IV.A.10 Development of Inexpensive Metal Alloy Electrodes for Cost-Competitive Solid Oxide Fuel Cells

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Objectives

- Improve the low temperature performance of electrodes using catalyst infiltration technology developed at LBNL. Three approaches are currently under development:
  - **Type 1:** Infiltration of ionically conductive network (non-functional) with nanoparticles to yield a functional (ionically and electronically interconnected) electrode structure.
  - **Type 2:** Infiltration of functional cathodes with mixed ionic-electronic conductors (MIECs) to improve electrode performance (e.g., ceria nanoparticles on $La_{0.6}Sr_{0.3}Co_{0.8}Fe_{0.2}O_3MnO_{3-\gamma}$ [LSCF] network).
  - **Type 3:** Infiltration of functional composite electrodes with nanoparticles (e.g., $La_{0.65}Sr_{0.3}MnO_{3-\gamma}$ [LSM] or ceria nanoparticles into a composite yttria-stabilized zirconia [YSZ]-LSM network) to improve low temperature performance.
- Standardized testing.
  - Design and fabrication of pressure-contact rigs.
  - Design and fabrication of a standard 5 x 5 cm solid oxide fuel cell (SOFC) stack.
  - Determination of performance and degradation rate in a standard stack.
  - Determination of degradation rate of commercial SOFC plates with and without catalyst infiltration.
- Engineer performance of interconnect alloys through control of oxide scale growth and conductivity.
- Mechanistic studies of Cr contamination of air electrode structures.

- Assist potential U.S. manufacturers of SOFC components through collaborative efforts.
- Technology transfer (through in-house training and instructional DVD production).

Approach

- Develop low-cost metal salt infiltration technology to boost the performance of the air electrode, particularly at temperatures below 700°C. The LBNL technology involves the use of simple catalyst impregnation to yield dispersed nano-particles, or a viscous catalyst precursor is vacuum impregnated into porous structures to yield a connected catalyst network. Vacuum impregnation can be accomplished with a porous electrolyte structure or and electrode/electrolyte (LSM/YSZ) network.
- Design and fabricate a standardized 2-cell SOFC stack to be used as a platform for comparative studies between universities, national labs, and industry.
- Measure the baseline performance and long-term stability of commercially produced air electrodes with and without an infiltrated catalyst.
- Determine the mechanism for Cr migration from steel-based interconnects into the air electrode and devise strategies to mitigate or minimize degradation behavior due to Cr poisoning.

Accomplishments

- **Refinement of infiltration technology:** The LBNL infiltration technology has undergone continual refinement over the past 24 months, and we are now able to infiltrate a variety of complex microstructures including conventional air electrodes and porous electrolyte networks. In one approach the LBNL team infiltrated a dispersed catalyst using simple nitrate precursors. We are now collecting data on commercial air electrodes with and without infiltration to see the effect of instantaneous performance and long-term degradation. In another approach, we impregnate a wide variety of microstructures with electrode catalysts using vacuum infiltration.
- **Completed design and fabrication of a standard SOFC stack:** The LBNL group worked with McAllister Technical Services to design the first standard 2-cell SOFC stack for 5 x 5 cm SOFC plates; the team also worked with Lane Wilson of the National Energy Technology Laboratory

(NETL) to refine the design and considered input from Argonne and Pacific Northwest National Laboratories in the final phases of the design.

- **Sulfur tolerance:** The LBNL team infiltrated a variety of anode structures with nanoparticulate ceria and demonstrated excellent tolerance to sulfur (as H_2S); LBNL is also working with industrial team members to determine if this technique can be used with their specific anode structures.

Future Directions

- **Optimize infiltration technology:** The LBNL team is continually refining the technology for catalyst infiltration to accommodate a wide range of air electrode (or anode) compositions and microstructures. This capability allows industrial teams to adapt the LBNL approach to their specific needs. The LBNL group has also begun to test its infiltration technology on industrial team structures and will continue to do so as part of the technology transfer process.

- **Determine long-term stability of infiltrated electrodes:** The LBNL team has redesigned its cell test rig for long-term testing and has placed an order with H.C. Starck/InDec for 3 cm SOFC discs and 5 cm x 5 cm SOFC plates. LBNL will use these for baseline testing and then compare degradation rates for infiltrated and non-infiltrated SOFC electrodes.

- **Short-term and long-term testing in a standard SOFC stack:** The LBNL team completed the design of the 5 x 5 cm standard stack and has received the machined parts for assembly. In the next contract period we will begin testing in the 2-cell stack. Initial studies will be focused on contact pastes and seals to assure reliable operation, followed by long-term testing for comparison to single-cell tests of infiltrated and non-infiltrated SOFC electrodes.

- **Elucidate the interplay of electrode composition and microstructure on cell performance:** As we continue to improve infiltration technology and understand its relationship to electrode performance and longevity, we will continue our limited work in transmission electron microscopy of electrode/electrolyte interfaces to elucidate the role of impurities and reaction products in limitations to cell life.

- **Technology transfer:** The LBNL team initiated technology transfer in FY 2007 through collaboration with industrial team members and by the hosting of an infiltration workshop at LBNL; the LBNL group also provided an instructional DVD to interested Solid State Energy Conversion Alliance (SECA) members.

Introduction

Among the most challenging hurdles to the commercialization of solid oxide fuel cell technology is the need to manage cost such that SOFCs are competitive with entrenched power generation technologies. The LBNL group has long maintained that the key to a cost-effective SOFC solution is to develop systems operating in the 650 to 700°C range. A number of SECA industrial teams are now pursuing that goal as well. In order to achieve the 40,000 hour life needed for distributed generation, it is clear that stainless steel interconnects will have to be maintained at temperatures below 800°C. Since electrode kinetics (and electrolyte conductivity) are thermally activated, it is not a trivial task to maintain SOFC performance as the operating temperature is lowered. The LBNL group has developed several infiltration techniques whereby standard LSM electrodes can be modified to perform well at temperatures as low as 650°C. Electrode modification can be as simple as infiltrating a metal nitrate such as $Co(NO_3)_2$, involve a mixture of precursors to form a known electrocatalyst such as $Sm_{0.6}Sr_{0.4}CoO_{3-\delta}$ (SSC), or use the newly developed LBNL technique of vacuum impregnation of porous structures with connected nano-particle architectures. The LBNL group has also performed extensive investigations into high temperature corrosion of stainless steel alloys for interconnects, determined the Cr vaporization rates for steels in humidified air, and developed low-cost coating technologies that reduce Cr vaporization to negligible levels while simultaneously improving oxidation behavior. The LBNL team has initiated measurement of degradation rates of infiltrated and non-infiltrated air electrodes produced in-house and by commercial suppliers. We are also conducting focused ion beam (FIB) and transmission electron microscopy (TEM) studies to aid in the elucidation of fundamental mechanisms for air electrode degradation and failure.

Approach

In order to achieve SECA commercialization targets, a number of SOFC developers are targeting reduced operating temperatures as a means of controlling cost. The LBNL effort is aligned with that goal through the use of electrode infiltration technology to boost the performance of the air electrode. The LBNL team has now focused its infiltration technology to cover three basic types of infiltration: 1) infiltration of ionically conductive network (non-functional) with nanoparticles to yield a functional (ionically and electronically interconnected) electrode structure; 2) infiltration of functional cathodes with MIECs to improve electrode performance (e.g., ceria nanoparticles

on LSCF network); and 3) infiltration of functional composite electrodes with nanoparticles (e.g., LSM or ceria nanoparticles into a composite YSZ-LSM network) to improve low-temperature performance. The LBNL team has also designed long-term test rigs and standardized stacks to verify the persistence of the performance boost afforded by infiltration technology. LBNL also works directly with industrial team members to determine whether or not the existing infiltration technology is compatible with vertical team SOFC structures or needs to be modified to suit their needs. We are also investigating the mechanism of Cr transport in a variety of cathode compositions and microstructures in order to generate strategies to minimize or eliminate air electrode performance degradation due to Cr poisoning.

Results

The infiltration (impregnation) of nanoscale particles, forming connected networks, into solid oxide fuel cell electrodes, has been shown to lead to considerable benefit in performance. Porous electrode skeletons (backbones), consisting of electrolyte material such as YSZ, when infiltrated, delivered results comparable to those of the standard Ni-YSZ and LSM-YSZ electrode configurations. Additionally, the performances of both single component mixed ionic electron conductor and of composite electrodes have been significantly enhanced by the connected nanoscale particle networks formed by infiltration.

Nanoscale materials (<100 nm) are receiving increased interest for application in devices where their unusual properties may possibly be exploited. In SOFCs they can be added as catalyst, where it has been theorized that the advantageous catalytic properties of nanosized oxides relate to an enhanced surface vacancy concentration and increased ionic and electronic conductivities. However, due to the elevated operating temperatures found in modern SOFCs, 500-750°C, the use of entirely nanostructured components would undoubtedly lead to structural instability. Hence, nanoparticles have been incorporated in conjunction with more stable micrometer-sized supporting functional architectures.

To enhance electrode performance at the lower operating temperatures, nanoparticulates are added to the internal surfaces of the porous electrodes to enhance some aspect of the electrode processes. The nanoparticulates are typically added through processes that involve the precipitation of a metal salt in the pores of the electrodes, and their subsequent decomposition, to generate the desired nanoparticulate metallic or oxide catalyst. This method of electrode enhancement has proved reasonably successful. Additionally, it has been found that higher electrode loading of nanoparticulate catalysts further increases performance. Unfortunately,

the particle distribution produced by typical infiltration methods necessitates a large number of repetitions to produce a connected network of nanoparticulates, causing pore filling besides the intended coating of pore walls. Progressive filling of the pores has the drawback of causing gas diffusion limitations within the electrodes, which in turn limit performance at higher current densities. It would therefore be advantageous to engineer a uniform networked nanoparticulate layer within the electrodes, involving a minimal number of processing steps. Previously, uniform and continuous networks of nanoparticulates were incorporated into porous electrodes by infiltration. Importantly, the infiltration could be completed in a single processing step on both electrodes. Additionally, since the method is independent of all other processing steps, it can be preformed at lower temperatures, allowing for the use of otherwise reactive nanoparticulate catalysts. The engineering of enhanced SOFC electrodes through the incorporation of networked nanoparticulate layers is more generally elaborated below. Advances in infiltration methods as well as their application to three SOFC electrode classes will be discussed. A single-step method is demonstrated, which not only improves performance in both fuel and air electrodes but additionally decreases the rate-limiting step in the cathode's oxygen reduction reaction at intermediate temperatures. The engineering of electrodes to such a level has broad implications for the improvement of SOFC performance.

In Figure 1, schematic illustrations of both a general and a nanostructured SOFC electrode are shown. The schematic can be used to describe the three classes of SOFC electrodes: (a) porous electrolyte backbones with infiltrated electrocatalyst; (b) single-component MIEC backbones; and (c) composite electrodes backbones. Both the nanoscale component of the electrode and the microscale backbone grains, which
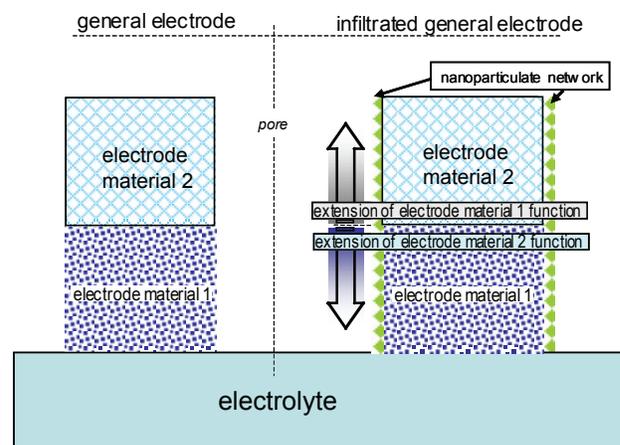

FIGURE 1. Cross-Sectional Illustration of Nanoparticulate Infiltration into a General Composite Electrode
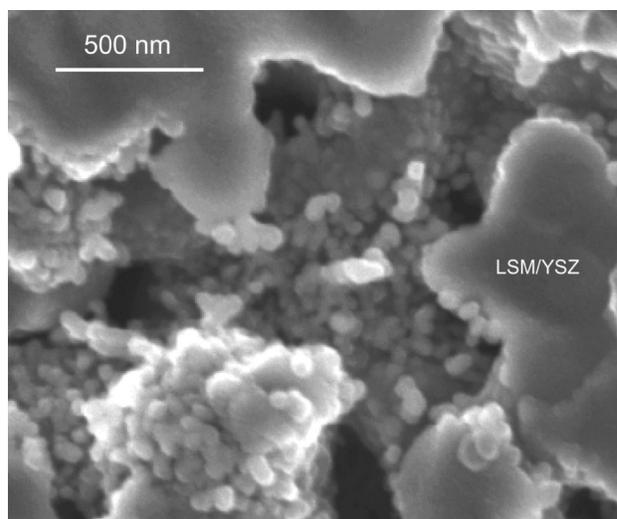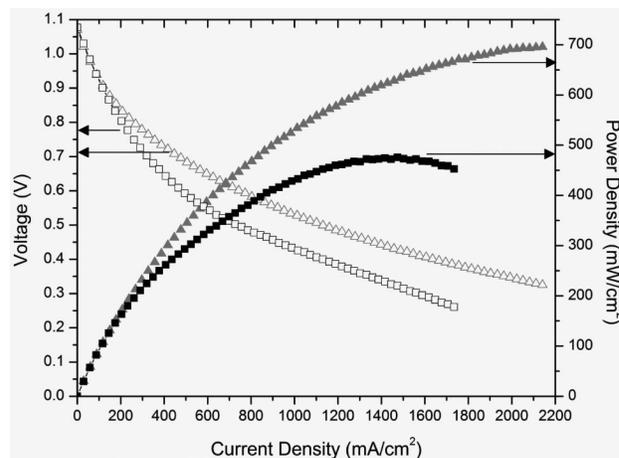
TABLE 1. Function of Backbone and Nanoparticles within Each Electrode Class

Porous Electrode Class	Backbone Function	Nanoparticle Functions
Single Component Electrolyte Composition	oxygen ion conduction	global electron supply -electrocatalyst
MIEC	oxygen ion and electron conduction -electrocatalyst	local oxygen ion conductivity -electrocatalyst
Composite	global oxygen ion and electron conductivity -electrocatalyst	local oxygen ion and electron conductivity -electrocatalyst

FIGURE 2. Secondary Electron Micrograph of Conventional LSM-YSZ Cermet Air Electrode Infiltrated with YDC

FIGURE 3. 700°C performance of anode supported cell with porous YSZ air electrode infiltrated with LSM (■) or LSF (▲). The power density at 0.7 V is about 15% higher for LSF compared to LSM infiltrated backbones.

they are built on, serve a distinct purpose within each of the SOFC electrode classes. These functions are listed in Table 1 and will be further described in the following sections. An important advance in the single-step infiltration procedure involved the modification of the chain length of the surfactant, Triton X, from n~10 for Triton X-100 to n~5 for Triton X-45. Assuming that micelles form in the precursor solutions and that the contents of the micelles are similar, a switch to a shorter chain length would yield a considerable increase in material deposited by the infiltration. This decrease in surfactant chain length has facilitated the formation of well-connected nanoparticulate networks in a single step within less open electrodes. A conventional LSM/YSZ composite air electrode infiltrated with this improved method is shown in Figure 2, showing nearly complete coverage in a single step as compared to earlier efforts where the infiltrated electrodes were of highly porous electrodes. With the ability to form well-connected nanoparticulate networks in a single processing step within conventional electrodes, focus can be shifted to decreasing the size of the nanonparticles, so as to exploit further the distinct properties that can be achieved at the nanoscale. For example, changes in infiltration procedure such as decreasing the concentration of the precursor solution, altering reaction rates, modifying the pH, or exploring other surfactants can yield micelles of the proper constitution to synthesize smaller nanoparticles within the porous electrodes.

(A) Infiltrated Porous Electrolyte Backbone Electrodes. Infiltration of porous electrodes is used to avoid solid-state reaction between the electrolyte and electrode materials that may otherwise occur at the elevated processing temperatures (~1,100-1,300°C) needed to sinter such structures. One type of backbone for such electrodes, as can be visualized using Figure 1, would consist of the backbone grains being composed of the same material as the electrolyte. However, since electrolyte material usually serves no catalytic purpose and only provides an ion-conducting pathway, it is

necessary to infiltrate a second material, which can form the electron pathways as well as the electrocatalytic sites within the electrode. The main advantage in this case is the ability to infiltrate superior electrocatalysts. As is shown in Figure 3, an LSM-infiltrated electrocatalyst is compared to a superior LSF infiltrated electrocatalyst. LSM has been the material of choice in composite air electrodes because of its minimal interactions with YSZ at the elevated processing temperatures; however, it is a relatively poor electrocatalyst at intermediate operating temperatures. Therefore, since the infiltration procedure only requires low-temperature sintering, 600-1,000°C, a reactive but otherwise effective electrocatalyst such as LSF can
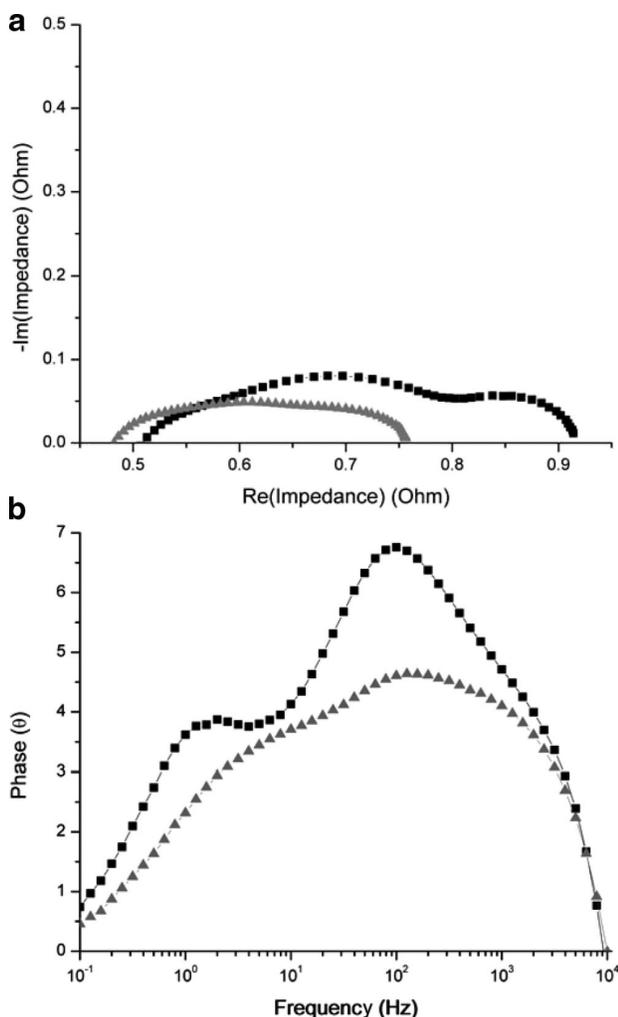
a

b

FIGURE 4. 700°C AC Impedance Characteristics of Electrolyte Supported LSCF Symmetric Cell at OCV, a) Nyquist and b) Bode Plots for Cathode Before (■) and After (▲) Infiltrating with YDC

be used. In the I-V cure in Figure 3, the enhanced electrocatalytic activity is illustrated by both the decreased overvoltage and the lower slope of the porous YSZ electrode activated by LSF infiltration.

(B) Infiltrated MIEC Backbone Electrodes. A major reason for LSF's superior electrocatalyic activity at lower operating temperatures is its mixed conductivity. The ability of MIECs to provide both electron and oxygen ion conduction pathways through an electrode, allows them to be utilized as single-component electrodes. To visualize these electrodes, consider both electrode grains to be composed of the MIEC in Figure 1. Even though MIEC electrodes are better electrocatalysts than LSM at intermediate temperatures, they can be improved by infiltration, as seen in Figure 4. Alternating current impedance characteristics of a LaSrCoFe (LSCF) symmetric cell provided by H.C. Stark are shown before and after the infiltration

with nanoparticulate $Y_{0.2}Ce_{0.8}O_{1.9}$ (YDC). Since LSCF already provides sufficient electronic conductivity, it only stands to benefit from the ionic conductivity of the infiltrated YDC and possibly from additional catalysis. The enhanced ionic conductivity in the electrode away from the electrolyte surface can be seen by the decrease in ohmic resistance in the Nyquist plot, Figure 4a, and by the decrease in the maximum phase shift of the high frequency arc of the Bode plot (~102 Hz), Figure 4b. Additionally, there is a decrease in the phase angle (θ) of the low frequency arc of the Bode plot (~1 Hz), Figure 4b, indicating that even LSFC, a good electrocatalyst at intermediate operating temperatures, can be catalytically enhanced by infiltrated nanoparticles.

(C) Composite Backbone Electrodes. As for MIEC electrodes, the incorporation of nanoparticulate networks into working electrodes can produce added electrocatalysis, but more importantly in the case of composite electrodes, it can expand the strict triple phase boundary (TPB) reaction area typical for composite electrodes. Following Figure 1, the electrode is now composed of both electrode and electrolyte grains, providing percolative networks for both electronic and ionic conduction, respectively. The nanoparticulate chosen for infiltration was YDC. YDC has a high ionic conductivity as well as sufficient electronic conductivity, especially in nanoparticulate form as has been demonstrated in the case of ceria, allowing for both ionic and electronic extension of the TPBs. Because composite electrodes already possess built-in electronic and ionic percolation networks through the electrode, the nanoparticulate YDC network layer does not need to be continuous throughout the electrode, since only short-range extension at the grain level dimension is needed. This significantly decreases the dependence of the cell on the morphological stability of the nanonparticulate networks, because a structurally stable backbone is already present.

Air Electrodes. Dramatic improvements in performance of a standard LSM-YSZ cathode are directly evident in the AC impedance characteristics, Figure 5. After infiltration with YDC, the Nyquist plot, Figure 5a, reduced in size to less than 50% of its original form. The lowering in overall cell impedance is more readily seen in the Bode plot which explicitly shows frequency information, Figure 5b. There is an overall decrease in the phase angle (θ) after infiltration, for both the intermediate ~10 Hz and high ~104 Hz frequency peaks, with the intermediate frequency peak at ~10 Hz most drastically reduced. This intermediate frequency peak is usually associated with slow surface kinetics on the LSM-YSZ air electrode. The strong decrease in the phase angle and in the overall impedance at
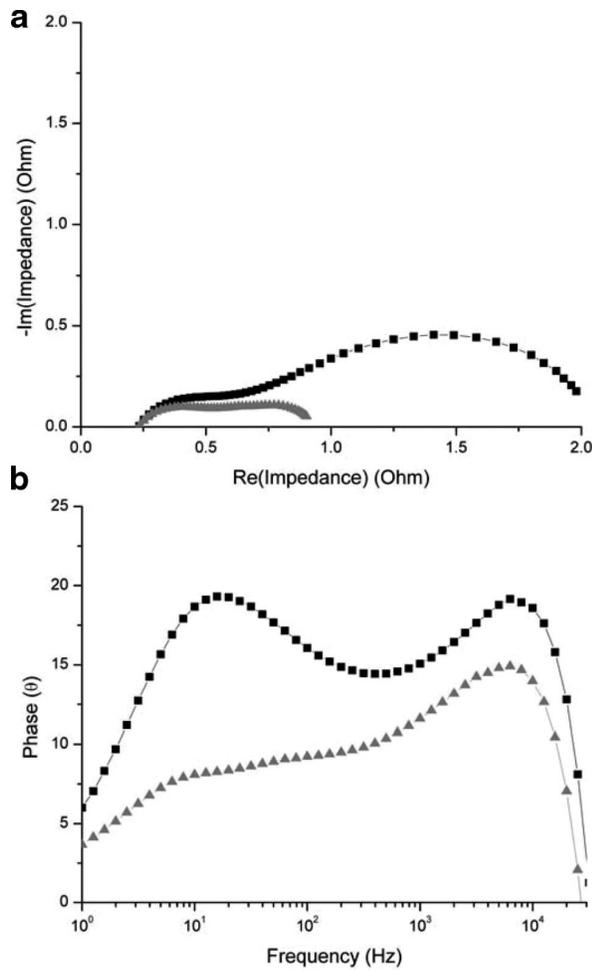
FIGURE 5. 700°C ac impedance characteristics of anode-supported cell with LSM-YSZ cathode: (a) Nyquist and (b) Bode plots before and after (2) infiltration of YDC.

this frequency following infiltration suggests that the enhanced microstructure minimizes the rate-limiting step in the reduction reaction within LSM-YSZ cathodes.

The result of the infiltration is a dramatic increase in cell performance, Figure 6. Even though the increase in peak power density from 208 to 519 mW/cm^2 before and after infiltration, respectively, is impressive, the most significant result of the infiltration is a dramatic increase in the power densities at low overpotentials. The cell shows a drastic enhancement of power density at 0.7 V from ~135 mW/cm^2 before infiltration to ~370 mW/cm^2 after infiltration. This decrease in "activation" losses is a marked improvement compared to infiltrated systems with isolated nanoparticulates.

Fuel Electrode. Though the largest improvements in performance at intermediate operating temperatures stand to be made within air electrodes, significant improvement in fuel electrode AC impedance
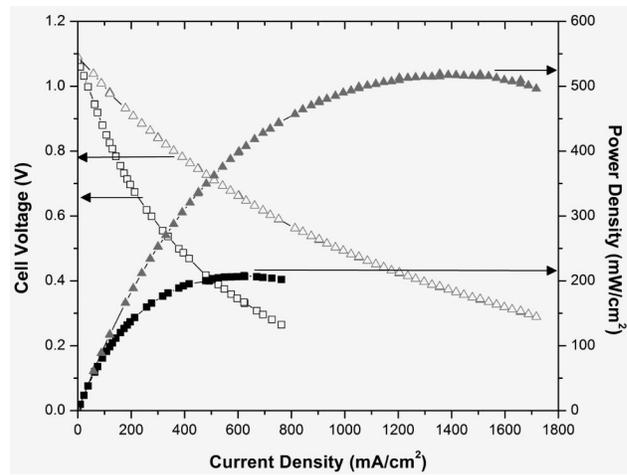

FIGURE 6. Enhancement of Anode Supported LSM-YSZ Cathode Before (■) and After (▲) Infiltration of YDC, at 700°C
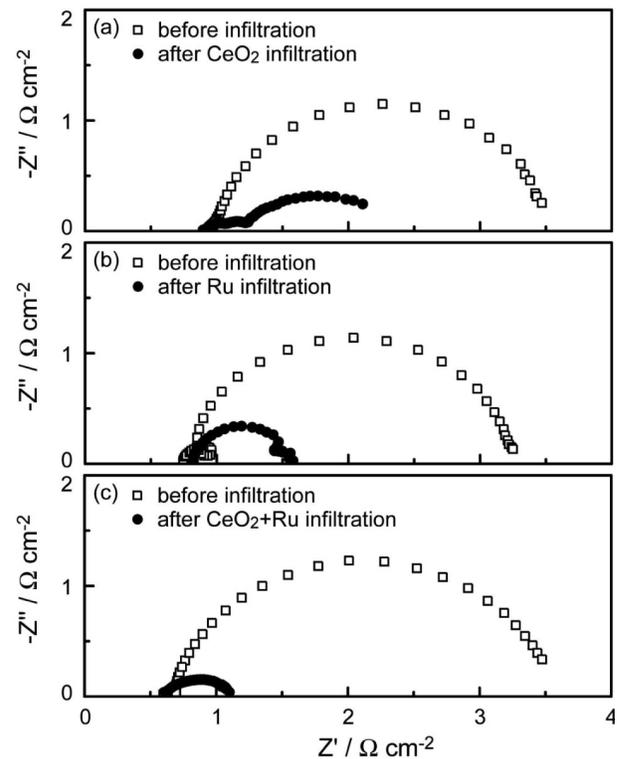

FIGURE 7. Impedance Spectra at 1,073 K for the Cells: (a) Before and After the Ceria Infiltration, (b) Before and After the Ru Infiltration, (c) Before and After the Ceria and Ru Infiltration

characteristics at open circuit voltage (OCV) are evident following infiltration of $Sm_{0.2}Ce_{0.8}O_{1.9}$ (SDC), Figure 7. Unlike for the air electrodes, it is the high-frequency peak at ~104 Hz that correlates with the pronounced decrease in the overall cell impedance seen in the Nyquist plot, Figure 7a. A decrease in phase angle (θ) at high frequencies is common to both air, Figure 5b, and
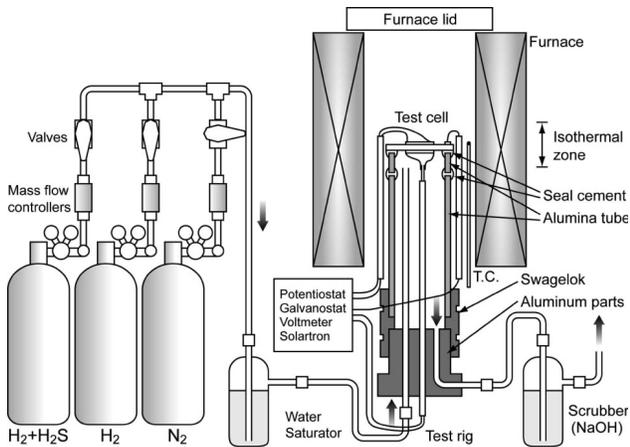
FIGURE 8. Schematic Diagram of Experimental Apparatus for Sulfur-Tolerant Anode Test

FIGURE 9. Cell Voltage as a Function of Time for Cells Exposed to 40 ppm H_2S at 973 K

fuel electrodes, Figure 7b, suggesting a common origin. While a number of electrode-specific processes have been associated with this high-frequency peak, they can be broadly grouped into the category of charge-transfer processes within the electrodes. As described earlier, the enhanced microstructure produced by the infiltration method will provide additional pathways through the electrodes, in essence minimizing the pathway for charge transfer, producing an increase in overall cell reaction area. While the improvement was seen in the cell's AC impedance characteristics at OCV after infiltration, it does not translate into significant improvement in cell performance at low overvoltages, Figure 7. However, the infiltration produces a measurable increase in peak power density, from ~348 to ~403 mW/cm².

While the increase in fuel electrode performance is the most immediate benefit of the SDC infiltration, a more vital result is the significant increase in sulfur tolerance that is obtained. A number of cells have been tested (see Figure 8 test apparatus) and have shown sustained sulfur tolerance up to 40 ppm H_2S using the conventional Ni-YSZ material set infiltrated with doped and undoped ceria. These preliminary tests indicate that it is possible to allow for the use of any commercial natural gas and promises that with further optimization of the anode microstructure and infiltration composition, stable sulfur tolerant anodes can be achieved using the conventional composite Ni-YSZ anodes. Additionally, the infiltration of ceria can aid the stability of Ni-YSZ fuel electrodes by preventing sintering, grain growth and agglomeration of the Ni phase, as well as providing the ability to directly reform hydrocarbons. Therefore, because doped ceria infiltration can enhance both the air and the fuel electrodes performance, it should be the preferred choice for single-step infiltration of both SOFC electrodes, while at the same time decreasing manufacturing time and cost.
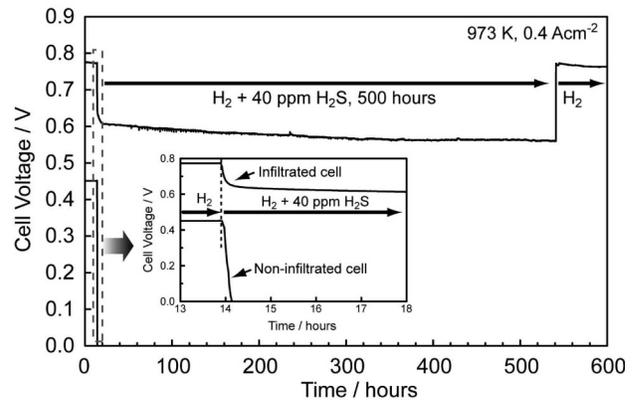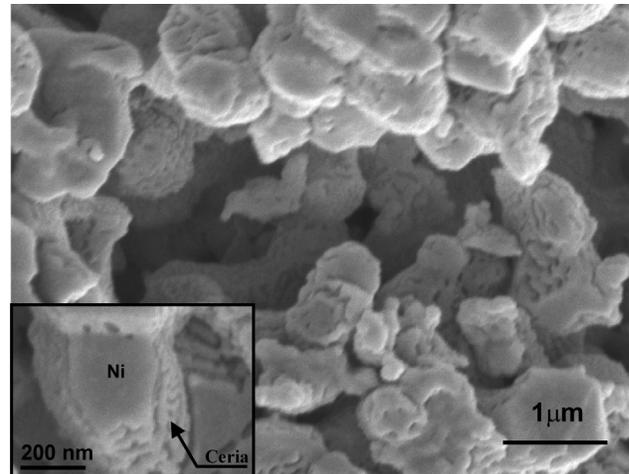

FIGURE 10. Scanning Electron Micrographs of Ceria Infiltrated Cathode Supported Cell After Exposure to 40 ppm H_2S for 500 Hours

The stability of the nanostructured SOFC electrodes under the fuel cell operating conditions is of potential concern. However, extended stability has been demonstrated for several systems: LSM-infiltrated porous electrolyte backbones have shown over 500 hours of continued performance enhancements at 650°C; ceria-infiltrated Ni-YSZ fuel electrodes, in humidified hydrogen containing significant concentrations of sulfur, were stable for over 500 hours at 700°C; and doped ceria-infiltrated LSM-YSZ air electrodes have been stable at 700°C in the 100+ hour tests conducted to date (see Figures 9 and 10).

Conclusion

A single-step infiltration method, producing connected nanoparticulate networks in porous SOFC backbone electrodes, improves both air and fuel electrode performance. The nanoscale nature of the

infiltrated material has shown advantages in enhancing all three electrode classes and is expected to yield further benefits with progress in decreasing infiltrated nanoparticle size.

FY 2007 Publications/Presentations

1. Tucker, M. C.; Kurokawa, H.; Jacobson, C. P.; De Jonghe, L. C.; Visco, S. J., "A fundamental study of chromium deposition on solid oxide fuel cell cathode materials," **Journal of Power Sources** 2006, 160, (1), 130. Publisher: Elsevier, Netherlands.

2. Sholklapper, T. Z.; Lu, C.; Jacobson, C. P.; Visco, S. J.; De Jonghe, L. C., "LSM-Infiltrated Solid Oxide Fuel Cell Cathodes," **Electrochemical and Solid-State Letters** 2006, 9, (8), A376. Publisher: The Electrochemical Society, USA.

3. Sholklapper, T. Z.; Radmilovic, V.; Jacobson, C. P.; Visco, S. J.; De Jonghe, L. C., "Synthesis and stability of a nanoparticle-infiltrated solid oxide fuel cell electrode," **Electrochemical and Solid-State Letters** 2007, 10, (4), 74–76. Publisher: The Electrochemical Society, USA.

4. Kurokawa, H.; Jacobson, C. P.; DeJonghe, L. C.; Visco, S. J., "Chromium vaporization of bare and of coated iron-chromium alloys at 1073 K," **Solid State Ionics** 2007, 178, (3-4), 287. Publisher: Elsevier, Netherlands.

5. Kurokawa, H.; Yang, L.; Jacobson, C. P.; De Jonghe, L. C.; Visco, S. J., "Y-doped SrTiO3 based sulfur tolerant anode for solid oxide fuel cells," **Journal of Power Sources** 2007, 164, (2), 510. Publisher: Elsevier, Netherlands.

6. Kurokawa, H.; Lau, G. Y.; Jacobson, C. P.; De Jonghe, L. C.; Visco, S. J., "Water-based binder system for SOFC porous steel substrates," **Journal of Materials Processing Technology** 2007, 182, (1-3), 469. Publisher: Elsevier, Netherlands.

7. Sholklapper, T.; Kurokawa, H.; Jacobson, C. P.; Visco, S. J.; De Jonghe, L. C., "Enhancing Cathode Performance and Anode Sulfur/Carbon Tolerance of SOFCs by Nano-Infiltration," **ECS Transactions** 2007, 7, (1), 837. Publisher: The Electrochemical Society, USA.

8. Sholklapper, T. Z.; Kurokawa, H.; Jacobson, C. P.; Visco, S. J.; DeJonghe, L. C., "Nanostructured Solid Oxide Fuel Cell Electrodes," **Nano Letters** 2007. in press. (available online June 9, 2007). Publisher: American Chemical Society, USA.

9. Kurokawa, H.; Sholklapper, T. Z.; Jacobson, C. P.; Visco, S. J.; De Jonghe, L. C., "Ceria Nanocoating for Sulfur Tolerant Ni-Based Anodes of Solid Oxide Fuel Cell," **Electrochemical and Solid-State Letters** 2007, 10, (9), in press. Publisher: The Electrochemical Society, USA.

10. Steve Visco, Hideto Kurokawa, Mike Tucker, Tal Sholklapper, Xuan Chen, Ken Lux, Craig Jacobson, Lutgard De Jonghe, "Cathode Infiltration," presentation at **7th Annual SECA Workshop and Peer Review**, Philadelphia, PA, September 13, 2006.

11. Steve Visco, Hideto Kurokawa, Mike Tucker, Inna Belogolovsky, Grace Lau, Craig Jacobson,

12. Peggy Hou, Lutgard De Jonghe, "Interconnects," presentation at **7th Annual SECA Workshop and Peer Review,** Philadelphia, PA, September 13, 2006.

13. Hideto Kurokawa, Craig Jacobson, Peggy Hou, Steve Visco and Lutgard De Jonghe, "The effect of protective coatings for alloy interconnect on oxidation and Cr vaporization," presentation at **Materials Science and Technology 2006**, Cincinnati, OH, October 15–19, 2006.

14. Mike Tucker, Craig Jacobson, Lutgard De Jonghe, and Steve Visco, "Metal-Supported Thin Film Electrolyte SOFCs," presentation at **Materials Science and Technology 2006**, Cincinnati, OH, October 15–19, 2006.

15. Tal Zvi Sholklapper, Craig Jacobson, Steve Visco, and Lutgard De Jonghe, "Advances in Single Step Electrode Infiltration," presentation at **Materials Science and Technology 2006**, Cincinnati, OH, October 15–19, 2006.

16. Michael Tucker, Craig Jacobson, Hideto Kurokawa, Tal Sholklapper, Lutgard DeJonghe, Steve Visco, "SOFC Designed for Rapid Thermal Cycling", presentation at **Fuel Cell Seminar**, Honolulu, HI, November 13–17, 2006.

17. Tal Sholklapper, Craig Jacobson, Steven Visco, Lutgard De Jonghe, "Stable Nanoparticulate SOFC Electrodes," presentation at **American Ceramic Society's 31st International Conference & Exposition on Advanced Ceramics and Composites**, Daytona Beach, FL, January 21–26, 2007.

18. Grace Lau, Michael Tucker, Hideto Kurokawa, Craig Jacobson, Steven Visco, and Lutgard DeJonghe, "Mechanism of Chromium Transport during Solid-State Diffusion on Cathode Materials of Solid Oxide Fuel Cells," presentation at **American Ceramic Society's 31st International Conference & Exposition on Advanced Ceramics and Composites**, Daytona Beach, FL, January 21–26, 2007.

19. Michael Tucker, Grace Lau, Craig Jacobson, Steven Visco, and Lutgard DeJonghe, "Advances in Metal-Supported SOFCs," presentation at **American Ceramic Society's 31st International Conference & Exposition on Advanced Ceramics and Composites**, Daytona Beach, FL, January 21–26, 2007.

20. Michael Tucker, Grace Lau, Craig Jacobson, Lutgard DeJonghe, and Steven Visco, "Metal Supported SOFCs," presentation at **Electrochemical Society's Tenth International Symposium on Solid Oxide Fuel Cells (SOFC X),** Nara, Japan, June 3–8, 2007.

Workshops & Instructional Videos

1. LBNL Infiltration Workshop, February 16, 2007, Berkeley, CA.

2. LBNL Infiltration Workshop DVD (available by request).

Special Recognitions & Awards/Patents Issued

1. United States Patent 7,163,713; Craig Jacobson, Steven J Visco, Lutgard C. DeJonghe, "Method for making dense crack free thin films", issued January 16, 2007.

2. United States Patent 7,118,777; Steven J Visco, Craig Jacobson, Lutgard C. DeJonghe, "Structures and fabrication techniques for solid state electrochemical devices", issued October 10, 2006.

3. Tal Sholklapper: Dr. Bernard S. Baker Award for Fuel Cell Research: 2nd Place Winner, Presented by the Fuel Cell Seminar and FuelCell Enegry, Inc., 2006.