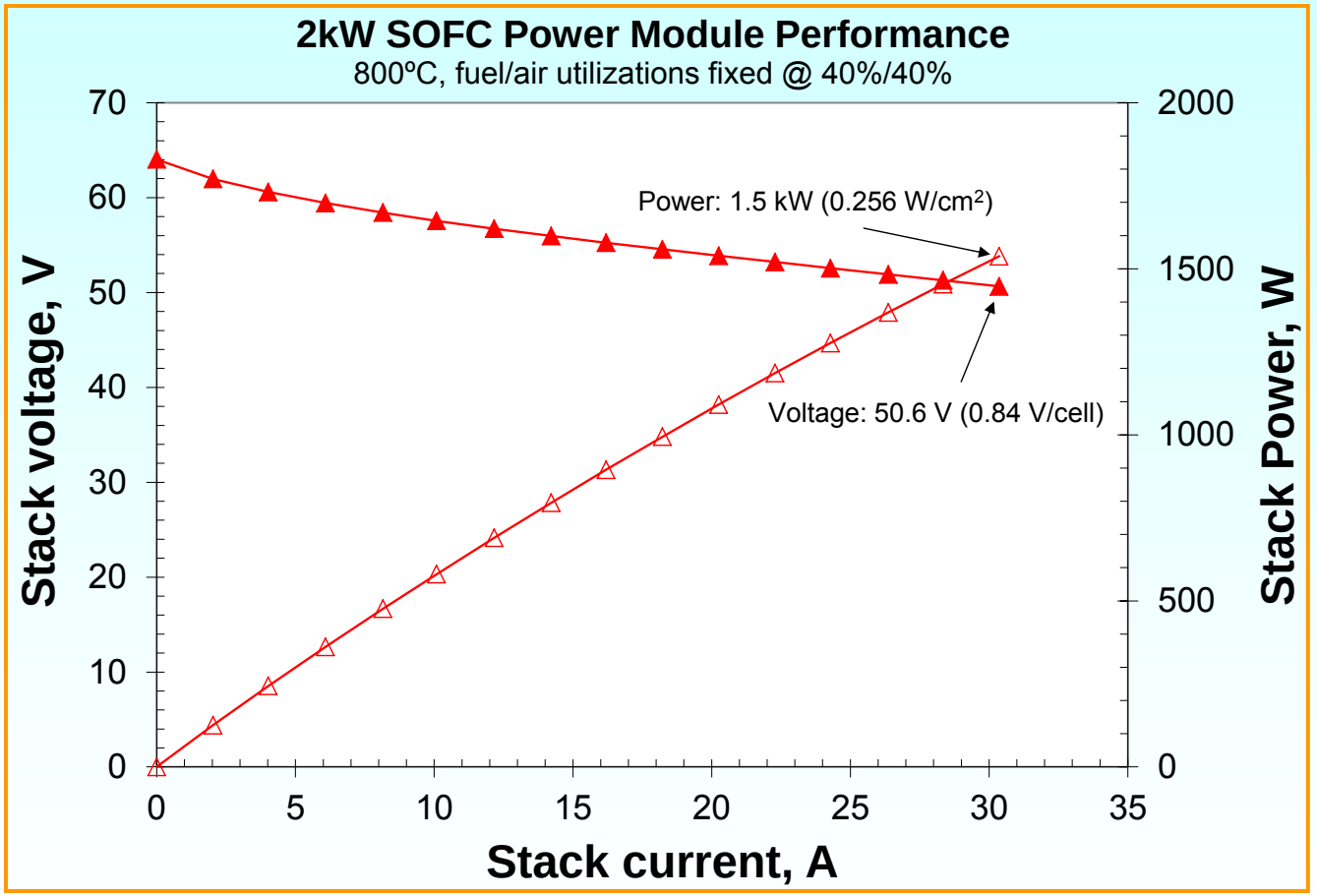
- Power density as high as 2.1 W/cm^2 on button-size cells
- > 5,000 hours with minimal degradation



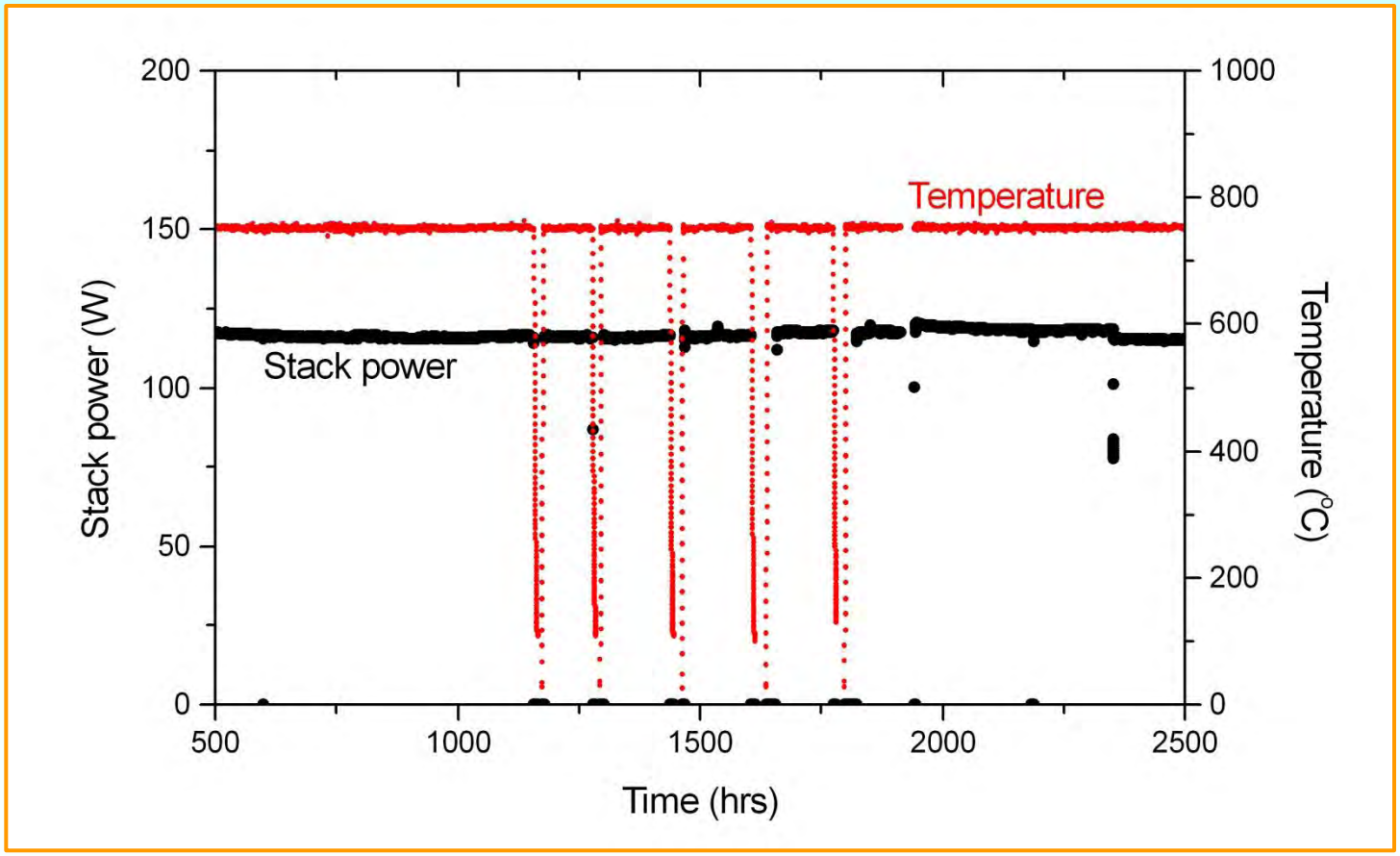
Fuel – humidified hydrogen, Oxidant - air

1 to 2 kW Capacity SOFC Stacks

kW-scale SOFC stack (100 cm² per-cell active area, 60 cells/stack)



SOFC Stack Long-Term Test with Thermal Cycles



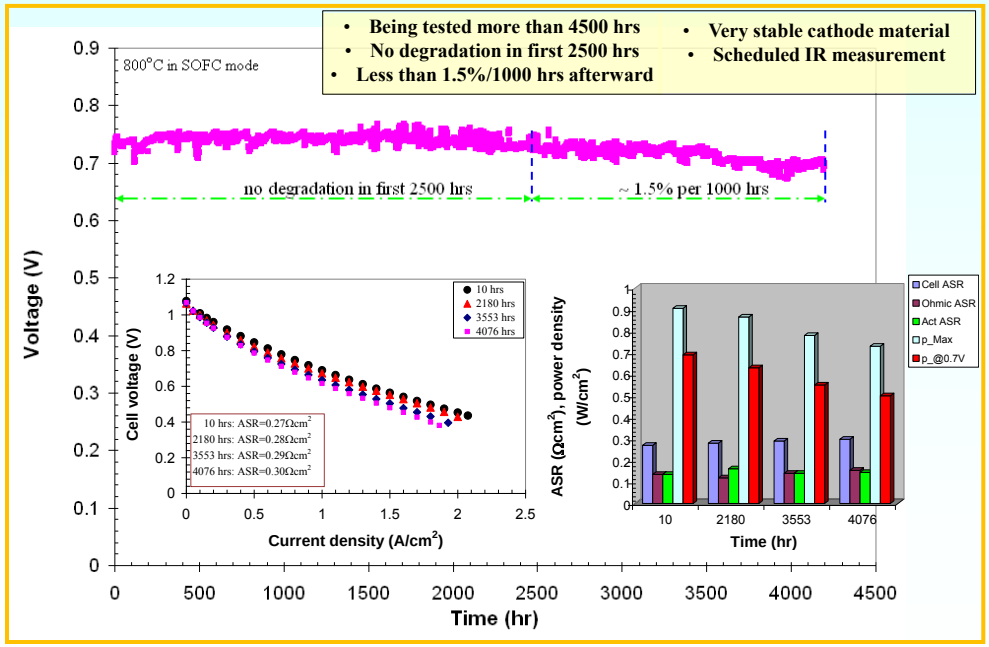
Power degradation rate = 0.85% /1000hrs over 2500 h testing

5 cell stack of 100 cm²/cell
50% H_2(bal. N_2) and air at 40% utilization @ 0.36A/cm²; 750°C
Metal interconnects
5 thermal cycles with no significant degradation

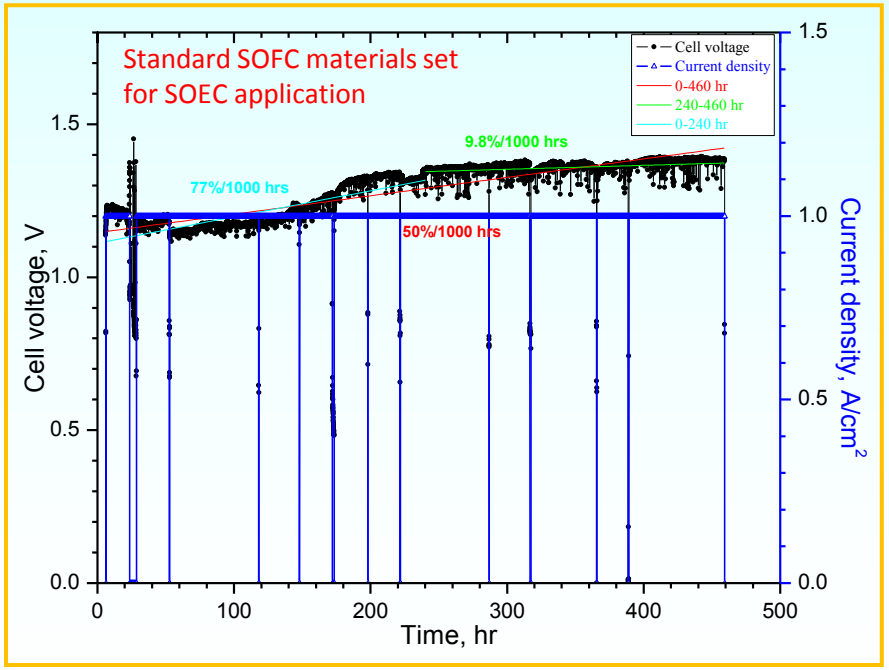
SOFC vs. SOEC Operation – (button cells)

- Long-term test results comparison between two button cells tested in SOFC and SOEC modes
  - SOFC test (0.7 A/cm^2) was interrupted on schedule to measure the ohmic losses via current-interruption
  - SOEC test (1 A/cm^2) was frequently interrupted for refilling the water tank

SOFC mode (power generation):
no degradation in 2500 hrs, and ~ 1.5%/1000 hrs afterward



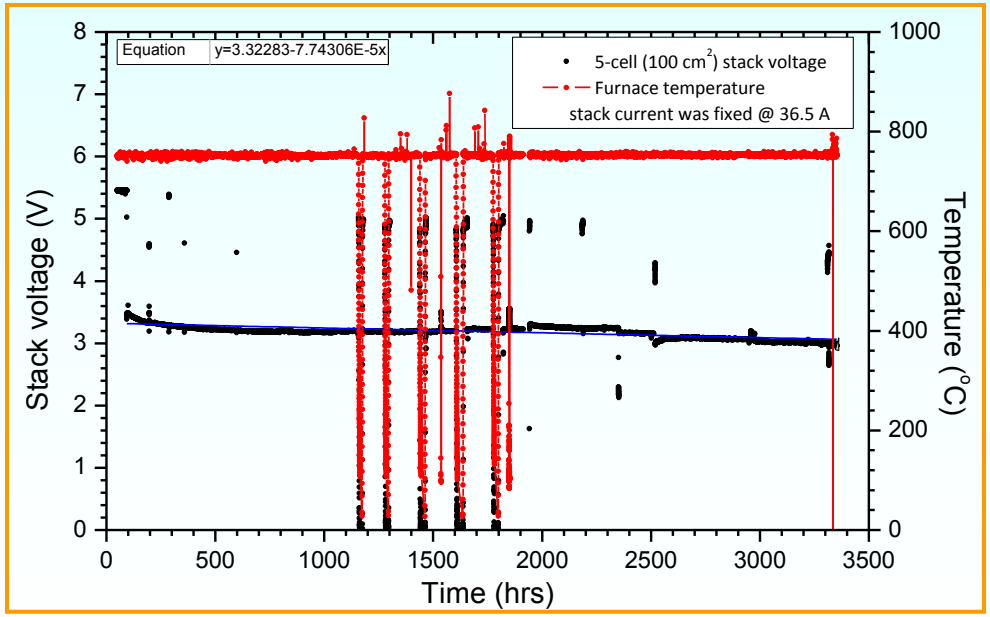
SOEC mode (hydrogen production):
Projected degradation rate ~ 50%/1000 hrs



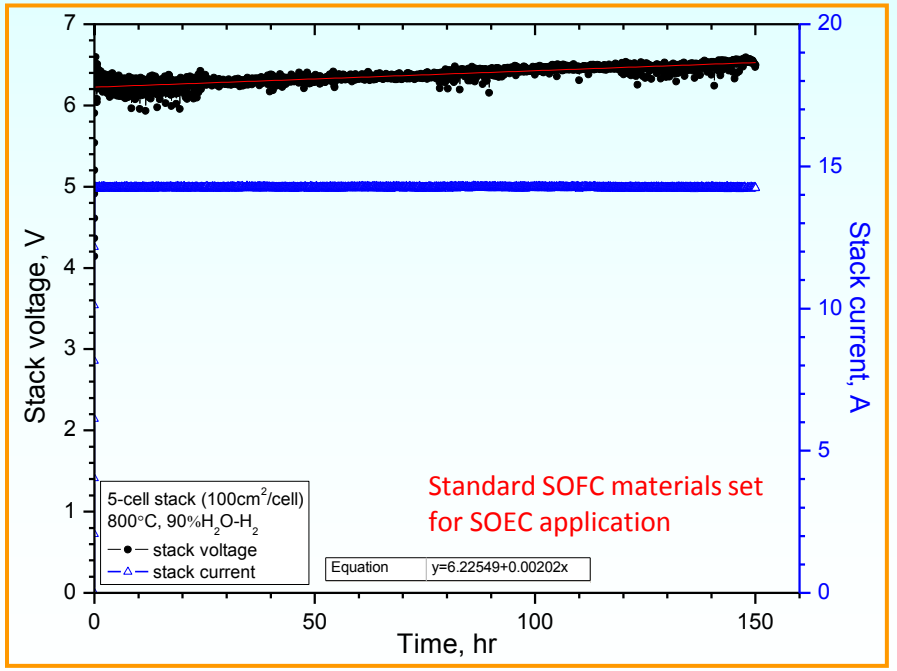
SOFC vs. SOEC Operation – (stacks)

- Long-term test results comparison between two 5-cell stacks tested in SOFC and SOEC modes
  - 100 cm^2 per cell active areas
  - Fixed reactant utilizations at 40%
  - Operating at fixed current mode (36.5 A and 14 A in SOFC and SOEC mode, respectively)

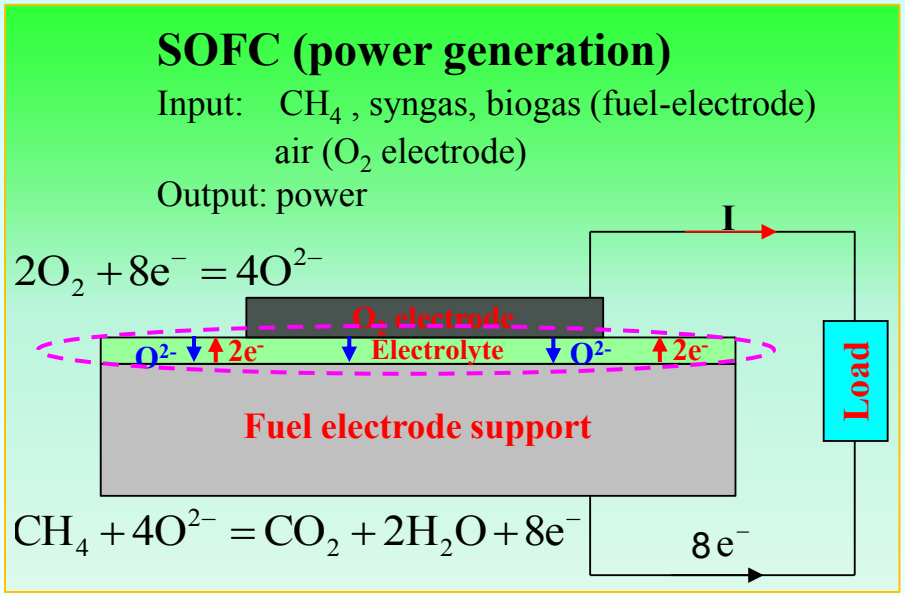
SOFC mode (power generation):
Voltage degradation rate < 2%/1000 hrs

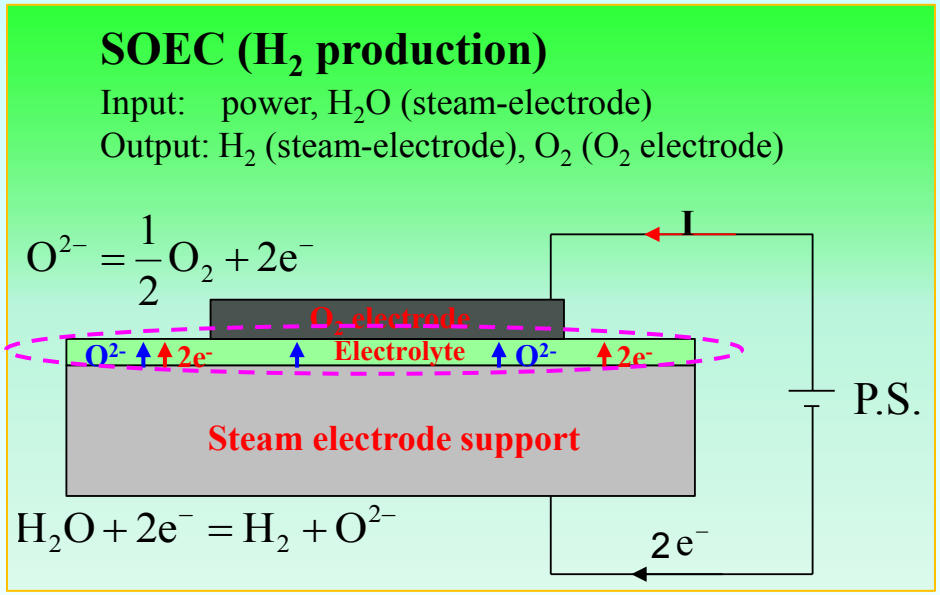


SOEC mode (hydrogen production):
Projected degradation rate ~ 30%/1000 hrs



SOFC Operation Vs. SOEC Operation

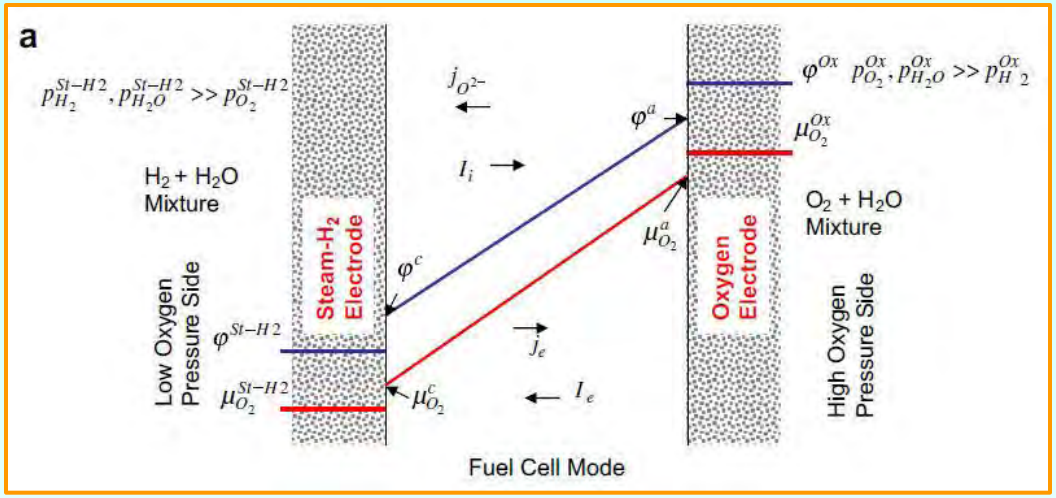


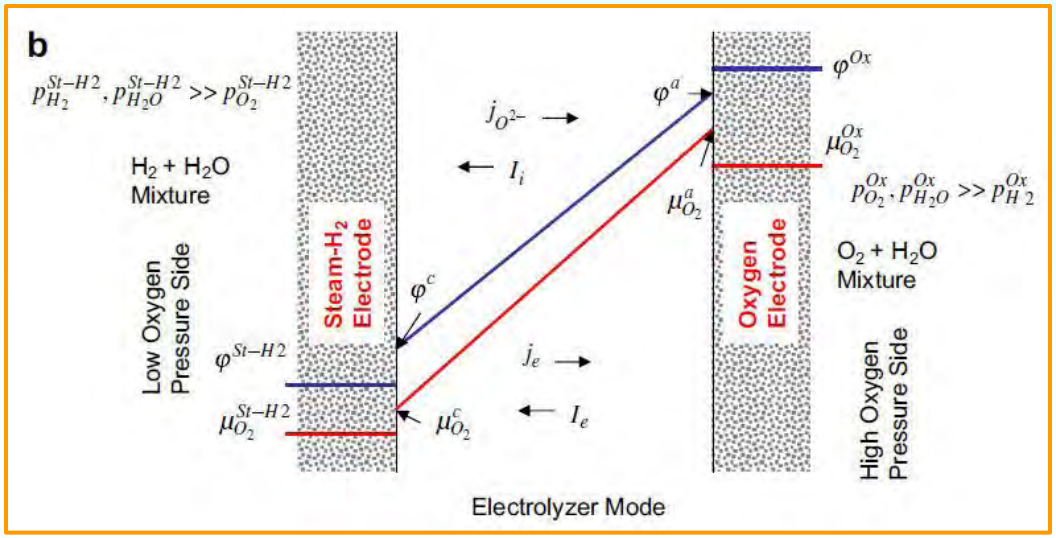


- SOFC operates typically at 700~850ºC
- Per cell voltage is 0.7~0.85 V
- Flux of oxygen ions and electrons are on the opposite direction inside the electrolyte

- SOEC operates typically at 700~850ºC
- Per cell voltage is 0.9~1.3 V
- Flux of oxygen ions and electrons are on the same direction inside the electrolyte
- High steam concentration (or high P_{O_2}) on steam electrode

Analysis of SOFC Vs. SOEC Operation*





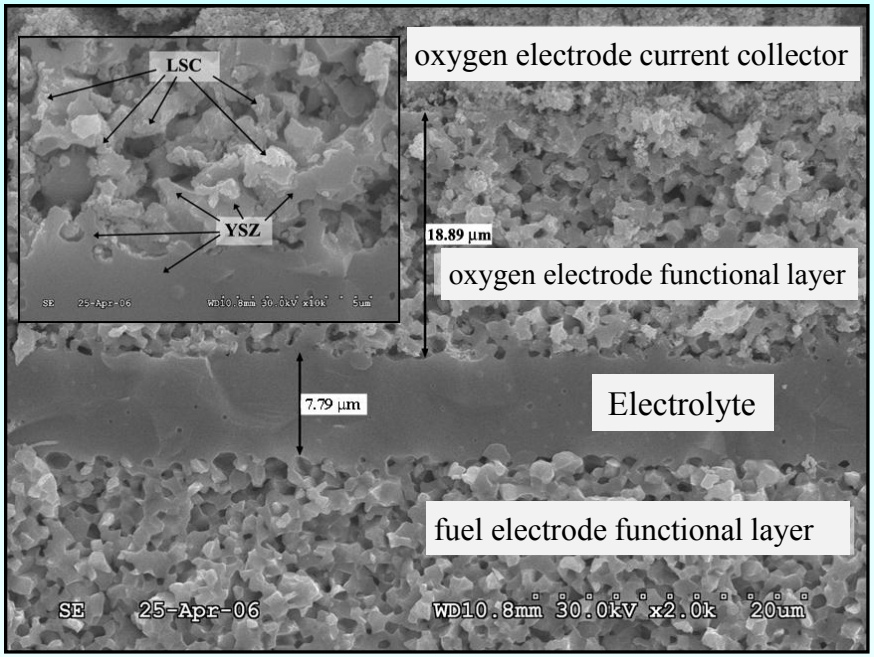
Schematic variation of **measurable** electric potential (φ) and oxygen chemical potential (μ_{O_2}) through the electrolyte in fuel cell mode (a) and electrolyzer mode (b).

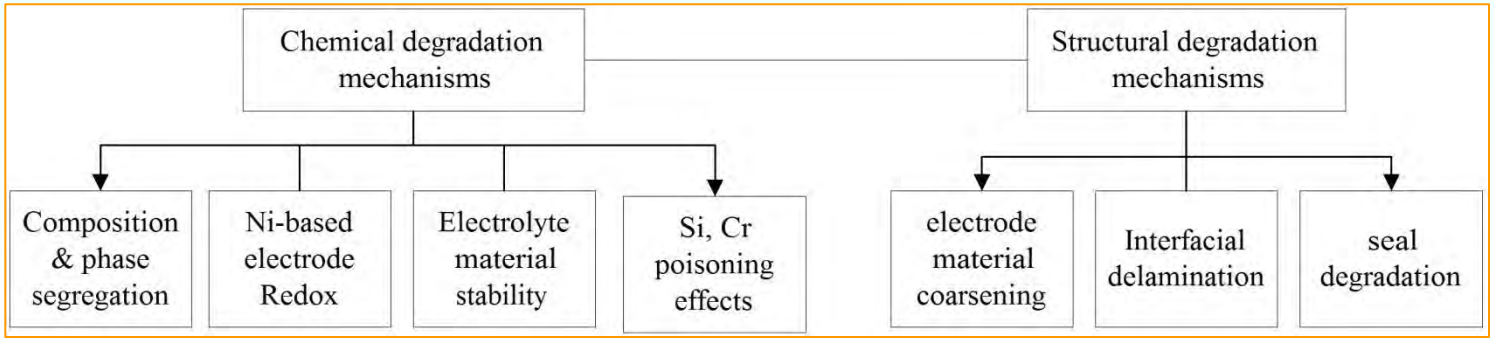
(a) In fuel cell normal operation mode, oxygen partial pressure inside the electrolyte is mathematically bounded by the oxygen partial pressures of two electrodes. High P_{O_2} is unlikely developed inside the electrolyte

(b) In the electrolyzer operation mode, the oxygen partial pressure inside the electrolyte is not mathematically bounded by the electrodes. Electrode delamination is possible under certain operation conditions

*: A.V. Virkar, "Mechanism of oxygen electrode delamination in solid oxide electrolyzer cells", Int. J. Hydrogen Energy 35 (2010) 9527-9543

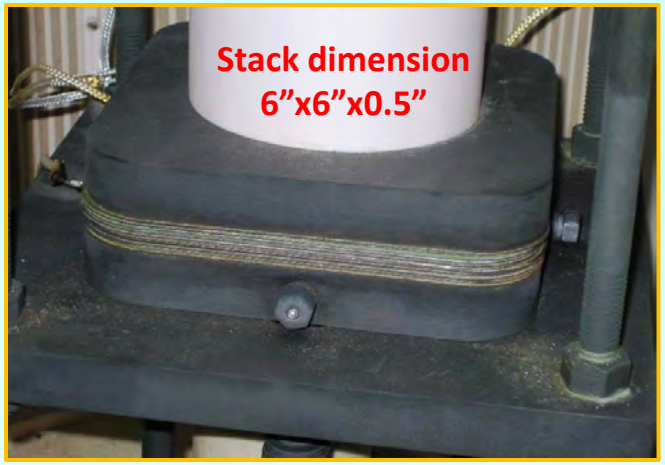
Dissection of SOEC Performance Degradation





- **Focus on materials modification**
- **Improve oxygen electrode stability**

SOEC Development – at a Stack Level (5-cell stack)

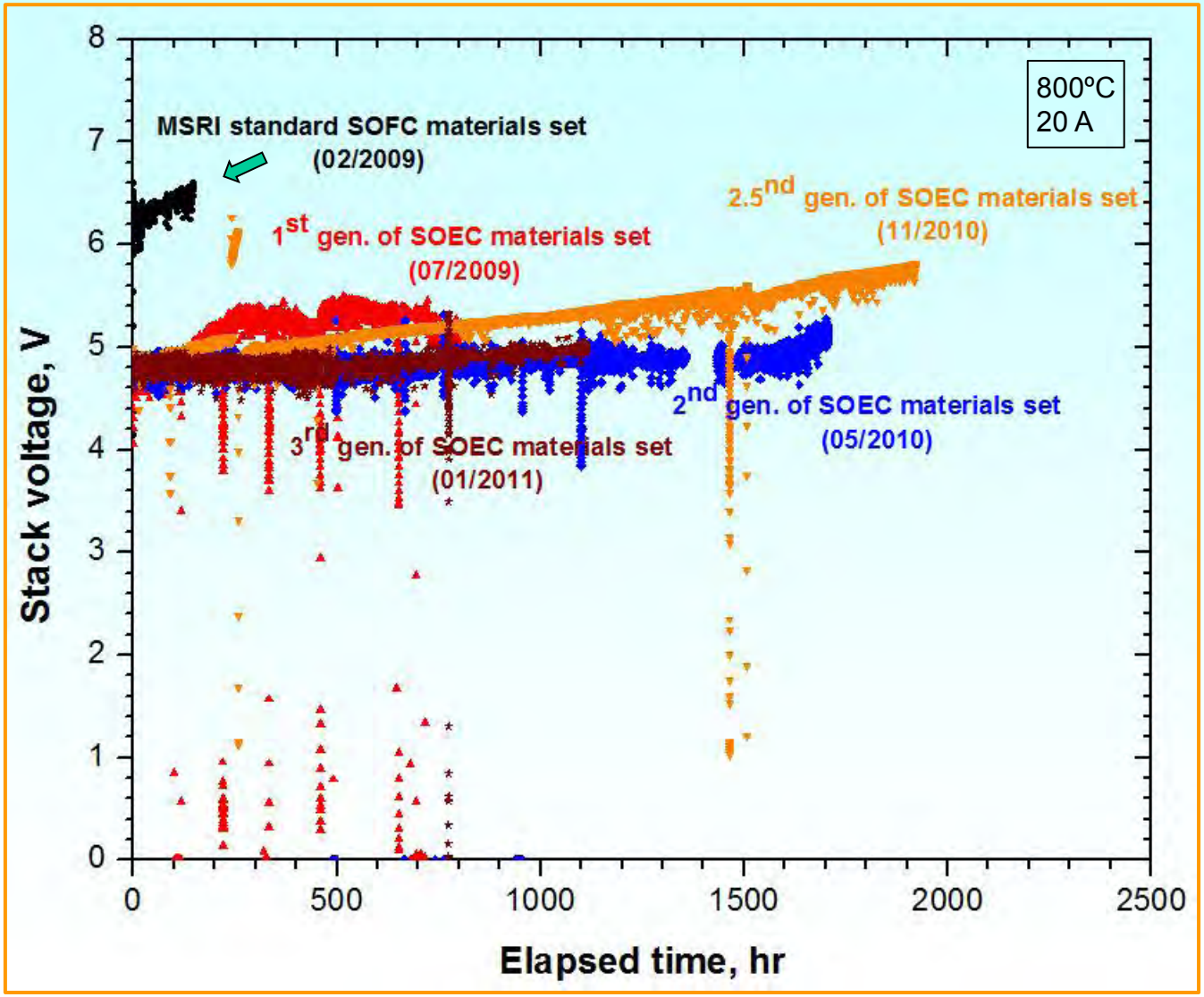


Five-cell stack assembly (post-test)

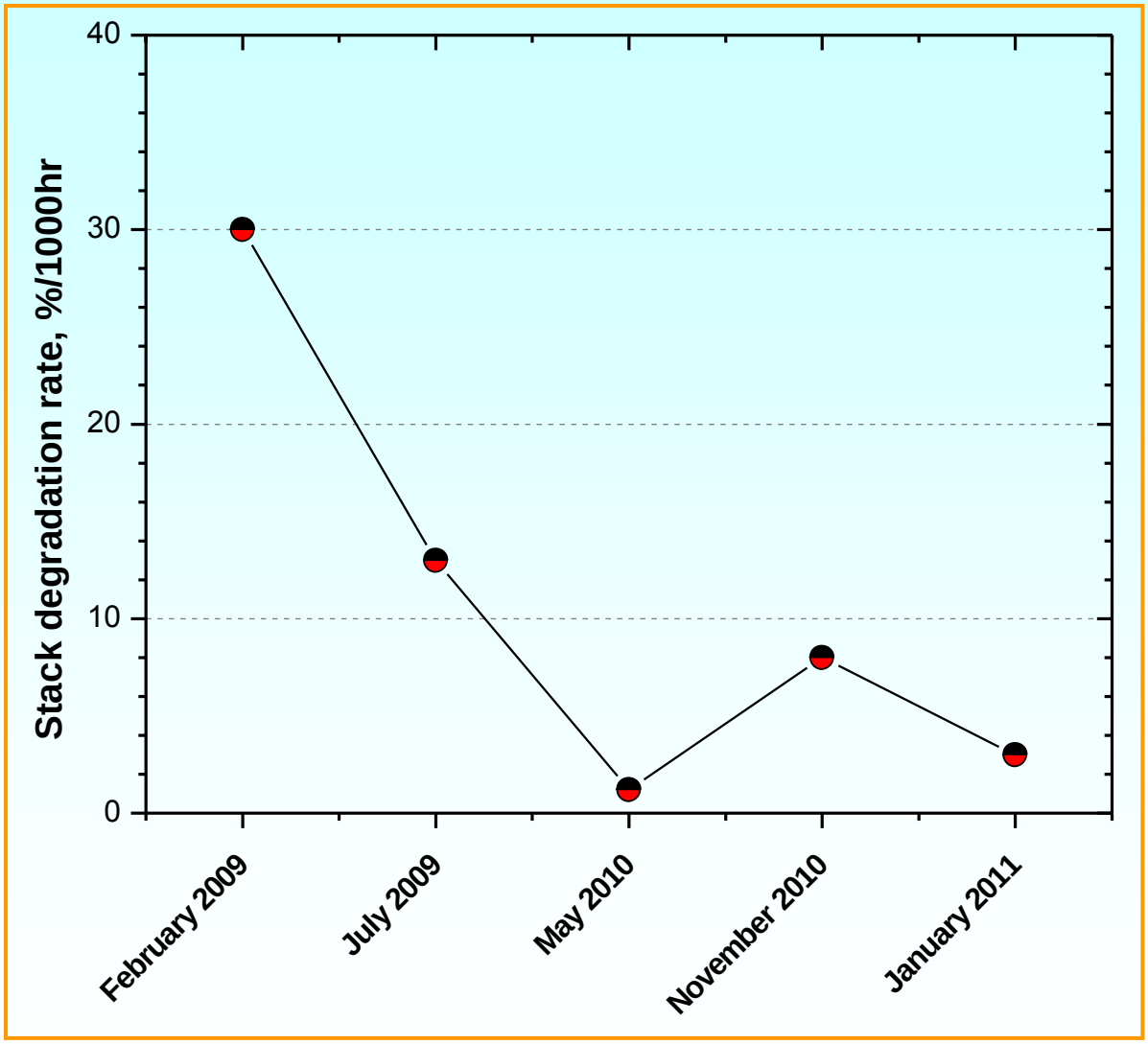
Stack testing protocol:

- 5-cell/stack, 100 cm^2/cell active area
- 800ºC
- Initial test was performed in the SOFC mode as a baseline, followed by SOEC tests
- The fuel-electrode gas compositions varied from pure H_2 to 10%H_2, bal. H_2O
- Long-term tests were performed for hydrogen production using 70%H_2O bal. H_2 as the reactant (SOEC mode)
- SOEC long-term tests were performed at a constant current (fixed current)
- In addition, the long-term SOEC tests were interrupted for scheduled SOFC tests

SOEC Stacks Long-term Degradation Study

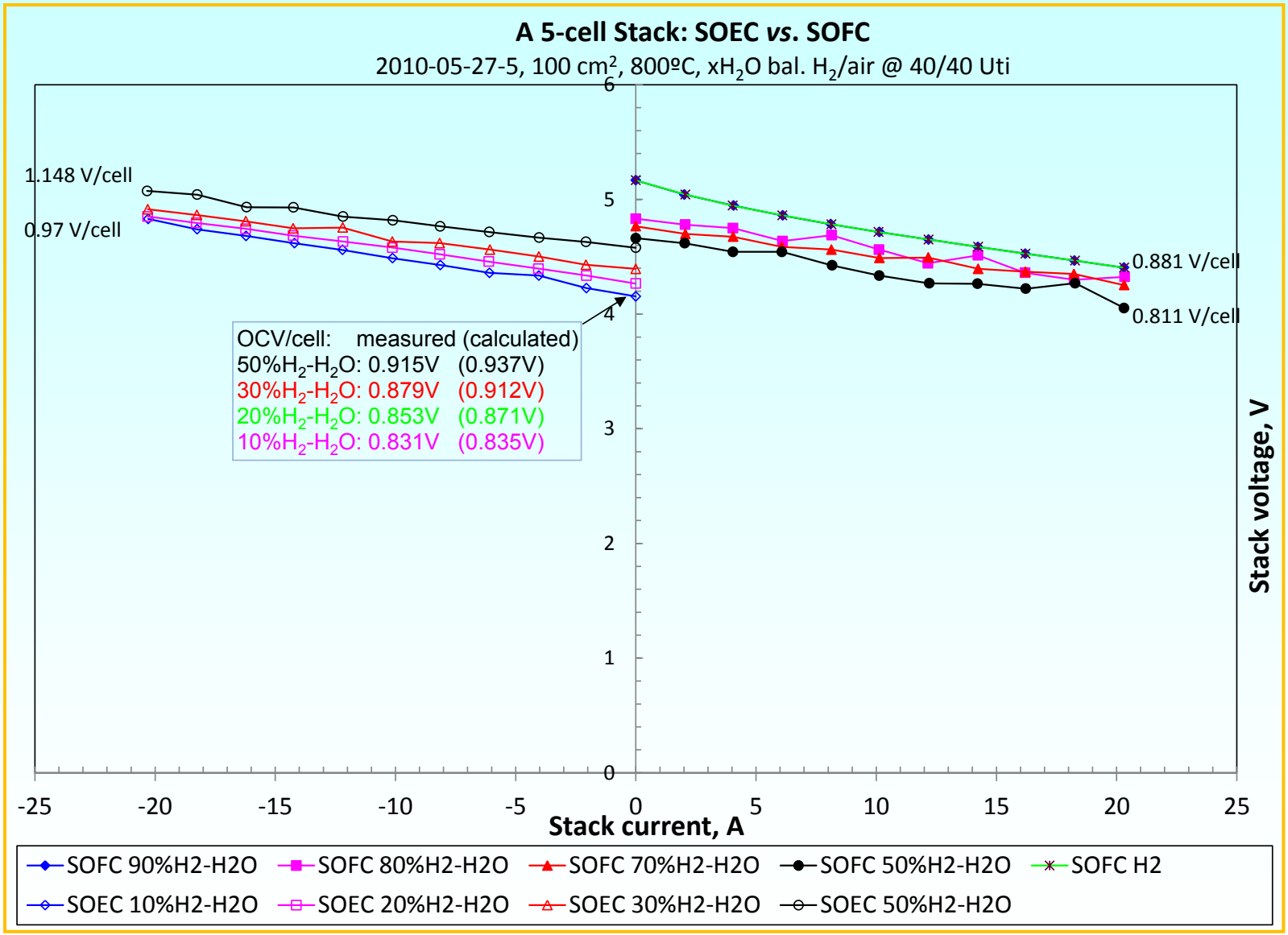


SOEC Degradation Study Progress



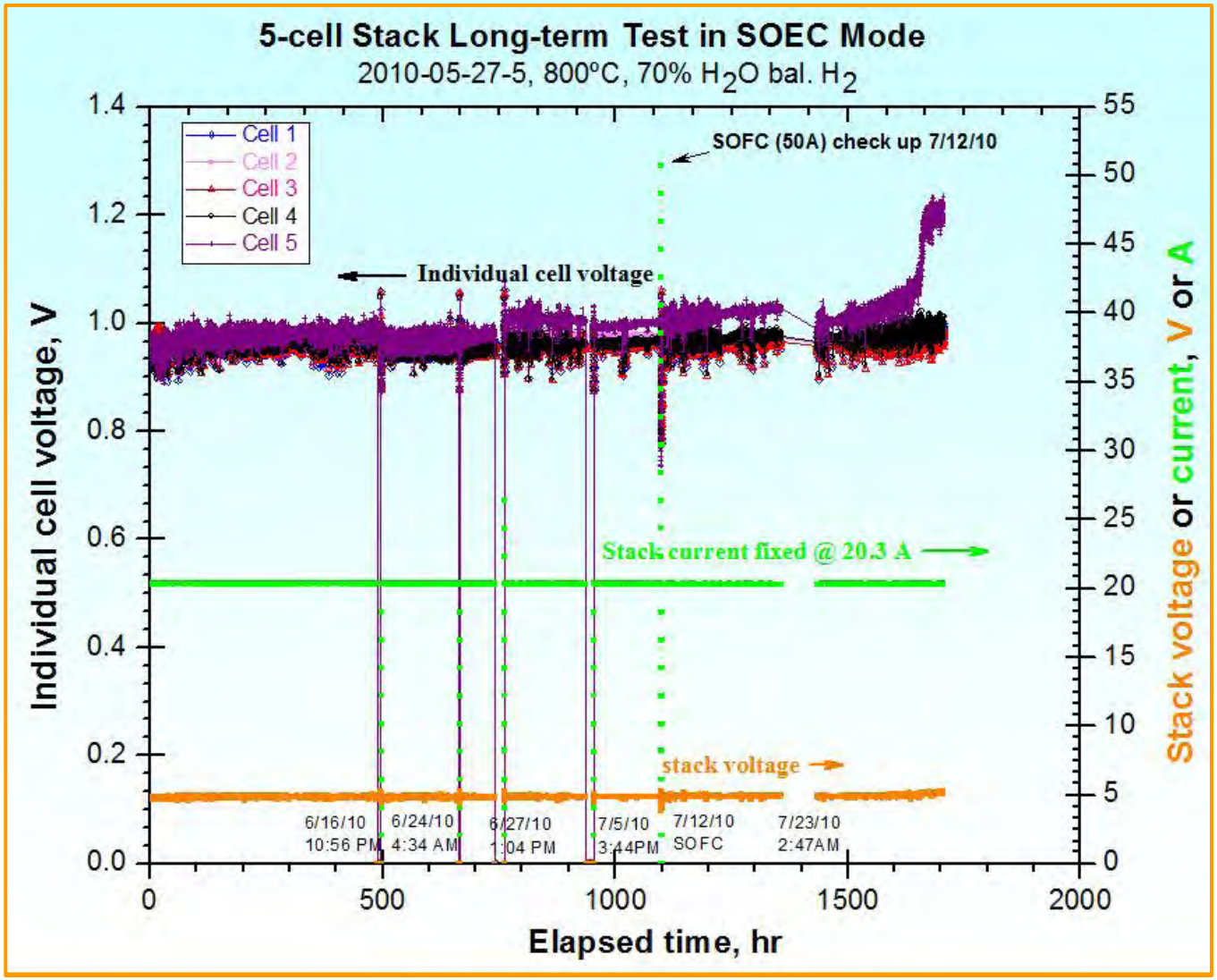
- MSRI has developed materials sets suitable for reversible SOFC/SOEC application
- In last 2 years, MSRI has tested 5-cell stacks in SOEC mode, with accumulated 10,000 stack-hours
- Degradation rate reduced from initial 30%/1000hrs to < 2%/1000hrs
- Independent tests on our 5-cell stacks by a third party achieved similar results

5-cell Stack Tests in SOFC & SOEC Modes

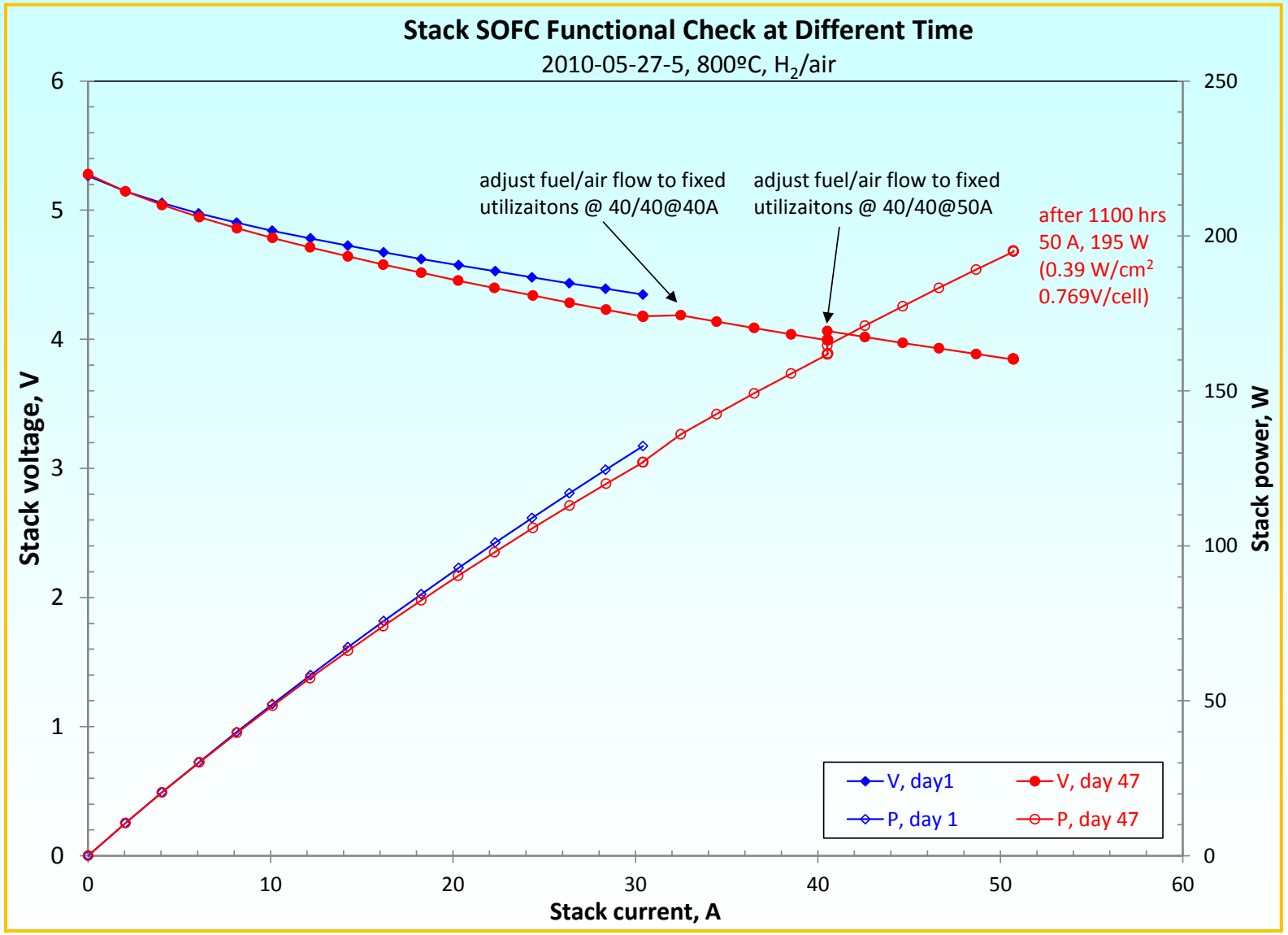


5-cell Stack Long-term Test in SOEC Mode

Fixed the stack current @ 20.3 A, degradation rate ~ 1.2%/1000 hrs



Scheduled SOFC Tests During SOEC Long-term Test @ Different Time



Summary

- Reversible SOFC/SOEC shows logical promise for storing renewable electricity/energy
- But for a near-term target, it is more applicable to distributed/decentralized storage applications
- Due to the different operation mechanisms between SOFC and SOEC, cell materials developed for SOFC may not be suitable for SOEC applications
- SOECs typically show a higher degradation rate than SOFCs
- MSRI has investigated and developed high-performing material sets for reversible SOFC/SOEC applications
- With knowledge gained from the accumulated 10,000 stack-hours tests, MSRI has successfully reduced the SOEC stack degradation rate from initial 30%/1000hrs to <2%/1000hrs
- Fundamental studies of cell materials are needed to further improve reversible SOFC/SOEC performance

Acknowledgements

- The SOEC degradation study is funded by the Idaho National Laboratory
- Support from Drs. Manohar Sohal, James O'Brien, Carl Stoots and Stephen Herring at the Idaho National Laboratory is much appreciated

Appendix D

Progress on the Development of Reversible SOFC Stack Technology

Mr. Casey Brown, Versa Power Systems

Versa Power Systems

Progress on the Development of Reversible SOFC Stack Technology

Presented by: Casey Brown

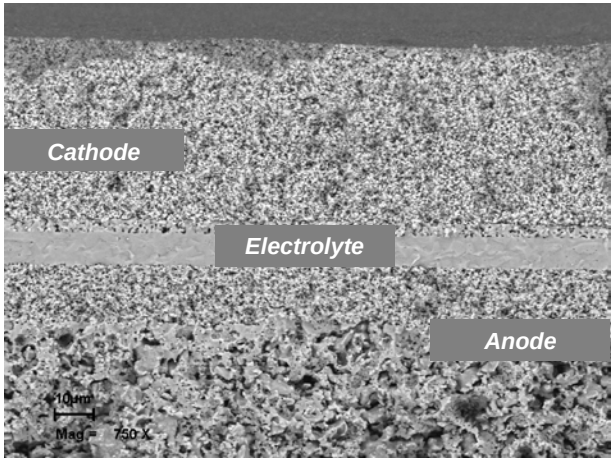
19 April 2011

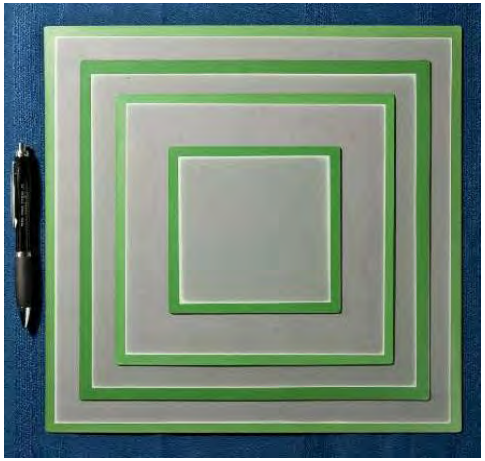
Versa Power Systems

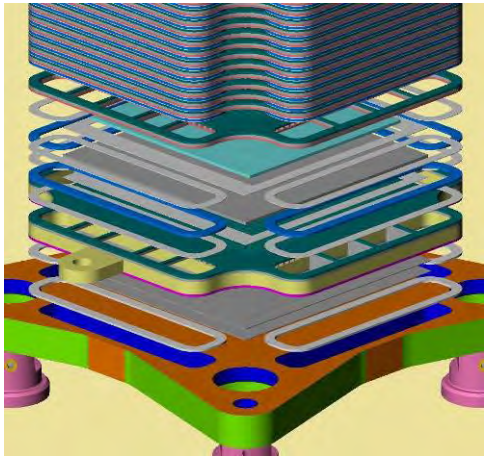
- **Versa Power Systems is a developer of planar solid oxide fuel cells (SOFCs)**
- **Privately held company headquartered in Littleton, Colorado, United States**
- **SOFC development facility in Calgary, Alberta, Canada**
- **Activities in both stationary and mobile SOFC development**

VPS Planar SOFC Cell and Stack

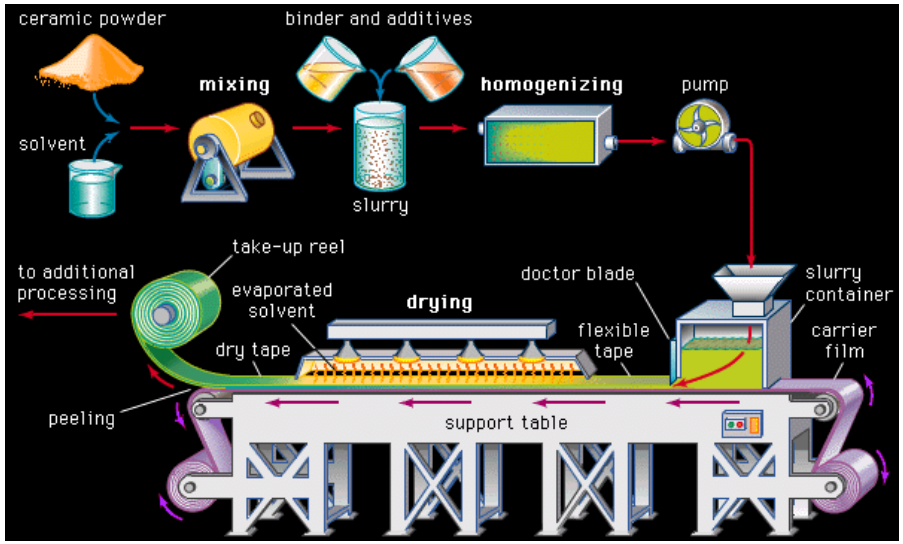
- Anode supported cells
- Operating temperature range of 650 C to 800°C
- Ferritic stainless steel sheet interconnect
- Cross-flow gas delivery
- Stack can be integrated into stack towers for various power applications



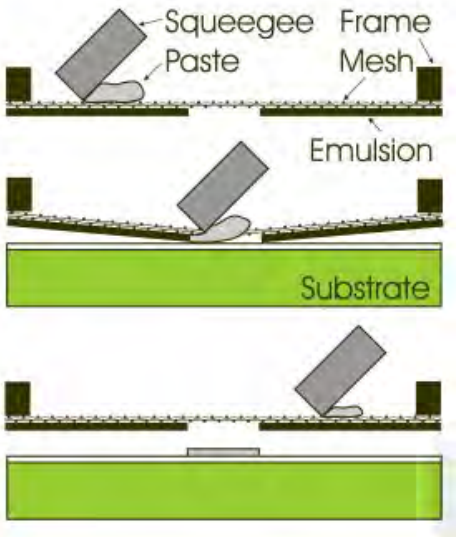




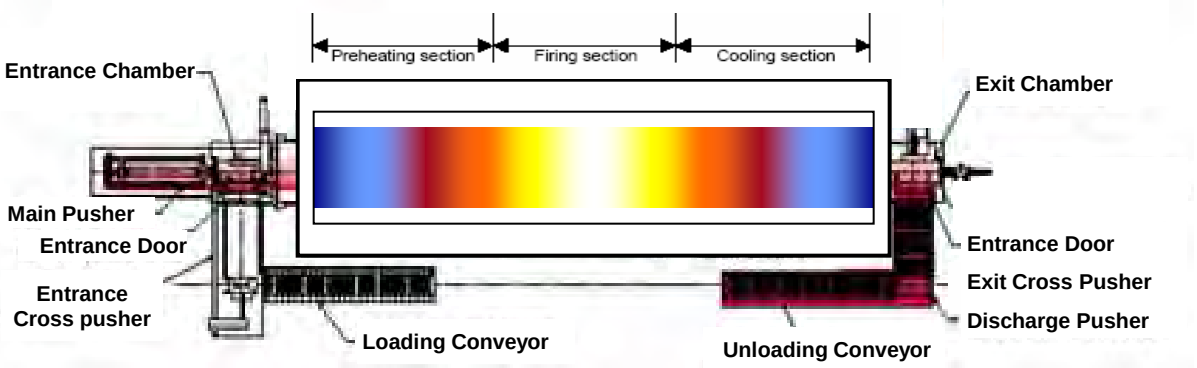
Tape Casting



Screen Printing



High Temperature Co-firing



TSC Cell Microstructure

VPS Processes

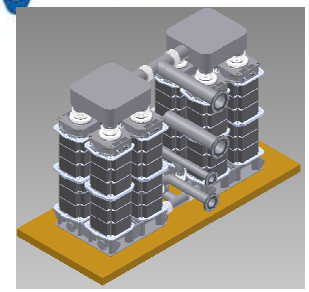

Tape Casting

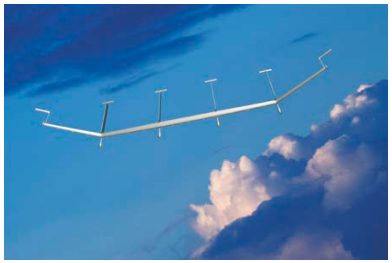

Screen Printing


Co-sintering

- **The established processes proved flexible enough to allow more than 8X increase in cell active area (121 → 1000 cm^2) without appreciable change in performance or yield**
- **25 x 25 cm^2 cells (550 cm^2 active area) are being used for SECA stack development**

VPS Activity Areas

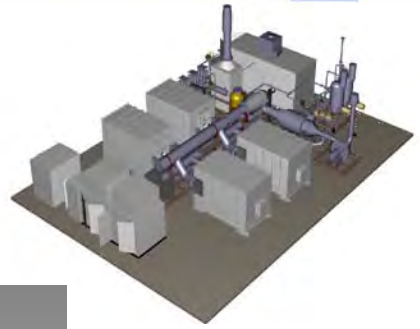




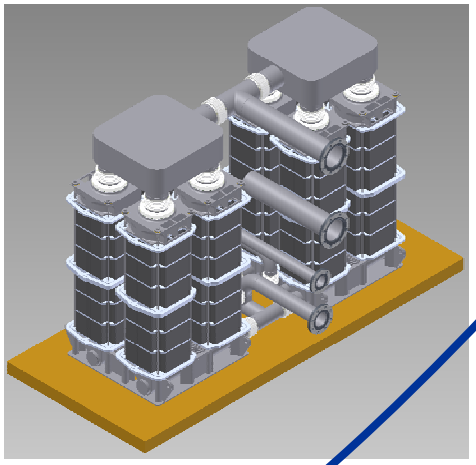
- US DOE Fossil Energy SECA
  Development and supply of SOFC technology for operation on gasified coal
  - Scale-up and R&D of SOFC for Coal-Based SOFC systems
  - Large area cells and high kW stacks
- Boeing // DARPA
  Vulture II : 5 year autonomous aircraft
  - Development and delivery of high efficiency energy storage system
  - High specific power
  - Low degradation
- US DOE EERE
  Advanced Materials for RSOFC Dual Mode Operation with Low Degradation
  - Reversible SOFC materials development and demonstration
  - kW stack demonstration
- INL
  Solid Oxide Electrolysis 1-kW Stack Testing to Investigate Degradation
  - Demonstration of 1 kW electrolysis stack
- VTT (Finnish National Laboratory)
  Demonstration of 10 kW Natural Gas fired system
  - Supply of 10 kW Solid Oxide module for integration and testing with balance of plant

U.S. DOE SECA Project

VPS participates in the U.S. Department of Energy's SECA program with a goal of developing large-scale SOFC power systems (project prime is FuelCell Energy)



SOFC Power Module



Stack Tower

10-20 kW Stack

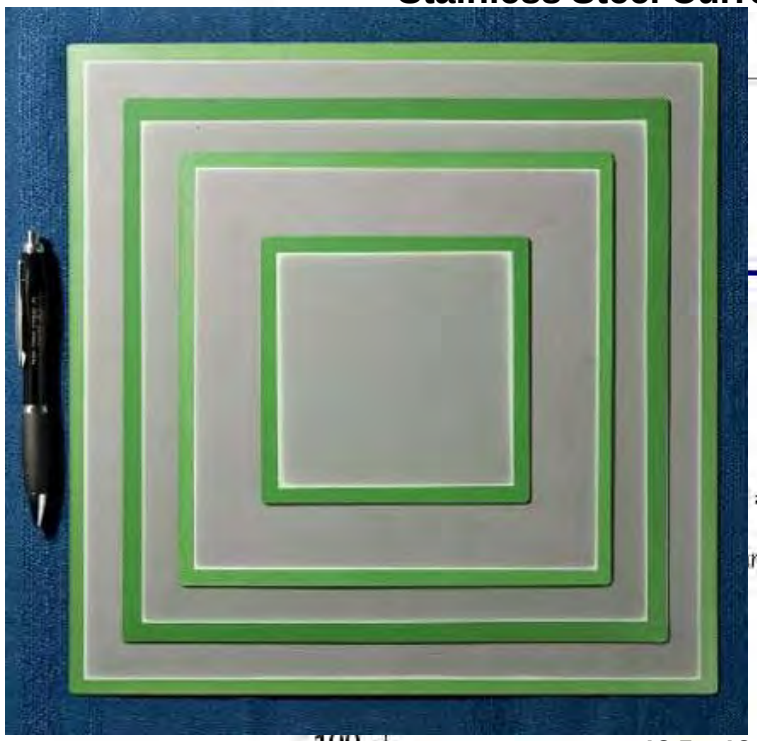
1 kW Stack

- VPS responsible for core cell & stack technology
- 25 x 25 cm^2 cell and 20 kW (96-cell) stack block has been selected as the development platform

FuelCell Energy

Cell Scale-Up Status

Stainless Steel Current Collectors, Cross-Flow Gas Delivery

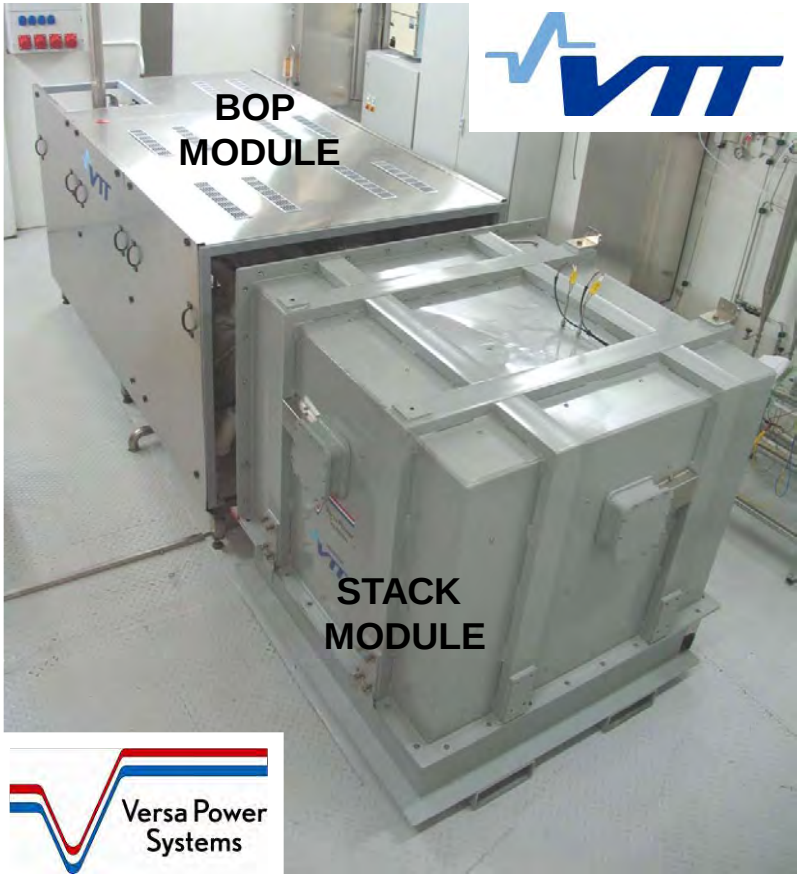


Power	49	72	214	346	612
Power Density	0.608	0.598	0.612	0.606	0.612

SECA

While not directly interested in electrolysis, the SECA program has enabled VPS to demonstrate scale up, performance and degradation improvements that could be applicable to electrolysis and energy storage systems.

10 kW SOFC Demo Unit



VPS has collaborated with VTT Technical Research Centre of Finland to produce a 10 kW fully integrated SOFC system

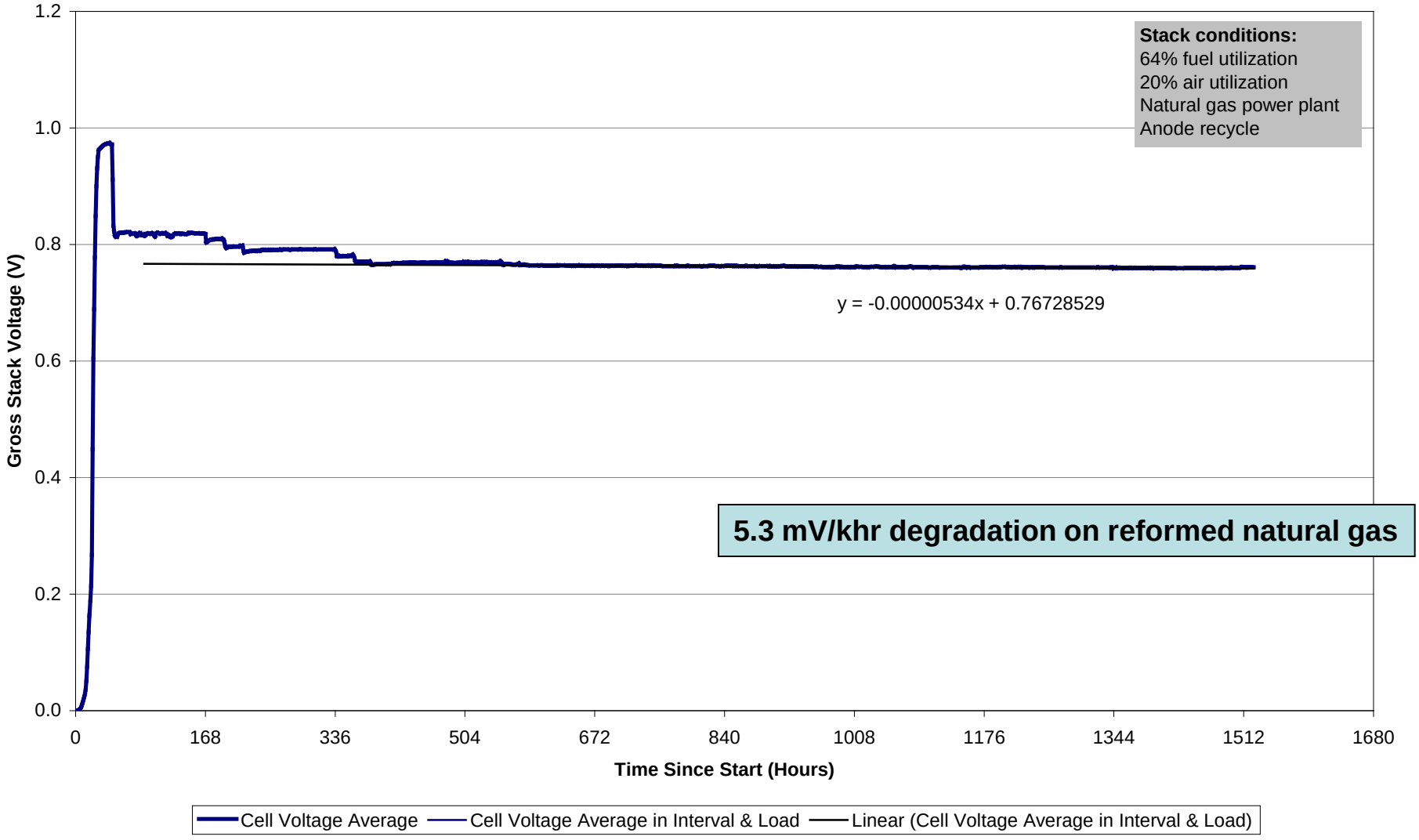
- VTT scope: system design & BoP-module
  - BoP-components: Heat exchangers, catalytic burner, reformer, recycle loop …
  - System control
- VPS scope: stack module
  - 10 kW class SOFC stack
  - Stack and module instrumentation
  - Assembled insulated vessel

Status:

- Modules integrated, operating, and meeting targets

10 kW System Demo Unit at VTT

VTT 10kW-2, System Test, Stack: GT057382-0005
Period Degradation, Hours: 589 - 1532 (943 h period duration)



Boeing / DARPA Vulture II

General Characteristics

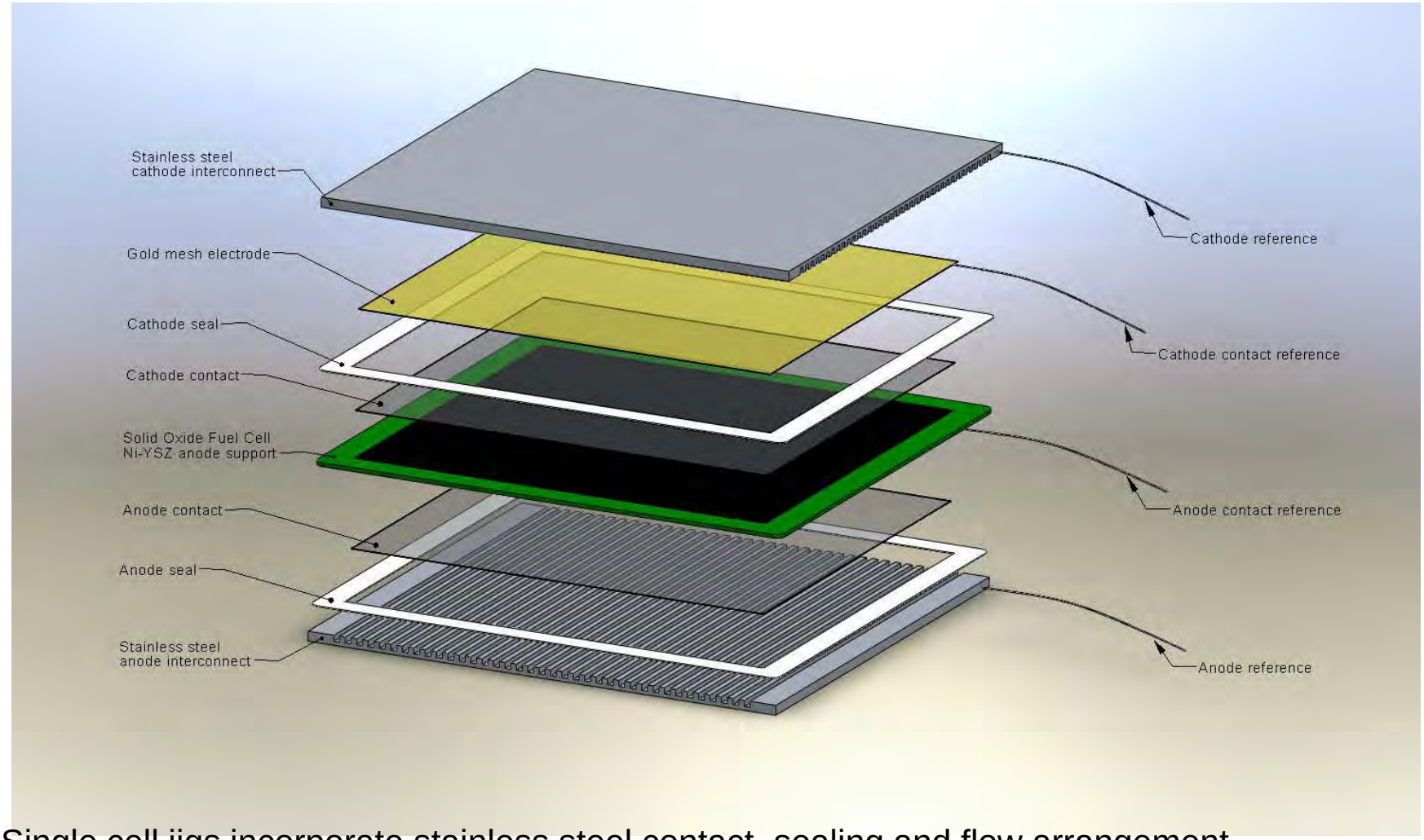
- Wingspan: 435 ft
- Altitude: 65000 ft
- Motors: solar/electric
- Endurance: 5 years
- Demonstrator first flight: 2014

- This is an aircraft program, not a fuel cell program. Reversible SOFC identified by Boeing as the best technology fit.
- VPS to deliver high efficiency, light weight, energy storage system

Single Cell Testing

Single cell testing allows controlled evaluation of new materials sets, and comparison to past results

Single Cell Testing at VPS



Single cell jigs incorporate stainless steel contact, sealing and flow arrangement representative of a stack

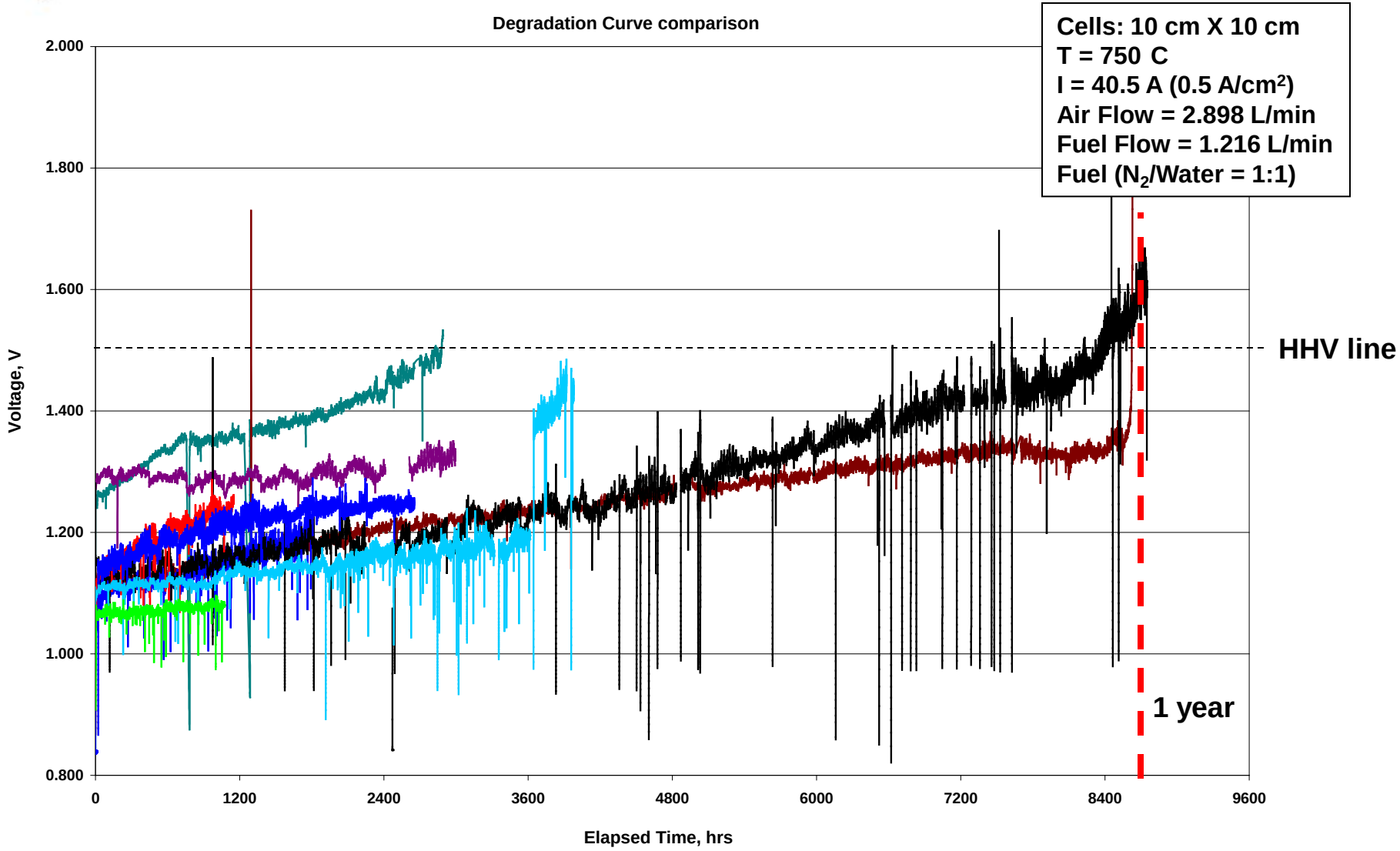
Degradation results include any jig degradation

Degradation Improvements

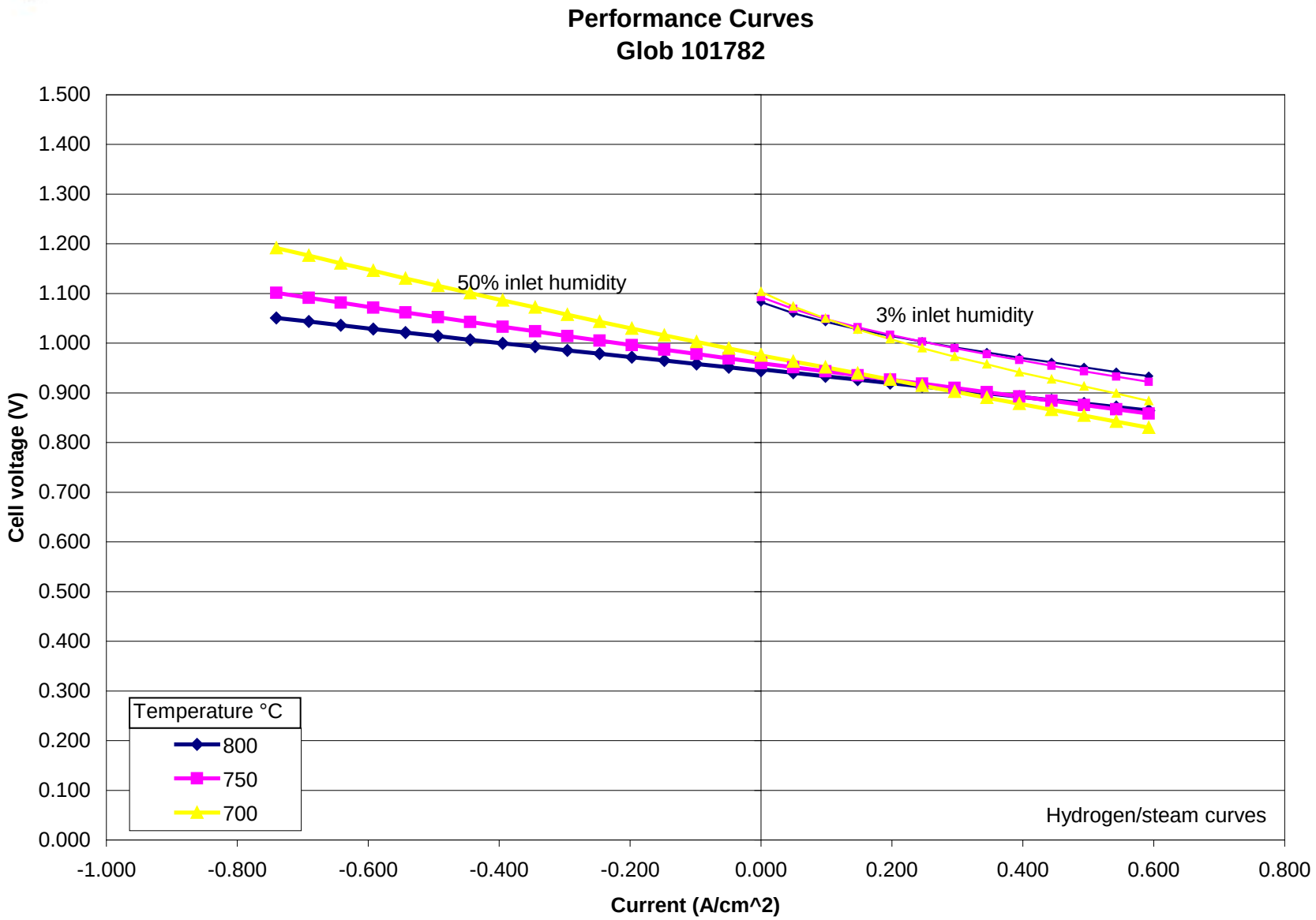
- 15 cell materials systems developed and tested since start of interest in electrolysis (~2008)
- 11 of these have been tested in excess of 1000 hours steady state electrolysis
- Summary of steady state results in table below
- Focus is now shifting to cyclic operation (FC/EL)

Cell Type	ELECTROLYSIS (SOEC)			Test No.
	Degradation		Test time (hours)	
	mV/1000 hrs	%/1000hrs		
TARGET	**< 50**	**< 4**	**1000**	**TARGET**
TSC-2	91	7.3	2893	GLOB 101670
EC-1	27	2.2	8465	GLOB 101695
EC-2	~0	~0	2400	GLOB 101706
EC-3	72	5.8	1792	GLOB 101728
RSOFC-1	35	2.8	8746	GLOB 101737
RSOFC-2	120	9.6	1152	GLOB 101738
RSOFC-3	42	3.4	2653	GLOB 101741
RSOFC-4	24	1.9	3618	GLOB 101744
MAC-RSOFC-5	51	4.1	1059	GLOB 101758
RSOFC-6	31	2.5	689	GLOB 101779
RSOFC-7	18	1.4	1071	GLOB 101780
RSOFC-8	24	1.9	498	GLOB 101782
RSOFC-9	25	2.0	1002	GLOB 101784

Some Electrolysis Holds



RSOFC Cell Development



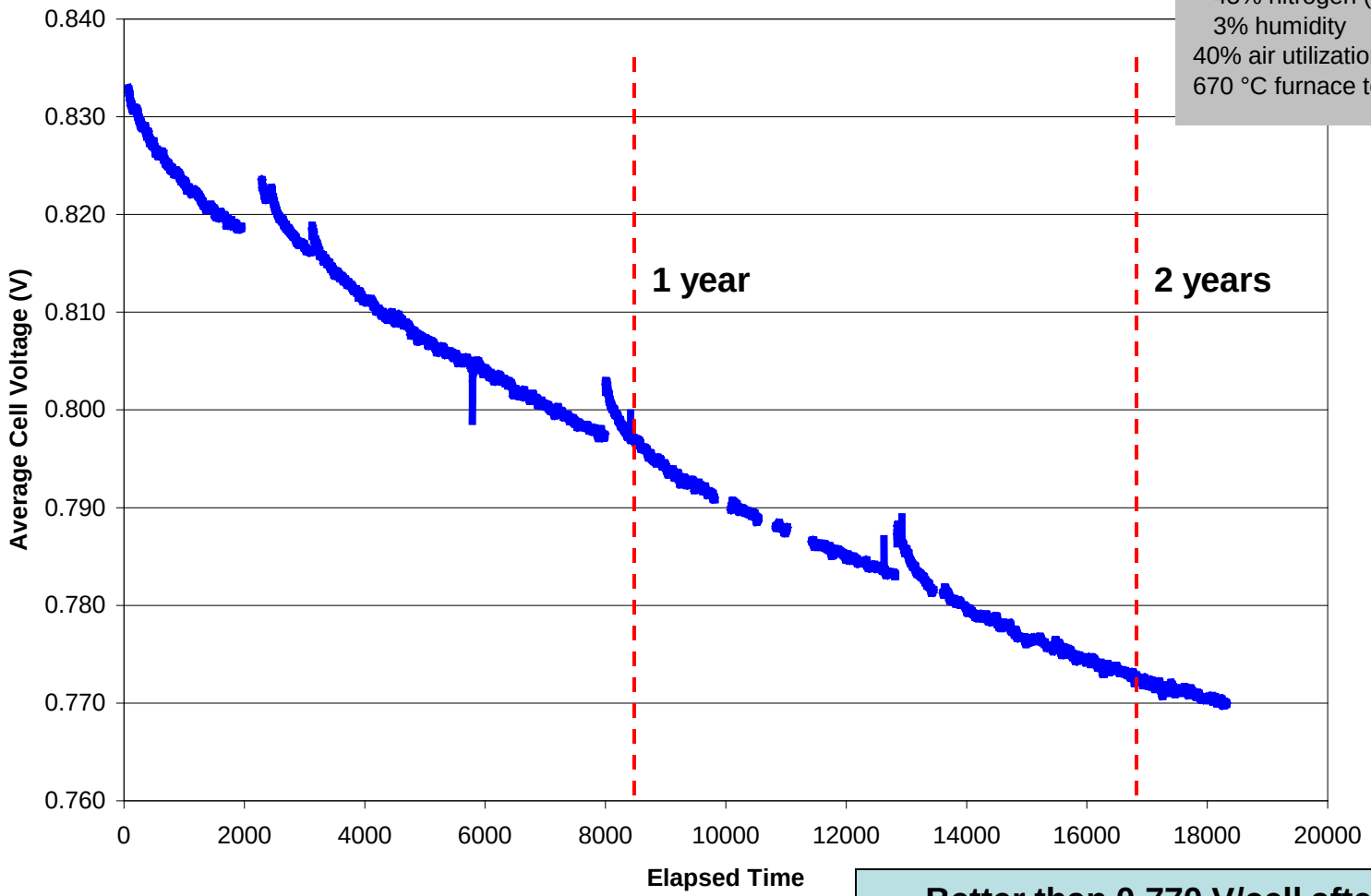
Stack Testing

In-stack testing demonstrates repeatability and stability of materials system in less controlled conditions than single cell

Stack Degradation (FC)

GT056019-0132 TC2 Hold - 09/Mar/09
28cell PCI - Test Stand 11

Conditions
0.37 A/cm^2
65% fuel utilization
55% hydrogen (dry basis)
45% nitrogen (dry basis)
3% humidity
40% air utilization
670 °C furnace temperature



Fuel Cell Mode Degradation: ~3.5 mV/khr

Better than 0.770 V/cell after 2 years
Projects to better than 0.7 V/cell at 4 years

Early Stack Degradation (EL)

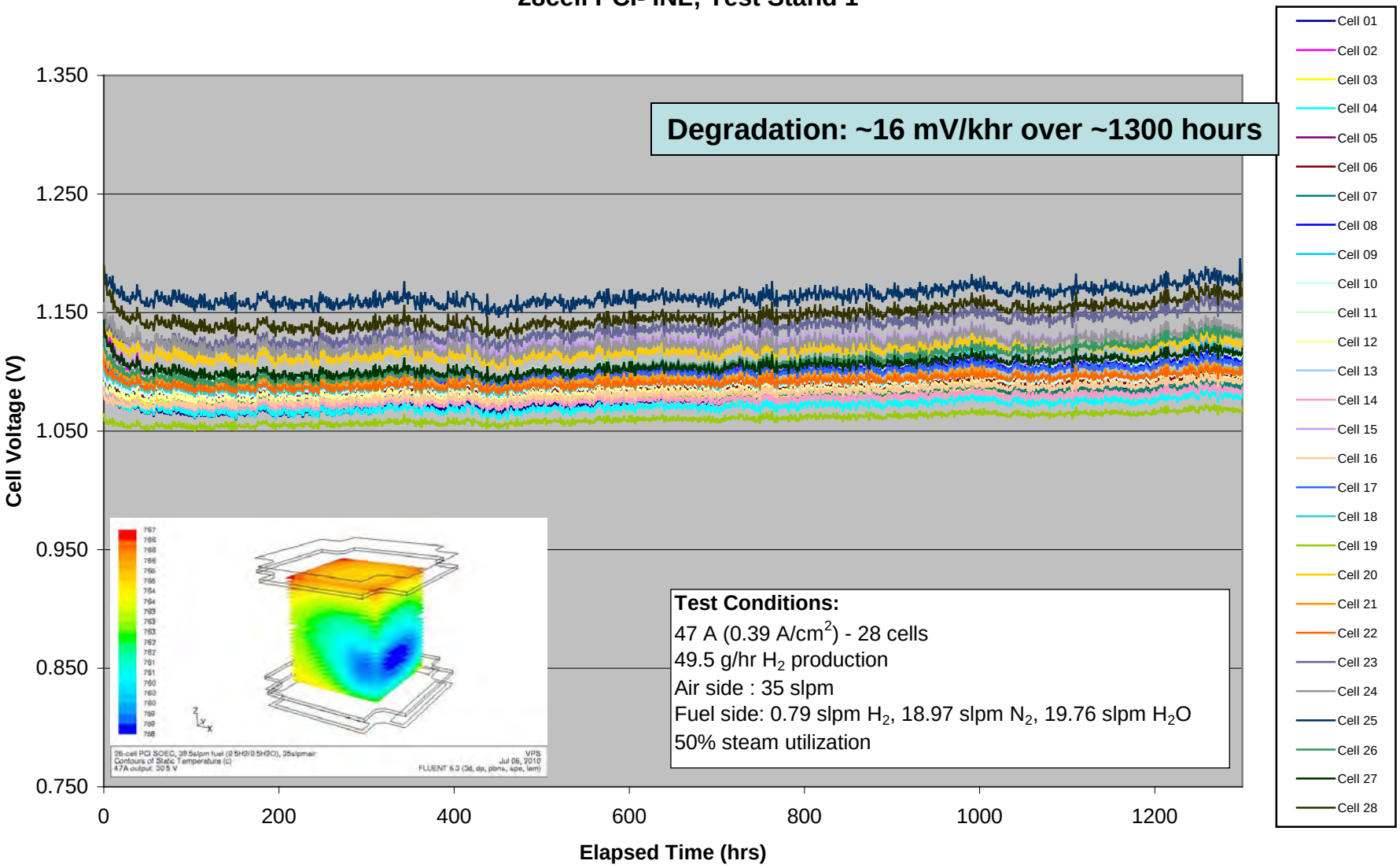
Test Conditions:
47 A (0.39 A/cm2) - 28 EC-1 cells
49.5 g/hr H_2 production
Air side : 47 slpm
Fuel side: 21.7 slpm H2, 21.7 slpm H_2O

Degradation: 48 mV/khr (3.8% /khr)
(includes a 25 mV step change at 1400 hours)

IRAD

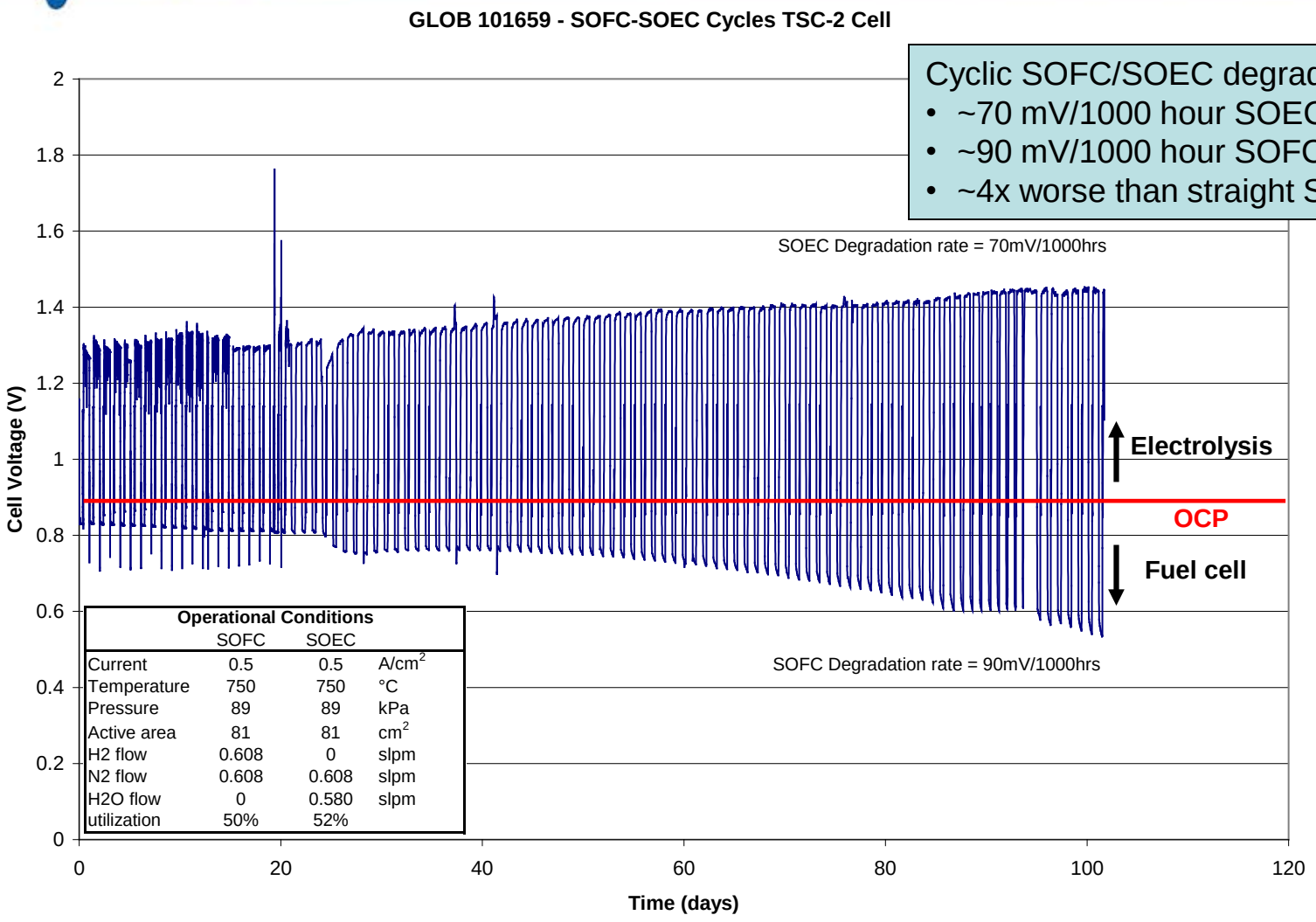
Stack Degradation (EL)

GT056019-0150 TC1 Hold - 23/Jun/10
28cell PCI- INL; Test Stand 1



Cyclic Testing (FC/EL cycles)

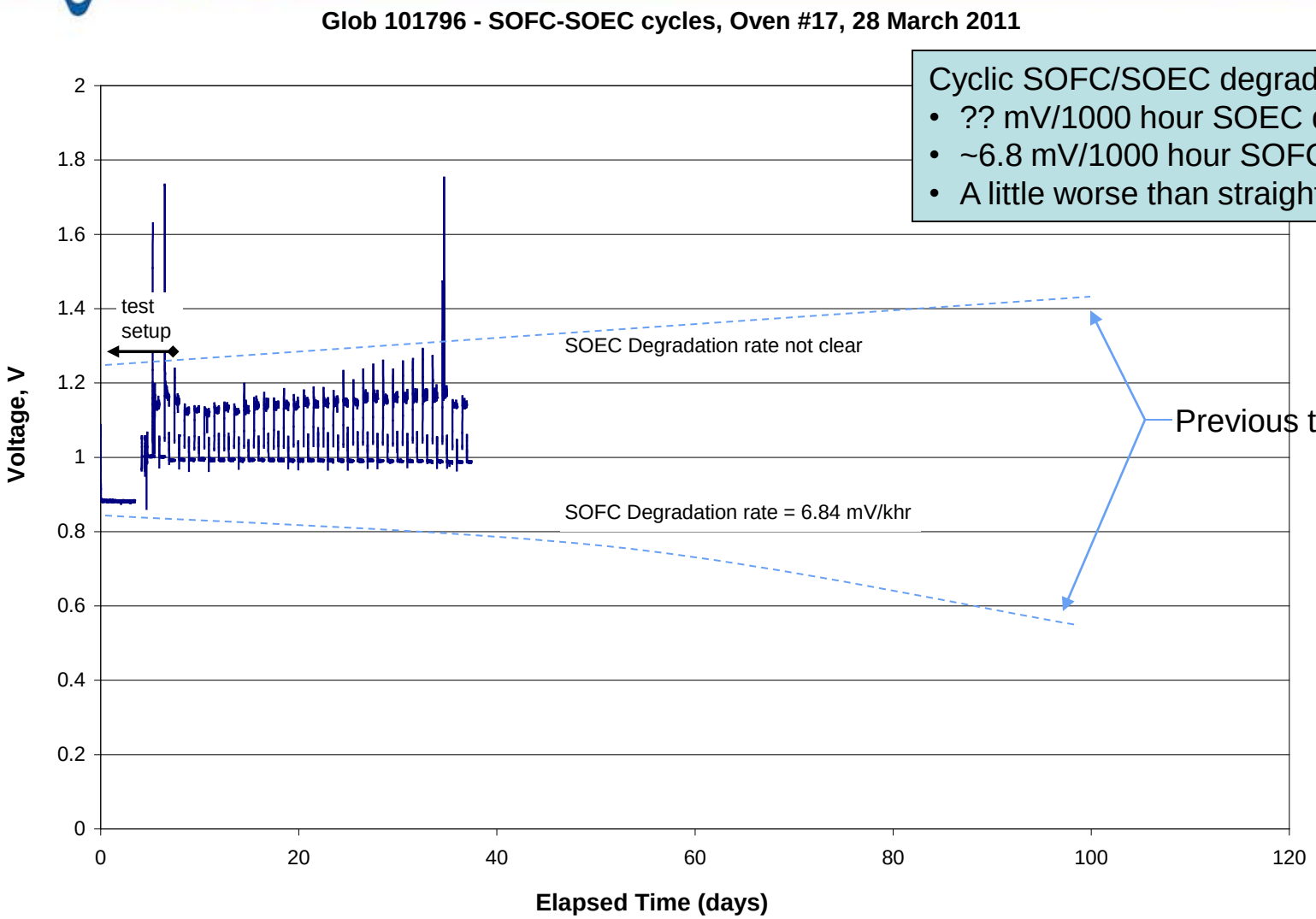
Early TSC2 Cyclic Testing



Cyclic SOFC/SOEC degradation
- ~70 mV/1000 hour SOEC degradation
- ~90 mV/1000 hour SOFC degradation
- ~4x worse than straight SOFC

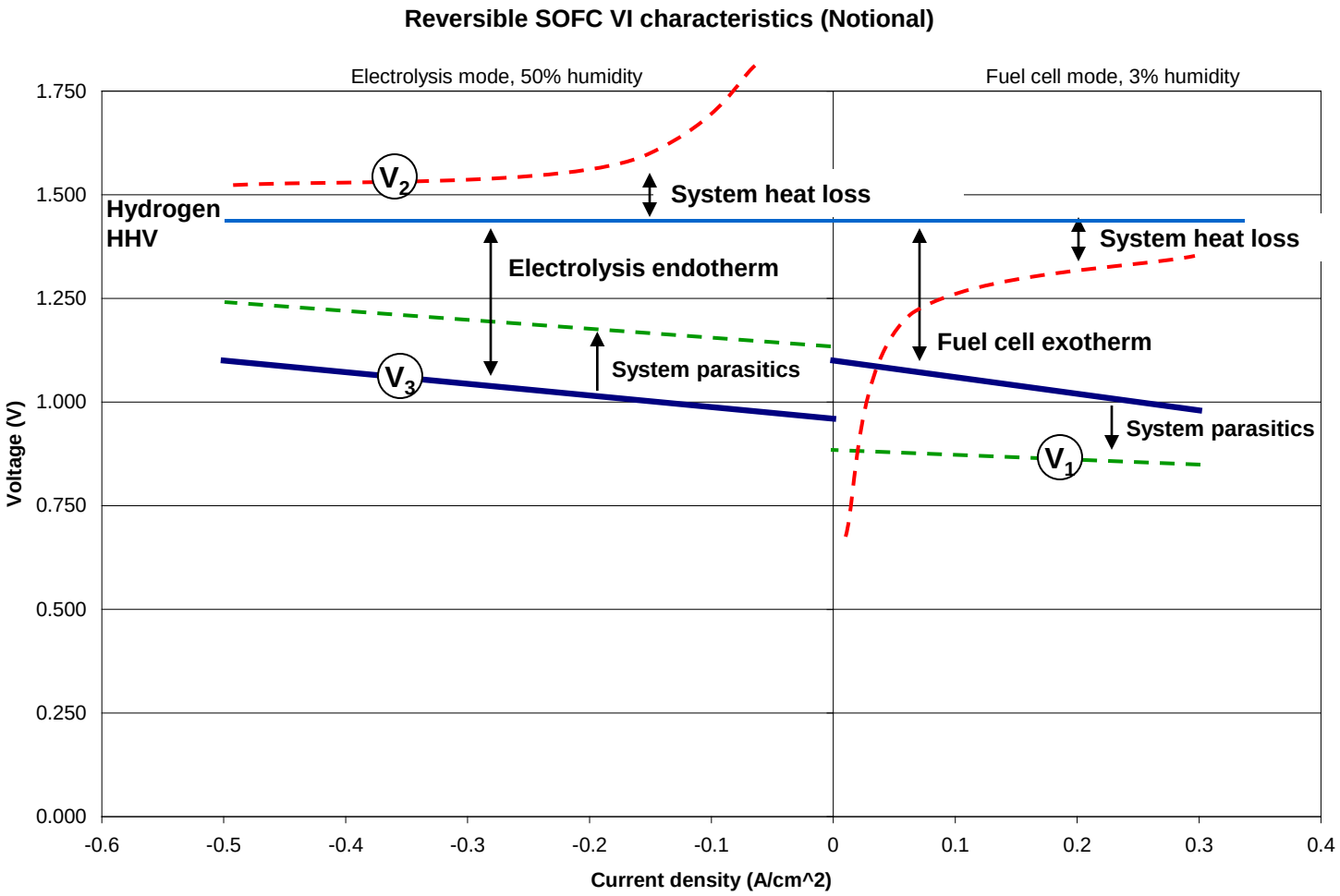
Compare to 91 mV/khr steady state EL degradation for material system
-> Cyclic operation does not appear to be driving degradation
-> EL degradation is showing up on FC portion of cycle

Ongoing Single Cell Test



Improved materials system delivering better than 10x improvement in cyclic impact on FC voltage
Uncertainty in real EL impact, more test time needed

Efficiency Review

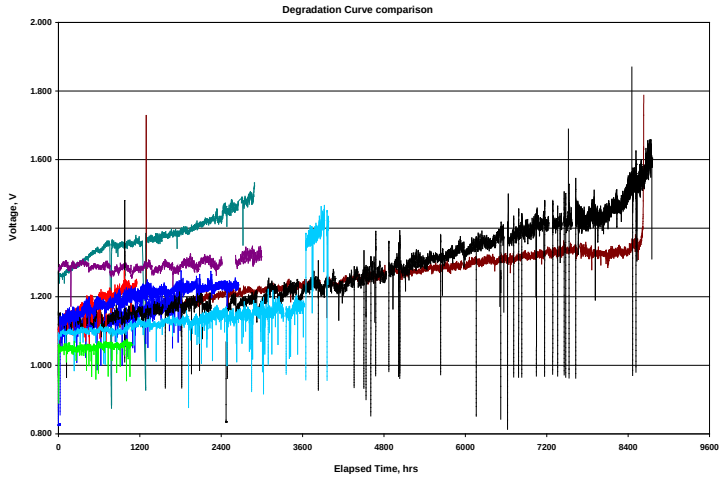


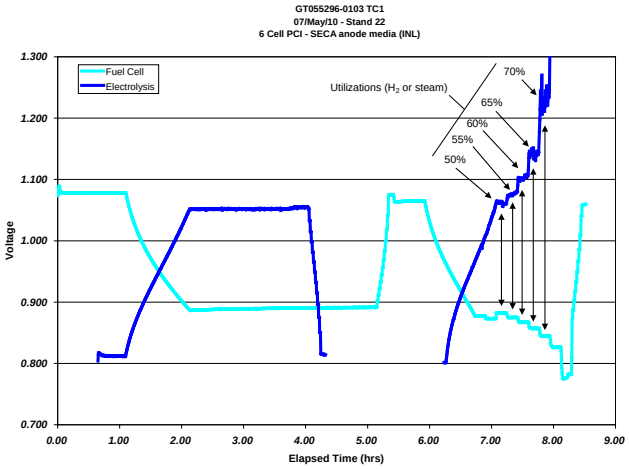
Round trip (storage) efficiency = V_1/V_2 (e.g.: 0.900/1.560 = 58%)
Maximizing efficiency requires focus on system heat loss (EL), fuel cell performance and system parasitics (FC)

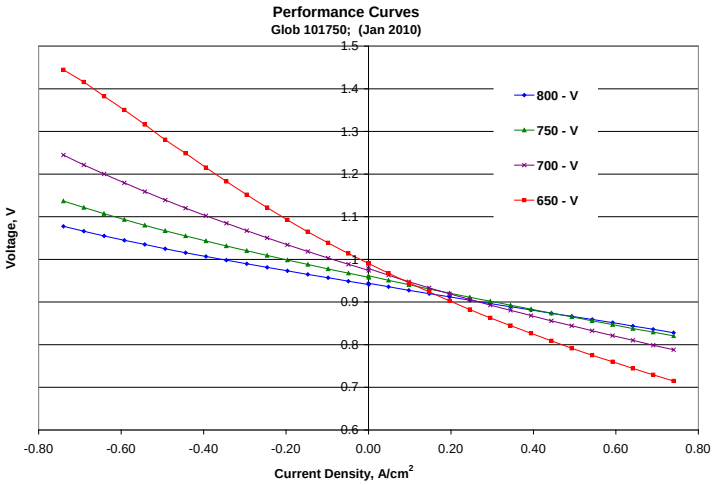
Degradation tolerance EL: $(V_2 - V_3)/dV$
e.g.: (1.560 – 1.100)/20 = 23 khrs (2.6 years)

Challenge Areas

- Compared to fuel cell history, VPS has relatively little EL experience
- Despite significant improvements, degradation remains higher in electrolysis than fuel cell
- Energy storage efficiency is strongly influenced by system design







Summary

1. Is this technology feasible for cost effective storage of renewable electricity?
   - A qualified ‘yes’

2. What are the materials and systems barriers to developing this technology?
   - Materials: Experience and confidence are lacking, but if demonstrated cell performance is stable and scalable, we already have 1+ year solutions. Degradation improvements always welcome
   - System: Need to understand real requirements, things like power profiles of different applications, in order to answer this. It would be nice to see demonstration systems running.
   - System: Low cost, high storage efficiency systems designs, that take advantage of SOFC potential.

3. What are the manufacturing issues that need to be addressed to be cost effective?
   - Solid oxide fuel cell: Build on SECA work, volume
   - System: ?

Acknowledgements

Thank you to the following funding agencies:

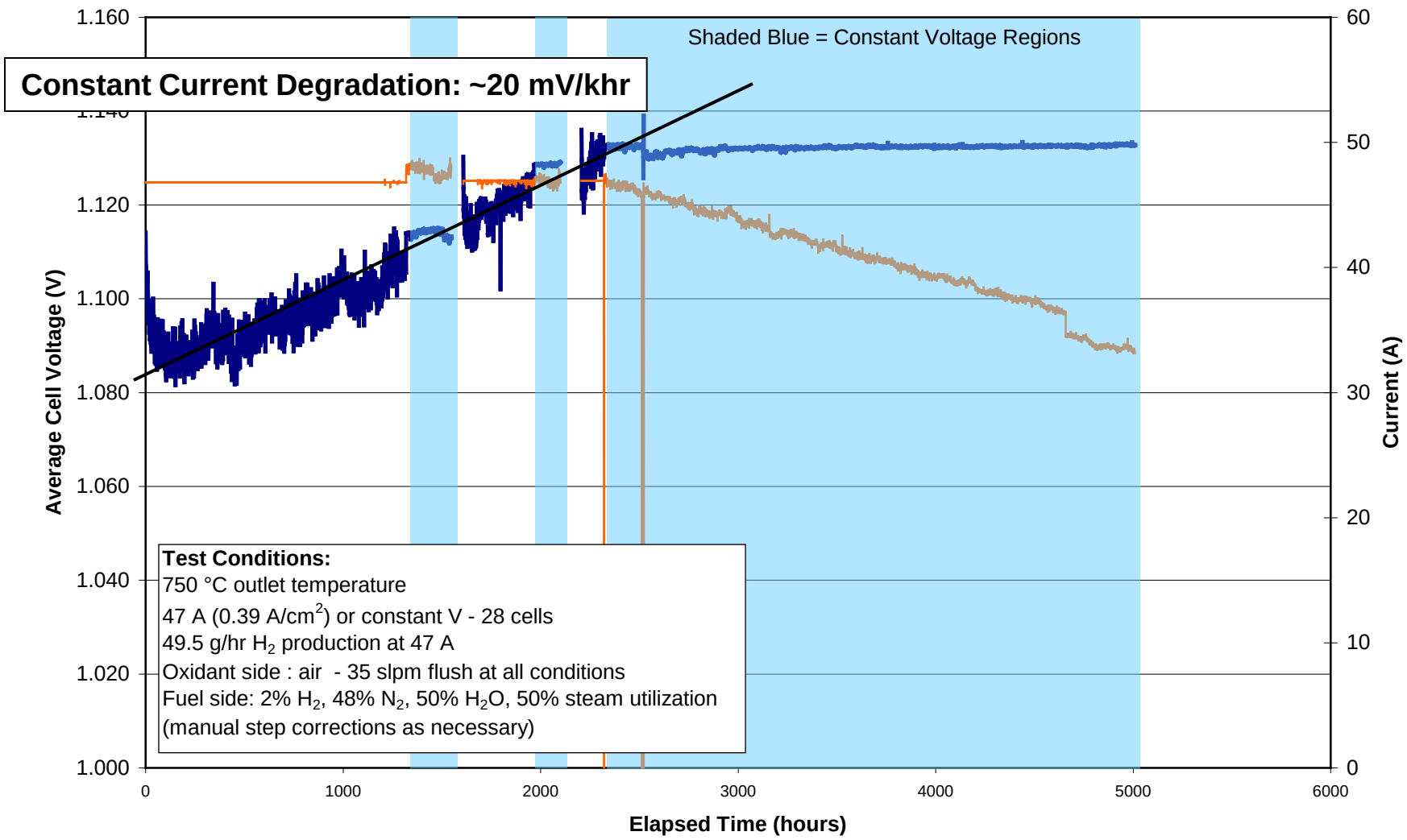
- US DOE Solid State Energy Conversion Alliance
- US DOE Office of Energy Efficiency and Renewable Energy Laboratory
  - FuelCell Energy (project prime)
- US DOE Idaho National Laboratory
- The Boeing Company (DARPA funded program)
- VTT Technical Research Centre of Finland
- Versa Power Systems internally funded R&D efforts

Thank you to the Versa Power Systems team

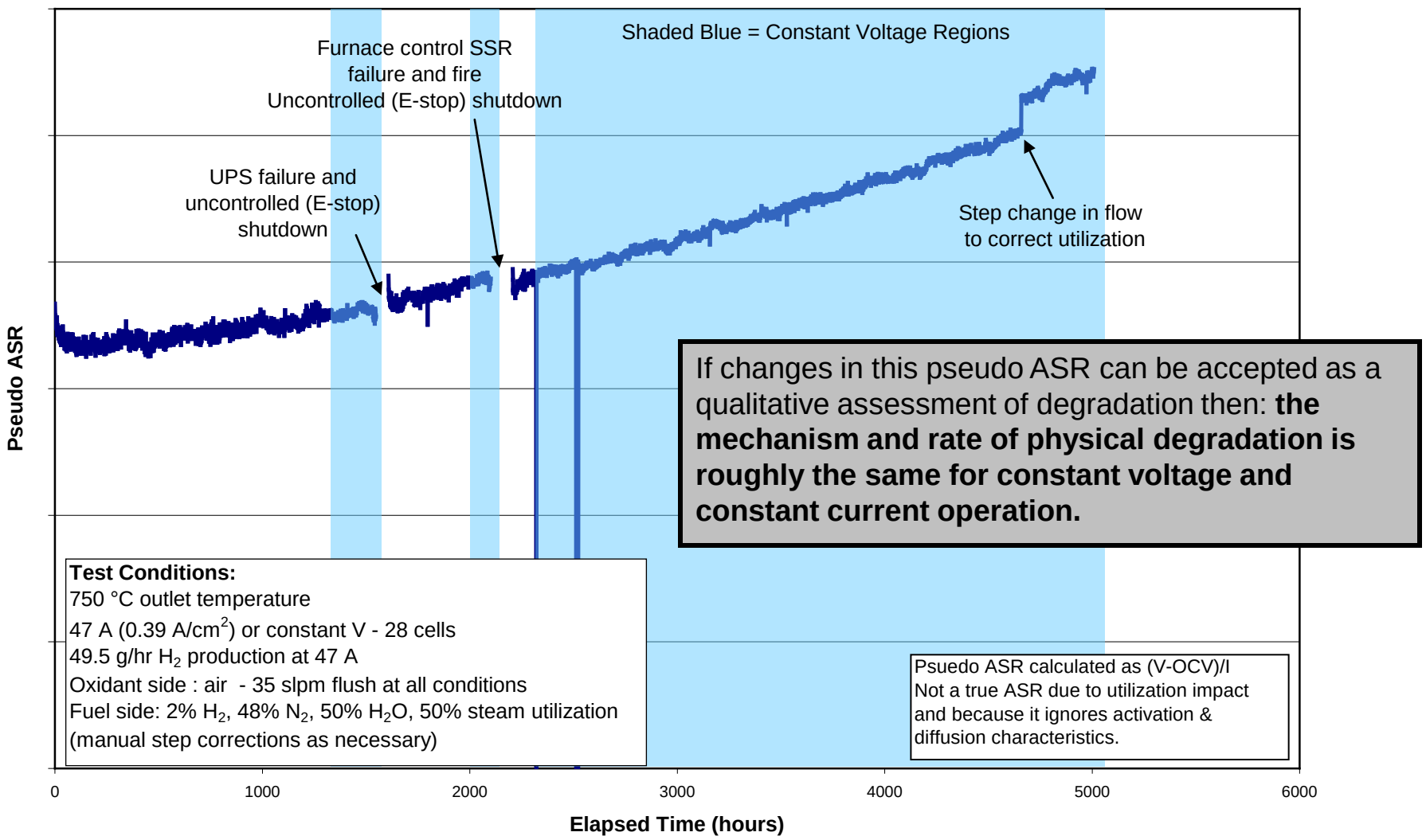
Versa Power Systems

Extra slides

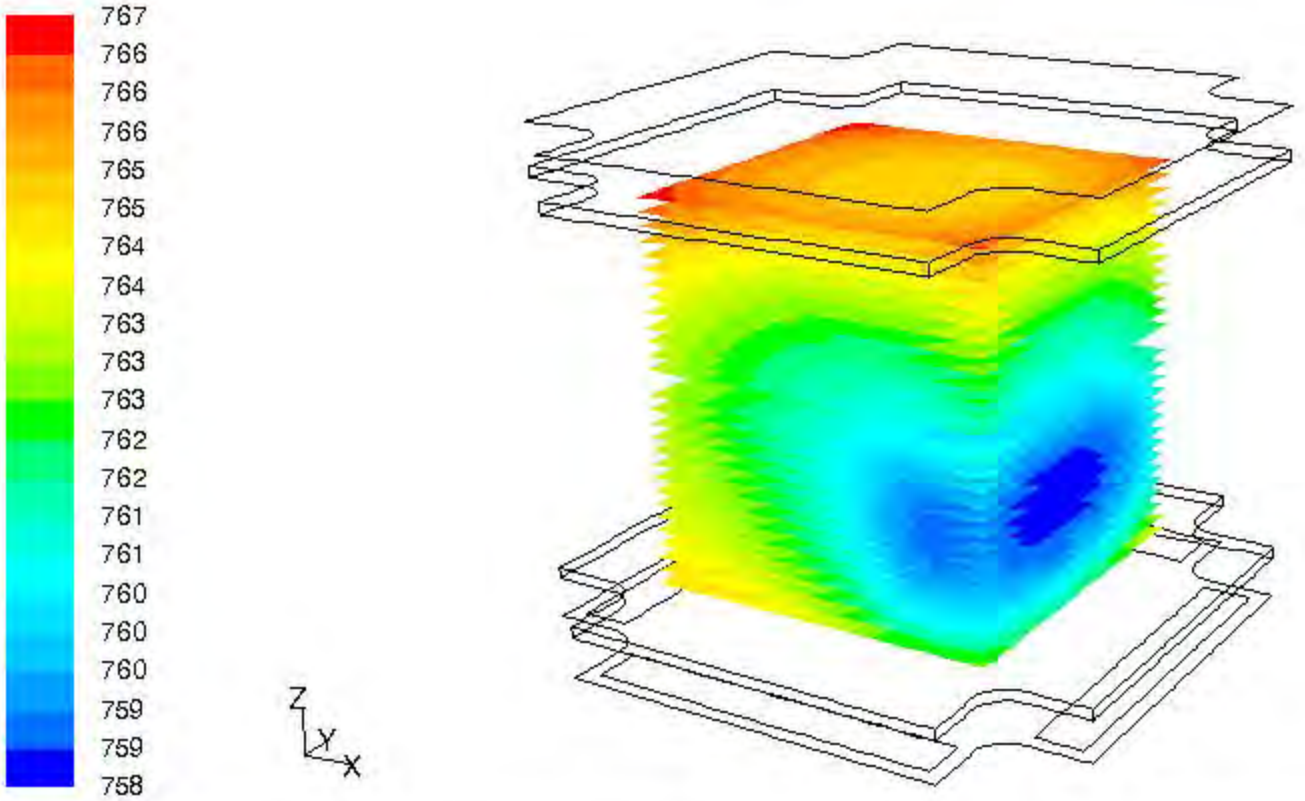
Longer Stack Data



Constant V vs I



Electrolysis Temperatures

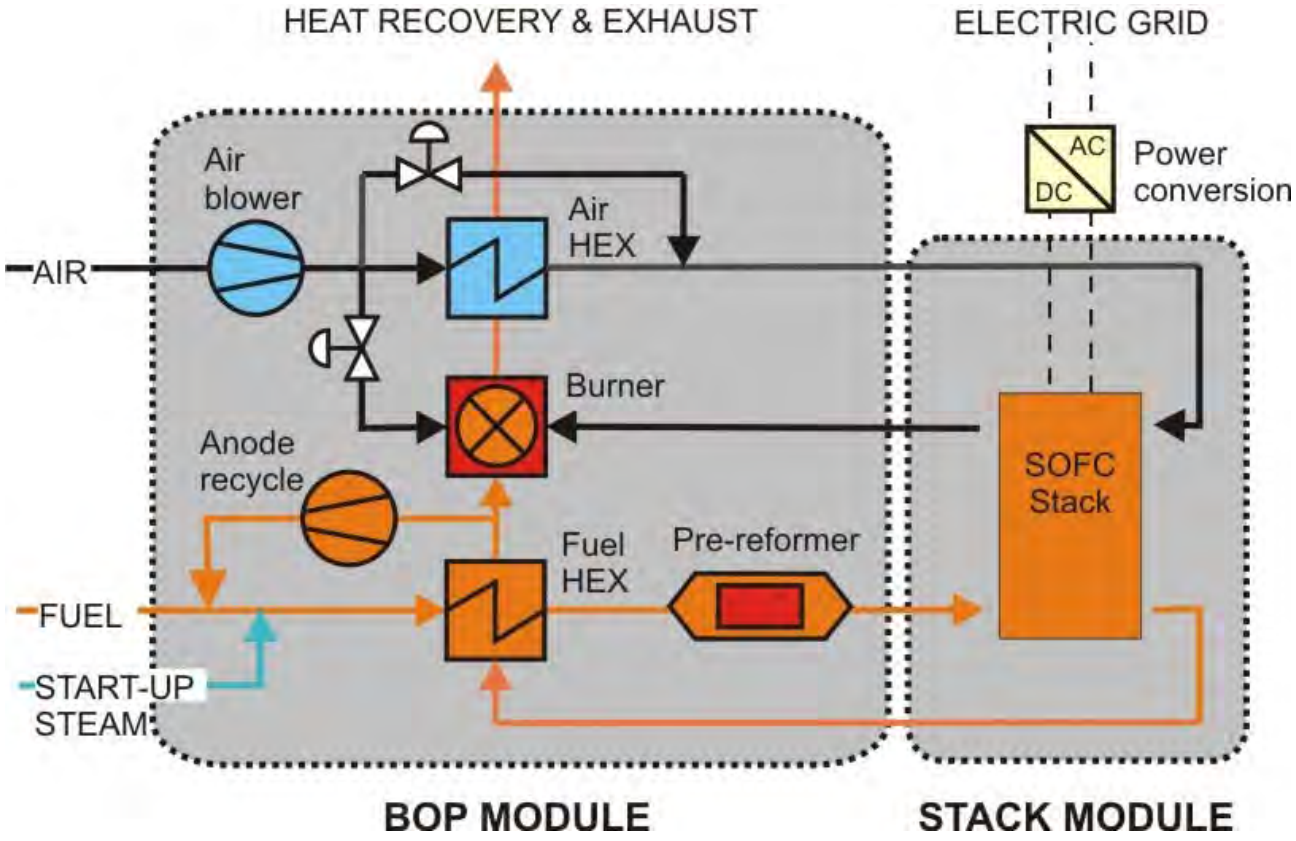


28-cell PCI SOEC, 39.5slpm fuel (0.5H2/0.5H2O), 35slpmair
Contours of Static Temperature (c)
47A output: 30.5 V

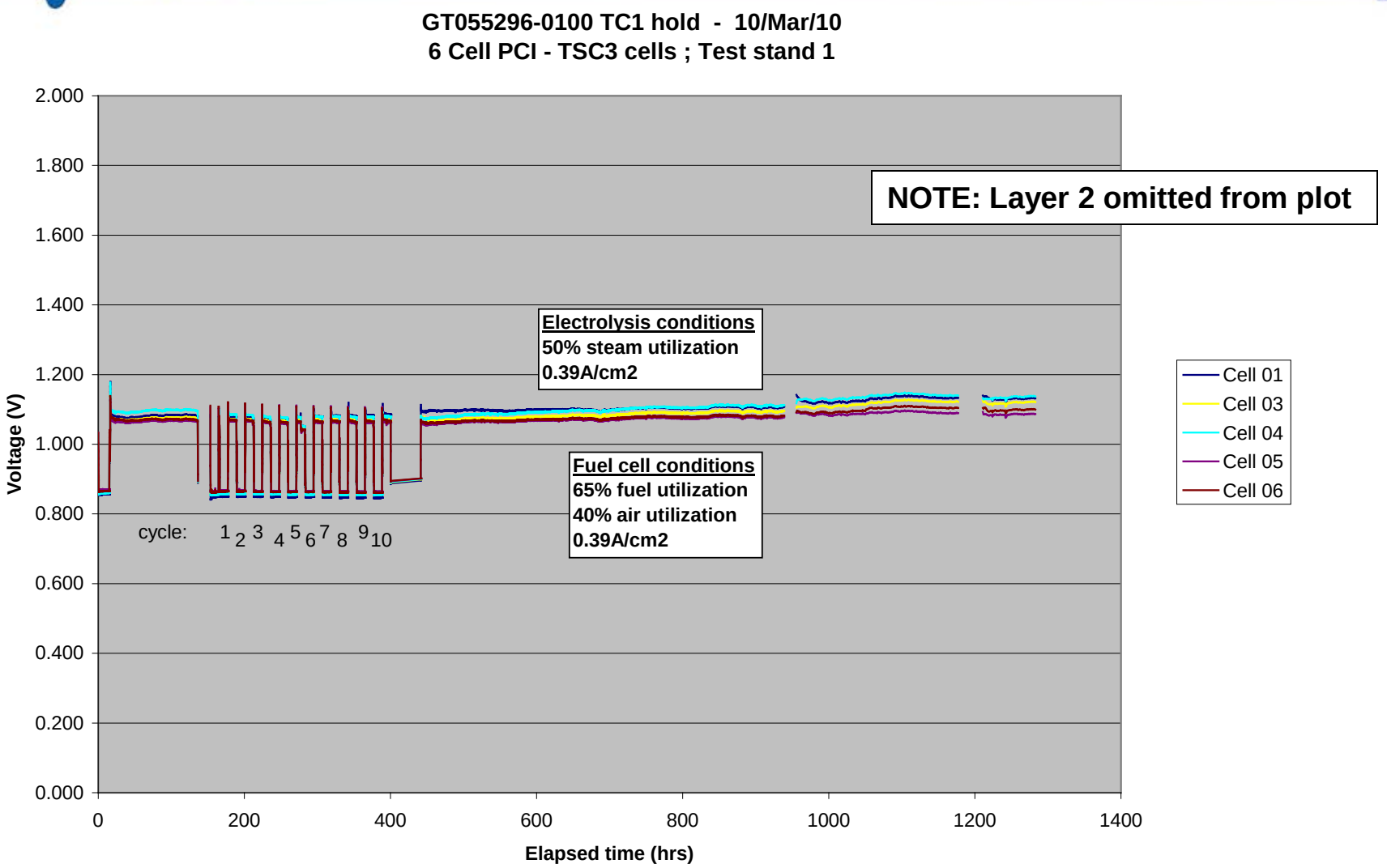
VPS
Jul 06, 2010
FLUENT 6.3 (3d, dp, pbns, spe, lam)

10 kW SOFC Demo Unit Layout

- **Modular design**
- **Natural gas fuelled**
- **Warm anode recycle loop**
- **Air by-pass to regulate stack and afterburner temperature**
- **Grid connected**
- **Thermally self-sustained**



Cyclic Testing in Stack



In stack, steady EL degradation again dominates
-> Results led to concerted focus on understanding and improving steady state degradation

Appendix E

Materials and System Issues with Reversible SOFC

Dr. S. Elangovan, CERAMATEC