Modular Solid Oxide Electrolysis Cell System for Efficient Hydrogen Production at High Current Density

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Subcontractor:
Versa Power Systems, Calgary, Alberta, Canada

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Project End Date: September 30, 2019

Overall Objectives

- Demonstrate the potential of solid oxide electrolysis cell (SOEC) systems to produce hydrogen at a cost of less than \$2.00/kg.
- Enhance cell and stack durability to enable dynamic load profiles associated with intermittent renewable integration (>1 A/cm^2 operation).
- Develop and validate a modular SOEC system that demonstrates proof of concept of both technical and economic objectives.

Fiscal Year (FY) 2018 Objectives

- Complete 1,000-hour test of a single cell demonstrating voltage degradation rate of ≤2%/1,000 h.
- Complete testing of a solid oxide electrolytic stack for ≥1,000 h validating electrical efficiency ≥95% (lower heating value based) at ≥1 A/cm^2 and degradation rate ≤4%/1,000 h.
- Complete detailed design of a >4 kg H_2/day SOEC demonstration system with estimated overall efficiency >75%.

Technical Barriers

This project addresses the following technical barriers related to hydrogen generation by water electrolysis from the Hydrogen Production section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan[1]:

(F) Capital Cost

(G) System Efficiency and Electricity Cost

(J) Renewable Electricity Generation Integration.

Contribution to Achievement of DOE Technology Acceleration 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 balance of plant'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)

[1] https://www.energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22

FY 2018 Accomplishments

- Demonstrated performance degradation rate of ≤2%/1,000 h resulting from long-term tests (~16,000 h) of a High Power Density (HiPoD) SOEC operating continuously at 1 A/cm^2.
- Verified performance of a 45-cell Compact SOEC Architecture (CSA) stack with less than 0.4%/1,000 h degradation rate over ~4,000 h of tests under simulated system conditions with electrical efficiency >95% (based on lower heating value of hydrogen) at ≥1 A/cm^2.
- Completed the detailed design of a >4 kg H_2/day prototype unit to demonstrate the system efficiency metrics (>90% electric) and to verify the operability of SOEC using intermittent renewables.

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 have the capabilities 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 SOEC systems 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, including 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%/1,000 h and stack degradation to <2%/1,000 h. 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, anode flush gas composition, and load cycling effects. Stack development efforts will focus on manufacturability, thermal management, and scale-up. A novel stack architecture will be utilized for electrolysis operation at moderate current density operation (1–2 A/cm^2). Stack manufacturing, testing, and validation will seek to demonstrate a 4 kg hydrogen per day 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/day) 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

Research work was continued on improving the performance endurance of the SOEC cells. FuelCell Energy's HiPoD cells [1], based on optimized cathode porosity, have shown superior performance at high current densities up to 6 A/cm^2. A HiPoD cell recently completed nearly two years of continuous operation at 1 A/cm^2 (17,051 hours) as shown in Figure 1. This cell achieved a degradation rate of 32 mV/1,000 h, following an initial stabilization period of ~1,200 h. Prior to an uncontrolled shutdown of the cell at approximately 16,000 h of operation (due to test stand malfunction), the cell performance degradation was below the target 2%/1,000 h. The project activities were also focused on establishing operating conditions (e.g., steam concentration and utilization) that may result in higher performance stability and endurance. A recent cell operating on higher steam utilization (50%)—but lower steam concentration (60%)—has shown a significantly lower degradation rate of 9 mV/1,000 h over the last 4,300 h (0.72%/1,000 h) of operation.

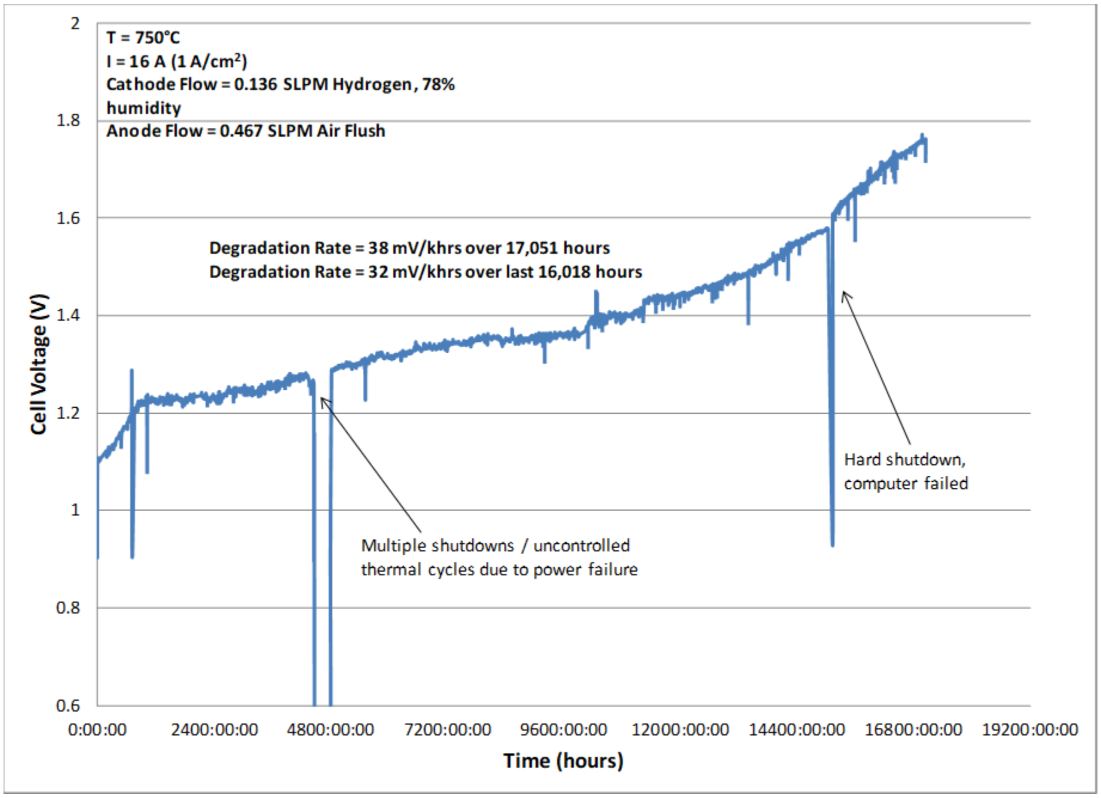

Figure 1. Test of HiPoD cell (5 cm x 5 cm x 0.03 cm) at 1 A/cm^2 demonstrated voltage degradation rate of less than 2%/1,000 h over ~16,000 h of operation

A 45-cell CSA stack, shown in Figure 2, was built with 300-µm-thick HiPoD cell technology. This stack ran for nearly 4,800 h on load with efficiency and degradation that exceeded the program targets. During operation, the stack underwent several unintended and uncontrolled thermal cycles. For the first 4,000 h elapsed time of operation, as shown in Figure 3, the stack was operated at 1 A/cm^2 with an average degradation rate of 4.4 mV or 0.35%/1,000 h. During that period, the stack exhibited a voltaic (dc) efficiency greater than 95% lower heating value of hydrogen. For the final 800 h of operation, the stack was transitioned to the higher current operating point of 1.22 A/cm^2, thereby increasing the hydrogen production rate to 4 kg/day, meeting another milestone for the project.

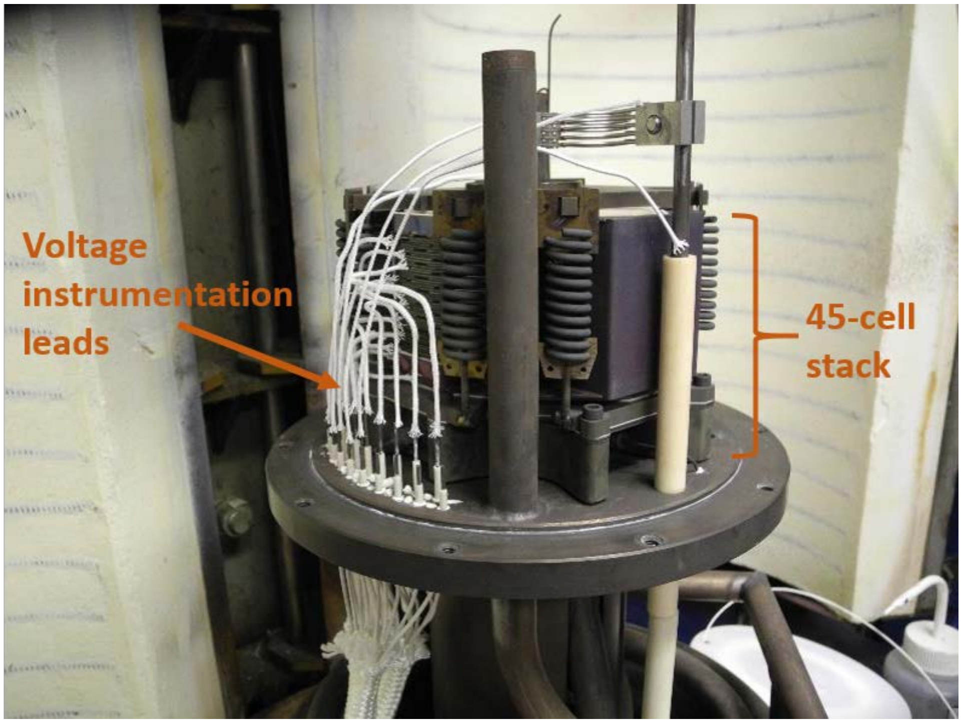

Figure 2. Picture of 45-cell CSA stack fabricated via an automated manufacturing process

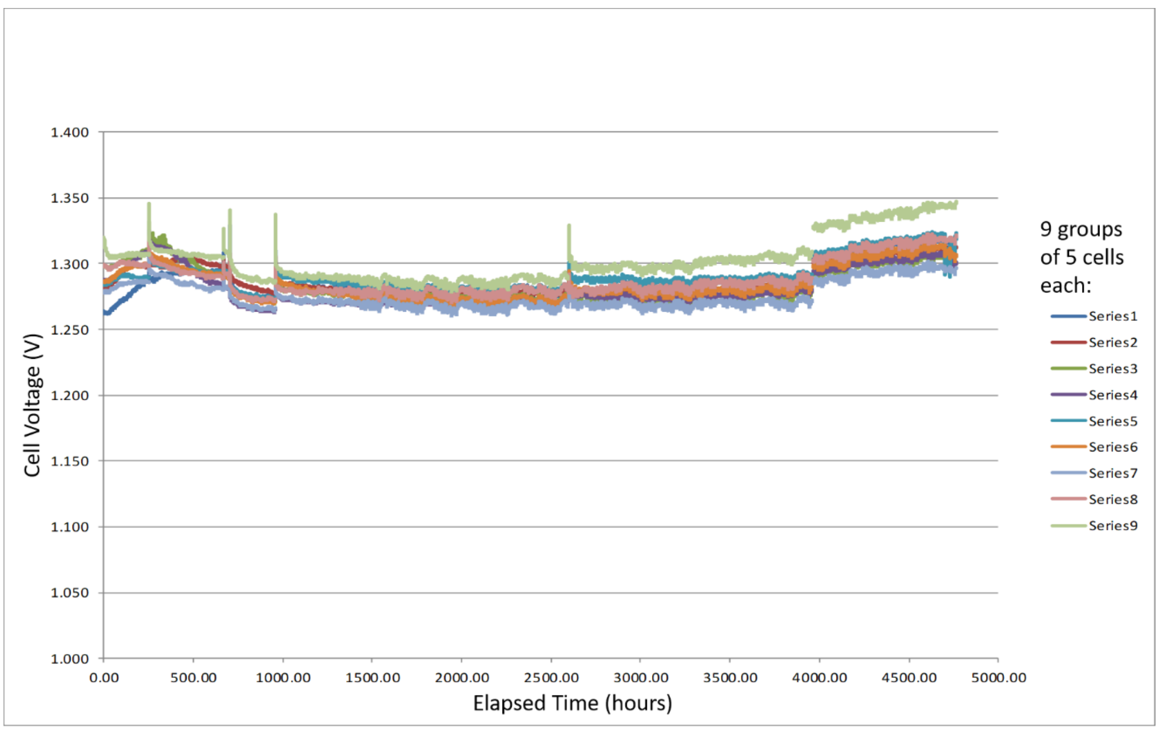

Figure 3. 45-cell CSA stack produced 3.3 kg/day hydrogen at 1 A/cm^2 and verified performance degradation of less than 2%/1,000 hours for a period of nearly 4,000 h

The detailed design for a >4 kg H_2/day demonstration system was completed. The design includes process models over a range of operating modes, piping and instrumentation diagrams, and 3-D module conceptual models. The process diagrams include the electrolyzer module, heat exchangers, recycle loops, instrumentation, and the control loops for pressure, temperature, and flow. Thermal integration within the demonstration system consists of heat recovery from the electrolyzer effluents (anode and cathode outlet streams) using heat exchangers to maximize the overall efficiency of the system. To simulate the integration of waste heat recovery from low-grade sources, electric heaters are incorporated in the design. The goal of the system demonstration is to show >75 % system efficiency and the ability to operate on intermittent load profiles. The demonstration system is based on an integrated electrolysis stack vessel, which includes balance of plant components that are more efficiently close-coupled with the stack thermal zone within the pressure boundary. Figure 4 shows the 3-D design concept developed for the >4 kg H_2/day demonstrator to be fabricated and tested in the next year of the project.

Figure 4. Rendering of the integrated 4 kg H_2/day pilot demonstration system consisting of a single vessel containing the SOEC module and balance-of-plant equipment

CONCLUSIONS AND UPCOMING ACTIVITIES

During FY 2018, work was continued on improving the SOEC robustness and performance stability. The very low performance degradation of the HiPoD technology was demonstrated by both single cell testing for a period of two years as well as a 45-cell stack producing >3 kg H_2/day. Additionally, the detailed design of a high-temperature water splitting demonstration unit capable of producing >4 kg H_2/day with expected overall efficiency (thermal + electric) of 75% (lower heating value hydrogen) was completed.

The future work on the cell and stack technology consists of studies to determine the operating conditions and cell material modifications that will further reduce cell degradation. Continued improvements in cell and stack manufacturing are anticipated to result in further reduction of stack degradation. The techno-economic analysis of a forecourt system (1,500 kg H_2/day) will be developed using the H2A (Hydrogen Analysis) methodology.

The system design and performance will be based on the lessons learned from stack tests. The system design optimization will be supported by the operation of the >4 kg H_2/day modular SOEC demonstration unit, which will be fabricated in the coming year. The modular SOEC system has the objective of demonstrating stable system operation over >1,000 h of steady-state testing, as well as showing successful operation on load profiles relevant to intermittent renewable energy sources.

FY 2018 PUBLICATIONS/PRESENTATIONS

1. H. Ghezel-Ayagh, "Modular SOEC System for Efficient H_2 Production at High Current Density," U.S. Department of Energy Hydrogen and Fuel Cells Program, 2018 Annual Merit Review and Peer Evaluation Meeting (AMR), Washington, D.C, June 13–15, 2018.
2. H. Ghezel-Ayagh, "SOFC Development Update at FuelCell Energy,", NETL 19th Annual Solid Oxide Fuel Cell (SOFC) Project Review Meeting, Washington, D.C, June 13–15, 2018.

REFERENCES

1. A. Wood, H. He, T. Joia, M. Krivy, and D. Steedman, "Communication—Electrolysis at High Efficiency with Remarkable Hydrogen Production Rates," *Journal of Electrochemical Society* 163, no. 5 (2016): F327–F329.