V.N.1 Advanced Materials for RSOFC Dual Operation with Low Degradation

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Objectives

The objective of project is to advance reversible solid oxide fuel cell (RSOFC) technology in the areas of endurance and performance.

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells and Production sections of the Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan [1]:

Fuel Cells

(A) Durability
(B) Cost
(C) Performance

Production

(G) Capital cost
(H) System efficiency
(I) Grid Electricity Emissions (for distributed)
(J) Renewable Electricity Generation Integration (for central)

Technical Targets

The project objectives are to meet the following performance and endurance targets in a kW-class RSOFC stack demonstration:

- RSOFC dual mode operation of 1,500 hours with more than 10 solid oxide fuel cell (SOFC)/solid oxide electrolysis cell (SOEC) transitions.
- Operating current density of more than 300 mA/cm^2 in both SOFC and SOEC modes.
- Overall decay rate of less than 4% per 1,000 hours of operation.

Meeting these performance and endurance technical targets will be key RSOFC technology development steps towards meeting DOE's Technical Targets for Distributed Water Electrolysis Hydrogen Production by an RSOFC system.

Accomplishments

- Developed several candidate cell material systems meeting both performance (area specific resistance [ASR] less than 0.3 Ω-cm^2) and endurance (degradation rate less than 4% per 1,000 hours) targets in both fuel cell and electrolysis modes.
- Validated cell material systems through long-term (1,000+ hours) tests, with two tests exceeding 8,400 and 6,400 hours exhibiting degradation rates under 3% per 1,000 hours.
- Conducted several RSOFC stack development tests in both SOFC and SOEC modes with SOEC/SOFC transients.

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Introduction

RSOFCs are energy conversion devices. They are capable of operating in both power generation mode (SOFC) and electrolysis modes (SOEC). RSOFCs can integrate renewable production of electricity and hydrogen when power generation and steam electrolysis are coupled in a system, which can turn intermittent solar and wind energy into "firm power". In order to address the technical and cost barriers, DOE funded a number of research projects over the past 10 years [2]. Although significant progress was made in those projects, further development is required especially in the areas of RSOFC performance and endurance. In this project, Versa Power Systems (VPS) is addressing performance and endurance issues for RSOFC cells and stacks.

Approach

VPS has identified four task areas in an effort to improve the performance and endurance of RSOFC systems: degradation mechanism study, cell material development, interconnect material development, and stack design and demonstration. In order to mitigate project risk, a stage-gate project management process is employed with a quantitative Go/No-Go decision point. The scope of the work has been carried out by:

- Building on VPS' strong SOFC cell and stack baseline and leveraging cell and stack advancements from the DOE Solid State Energy Conversion Alliance (SECA) project.
- Carrying out parallel materials development activities and integrating them with cell production technology development.
- Conducting RSOFC stack and process designs to address durability, performance, and cost in both fuel cell and electrolysis operating modes.

Results

The development path for RSOFC cell material systems thus far can be summarized in Figure 1. Prior to the current project, three cell types–EC-1, EC-2, and EC-3–were developed based on VPS' baseline TSC-2 cell. In the project, four RSOFC cell types were developed from the base of EC-1 and EC-2 cells. Most recently, two additional cell types–MAC-RSOFC-1 and MAC-RSOFC-5–were developed and tested. In total, 10 materials systems have now been evaluated for performance in SOFC and SOEC modes, some of which have already run for significant time periods under steady-state electrolysis conditions. Table 1 summarizes cell material systems' ASR under both electrolysis and fuel cell conditions. It shows that several of these materials systems are now capable of meeting the ASR targets at 750°C.

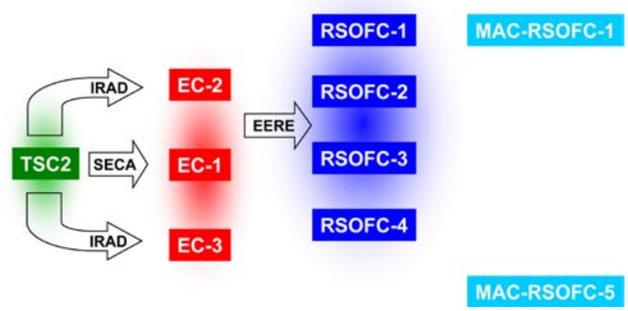

FIGURE 1. RSOFC Cell Development Path at VPS

Another key target is to achieve degradation rates under 4% per 1,000 hours of operation at more than 300 mA/cm^2 current density. Table 2 shows degradation rates in electrolysis mode at fixed operating conditions (750°C, 0.5 A/cm^2 and 50% steam utilization) in both mV and percent per 1,000 hours (percentages were calculated using a fixed voltage of 1.25 V). Figure 2 shows the steady-state operation of RSOFC-1 cell system in SOEC mode at 750°C and 0.5 A/cm^2. The degradation rate is about 2.7% per 1,000 hours for over 6,400 hours.

Interconnect material development has focused on testing in high steam and pure oxygen environments. Six different steel alloys (430, 434LN2, Sanergy, ZMG232, ZMG232L, and Haynes 230) have been tested in a high steam environment while three (434LN2, Sanergy, and Haynes 230) have undergone pure oxygen testing (one still in progress). 434LN2 had the best oxidation

TABLE 1. Summary of Cell ASR under SOFC and SOEC Operation

Cell Type	Electrolysis (SOEC) ASR (mΩ-cm^2) at 50% humidity				Fuel Cell (SOFC) ASR (mΩ-cm^2) at 3% humidity				Test No.
	650°C	700°C	750°C	800°C	650°C	700°C	750°C	800°C	
Target	<300				<300				
TSC-2	547	372	275	241	501	359	269	182	101670
EC-1	954	587	366	266	474	350	281	241	101695
EC-2	--	526	362	284	--	521	393	374	101706
EC-3	726	422	278	221	425	311	251	218	101728
RSOFC-1	784	466	308	245	405	298	245	214	101737
MAC- RSOFC-1	671	383	251	189	392	290	229	204	101750
RSOFC-2	754	422	285	229	502	365	295	254	101738
RSOFC-3	1,003	623	386	279	495	359	283	238	101741
RSOFC-4	711	413	268	203	397	293	238	207	101744
MAC-RSOFC-5	957	530	341	254	404	304	253	218	101758

TABLE 2. Summary of Cell Degradation Rates under Fixed Electrolysis Operation

Cell Type	Electrolysis (SOEC) Degradation			Test No.
	mV/1,000 hrs	%/1,000 hrs	Test Duration (hrs)	
Target	<50	<4	>1,000	
TSC-2	91	7.3	2,893	101670
EC-1	27	2.2	8,465	101695
EC-2	~0	~0	2,400	101706
EC-3	72	5.8	1,792	101728
RSOFC-1	34	2.7	6,472	101737
RSOFC-2	120	9.6	1,152	101738
RSOFC-3	42	3.4	2,653	101741
RSOFC-4	26	2.1	2,637	101744
MAC-RSOFC-5	34	2.7	935	101758

behavior (lest amount of weight gain) in a high steam environment. The pure oxygen testing was performed in a thermo-gravimetric analyzer at 800°C for over 800 hours while monitoring each test coupon's weight gain. Thorough analyses of the surface oxide and oxide thickness in cross section were carried out by scanning electron microscope. The chemical compositions of the oxides were determined by energy dispersive spectroscopy and X-ray diffraction. The final alloy selection will be made for stack development once all tests and analyses are complete.

VPS has developed electrochemical modeling code that integrates with Fluent to allow fully coupled

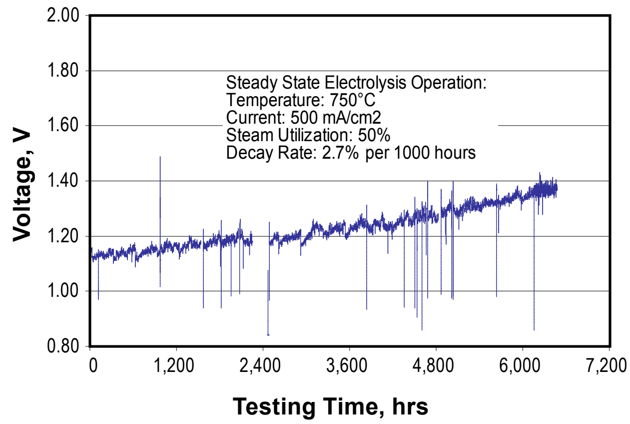

FIGURE 2. Single Cell Steady-State Electrolysis Test of a RSOFC-1 Cell Over 6.400 Hours

electrochemical, thermal, and flow modeling of an operating solid oxide stack. This tool is used extensively in stack design and operating condition selection. Figure 3 shows the temperature distribution across the cells in a 28-cell stack with 121 cm^2 active area cells (1.4 kW SOEC stack). Modeling results indicate that the total temperature range across all cells is 9°C, representing an almost ideal thermal environment for the operating stack in SOEC mode.

A preliminary stack test protocol was proposed and evaluated in a short stack test. A six-cell stack was built and tested to the protocol. As shown in Figure 4, it had completed 10 fuel cell-to-electrolysis cycles and a steady-state hold in SOEC mode. The electrochemical performance and degradation of the cells in stack are comparable to that of single cell test. Some degradation was observed over the 10 reversible cycles. In addition,

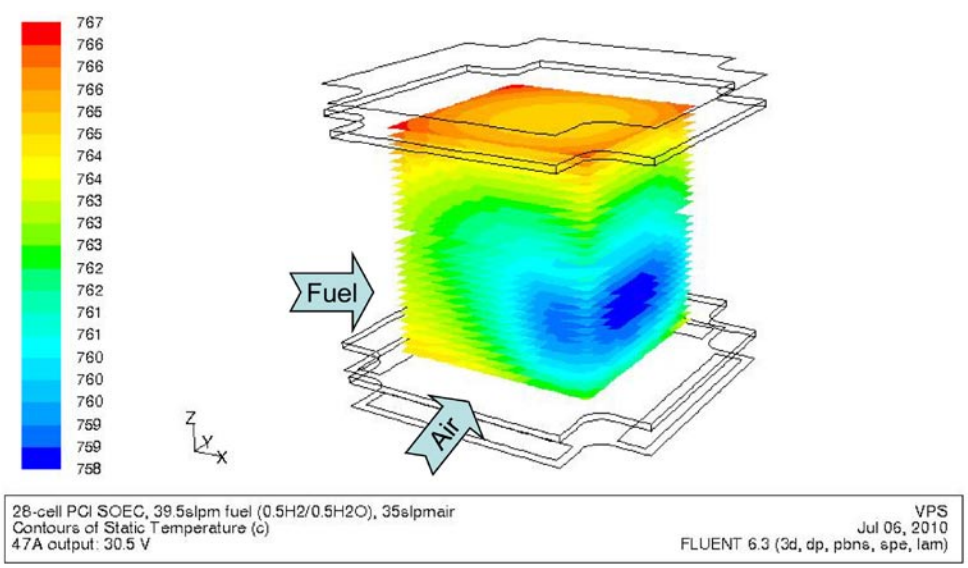

FIGURE 3. Temperature Distribution across Cells under Electrolysis Conditions (Modeled)

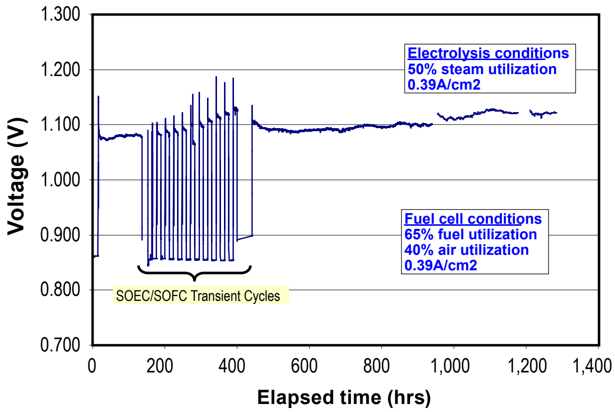

FIGURE 4. RSOFC Stack (6-Cell) Test in Both Steady-State SOEC Mode and SOEC/SOFC Transient (Based on Proposed Testing Protocol)

RSOFC-1 cells have been incorporated into two stack tests. Both tests focus on steady-state electrolysis at the six-cell (250 W) and 28-cell (1.4 kW) levels. These tests incorporated advances in contact design that had been developed by VPS under the DOE SECA program 550 cm^2 active area cells [3]. Some adjustment was made to fit the smaller 121 cm^2 cells used in this testing, and the results are promising. These advances will be rolled into future stack tests.

Conclusions and Future Directions

In the coming year, the project team will continue on the current development path. This includes:

- Testing of different conditions (temperature, current density, and utilization) for the chosen cell materials and reversible cyclic testing of cells in short stacks.
- Concluding the degradation mechanism study.
- Selecting final alloys following the completion of all tests.
- Continuing RSOFC stack development and testing.

FY 2010 Publications/Presentations

1. An oral presentation for this effort was made at the 2010 DOE Hydrogen and Vehicle Technologies Programs Annual Merit Review and Peer Evaluation Meeting.

References

1. DOE EERE Multi-Year Research, Development and Demonstration Plan, Page 3.1-7 (2007).

2. J. Guan, et al., High Performance Flexible Reversible Solid Oxide Fuel Cell, Final Technical Report, DOE DE-FC36-04GO14351.

3. B. Borglum, et al., Development of Solid Oxide Fuel Cells at Versa Power Systems 8th European SOFC Forum (2008), Lucerne, Switzerland.