# VII.C.4 Modular SOEC System for Efficient Hydrogen Production at High Current Density

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## Overall Objectives

- Demonstrate the potential of solid oxide electrolysis cell (SOEC) systems to produce hydrogen at a cost of less than \$2.00/kg $H_2$, exclusive of delivery, compression, storage, and dispensing.
- Improve SOEC stack performance to achieve >95% stack electrical efficiency based on the lower heating value of hydrogen (>90% system electrical efficiency), resulting in significant reduction in cost of electricity usage for electrolysis.
- Enhance cell and stack durability to enable dynamic load profiles associated with intermittent renewable integration.
- Design, fabricate, and test a >4 kg $H_2$/d SOEC proof-of-concept system validating the technical and economic objectives.

## Fiscal Year (FY) 2017 Objectives

- Validate electrolysis cell degradation rate of ≤4%/1,000 hours in tests of a single cell for greater than 1,000 hours.
- Develop electrolysis performance characteristic maps of system operating parameters to be used for optimization.
- Identify system design improvements by testing of a stack across a matrix of ≥5 operating points for >500 hours.
- Develop SOEC system design configuration to achieve >75% overall (thermal + electric) efficiency.

## Technical Barriers

This project addresses the following technical barriers from the Hydrogen Production section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan, subsection Hydrogen Generation by Water Electrolysis.

(F) Capital Cost

(G) System Efficiency and Electricity Cost

(J) Renewable Electricity Generation Integration (for central)

## Contribution to Achievement of DOE Hydrogen Production Milestones

This project will contribute to achievement of the following DOE milestones from the Hydrogen Production - Advanced Electrolysis Technologies section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.

- Milestone 2.9: Verify the BOP's ability to meet the 2020 system efficiency targets. (Q1, 2018)
- Milestone 2.10: Create modularized designs for optimized central electrolysis systems projected to meet 2020 capital and hydrogen production cost targets. (Q3, 2018)
- Milestone 2.11: Verify the stack and system efficiencies against the 2020 targets. (Q1, 2020)

## FY 2017 Accomplishments

- Baseline degradation testing of High Power Density (HiPoD) solid oxide electrolysis cell was completed over 4,500 h of continuous operation at 1 $A/cm^2$ and 2 $A/cm^2$ with degradation rates of 1.3%/1,000 h and 2.6%/1,000 h, respectively, after the initial stabilization period.
- Parametric tests of an electrolysis cell were performed, generating nearly 600 distinct voltage–current curves to determine optimal system operating conditions.
- Stack baseline parametric testing was completed for a range of nine separate operating conditions examined over a total of 1,750 h.

- The second iteration of the HiPoD cells, identified as Low Temperature Firing, were developed, manufactured, and have completed over 1,200 h of continuous long-term degradation testing.
- Baseline system design was developed and a system flowsheet was incorporated in a computer simulation program.
- Preliminary system simulation runs including heat and materials balances were completed.
- System parametric tradeoff analysis was initiated to investigate the impact of operating conditions and balance of plant (BOP) equipment on the system performance.

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## INTRODUCTION

The overall objective of the project is to demonstrate the potential of SOEC systems to produce hydrogen at a cost of \$2.00/kg $H_2$ or less (excluding delivery, compression, storage, and dispensing). An additional objective of the project is to enhance stack endurance and impart subsystem robustness for operation on load profiles compatible with intermittent renewable energy sources. Advanced high temperature electrolysis systems are able to vary the composition of energy input between thermal and electrical energy which offers the possibility of upgrading low value waste heat into high value hydrogen. This feature enables an SOEC system with extremely high electricity-to-hydrogen conversion efficiency, which is not feasible by conventional low temperature electrolysis.

The project work plan, focused on achieving the techno-economic targets, includes research and development in a wide range of disciplines covering from cell performance and stability improvements through system design, modeling, optimization, and performance verification. Cell and stack endurance are planned to be improved by reducing cell degradation rates to <1%/kh and stack degradation to <2%/kh. These reduced degradation rates will be achieved at current densities greater than 1 A/cm$^2$ to meet capital cost targets. System efficiencies will exceed 95% stack electrical efficiency, 90% system electrical efficiency and 75% total (electric + thermal) efficiency. This corresponds to less than 37 kWh electricity consumed per kilogram of hydrogen produced, with the remainder of energy supplied thermally. A modular system architecture will reduce system cost, increase scalability, and impart the required flexibility and robustness to operate on dynamic load profiles such as those supplied by intermittent energy sources.

## APPROACH

The approach to meeting the objectives of the project consists of both cell and stack technology development as well as system design and verification.

Cell development activities include materials development, single-cell testing, and post-test microstructural analysis. In particular, the optimal intersection between system operational parameters, cell performance, and degradation will be thoroughly investigated. This includes the effect of inlet steam concentration and utilization, operating temperature, current density, system pressure, flush gas composition, and load cycling effects. Stack development efforts will focus on manufacturability and thermal management. A novel stack architecture will be utilized for electrolysis operation at moderate current density (1–2 A/cm$^2$). Stack manufacturing, testing, and validation will seek to demonstrate a 4 kg $H_2$/d production rate at greater than 95% electrical efficiency with less than 2%/1,000 h degradation.

System development and techno-economic analysis will focus on system architecture, operational parameter selection, and tradeoff analyses to determine an optimal system layout and operating regime. Due to the broad range of potential operating conditions, a baseline system will be developed for comparison purposes in the examination of potential system architectures. Quantitative comparative metrics will be developed to determine the relative effects of different operating conditions on the overall system performance, cost, and flexibility. A breadboard demonstration system (>4 kg $H_2$/d) will be designed, manufactured, and tested to validate the system performance. Finally, techno-economic analyses will be performed throughout the system development process to investigate the cost and performance impact of system operation parameters and layout.

## RESULTS

Work was focused on characterizing the performance and degradation behavior of the HiPoD cell across a broad spectrum of system relevant conditions. Steady-state degradation tests of the electrolysis cells completed over 4,500 hours of operation at 1 A/cm$^2$ and 2 A/cm$^2$, showing degradation rates of 1.3%/1,000 h and 2.6%/1,000 h, respectively, well below the 4% value as the upper limit target. The microstructure of the HiPoD cells, shown in Figure 1, is based on FuelCell Energy's recent cell technology using optimized porosity [1] which had demonstrated an unprecedented hydrogen production rate at 6 A/cm$^2$ and 78% electrical efficiency. A new generation of the cell design has been developed to reduce degradation rates further and is currently undergoing degradation testing with nearly 1,200 h of operation completed to date.

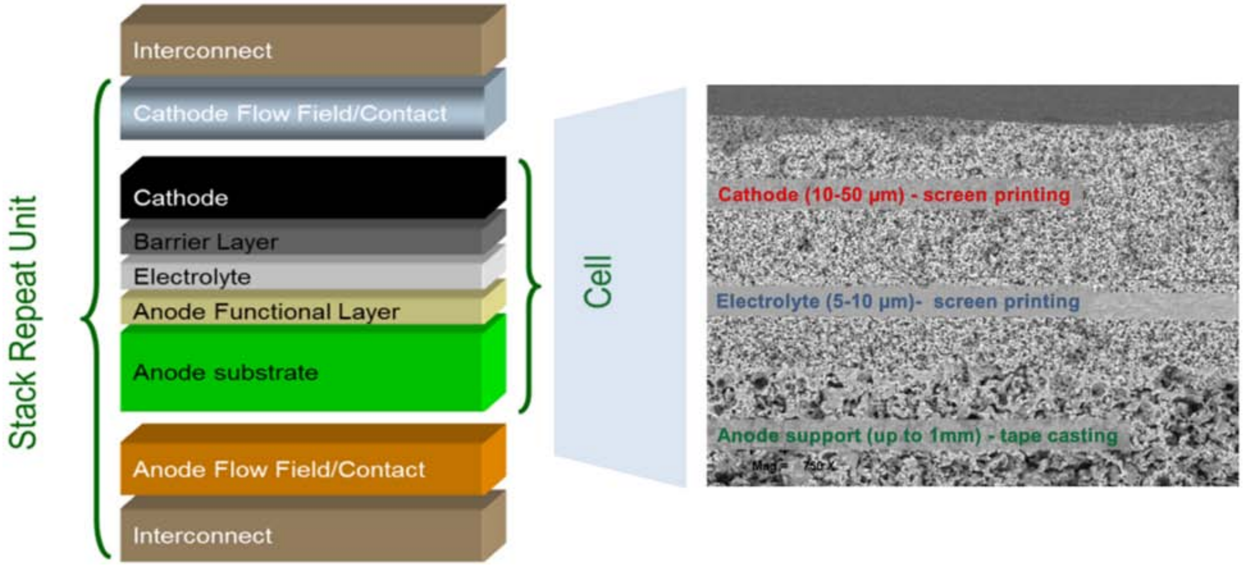


**FIGURE 1.** HiPod cell materials and architecture are based on FuelCell Energy's conventional tape cast/screen printed cell with nearly identical materials and proportions. A novel approach to optimization of the support layer porosity has demonstrated substantial performance improvements.

Parametric cell testing has generated nearly 600 distinct polarization curves across a wide spectrum of system operating conditions including pressure, inlet humidity, temperature, steam utilization, current density, and flush gas composition. The bulk effects of these independent parameters are summarized in Table 1, with a specific example of pressure dependence shown in Figure 2. A similar parametric testing effort was completed at the stack level with 1,750 h of testing across nine operating points, in order to establish a desirable and efficient operating window for the system design. Additionally, stack manufacturing validation of the hardware components for the Compact Stack Architecture stack [2], shown in Figure 3, has been initiated.

System level investigations have focused specifically on the effects of system operating parameters and system architecture on overall system efficiency and economic feasibility. Initial work was focused on first principles analysis of high temperature electrolysis and on the development of complete system process models. The

**TABLE 1.** Parametric Cell Testing Results

| Operating Parameter | Range | System Impacts at Higher End of Range |
|---|---|---|
| Current | 1–2 A/cm$^2$ (Target 1.1–1.32 V/cell) | 1- Reduced Stack Cost<br>2- Higher Stack Exit Temperature for Heat Recovery<br>3- Lower Stack Efficiency<br>4- Life Impact |
| Steam Utilization (Stack) | 50%–95% | 1- Simpler $H_2$ Purification<br>2- Lower Stack Efficiency |
| Steam Inlet Concentration | 40%–100% | 1- Higher Stack Efficiency<br>2- Less Recycle (Reduced BOP Cost)<br>3- Harder $H_2$ Purification<br>4- Potential Life Impact |
| Cell Pressure | 1–10 bara | 1- Higher Stack Efficiency (First ~4 bar)<br>2- Simpler $H_2$ Purification<br>3- Lower Stack Efficiency (Above ~5 bar)<br>4- Potential Life Impact |
| Anode $O_2$ Concentration (outlet) | 40%–100% | 1- Less Air Flow to Anode (Less BOP Cost)<br>2- Simpler for Pressurized Operation (Less BOP Cost)<br>3- Higher Voltage (Less Efficient) |
| Operating Temperature | 650°C to 800°C | 1- Higher Stack Efficiency<br>2- Potential Life Impact |

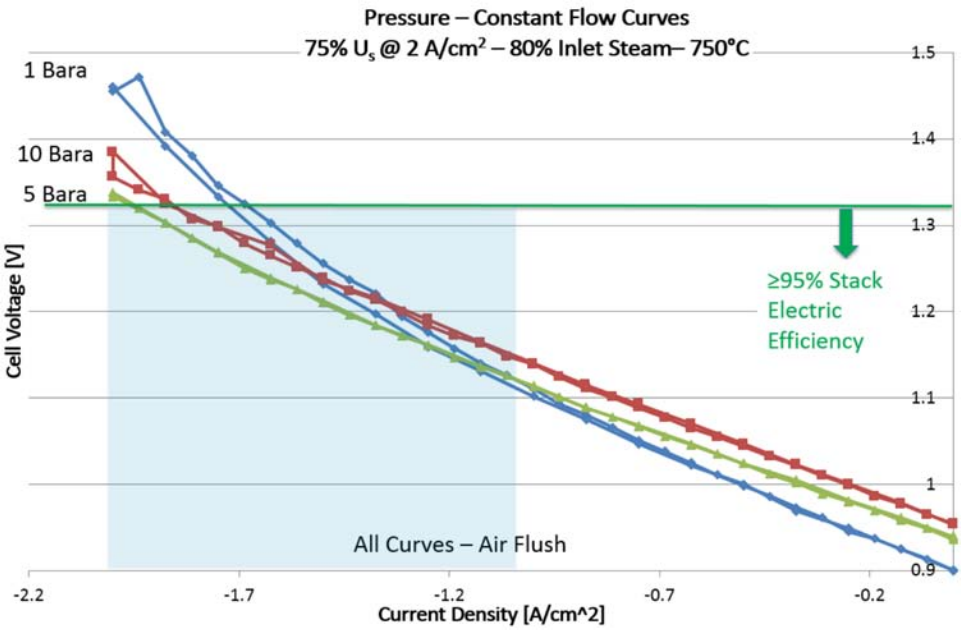


**FIGURE 2.** The impact of pressurization on cell performance in electrolysis operation. The higher pressure operation results in reduced cell voltage at low current densities (due to lower Nernst potential), whereas, yields higher voltage at increased current densities due to the decrease in activation and concentration losses.


**FIGURE 3.** The Compact Stack Architecture capitalizes on an automated manufacturing approach that enables high cell density and low material usage resulting in high volumetric and gravimetric power density while reducing cost.

baseline system process model, utilizing the process flow diagram shown in Figure 4, was completed. Work was also initiated on alternative system architectures and operating conditions in comparison with the baseline system to allow a quantitative tradeoff analyses to be performed.

## CONCLUSIONS AND UPCOMING ACTIVITIES

During FY 2017 work was initiated on cell, stack, and system level technology development and verification. Initial degradation measurements were performed and data collected was utilized for improvement of the cell technology for its durability. Cell and stack parametric testing across a wide range of potential operating conditions was completed and the resulting data is being utilized in the system design process. Finally the baseline system process model has been completed and tradeoff analysis is ongoing to determine optimal system architecture and operating conditions. Future work will focus on further improvements in cell and stack endurance, forecourt system optimization, and detailed system design for the >4 kg $H_{2/}$d breadboard demonstration system.

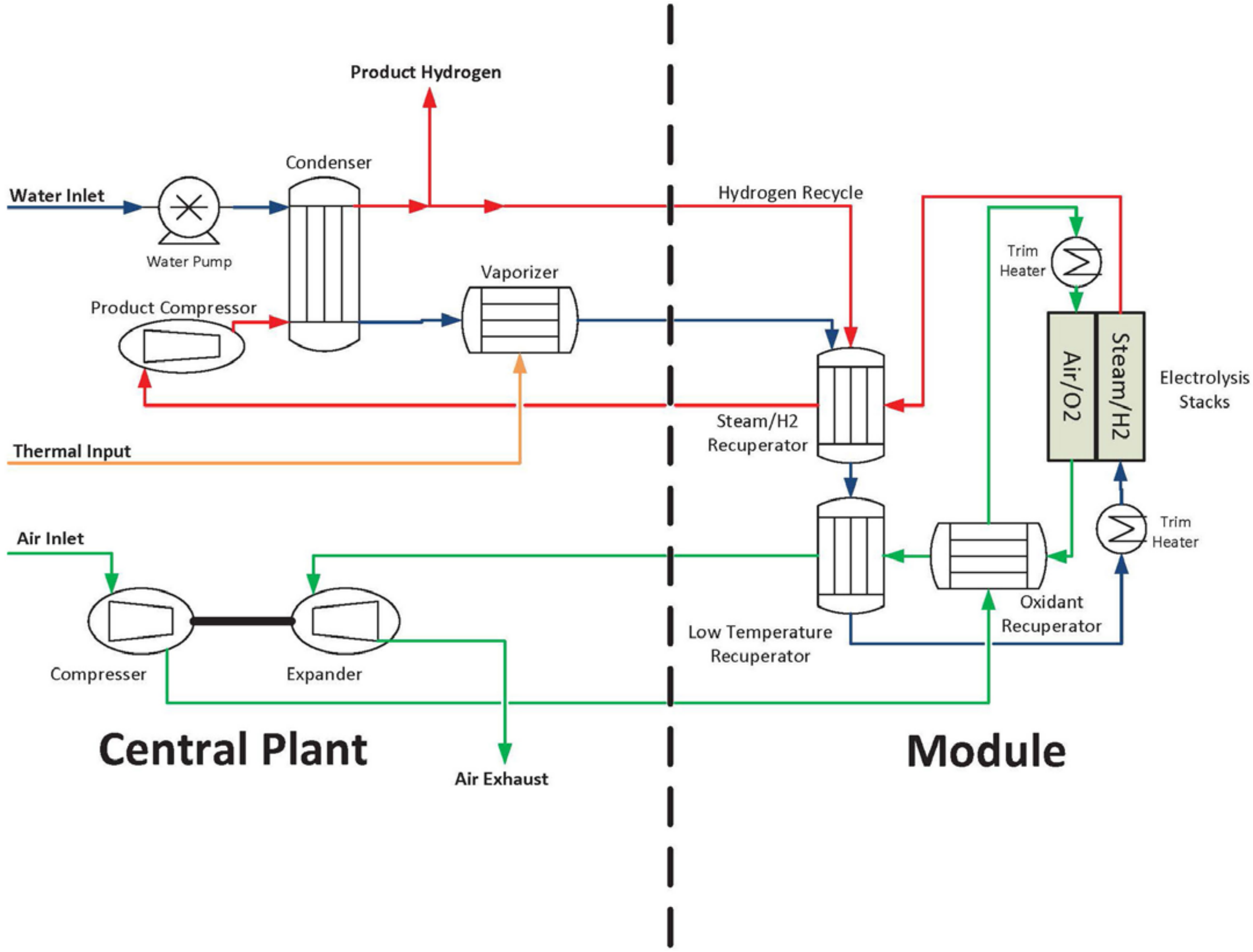


**FIGURE 4.** The modular system approach segregates system functions between "plant side" and "module side" to provide the optimal integration of unit operations while allow for system size scalability and operational flexibility. The baseline system utilizes a simple steam condensation approach for hydrogen separation.

## REFERENCES

**1.** A. Wood, H. He, T. Joia, M. Krivy, D. Steedman; "Communication—Electrolysis at High Efficiency with Remarkable Hydrogen Production Rates," Journal of Electrochemical Society, 2016 volume 163, issue 5, F327–F329.

**2.** H. Ghezel-Ayagh, "Advances in SOFC Power System Development," 17th Annual Solid Oxide Fuel Cell (SOFC) Project Review Meeting, Pittsburgh, PA, July 19–21, 2016, https://www.netl.doe.gov/File%20Library/Events/2016/sofc/Ghezel-Ayagh.pdf