II.B.5 Solid Oxide Based Electrolysis and Stack Technology with Ultra-High Electrolysis Current Density (>3 A/cm^2) and Efficiency

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Subcontractor:
Versa Power Systems Ltd., Calgary, AB, Canada

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Project End Date: December 31, 2017

Overall Objective

- Develop solid oxide electrolysis cell (SOEC) technology capable of operating at ultra-high current density (>3 A/cm^2) with an operating cell voltage upper limit of 1.6 V—equivalent to 77% efficiency, lower heating value (LHV).

Fiscal Year (FY) 2017 Objectives

- Demonstrate stable solid oxide electrolysis stack operation with high current density of more than 2 A/cm^2 for 1,000 h.
- Complete a solid oxide electrolyzer process and system design that accommodates the ultra-high operating current density platform—all to meet the Department of Energy (DOE) 2020 target for advanced electrolysis technologies (2020 System Energy Efficiency Target: 75% LHV).

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.

(F) Capital Cost

(G) System Efficiency and Electricity Cost

(J) Renewable Electricity Generation Integration

Technical Targets

- Develop a SOEC platform capable of operating with current density up to 4 A/cm^2 at or below a voltage of 1.6 V (2020 Stack Energy Efficiency Target: 77% LHV).
- Demonstrate stable SOEC operation with high current density of 3 A/cm^2 for 1,000 h.
- Design a solid oxide electrolysis stack platform capable of operating with the high current density (>3 A/cm^2) cell technology at an upper voltage limit of 1.6 V/cell (2020 Stack Energy Efficiency Target: 77% LHV).
- Demonstrate stable solid oxide electrolysis stack operation with high current density of more than 2 A/cm^2 for 1,000 h.
- Complete a solid oxide electrolyzer process and system design that accommodates the ultra-high operating current density platform—all to meet the DOE 2020 target for advanced electrolysis technologies (2020 System Energy Efficiency Target: 75% LHV).

FY 2017 Accomplishments

- Completed 10 kW rated SOEC stack design freeze incorporating final design changes suggested by stack test results and any further modeling effort as well as final design elements that permit stacking into a 10 kW stack package.
- Completed in-depth SOEC hot module configuration design with emphasis on the detailed physical design of the module and validation of the process model in physical space.
- Coordinated this project with the stack design freeze and prototype repeat- and non-repeat-part stack development from the DOE Office of Fossil Energy (FE) innovative project for the ultra-compact, low-cost stack design platform, called the compact solid oxide fuel cell (SOFC) architecture, thus enabling a single/common stack design platform that can operate in fuel cell systems in electrolysis systems, as well as in reversible SOFC systems for energy storage applications.

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INTRODUCTION

Hydrogen, a valuable commodity gas, is being increasingly recognized as an important fuel and energy storage pathway of the future. Demand for hydrogen as a fuel for fuel cells, in both transport and stationary applications, will continue to grow alongside hydrogen for H2@Scale production and sales (industrial ammonia, chemicals/oil upgrades, and mobility for fuel cell electric vehicles), as well as energy storage (including power-to-gas and power-to-liquid-pathways). The renewed interest in developing electrolysis systems is driven, in part, by burgeoning solar and wind industries and the need for an energy conversion and storage technology that can serve as the vehicle for converting intermittent solar and wind energy into the production of hydrogen. Although current electrolysis systems have the potential to integrate with wind and solar energy sources, the key challenges are low system efficiency and high capital costs. This project aims to address these barriers with an innovative SOFC-based electrolysis and stack technology with ultra-high steam electrolysis current (>3 A/cm^2) for potentially ultra-low-cost, highly efficient hydrogen production from diverse renewable sources.

APPROACH

FCE (previously Versa Power Systems Inc.) has a strong solid oxide cell and stack development history through its previous Office of Energy Efficiency and Renewable Energy sponsored project and through over 15 years of cell and stack advancements from previous efforts (DOE, Solid State Energy Conversion Alliance, and Defense Advanced Research Projects Agency projects). Leveraging this experience, the project objectives will be met by executing the following scope:

- Addressing high current density electrolysis cell performance limitations by conducting multiple materials development and cell designs-of-experiment, integrating them with cell production technology development.
- Developing SOEC stack engineering modeling and process fabrication designs to address high current density operating requirements and identifying key operating parameters for the design of an integrated, SOEC-based energy conversion and storage system for renewable energy sources (wind and solar).
- Down-selecting cell technology developments and demonstrating high current density SOEC operation via single cell and stack tests.
- Investigating a high current density solid oxide electrolyzer system, including the option of integration with renewable energy sources, to meet DOE 2020 Advanced Electrolysis Technologies targets.

RESULTS

In this project, the next generation solid oxide-based high power density cells have been developed such that, when run in electrolysis mode, they are capable of operating at ultra-high electrolysis current density. These *cathode supported cells* have been developed using conventional SOFC materials comprising a nickel oxide and yttria stabilized zirconia cathode and 8 mole-% yttria stabilized zirconia electrolyte. (Note: electrolysis electrochemical nomenclature is used here. In fuel cell mode, these same cells are called *anode supported;* in electrolysis mode, it is technically accurate to refer to these cells as *cathode supported*.) The SOEC cell utilizes an all-ceramic anode with no noble metals. Electrochemical testing (current-voltage response) of the cells was performed up to 6 A/cm^2 in electrolysis mode. The steam and air are supplied in the horizontal plane, perpendicular to one another, in what is termed a cross-flow geometry. The test housing (and current collection) is made from low-cost ferritic stainless steel, and the current collection and seal materials used are the same as those used in SOFC stacks. The cell voltage includes all interfaces and the stainless steel current collection jigs and, as such, is believed to be representative of the stack-repeat-unit-cell of an FCE electrolysis stack. The cell planform dimensions are 5 x 5 x 0.03 cm with an active electrode area of 16 cm^2. This area requires a current input of 96 A to reach a current density of 6 A/cm^2 during electrolysis testing. A remarkable cell voltage of 1.67 V at 6 A/cm^2 was achieved at 800°C. Even at 750°C, the cell exceeded the project performance target of 4 A/cm^2 at 1.6 V. A long-term steady-state electrolysis test of a high power density stack-repeat-unit-cell has been operating for more than 1,000 h at 3 A/cm^2 current density with a low degradation rate of 1.8% per 1,000 h.

A 20-cell electrolysis stack was built using high power density cells and an ultra-compact, low-cost stack design platform. This stack was used to explore the boundaries of high current density electrolysis operation and achieved an incredible stack current density of 3 A/cm^2 (67 A) with an average cell voltage of only 1.493 V. The cathode test gas composition was 78% water and 22% hydrogen (20.11 SLPM water [calculated], 5.672 SLPM hydrogen) for a steam utilization of 50.0%. After load-up and tuning, a stack voltage of 29.856 V (1.493 V/cell) at stack current of 67 A (3.004 A/cm^2) was demonstrated. At this test condition, the stack produced 50.3 g/h hydrogen with a stack volume of only 200 cm^3 using 2 kW input. This equates to 2.5 kg H_2 per day for a single, 225-cell stack of this platform design. The stack was then further operated in steady-state electrolysis at 2 A/cm^2 for more than 1,000 h as shown in Figure 1. Early in the 1,000 h hold (first 300 h), three unplanned and uncontrolled test interruptions occurred which resulted in full thermal cycles. The degradation appears to have increased for a period after the first interruption, but the

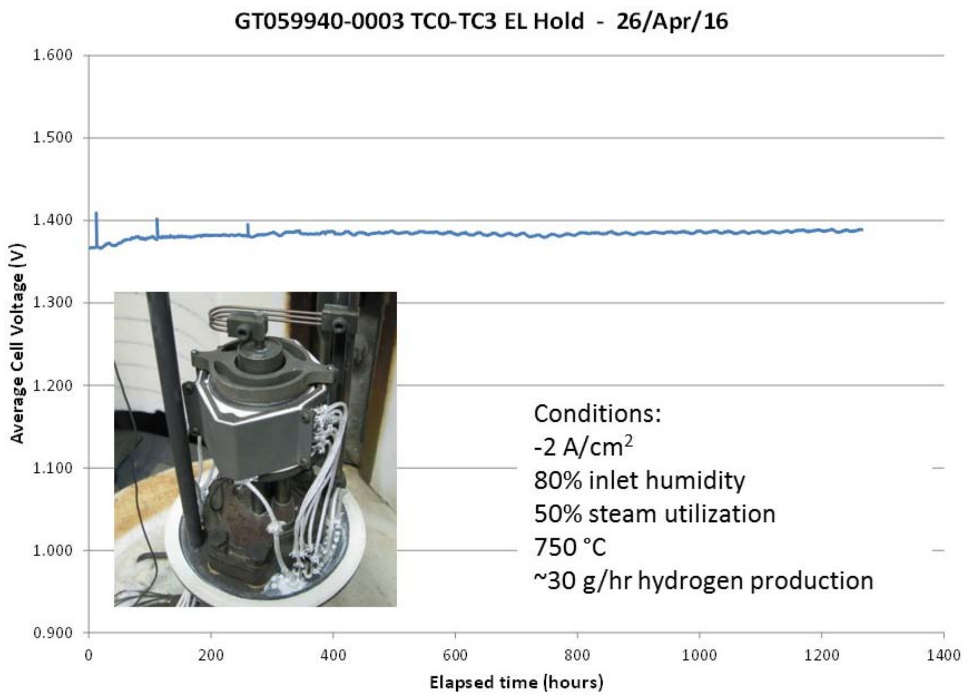

FIGURE 1. Sustained 2 A/cm^2 electrolysis test for over 1,000 h

overall degradation for the test period was relatively low, at 7.2 mV per 1,000 h per cell or 0.57% per 1,000 h.

After demonstrating stable stack operation at 2 A/cm^2 for over 1,000 h and with an improved understanding of the thermal conditions this operating point imposed on the stack, a strategic decision was made to homogenize the stack platform between this project (DE-EE006961) and an SOFC specific project (DE-FE0026093, through DOE FE). The basis for this decision was that the thermal condition at 2 A/cm^2 was not as severe as originally anticipated and therefore less compromise was required in the stack design for thermal management, thus enabling a *single/common*, ultra-compact, low-cost stack design platform called the compact SOFC architecture that can operate in fuel cell systems, in electrolysis systems, as well as in reversible SOFC systems for energy storage applications.

With that strategic shift, the main effort for stack development moved to project DE-FE0026093 (DOE FE "Innovative SOFC Stack" project). Under that project, the stack reached the point of design review and release for production, and parts and production tooling are currently on order.

Figure 2 shows the three planned compact SOFC architecture stack sizes where the commonality of design is shown. All parts through the core of the stack remain the same and are independent of stack height. The shortest stack (45 cells) is the deliverable stack for this program to meet the 10 kWe and 250 g/h program targets. Only the manifolds

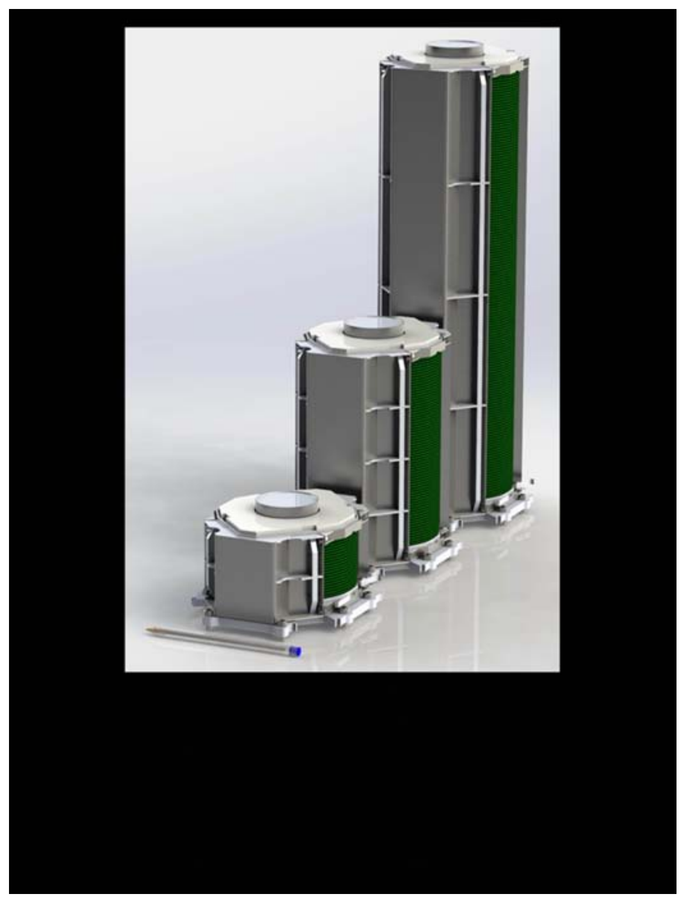

FIGURE 2. Comparing the three stack sizes

and the details of the compression system hardware differ between the various stack heights. In practice, other intermediate heights would be possible if there was a specific need due to the discrete nature of the non-repeat components. By constraining development to three target stack sizes, tooling and parts can be more easily optimized.

A preliminary system design was developed by integrating the inputs from electrochemistry, cell/stack performance data, and system level implications of configuration and operational parameters. Several variations were hypothesized and modeled with the most promising design and conditions iterated several times in order to determine the best-case baseline system. The resulting system design is yet to be fully optimized; however, it provides excellent insights to the potential of a high current density, high temperature water-splitting system.

The emphasis in FY 2017 has been focused on detailed physical design of the module and validation of the process model in physical space. The general approach to develop the SOEC module was to work from the CHEMCAD process model and attempt to realize process model components, influenced and integrated with FCE's deep experience in real physical unit operations components. While this is a somewhat contrived approach, it is otherwise common to find substantial differences between the process simulation model and physical system; it served as a valuable first draft approach to creating a realistic system.

A module design was created based on a circular array of six stacks surrounded by a cool pressure vessel. Further architectural and controls philosophy impacts such as stack power control and instrumentation were determined through the development of the module. The basis of the module design included a close mechanical and thermal coupling of all aspects of the module to avoid transferring losses between components. This resulted in what is termed the Integrated Hot Module approach, shown in Figure 3. The approach integrates several heat exchangers, trim heaters, and even potentially some aspects of the vaporizer into the hot module, along with the stacks. In theory this serves to dramatically reduce nozzle or boundary temperatures in and out of the pressure vessel, thermally coupling all high temperature heat exchangers, and reduce the overall size of the plant. The six-stack circular array also naturally provides multiple physical locations for heat exchanger placement.

The basic module layout includes six stacks arrayed in a circular pattern, all around a central multi-fluid heat exchanger with radiant heat exchangers positioned between the stacks, as shown in Figure 4. The base plate performs the fluid distribution function with the exception of the air inlet flush. Following preheating in the triangular radiant heat exchangers, inlet air is flushed into the module and thoroughly mixes before entering the sides of the stack.

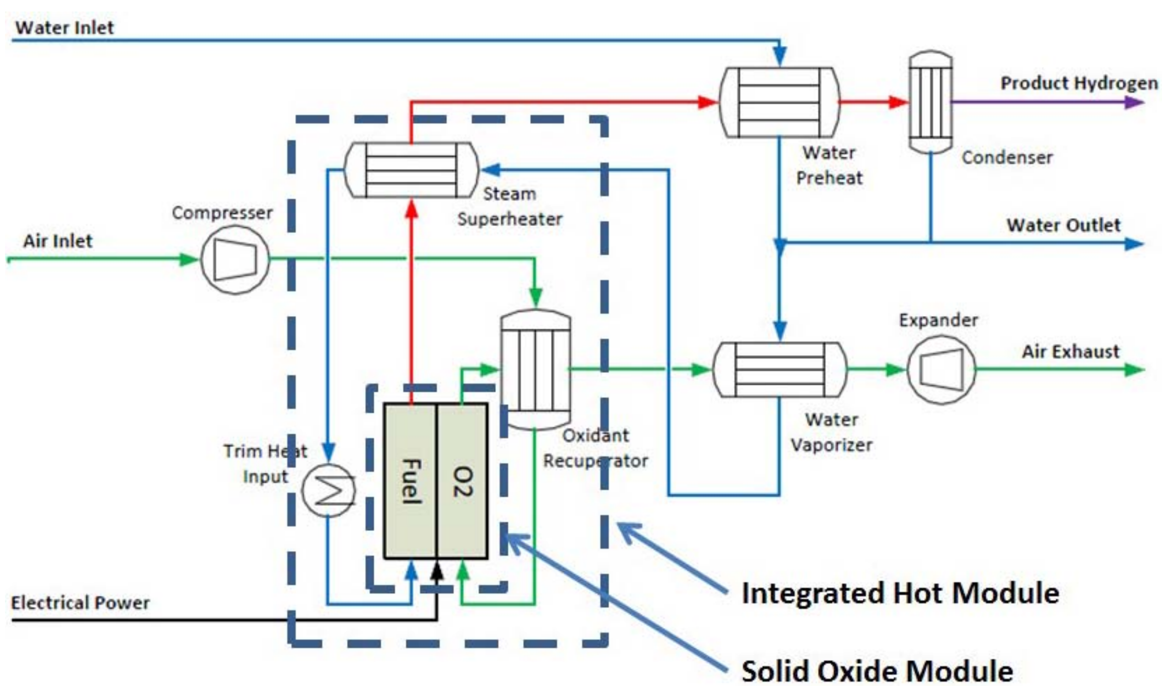

FIGURE 3. SOEC system process flow diagram

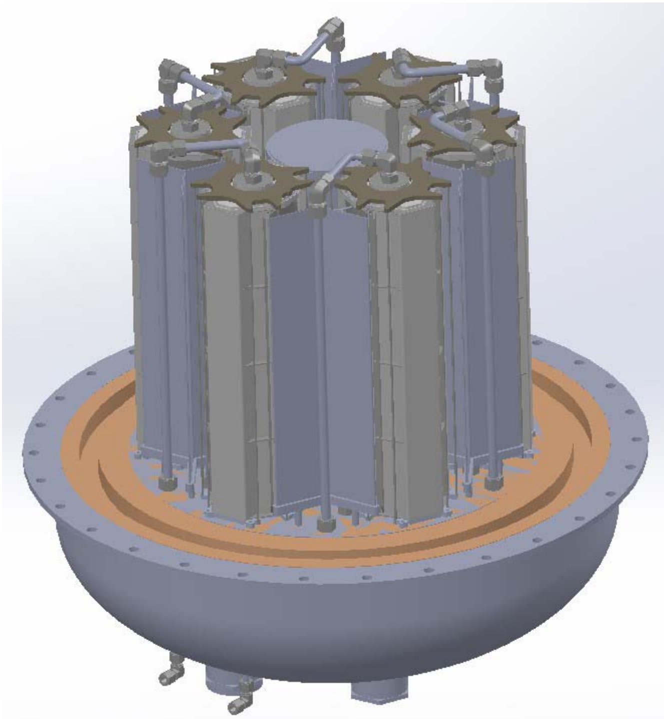

FIGURE 4. SOEC module layout

CONCLUSIONS AND UPCOMING ACTIVITIES

The project team will continue on the current development path. This includes the objectives to:

1. Demonstrate an SOEC stack with 250 g/h hydrogen production as well as demonstrating stable operation at a current density of more than 2 A/cm^2.

2. Complete a comprehensive techno-economic study of an ultra-high current density SOEC system integrated with renewable energy sources.

FY 2017 PUBLICATIONS/PRESENTATIONS

1. Oral presentation at the 2017 DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meeting in June 2017.

2. Planned presentation at the 2017 Fuel Cell Seminar.