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

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Versa Power Systems, Calgary, Alberta, Canada

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Project End Date: June 30, 2020

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) 2019 Objectives

- Complete a 1,000-h test of an SOEC single cell demonstrating voltage degradation rate of ≤1%/1,000 h.
- Complete demonstration testing of an SOEC stack capable of >4 kg H_2/day for ≥1,000 h and a performance degradation rate of <2%/1,000 h.
- Complete procurement and assembly of a >4 kg H_2/day SOEC prototype system to demonstrate >1,000 h of steady-state operation including on-load profiles relevant to intermittent renewable energy sources.
- Complete conceptual process design for a forecourt high-temperature water splitting (HTWS) plant with a system electrical efficiency >90% (based on lower heating value [LHV] of H_2), an overall system efficiency (electrical + thermal) >75%, and ability to operate intermittently.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Production section (Hydrogen Generation by Water Electrolysis subsection) 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 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 (balance of plant) 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 2019 Accomplishments

- Achieved a low performance degradation rate of 0.88%/1,000 h in >2,000 h of testing by an electrolytic cell with active area of 16 cm^2 using a modified electrolyte composition and reduced cathode flow field height.
- Built and tested a first-of-a-kind 150-cell compact SOEC architecture (CSA) stack at 0.5 A/cm^2 for >3,000 h resulting in 5.5 kg/day of hydrogen production and an overall degradation of 0.31%/1,000 h.
- Developed the conceptual process design of a 1,500 kg H_2/day forecourt HTWS system projected to achieve a system electrical efficiency of 93.4% (based on LHV of H_2) and an overall system efficiency (electrical + thermal) of 79%.
- Proceeded with the construction of the >4 kg H_2/day SOEC system prototype, initiated by fabrication of major balance-of-plant equipment and completion of skid structure for housing the entire system.

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 in 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 purge 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 H_2/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

The project activities related to improvements of SOEC performance and durability were continued. FCE's High Power Density (HiPoD) cells [1], based on optimized cathode porosity, have shown superior performance at high current densities up to 6 A/cm^2. Last year, FCE reported a HiPoD cell completing nearly two years of continuous operation at 1 A/cm^2 (17,051 h) and achieving a degradation rate of 39 mV/1,000 h (3%/1,000 h) following an initial stabilization period. As a continued cell performance improvement effort, a new generation of HiPoD cells using a modified and thicker electrolyte layer and reduced cathode flow field (down to 0.5 mm) has resulted in significantly better performance endurance and stability even at high cathode inlet steam concentrations. As an example, the cell in Figure 1 has shown a performance degradation of 0.88%/1,000 h in the last 2,400 h at steady state current density of 1 A/cm^2 and steam concentration of 78% at the cathode inlet. As shown in Figure 1, this cell has operated over 4,000 h surviving the facility humidifier issues in the initial period of operation. The testing of the cell is planned to continue at the time of writing this report.

The scale-up of the CSA stack technology progressed from a 45-cell CSA stack in 2018 to a 150-cell SOEC stack in in 2019 (Figure 2) using 300-µm-thick HiPoD cell technology. This stack ran for nearly 3,000 h on load producing 5.5 kg/day of hydrogen (equivalent to 0.5 A/cm^2) with a degradation that exceeded the program targets. This stack incorporates cells with bar code labels printed directly onto the anode supports, an important procedure for quality control in the future manufacturing settings. The results of the stack operation, shown in Figure 3, indicate that there is no apparent difference between cells with labels and without labels. Although the 150-cell stack ran stably for 3,000 h, replicating the very low degradation previously observed in the shorter 45-cell stack, it was discovered that a batch of interconnects had been produced upside down with respect to their surface coatings (chrome barrier coating and nickel contact coating ending up on the wrong sides). This mishap caused localized damage around cell 80 resulting in accelerated degradation of the cell at the end of the test campaign.

The detailed design of the >4 kg H_2/day demonstration prototype system including piping and instrumentation diagram, process modeling, equipment selection, and 3-D CAD solid modeling were completed (Figure 4). Fabrication of the SOEC system's major balance-of-plant components was initiated, including the skid frame providing mounting points for all equipment. Heat exchangers for preheating the steam and air were built and have undergone factory acceptance tests. The power supply for providing dc power to the stack was fabricated.

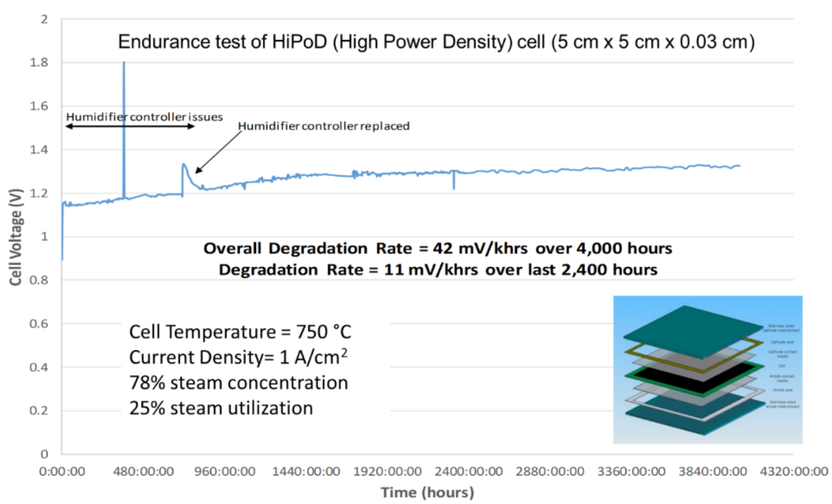

Figure 1. Test of HiPoD cell (5 cm x 5 cm x 0.03 cm) at 1 A/cm^2 demonstrated voltage degradation rate of less than 1%/1,000 h over the last ~2,400 h of operation

Figure 2. Picture of the 150-cell CSA stack fabricated via an automated manufacturing process

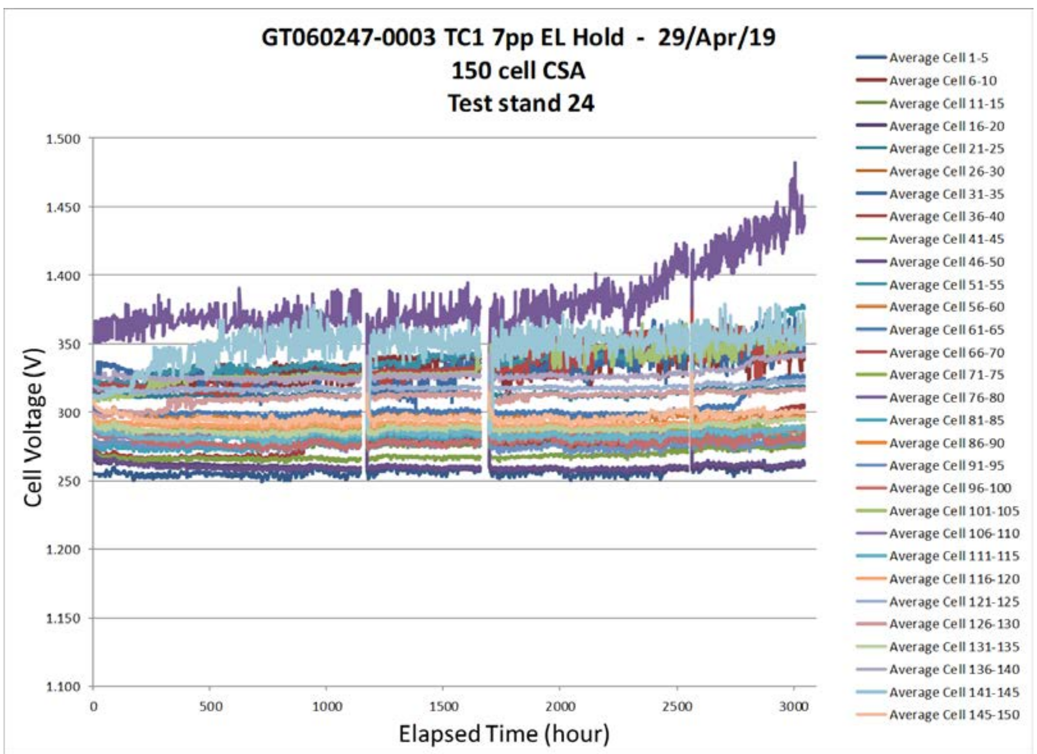

Figure 3. The 150-cell CSA stack produced 5.5 kg/day hydrogen at 0.5 A/cm^2 and verified performance degradation of less than 1%/1,000 h for a period of nearly 3,000 h

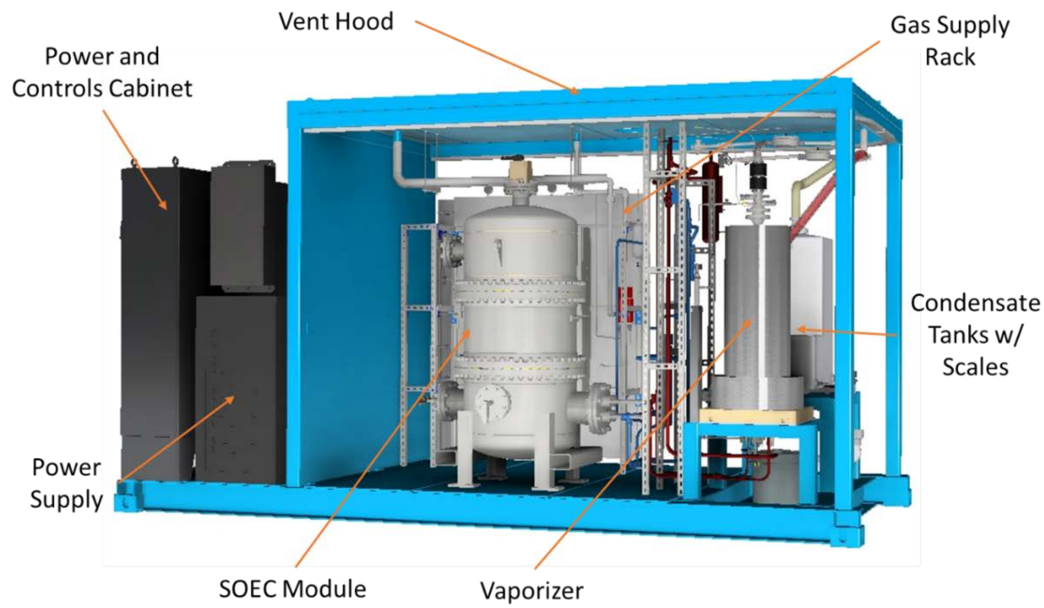

Figure 4. Rendering of the integrated 4 kg H_2/day pilot demonstration system consisting of a single skid containing the SOEC stack module and balance-of-plant equipment

The conceptual process design of a 1,500 kg H_2/day (forecourt) HTWS system was developed. CHEMCAD simulation software was used to perform system mass and energy balances. The assumed system operating conditions are shown in Table 1. The system is projected to achieve a system electrical efficiency >90% (based on LHV of H_2) and an overall system efficiency (electrical + thermal) >75% as shown in Table 2.

Table 1. SOEC and System Operating Conditions

Parameter	Value
Cell voltage	1.285 V/cell
Current density	~1 A/cm^2
Operating temperature	700°–750°C
Operating pressure	5 bara (60 psig)
Flush gas inlet	air
Flush exhaust composition	60% N_2, 40% O_2
Inlet composition	50% H_2, 50% steam
Steam utilization, stack	60%
Steam utilization, system	88%
Product hydrogen pressure	300 psig
Product composition	99.95% H_2, 0.05% H_2O

Table 2. Forecourt System Characteristics

System Parameter	Performance
Stack electrical efficiency (LHV)[a]	97.5%
System electrical efficiency (LHV)[a]	90.9%
System total efficiency (LHV)[a]	78.0%
Electricity consumption [b]	36.8 kWh/kg
Thermal consumption (kWh/kg)	5.9 kWh/kg
Total energy consumption[a]	42.7 kWh/kg

[a] Based on 98% rectifier efficiency and other balance of plant parasitic power
[b] Total electrical consumption includes stack, balance of plant, and high-temperature thermal input

CONCLUSIONS AND UPCOMING ACTIVITIES

Work progressed on improving SOEC robustness and performance stability. A combination of electrolyte materials and cell hardware modifications resulted in reduction of cell performance degradation to below the 1%/1,000 h targeted value. For the first time, a 150-cell electrolysis stack was built and tested. Even with flaws in the vendor-supplied interconnect coatings, the stack ran for >3,000 h with good stability in performance, validating the robustness of the CSA stack design. The concept design for a forecourt system (1.5 tonnes per day H_2) with an overall efficiency of 78% was completed. One of the main objectives of the design was minimization of the electric power input to reduce the consumption of electricity, which is an important operating cost. The construction of a >4 kg H_2/day modular SOEC demonstration prototype was initiated to proceed by fabrication of balance of plant components and stack pressure vessel.

The future activities will focus on continued improvements in cell performance and stack manufacturing with the objective of further reduction in stack performance degradation. The techno-economic analysis of a forecourt system (1,500 kg H_2/day) will be developed using the H2A methodology. The stack factory cost and system balance of plant cost will be determined and used as input to the H2A analysis. The system design optimization will be supported by the operation of the >4 kg H_2/day modular SOEC demonstration prototype, which will be assembled in the coming year subsequent to the fabrication of the stack module and balance of plant components. The prototype system has the objective of demonstrating stable 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 2019 PUBLICATIONS/PRESENTATIONS

1. H. Ghezel-Ayagh, "Modular SOEC System for Efficient H_2 Production at High Current Density," DOE Hydrogen and Fuel Cells Program 2019 Annual Merit Review and Peer Evaluation Meeting, Crystal City, Virginia, April 29–May 1, 2019.
2. H. Ghezel-Ayagh, "Progress in SOFC Technology Development at FuelCell Energy," 20th Annual Solid Oxide Fuel Cell (SOFC) Project Review Meeting, Crystal City, Virginia, April 30, 2019.

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 the Electrochemical Society* 163, no. 5 (2016): F327–F329.