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Poster Abstracts

Nickel Coarsening Study on SOFCs Operated at High Fuel Utilization

Pacific Northwest National Laboratory
Olga A. Marina, Larry A. Chick, Dan J. Edwards, and Jeffry W. Stevenson
e-mail: Olga.Marina@pnnl.gov phone: (509) 375-2337

The effect of high humidity in simulated reformate on the stability of nickel/yttria-stabilized zirconia (YSZ) anodes was evaluated at 700-1000°C. The humidity level was adjusted to that corresponding to 75-90% fuel utilization. Multiple button cells were tested simultaneously in one furnace for up to 4,000 hours at a constant current corresponding to either 0.8 or 0.7 V, while monitoring the cell voltage. Each furnace also contained a control cell operating on reformate with low humidity. Anode degradation was monitored using electrochemical impedance spectroscopy. The anode degradation was accelerated at higher levels of humidity corresponding to 85% fuel utilization. Post-test anode characterization revealed microstructural changes in the active anode.

Development of Dip Coating Processed Reactive Air Aluminization for Planar SOFC Stacks

Pacific Northwest National Laboratory
Jung Pyung Choi, Jeffry W. Stevenson, Diana Tran, Jeff F. Bonnett, and Yeong-Shyung Chou
e-mail: jungpyung.choi@pnnl.gov phone: (509) 375-2120

Low-cost ferritic stainless steels are used as interconnect materials for planar type SOFC, because of their high oxidation resistance and good thermal expansion match at high operating temperatures. However, volatile Cr-containing species, which originate from the ferritic stainless steel's oxide scale, can poison the cathode material in the cells and subsequently cause power deterioration in the device. To prevent this, an electrically conductive MnCo spinel coating has been developed. However, this coating is not compatible with the formation of hermetic seals between the interconnect frame component and the ceramic cell. Thus, a new aluminizing process (Reactive Air Aluminization: RAA) has been developed to enable durable sealing, prevent Cr evaporation, and maintain electrical insulation between stack repeat units. Recently, the demand for aluminization of complicated shapes including the outside and inside surfaces of pipes and tubes has arisen. To accommodate this need, a dip-coating process for fabrication of RAA coatings is under development. This paper will present recent progress regarding these novel coatings.

In-Operando XRD of LSCF Cathodes on Anode-Supported SOFCs in Humid Air

Pacific Northwest National Laboratory
John S. Hardy, Jared W. Templeton, Christopher A. Coyle, and Jeffry W. Stevenson
e-mail: John.Hardy@pnnl.gov phone: (509) 375-2627

X-ray diffraction (XRD) of the LSCF cathode on an anode-supported solid oxide fuel cell was performed continuously for over 700 hours while the cell was operated at 650°C in humid air (~3% H_2O) at a constant current approximating an operating voltage of 0.8 V. The air was delivered to the cathode at a flow rate of 350 sccm. The resulting XRD patterns were inspected to detect whether changes occurred in the atomic structure of the cathode over the entire duration of the cell test. Summation of the entire collection of XRD patterns accumulated over the 700+ hours of testing resulted in cumulative count times that greatly enhanced the signal to noise ratio of peaks associated with minor phases, making it possible to identify phases present in the cathode in quantities as low as tenths of a percent as well as the changes that occur in those phases. The results of this investigation in humid air are compared to those of a previous in-operando XRD study in dry air.

Evaluation of Stack Performance Using Updated SOFC-MP Modeling Tools

Pacific Northwest National Laboratory
Kevin Lai, Brian Koeppel, and Wei Xu
e-mail: canhai.lai@pnnl.gov phone: (509) 372-6461

Solid Oxide Fuel Cell Multi-Physics (SOFC-MP) is a custom software suite developed at PNNL to enable SOFC designers to numerically test changes in stack design, component materials, and operating conditions. The SOFC-MP modeling tool consists of i) an efficient 2D module that can quickly compute the distributions of current, voltage, temperature, and species composition in a tall stack, ii) and the 3D module that provides detailed spatial distribution of the same results but can be used to analyze thermal stresses in structural analysis through integration with both ABAQUS and ANSYS FEM solvers. A user friendly GUI and a reduced order modeling (ROM) tool are also part of the software suite.

This poster focuses on demonstration cases for features recently added to the SOFC-MP 2D and 3D tools. First, the effect of fuel/oxidant heating in the manifold on the overall thermal and electrochemistry performance is simulated using the 2D module. Second, the impact of different operating conditions on the stack performance, thermal distribution, and resulting component stresses are evaluated using the enhanced 3D module, where the predicted steady-state temperature fields are subsequently mapped onto a thermo-mechanical FE model to carry out the stress analyses. Finally, a plan to integrate the 2D/3D modules, ROM tool, and GUI with pre- and post-processing capabilities into a single software package is presented.

Recent Progress of Stack Fixture Tests at Pacific Northwest National Laboratory

Pacific Northwest National Laboratory
Yeong-Shyung Chou, Jung-Pyung Choi, Jeffry W. Stevenson, and Elizabeth Stephens
e-mail: Yeong-Shyung.Chou@pnnl.gov phone: (509) 375-2527

To bridge the gap between "button" cell testing and full-sized SOFCs of SECA industry teams, Pacific Northwest National Laboratory has developed a generic stack test fixture for validation and evaluation of candidate SOFC materials, fabrication processes, and test conditions. In FY14, the long-term evaluation of spinel-coated, surface-treated AISI441 interconnect material was completed. Previously, surface blasting was found to improve oxide scale adhesion on small metal coupons during long-term oxidation and thermal cycling. For the long-term validation tests, LSM-based single cells of 2"x2" size were tested with interconnect metal surface-blasted with two grits (#40 and #80) at 800°C for 6000h in hydrogen fuel (50%) and air. The cell electrochemical performance and impedance spectra will be reported. Post-test and microstructures of the cell and interfaces will also be characterized.

In addition to the long-term test of the interconnect surface treatment, the effect of current density on LSCF-based cells was also studied at 800°C with 50% hydrogen fuel versus air. Four single cells were tested at current density of 0, 125, 313, and 500 mA/cm^2 for times up to 1000h. Cell performance, impedance spectra, and I-V sweeps will be reported, and microstructure analysis of the cathode will also be discussed.

Mechanical Reliability Predictions for Compliant Engineering Seal Designs

Pacific Northwest National Laboratory
Wei Xu, Elizabeth Stephens, and Brian J. Koeppel
e-mail: Wei.Xu@pnnl.gov phone: (509) 375-7214

Further development and optimization of compliant engineering seal designs within SOFC stacks require a fundamental and thorough understanding of their essential nonlinear thermo-mechanical behaviors. In the present study, a continuum three-dimensional, thermo-visco-elastic-damage-healing model has been developed to resolve the unique stress-strain characteristics of compliant seal glass. Different physically-driven evolution kinetics have been unified to describe the distinct major mechanical degradation phenomena in terms of the evolution of structural damages, i.e. the CTE mismatch induced mechanical cracks and the internal pores, so that the strong coupling and interactions between the high-temperature operation conditions and the seal response can be explicitly resolved. The proposed constitutive model is then implemented into the finite element analyses. Effects of various loading conditions and material properties on the mechanical performance of single- and multi-cell SOFC stacks have been investigated.

Compliant Glass Seal Development at Pacific Northwest National Laboratory

Pacific Northwest National Laboratory
Yeong-Shyung Chou, Jung-Pyung Choi, and Jeffry W. Stevenson
e-mail: Yeong-Shyung.Chou@pnnl.gov phone: (509) 375-2527

Sealing for solid oxide fuel cells (SOFCs) remains a technical challenge, due to the stringent requirements in thermal, mechanical, electrical, chemical, and physical properties in a dual environment. Over the last several years, Pacific Northwest National Laboratory, in collaboration with Oak Ridge National Laboratory, has developed seals based on a compliant glass which tended to resist crystallization at elevated temperatures. In FY14, PNNL completed the long-term evaluation of an engineered compliant glass seal (SCN-1 glass with 15% ZrO_2 short fibers) at 800°C for ~6000h. A commercial LSM-based 2"x2" cell was sealed with the engineered compliant glass onto an aluminized AISI441 window frame plate, and tested in constant current mode with dilute fuel (50% H_2) and air. Cell voltage showed a similar degradation rate to that of a conventional glass-ceramic type seal. Microstructures of the glass and the interfaces with YSZ and aluminized AISI441 will be presented and discussed.

In addition to the engineered compliant glass SCN-1, which is a silicate glass with ~17% alkalis but no boron, a newly developed compliant glass (G102) from another SECA participant was also evaluated in the generic stack fixture at 800°C. The cell's electrochemical performance over 1500h will be reported. Post-test analysis and issues of glass spreading will be also discussed.

Engineered Glass Seals for SOFCs

Oak Ridge National Laboratory
Edgar Lara-Curzio
e-mail: laracurzioe@ornl.gov phone: (865) 574-1749

The effect of time of exposure to air and gas mixtures of H2+H2O+N2 on the microstructure of SCN and G6 glasses (barium alkali silicate glasses) was investigated. Results from the characterization of the microstructure and chemical composition of these glasses and their interfaces with 8YSZ and Al2O3 substrates after 25,000 hours will be presented. The implications of these microstructural changes on the durability and reliability of seals manufactured with these glasses will be discussed.

Manufacturing processes to fabricate engineered glass seals will be reviewed.

Alkali-Free Viscous Sealing Glasses for Solid Oxide Fuel Cells

MO-SCI Corporation-Missouri University of Science and Technology
Cheol-Woon Kim,[1] Joe Szabo,[1] Ray Crouch,[1] and Rob Baird[1]
Richard K. Brow,[2] Jen Hsien Hsu,[2] and Raphael Reis[2]
[1]MO-SCI Corporation and [2]Missouri University of Science and Technology
e-mail: ckim@mo-sci.com phone: (573) 364-2338

G102 is an alkali-free barium borosilicate glass and exhibits stable thermo-mechanical/thermo-chemical properties as a viscous sealing glass for an SOFC application. G102 has excellent thermal stability against crystallization within the SOFC operating temperature range. No bulk crystals were observed in samples of G102 isothermally held at 650, 750, and 850°C for up to 2000 hours in air. Even when G102 samples were thermally cycled for 21 days (84 cycles) through a temperature range (610-800°C) that covers the nucleation and growth regions, only surface crystallization was observed. There are no significant changes in the composition or properties (CTE and viscosity) for samples of G102 held for 2000 hours at 800°C in air. The long-term (2000 hrs) volatility of G102 is minimal and comparable to that of other sealing glasses at operational temperatures. The Al-SS441/G102/YSZ-bilayer sandwich seals remain hermetic after 148 thermal cycles (between room temperature and 800°C, total process time about 5200 hours) in dry air and wet forming gas. Self-healing of G102 seals cracked by thermal shock was demonstrated. A seal cracked by thermal shock (>25°C/s) was resealed after two hours at temperatures as low as 744°C in air, and this seal held pressure to 2 psi when cooled to room temperature.

Development of Cost-Effective YSZ Coating Methods for SOFC Interconnects

MO-SCI Corporation-Missouri University of Science and Technology
Cheol-Woon Kim,[1] Joe Szabo,[1] and Duane Spurgin[1]
Richard K. Brow,[2] Fatih Dogan,[2] and James Byron Claypool[2]
[1]MO-SCI Corporation and [2]Missouri University of Science and Technology, Dept. of Materials Science and Engineering and the Graduate Center for Materials Research
e-mail: ckim@mo-sci.com phone: (573) 364-2338

Solid oxide fuel cells (SOFCs) require robust seals that can prevent intermixing of air and fuel, remain inert in reducing and oxidizing environments while in contact with SOFC materials, and maintain their effectiveness through repeated thermal cycles. Recent research has focused on “compliant (or viscous)” glasses that remain vitreous over time in the SOFC stack operating environment, and are able to tolerate relative motion between the surfaces being sealed without the development of permanent leaks. Certain glasses (under investigation by MO-SCI and others) considered for this sealing application have broadly desirable thermo-mechanical properties and thermo-chemical characteristics, but have been found to chemically react with both bare and aluminized stainless steel SOFC interconnects, consequently forming phases that may adversely affect the integrity of the seal. On the other hand, these glasses do not react with the yttria-stabilized zirconia (YSZ) electrolyte used in most SOFC designs. Thus, YSZ could be an attractive barrier layer between the metallic SOFC interconnect and the sealing glass. Using a YSZ polymeric precursor solution method, well-adhered crack-free coatings of YSZ were formed on 441 stainless steel substrates. The YSZ-coating adhesion strengths were measured by a stud-pull method and were greater than 30 MPa. Coating parameters and micrographic studies will be discussed.

YSZ Coated Ferritic Stainless Steel

InnoSense LLC
Raymond Winter
e-mail: raymond.winter@innosense.us phone: (310) 530-2011

Solid oxide fuel cells (SOFCs) can potentially extend the nation's energy reserves. However, to be reliable, the fuel cell chambers must be sealed to prevent leakage between the existing glass layers and the metal interconnects. InnoSense LLC (ISL) is producing a cost-effective thin yttria- stabilized zirconia (YSZ) coating system to provide a barrier layer between SOFC compliant glasses and both bare ferritic stainless steel and spinel-coated ferritic stainless steel (Allegheny Ludlum SS441). This will result in high-quality YSZ coatings to SOFC interconnects for mass production by silk screening or spraying a metallo-organic solvent formulation, then drying and firing in commercially available thick film furnaces. Silk screening affords a low cost, fast design cycle technology that allows endless shapes to be successfully printed on a flat surface.

ISL is focusing on cost-effective application of thin, dense, adherent YSZ coatings on select portions (i.e., a square annulus) of SOFC interconnects.

ISL has developed a thixotropic formulation for screen printing and a non-thixotropic formulation for spray applications. In addition, the transparent glass-like films produced by firing these formulations will be rendered to fine micro-crystalline films, to prevent attack of the interconnects by the compliant glasses. ISL will conduct adhesion testing of our initial coatings on 304 stainless steel test plaques. YSZ coating applied to commercial Allegheny Ludlum 441 stainless steel will be subjected to compatibility testing by our fuel cell industrial partner.

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Cost Effective Highly Robust SOFC Interconnect Process

Sonata LLC-FuelCell Energy, Inc.
Jeffrey F. Roeder,[1] Peter C. Van Buskirk,[1] Joseph Barton,[2] Carl Willman,[2] and Hossein Ghezel-Ayagh[2]
[1]Sonata LLC and [2]FuelCell Energy, Inc.
e-mail: jr@sonatamaterials.com

Interdiffusion of materials presents a major challenge to joining technologies used to seal solid oxide fuel cell (SOFC) stacks. This Phase I SBIR project seeks to apply a highly robust thin film yttria stabilized zirconia (YSZ) coating to the perimeter area of ferritic stainless steel interconnects for SOFCs. YSZ has been shown to be an effective barrier to prevent formation of deleterious rare earth chromite (MCrO4, M=Mg, Ca, Sr, Ba) phases that form as a result of reaction of the interconnect with alkai-earth containing vitreous seal glasses. In Phase I, an atomic layer deposition (ALD) process will be developed for the coating. ALD offers the ability to deposit extremely dense, high quality films over large areas with highly uniform thickness over rough surfaces. A cost model demonstrating a pathway to cost-effective use of this technique by simultaneously coating large numbers of interconnect substrates will also be developed.

The ALD process uses amide-based precursors that are used extensively for high volume manufacturing of related thin films today. Initial film results will be described, along with surface pre-treat methods to enhance uniform deposition and masking approaches to limit deposition to the perimeter of the interconnect. An experimental method to detect the formation of rare-earth chromite phases via x-ray diffraction (XRD) will also be described. A preliminary cost model shows that the approach has significant promise to be cost-effective and to meet the demands of throughput and cost per unit.

Electrodeposited Mn-Co Alloy Coating For SOFC Interconnects

Faraday Technology Inc.-West Virginia University
H.A. McCrabb,[1] Savidra Lucatero,[1] T.D. Hall,[1] H. Zhang,[2] X. Liu,[2] S. Snyder,[1] and E.J. Taylor[1]
[1]Faraday Technology Inc. and [2]West Virginia University
e-mail: heathermccrabb@faradaytechnology.com phone: (937) 836-7749

Faraday Technology and WVU have continued to optimize and validate the FARADAYIC® Electrodeposition Process for surface modification of solid oxide fuel cell interconnects with a Mn-Co alloy that is subsequently oxidized to a spinel by thermal exposure at high temperatures in an oxidizing environment. The process has been scaled from 5 cm^2 laboratory scale button cells to 115 cm^2 industrial scale metallic interconnects containing gas flow field features. The alloy composition is influenced and can be controlled by the electrodeposition parameters to tune the spinel composition. Long term exposure at elevated temperatures has shown that the coatings function as a barrier to chrome diffusion toward the surface with minimal increase in the area specific resistance (ASR) suggesting a well-adhered chromia scale. Long term on-cell performance tests using coated button cells displayed minimal voltage decay, indicating cell stability. The poster will present the results obtained to date and provide a path forward for the technology.

On the Mechanisms of Cathode Degradation in Solid Oxide Fuel Cells: A Phase-Field Model

National Energy Technology Laboratory-The Pennsylvania State University
Liang Hong,[1,2] Jia-Mian Hu,[1,2] Linyun Liang,[1,2] Kirk Gerdes,[1] and Long-Qing Chen[1,2]
[1]National Energy Technology Laboratory and [2]The Pennsylvania State University, Dept. of Materials Science and Engineering
e-mail: lqc3@psu.edu phone: (814) 863-8101

A comprehensive phase-field simulation package has been developed to understand the mechanisms of cathode degradation in solid oxide fuel cells (SOFCs). Remarkably, this package can be used to predict time-dependent changes in both the microstructure of the composite cathode (viz., distributions of constituent phases and grains) and the ionic transport across/along either the grain boundaries within one phase or the interphase boundaries, and the influence of ionic transport on microstructure evolution. In this work, we summarize our recent progress in 1) simulating the particle coarsening and grain growth (both in 3D) in a typical three-phase or infiltrated cathode; 2) predicting the concentration profiles of multiple cations, oxygen vacancies, and electrons across the electrolyte-electrode interface with or without loading currents. All simulations results obtained agree well with existing experiments or electrochemical behaviors and may suggest promising recipes for improving the durability of SOFCs.

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Bayesian Calibration in Electrical Conductivity Relaxation and Electrode Modeling

National Energy Technology Laboratory-West Virginia University
David S. Mebane,[1,2] Joshua Blair,[1,2] Giuseppe Brunello,[1,2] and Kirk Gerdes[1]
[1]National Energy Technology Laboratory and [2]West Virginia University, Dept. of Mechanical and Aerospace Engineering
e-mail: david.mebane@mail.wvu.edu phone: (304) 293-3426

Multi-scale modeling is an important avenue through which the fundamental understanding of fuel cell electrochemistry influences the design of fuel cell systems. And uncertainty quantification is a critical aspect of multi-scale modeling, since it enables an assessment of the accuracy of up-scaling strategies. In this work, the power of Bayesian methods in uncertainty quantification have been demonstrated in an initial application to electrical conductivity relaxation experiments. Bayesian calibration leads to a joint distribution for parameters of interest (k* and D*) as opposed to a single, “point” parameter estimate obtained through nonlinear least squares. The uncertainty in the distribution can be easily propagated through to the scale of electrode and stack models. Plans for applying Bayesian calibration techniques to impedance experiments on fuel cell electrodes are detailed.

Surface Transport Mechanism and Bi-pathway ORR Kinetics for SOFC Cathode

National Energy Technology Laboratory-West Virginia University
Hui Zhang,[1,2] Mingyang Gong,[1,2] Kirk Gerdes,[1] and Xingbo Liu[1,2]
[1]National Energy Technology Laboratory and [2]Dept. of Mechanical and Aerospace Engineering, West Virginia University
e-mail: hui.zhang@mail.wvu.edu phone: (304) 293-7636

A one-dimensional continuum model related to close-packing theory has been developed to produce insights into the oxygen reduction reaction (ORR) process in a dense LSM-type cathode system. By incorporating SOFC cathode particle size, the modeling simulations reveal detailed surface processes and parallel reaction pathways responding to polarization-induced changes. A formula to distinguish the contributions of surface diffusion and local reactions to total 3PB is presented, which allows an estimation of the detailed influencing factor for 3PB/2PB transition. The results reveal that the essential correspondence in spatial domains of surface adsorbates and oxygen vacancies implies tight coupling behavior for 3PB/2PB kinetic competition. Identification on the kinetic domination conversion of surface reactions between oxygen adsorption and incorporate demonstrates the importance of the harmonization between surface active and ionic conduction for improving the overall electrochemical performance of SOFC cathode. Such mechanistic studies suggest means of rational design of more active cathodes to optimize the overall electrochemical performance.

Transient Aging Behavior of LSM in Response to Thermal Gradients

National Energy Technology Laboratory-URS-West Virginia University
Harry Abernathy,[1] Harry Finklea,[1,3] David Mebane,[1,4] Xueyan Song,[1,4] Yun Chen,[1,4], and Kirk Gerdes[1]
[1]National Energy Technology Laboratory; [2]URS; and
West Virginia University: [3]Dept. of Chemistry and [4]Dept. of Mechanical & Aerospace Engineering
e-mail: Harry.Abernathy@contr.netl.doe.gov phone: (304) 285-4632

The NETL Fuel Cell team has recently reported interesting aging behavior of $(La_{0.8}Sr_{0.2})_{0.95}MnO_3$ (LSM) cathodes at open circuit when subjected to thermal cycling within the temperature range of 700-850ºC. When the temperature increases, the electrode's polarization resistance will slowly decrease to its equilibrium value. In contrast, whenever the temperature decreases, the polarization resistance will increase with time over a few days. The behavior is reversible as the sample is cycled between any two temperatures in the given temperature range. Analysis by TEM, SEM, and XPS of dense LSM pellets sharing the same thermal history of the LSM electrodes does not show any large scale change in the surface composition of the LSM during the thermal cycling. The authors propose that the changes in polarization resistance during the aging is the result of changes in the defect concentrations in LSM with temperature, and the timescale of the aging is the result of the slow diffusion of cations in the LSM lattice as the material reaches new equilibrium values. Quantifying the aging behavior of SOFC cathodes is important with respect to developing a proper testing protocol for comparing different SOFC cathode samples and with respect to modeling transient behavior of SOFCs subjected to thermal and loading gradients during short- and long-term operation.

Electrochemical Impedance Analyses of Solid Oxide Fuel Cells

National Energy Technology Laboratory-West Virginia University
Harry Finklea,[1,2] Kirk Gerdes,[2] Shiwoo Lee,[2] Lynn Fann,[2] Gregory Hackett,[2] and Harry Abernathy[2]
[1]Dept. of Chemistry, West Virginia University and [2]National Energy Technology Laboratory
e-mail: Harry.Finklea@mail.wvu.edu phone: (304) 293-4742

Electrochemical impedance analyses are routinely applied to solid oxide fuel cells. Most commonly, the data are interpreted in terms of the ohmic resistance and polarization resistance of the SOFC through the Nyquist plot (out-of-phase impedance -Z" plotted against in-phase impedance Z') with data collected over a wide range of frequencies. More sophisticated analyses use equivalent circuits with elements that correspond to processes in the SOFC. We describe here a protocol for developing an appropriate equivalent circuit and obtaining values of the parameters of the equivalent circuit that best fit the data. The protocol uses deconvolution performed on a spreadsheet and a software package LEVM available free on the internet. The impedance data are tested for compliance with the Kronig-Kramers transform. Compliance indicates that the impedance of the SOFC is not evolving during data collection. To separate the impedance components for the anode and the cathode from the total impedance, impedance is collected while varying the gas composition either to the anode or to the cathode. Examples are given of analyses of operating SOFCs.

Analysis of SOFC Impedance Using Simulation and Experiment Together

National Energy Technology Laboratory-West Virginia University
I. B. Celik,[1,2] T. Yang,[1,2] H. Sezer,[1,2] H. O. Finklea,[1,3] and K. Gerdes[1]
[1]National Energy Technology Laboratory;
West Virginia University: [2]Mechanical and Aerospace Engineering Dept. and [3]Chemistry Dept.
e-mail: Ismail.Celik@mail.wvu.edu phone: (304)293-3209

In this study, a polarization model and physics based numerical simulations are developed to analyze the performances of solid oxide fuel cells (SOFCs). We propose a polarization model to extract essential information of fuel cells from the measured polarization curves. This model incorporates the ohmic resistance obtained from 2D electric field simulation and concentration losses from analysis of cases with different air and fuel utilization conditions. The values of parameters obtained from the proposed model are then used to derive the parameters used in our multi-dimensional numerical simulations. Our transient multi-dimensional simulations are developed to solve the multi-physics problems involved in the processes occurring in Solid Oxide Fuel Cells (SOFCs) including charge conservation, electrochemical reactions, diffusive transport within the porous electrodes etc. Realistic configurations and realistic distributions of properties (e.g. porosity, tortuosity, conductivity etc.) are also taken into account in our computational model. The computational tools are utilized to investigate polarization curves and impedance behavior of SOFCs for different utilization cases, which shows fairly good agreement with impedance measurements. The contributions of anode and cathode to the impedance of full cell are also analyzed with properly chosen reference electrodes. It is demonstrated that the proposed modeling and simulation strategy reduces the uncertainty involved in the model parameters used, while improving accuracy of the predictions.

Electrochemical Impedance Spectroscopy Study of Metal Ferrite Infiltrated LSM/YSZ Solid Oxide Fuel Cells

URS-National Energy Technology Laboratory
Yueying Lynn Fan,[1,2] Shiwoo Lee,[2] and Kirk Gerdes[2]
[1]URS and [2]National Energy Technology Laboratory
e-mail: Yueying.Fan@contr.netl.doe.gov phone: (304) 285-0205

The effect of seven metal ferrites including MFe_2O_4 (M=Co, Ni, Cu, Mn, Ba and Sr) and $CuFeMnO_4$ infiltrated commercial LSM/YSZ cells was evaluated by electrochemical impedance spectroscopy (EIS). $BaFe_2O_4$ and $SrFe_2O_4$ infiltrated LSM/YSZ cells demonstrated the best performance among all the tested metal ferrite infiltrated cells. The impedance of $BaFe_2O_4$ and $SrFe_2O_4$ infiltrated LSM/YSZ cells with frequency related to cathode (10-1000HZ) and anode (above 1000HZ) were both decreased significantly. Power density of $BaFe_2O_4$ and $SrFe_2O_4$ infiltrated LSM/YSZ cells was increased by 60% in zero hour, and reached the highest in 24h with 68% increased performance compared to the baseline cell. Performance of the infiltrated cell was slowly decreased after 24h, but stabilized after 200h. 800h operation on the $BaFe_2O_4$ infiltrated cell still showed 50% increased power density compared with LSM/YSZ baseline cell. The performance range measured for the various materials indicates that cathode activity can be customized by careful selection of infiltrate materials.

Bio-Template Assisted Nano-Catalyst Impregnation of SOFC Electrodes

National Energy Technology Laboratory-West Virginia University
Ozcan Ozmen,[1,2] Shiwoo Lee,[1] Kirk Gerdes,[1] John W. Zondlo,[3] Katarzyna Sabolsky,[2] Edward M. Sabolsky[1,2]
[1]National Energy Technology Laboratory;
West Virginia University: [2]Dept. of Mechanical & Aerospace Engineering, [3] Dept. of Chemical Engineering
e-mail: ed.sabolsky@mail.wvu.edu

Nano-catalyst impregnation is a well utilized technique to enhance electrochemical performance of solid-oxide fuel cells (SOFCs). One drawback of conventional impregnation methods is that the process requires multiple deposition steps in order to achieve the desired amount of catalyst incorporation. In our study, a facile impregnation method was investigated for SOFC electrodes. In the first part of this work, a protocol was adapted to enhance the nano-catalyst impregnation efficiency and uniformity in one step. In that way, the amount of catalyst can be easily tuned and controlled by optimizing catalyst precursor and deposition time. In the second part of the study, the self-adhesive properties of catechol based bio-template was used in the protocol to deposit a higher level of catalyst deep into both the electrode microstructure. The correlation between the deposition rates versus the electrochemical performance was assessed using current-voltage-power measurements and impedance spectroscopy. The result showed that the bio-templated impregnation method resulted in a uniform distribution of the nano-catalyst within the 3-D electrode architecture and enhanced the performance of the commercial button SOFC.

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Long Term Operation Stability of Interfacial Nanostructure from the Anode and Cathode of Solid Oxide Fuel Cells

National Energy Technology Laboratory-West Virginia University
Xueyan Song,[a,b] Yun Chen,[a,b] Shiwoo Lee,[a] and Kirk Gerdes[a]
[a]National Energy Technology Laboratory-Regional University Alliance and
[b]Dept. of Mechanical & Aerospace Engineering, West Virginia University
e-mail: xueyan.song@mail.wvu.edu phone: (304) 293-3269

The ever-growing demands for advancement in reliability, robustness, and endurance of low-cost solid oxide fuel cells (SOFCs) have stimulated great interest in developing SOFCs with a low degradation rate. In SOFCs, degradation may originate from myriad physical sources, with thermal, electrostatic, and chemical potential drivers being particularly prominent. Electrochemical reactions take place at the triple-phase boundaries (TPBs) between the electrolyte, the electrode and the gaseous reactant, and small changes in TPB structure or chemistry, and the interface between electrode and electrolyte can drastically affect SOFC performance and lifetime. However, very limited experimental work has been reported on the nanostructure and chemistry evolution of the interface and TPBs in the SOFC upon cell operation, especially upon long term operation of over 1500 hours. The present work employed Transmission Electron Microscopy (TEM) to investigate the nanostructure and chemistry of the grain boundaries and interfaces, including TPB in both anode and cathodes of SOFC, over the long term operation of 3000 hours and 1500 hours.

To investigate the origin of anode degradation, the evolution of grain boundary and interface nanostructure and chemical composition were systematically examined. For the commercial MSRI button cells operated at 0.6A/cm^2, over 300 hours operation, the electrochemical data show increased polarization resistance and decreased power density. Accompanying the electrochemical performance degradation are significant nanostructure changes observed at the YSZ/YSZ grain boundaries in the anode. Nano-scale void-like features were observed at the YSZ/YSZ grain boundaries from the cell operated for 3000 hours. The observation starkly contrasts with the as-received cell, which possesses intact boundaries between the YSZ/YSZ grains. The voids were oval shaped with a long axis of ~30nm, and were discretely distributed across the grain boundary planes. TEM observations over several tens of different YSZ grain boundaries from the active layer of anode consistently indicate that the void-like features are common in the cell operated for 3000 hours. The nano-structure and chemistry of those void regions at the YSZ/YSZ grain boundaries, and the origin of their formation and the possible impact on the overall cell performance are discussed. For the cathode of commercial cells, cathode infiltration of nanomaterials has been proven to be effective in introducing eletro-catalyst to the intrinsically functional electrodes and enhancing the performance of the as-prepared SOFCs. However, limited fundamental research has focused on study of the stability of such infiltrated nano-particles upon long-term operation. In the present study, the nanostructure and chemistry of the infiltrated $La_{0.6}Sr_{0.4}CoO_3$ electro-catalyst and its evolution upon operation were analyzed by TEM for cells that were electrochemically characterized under industrially relevant conditions.

Nanoscale X-ray Computed Tomography of Solid Oxide Fuel Cell Electrodes

National Energy Technology Laboratory-Carnegie Mellon University
William K Epting,[1-3] Shawn Litster,[3] Kerk Gerdes,[1] and Paul A Salvador[1,2]
[1]National Energy Technology Laboratory;
Carnegie Mellon University: [2]Dept. of Materials Science & Engineering, [3]Dept. of Mechanical Engineering

We present the imaging and analysis of SOFC electrodes using nanoscale X-ray computed tomography (nano-CT) in 3D, with a resolution of 120 nm and a field of view of 65 µm. Compared to electron microscopy techniques, nano-CT's larger field of view allows a more statistically representative sampling of a wider variety of SOFC builds, some of which contain heterogeneities on a scale of several micrometers. Meanwhile, the resolution of nano-CT is sufficient for the feature sizes (usually on the order of 1 µm) present in these cells. This poster details the sample preparation and nano-CT imaging of one such sample. We then demonstrate a multiphase imaging artifact common to multiple methods of characterization of systems with 3+ phases, and our approach to removing this artifact on large volumes of data. Finally, we examine the heterogeneities present in the imaged system, and discuss the length scales of these heterogeneities and the implications for choice of characterization method.

Electrochemical Evaluation of a Planer SOFC under Phosphine Induced Degradation

National Energy Technology Center-West Virginia University
H. Sezer,[1,2] T. Yang,[1,2]and I. B. Celik[1,2]
[1]National Energy Technology Laboratory and [2]West Virginia University, Dept. of Mechanical and Aerospace Engineering
e-mail: Ismail.Celik@mail.wvu.edu phone: (304)293-3209

A multi-dimensional code (DREAM-SOFC) designed for simulation of large scale planar solid oxide fuel cells is extended by implementing a one-dimensional degradation model to predict the typical degradation patterns observed in SOFCs when anode is exposed to phosphine. The empirical model parameters for the degradation part are calibrated using the accelerated button cell experiments as a guide. These parameters are then used in DREAM SOFC to predict phosphine induced performance degradation of the planar cell. For brevity a planar cell with 10 channels is represented by only one channel cell which is exposed to phosphine so that the transient degradation due to phosphine exposure can be observed. The results from the three dimensional model show that the contaminant coverage of nickel and fuel distribution inside the anode is highly non-uniform. These non-uniform distributions are caused by the geometrical alignment of gas channels and current collectors, as well as the variation of gas concentration along the flow direction. The non-uniform deactivation of the anode alters current distribution inside the planar cell such that the cell can still produce current even when some regions of the anode are partially inactive due to fuel starvation. In order to assess overall performance of the cell at different degradation levels, additional simulations are performed to predict the polarization behavior and the impedance response of the cell. The V-I curves obtained at different levels of degradation show that PH_3 coverage increases overall polarization, slowly at first and rapidly after some time. The calculated impedance curves show the predicted impedance response of the anode supported cell while anode exposed to phosphine over time. The impedance curves indicate that, the increase in activation losses in the anode is mainly responsible for cell degradation and they increase abruptly after long exposure time.

Mitigation of Degradation Associated with Elevated Steam Content in SOFC Cathode Oxidant by Surface Modification

National Energy Technology Laboratory
Shiwoo Lee, Gregory Hackett, and Kirk Gerdes
e-mail: leesn@contr.netl.doe.gov phone: (304) 285-4594

Commercially available anode supported cells with LSM/YSZ cathode were surface-modified with manganese species by solution infiltration method and compared with un-modified baseline cells in the aspect of performance degradation under highly humid cathode air. Saturated steam is pressure/temperature controlled and elevated steam concentrations were precisely injected through a resistive flow orifice at choked flow conditions. The cells were operated at either 0.25 or 0.75 A/cm^2 current density, and 10 or 20 % steam content / balance air at 800ºC. Under 20 % steam in air condition, baseline cells exhibited immediate rapid degradation (> 20%) followed slower degradation at extended operating times at 0.25 A/cm^2. For the Mn infiltrated cells, short duration testing did not reveal performance degradation: Conversely, cell performance increased over the first 100 hours. A similar trend was exhibited in two long-term repeat tests: An initial 100 - 150 h performance increase was followed by 5 - 8%/1000h degradation. The stabilizing effect of the surface-modifier is discussed in the context of impedance spectra obtained during the operations and post-mortem microstructure/elemental analysis.

Strategies to Mitigate the Degradation of LSCF Cathodes Against Contaminants (Cr, H_2O, and CO_2)

Georgia Institute of Technology
Dong Ding, Xiaxi Li, Samson Lai, and Meilin Liu
e-mail: Meilin.Liu@mse.gatech.edu phone: (404) 894-6114

Cathode durability is critical to long-term SOFC performance for commercial deployment. The state-of-the-art LSCF cathodes are exposed to various contaminants under realistic operating conditions (ROC) that may affect their stability. The contaminants commonly encountered in air (e.g., CO_2 and H_2O) and/or Cr-containing alloy interconnect may activate or accelerate the degradation of the LSCF cathode. Electrochemical characterization of LSCF cathodes exposed to such contaminants along with surface enhanced Raman spectroscopy (SERS), synchrotron-based X-ray absorption spectroscopy (XAS), and X-ray photoelectron spectroscopy (XPS) provided us critical insights into unraveling the degradation mechanisms of the LSCF cathodes. This fundamental understanding helped us to develop effective strategies to mitigate the stability issues, especially solution infiltration of proper catalysts with desired composition, morphology, and microstructure under a wide range of operating conditions.

Carbon Dioxide Effects on LSCF Cathodes for Solid Oxide Fuel Cells

Boston University
Yang Yu, Heng Luo, Deniz Cetin, Soumendra Basu, Karl Ludwig, Xi Lin, Uday Pal, and Srikanth Gopalan
e-mail: sgopalan@bu.edu phone: (617) 358-2297

Perovskite materials of the composition family $La_{1-x}Sr_xCo_yFe_{1-y}O_3$ (LSCF) are being studied intensively for applications in solid oxide fuel cells (SOFCs). In this poster presentation we report on cation segregation effects in LSCF, and the effect of carbon dioxide on cation segregation and the formation of second phases at the LSCF – air interfaces. In particular, we have studied the segregation of strontium to the LSCF surfaces using total x-ray fluorescence and hard x-ray photoelectron (HAXPES) spectroscopy. In parallel we have performed density function theory (DFT) studies of Sr segregation to the LSCF surfaces and the thermodynamics of strontium carbonate formation. The effects of Sr segregation and formation surface phases on LSCF on the electrochemical performance of cathodes are presently being investigated. Based on prior work on patterned electrode measurements, we suggest potential effects of the formation of the surface phases on the electrochemical performance of these cathodes.

Mechanistic Understanding of LSM Cathode Interaction with H_2O and CO_2

University of Connecticut-University of California San Diego-Alfred University
Boxun Hu,[1] Manoj K. Mahapatra,[1] Vinit Sharma,[1] Rampi Ramprasad,[1] Nguyen Minh,[2] Scott Misture,[3] and Prabhakar Singh[1]
[1]University of Connecticut, [2]University of California San Diego, and [3]Alfred University
e-mail: singh@engr.uconn.edu phone: (860) 486 8379

The stability of the strontium (20%) doped lanthanum manganite (LSM) cathode has been studied in air using LSM/YSZ/LSM symmetric cells under a wide range of humidification (0-50%) and CO_2 levels (0-10%) in 750-850ºC temperature range and cathodic bias of 0-0.5 V. In the humidified air, electrochemical impedance spectra showed an increase in non-ohmic resistance with increasing H_2O/O_2 ratio, temperature, and cathodic bias. Post-test surface and interface studies performed using X-ray photoelectron spectroscopy, energy dispersive X-ray spectroscopy, and X-ray diffraction analyses revealed the formation and segregation of SrO particles on the LSM surfaces and formation of MnO_x and $La_2Zr_2O_7$ compounds at the LSM (cathode)/YSZ interface. In CO_2-containing air, the current density of the LSM cathode remained relatively stable after an initial decay. Our observations also indicate that the lower levels of CO_2 (<0.5% CO_2) may not affect the current density after initial pre-activation of LSM in air. Surface analysis of the pre-test and post-test LSM cathodes using Auger electron spectroscopy (AES) and attenuated total reflectance-Fourier transform infrared spectroscopy (ATR-FTIR) techniques suggests that the formation of $SrCO_3$ at the LSM surface leads to an initial performance degradation. Reaction processes during exposure to H_2O and CO_2 are proposed.

Understanding and Mitigating Reactivity of LSM with YSZ

Alfred University-University of Connecticut-University of California San Diego
Kyle M. McDevitt,[1] Boxun Hu,[2] Manoj K. Mahapatra,[2] Vinit Sharma,[2] Rampi Ramprasad,[2]
Nguyen Minh,[3] Prabhakar Singh,[2] and Scott T. Misture[1]
[1]Alfred University, [2]University of Connecticut, and [3]University of California San Diego
e-mail: misture@alfred.edu phone: 607-871-2438

Reaction studies of mixed LSM and YSZ powders as well as LSM on YSZ electrolytes were conducted to 1000 hours at 850 and 1350°C under controlled atmospheres including in 10% CO_2 in air and 3% H_2O in air. Commercial LSM was used as well as bulk modified LSM with Ni and Ca substitutions. Three new LSM compositions were tested, including $La_{0.8}Sr_{0.1}Ca_{0.1}MnO_3$, $La_{0.8}Sr_{0.2}Mn_{0.7}Ni_{0.3}O_3$ and $La_{0.8}Sr_{0.1}Ca_{0.1}Mn_{0.7}Ni_{0.3}O_3$.

Accelerated testing at 1350°C shows that LSM reacts with YSZ to partially destabilize the YSZ to the tetragonal form. We find that 3% H_2O vapor at 1350°C under air prevents the destabilization of YSZ to the tetragonal form, and that both the Ni and (Ni+Ca) modifications of LSM likewise eliminate the degradation.

Testing at 1350°C under 10% CO_2 in air led to several new observations. Firstly, lanthanum zirconate forms in base LSM and Ni- and Ca-modified LSM powders. For Ca-modified LSM, we find two YSZ phases, one appears to be Ca-stabilized and the other Y-stabilized, with differing lattice constants. Finally, we note that the Ca-modified LSM converts from rhombohedral (R-3c) to orthorhombic (Pnma) over the course of 500+ hours. Taken together, the results suggest that $La_{0.8}Sr_{0.1}Ca_{0.1}Mn_{0.7}Ni_{0.3}O_3$ should be considered as a strong candidate for mitigating the SOFC cell degradation at the cathode/YSZ interface.

Cationic Surface Segregation in Doped $LaMnO_3$: A First Principles Thermodynamics Study

University of Connecticut-University of California San Diego-Alfred University
Vinit Sharma,[1] Sridevi Krishnan,[1] Boxun Hu,[1] Manoj K. Mahapatra,[1] Nguyen Minh,[2] Scott Misture,[3]
Prabhakar Singh,[1] and Rampi Ramprasad[1]
[1]University of Connecticut, [2]University of California San Diego, and [3]Alfred University
e-mail: rampi@uconn.edu phone: (860) 486 4102

The surface cation chemistry in $LaMnO_3$ doped at the La site by Ca, Sr or Ba when exposed to pure oxygen or water vapor reservoirs is investigated using first-principles thermodynamics. We find that all three dopants tend to segregate to the surface over a wide range of temperature and pressure conditions and the tendency for segregation increases with the increase in the dopant cationic size. Under low oxygen pressure, dopants prefer to remain in the bulk regions accompanied by the appropriate number of charge compensating oxygen vacancies. However, this desired situation tends to occur close to the thermodynamic conditions that also favor the decomposition of $LaMnO_3$. In the presence of moisture, about 25% of the surface is predicted to be covered by dissociated water species, accompanied by enhanced a tendency for surface cationic segregation.

Microstructural and Performance Changes in LSM-Based SOFC Cathodes Under Extended Operation

Case Western Reserve University
Naima Hilli,[1*] Hsiang-Jen Wang,[1] Harshil Parikh,[1] Zhengliang Xing,[2] Zhien Liu,[2] Richard Goettler,[2] Mark R. De Guire,[1] and Arthur H. Heuer[1]
[1]Department of Materials Science and Engineering, Case Western Reserve University
[2]LG Fuel Cell Systems Inc.
e-mail: [*]nxh146@case.edu phone: 216-368-4128

Loss of performance in solid oxide fuel cells (SOFCs) is often accompanied by physical and chemical changes in the cell materials during operation. Among these changes are bulk or surface chemical reactions of the cell components with each other and their environment, and gradual microstructural changes that alter the electrochemical transport properties of the cell components. Detailed microstructural and microanalytical studies have been conducted on SOFC cathodes based on lanthanum strontium manganite ($(La,Sr)MnO_3$, LSM) after extended cell operation (up to 16 kh) under practical operating conditions. Techniques used include transmission electron microscopy (TEM) combined with energy-dispersive x-ray spectroscopy (EDXS) and electron energy los spectroscopy (EELS), and 3-D reconstruction using dual focused ion beam scanning electron microscopy (FIB-SEM). The following microstructural effects have been observed:

- Changes in phase fraction and their distribution across the cathode, particularly densification/loss of porosity near the cathode-electrolyte interface;
- Changes in (active) triple-phase boundary (TPB) density;
- Formation of manganese oxides (MnxOy) and their distribution across the cathode;
- Interdiffusion between LSM and zirconia at the cathode/electrolyte interface and in the composite cathode.

Effects of the (La + Sr)/Mn ratio and of the zirconia composition on the nature, magnitude, and extent of these changes will be reported.

Understanding the Performance of p-type Perovskite Solid Oxide Fuel Cell Cathodes Using Non-Linear Electrochemical Impedance Spectroscopy

University of Washington, Seattle
T. J. McDonald, T. C. Geary, and S. B. Adler
e-mail: stuadler@u.washington.edu phone: 206-543-2131

Non-Linear Electrochemical Impedance Spectroscopy (NLEIS) can be used to distinguish the roles of key processes governing SOFC cathode performance. Harmonics measured by the NLEIS technique are sensitive to the specific mechanism for oxygen reduction, thermodynamic behavior of the bulk and surface of the electrode, and the relative rates of surface transport, bulk transport, and oxygen kinetics. Fundamental understanding of these processes as well as their dependencies on material properties is critical for the engineering of better performing cathode materials.

We have studied the behavior of p-type semiconducting $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$ and $La_{0.9}Ca_{0.1}FeO_{3-\delta}$ electrodes using both Linear EIS and NLEIS. These measurements suggest that the reducibility of these materials is significantly enhanced at the surface relative to the bulk, and that surface diffusion plays a significant role in the overall overpotential. Short term changes in performance (100~1000 hours) appear to be associated primarily with changes in the surface rate coefficient for O_2 reduction.

Ab initio Based Modeling of Solid Oxide Fuel Cell Cathodes

University of Wisconsin - Madison
Yueh-Lin Lee, Milind Gadre, and Dane Morgan
e-mail: ddmorgan@wisc.edu phone: (608) 265-5879

The performance of Solid Oxide Fuel Cells (SOFCs) depends critically on the cathode oxygen reduction reaction (ORR) activity on transition metal perovskite materials. Key challenges in understanding perovskites for SOFC cathodes include defect chemistry of bulk and surfaces/interfaces, and surface kinetics associated with the ORR. In this work we describe how ab initio techniques can be used to model perovskite chemistry near the surfaces/interfaces. We predict strong Sr surface segregation tendencies for $(La,Sr)CoO_3$ and $(La,Sr)(Co,Fe)O_3$ systems, and show that (La,Sr)O type termination is most stable for (001) surfaces under SOFC conditions. These results are in good agreement with recent experimental data. We further demonstrate the Sr segregation tendencies between $(La,Sr)CoO_3$, $(La,Sr)(Co,Fe)O_3$, and $(La,Sr)_2CoO_4$ systems, including their interfaces, and suggest how this might impact performance of $(La,Sr)_2CoO_4/(La,Sr)CoO_3$ interfaces.

The Effect of $(La,Sr)_2CoO_{4\pm\delta}/La_{0.8}Sr_{0.2}MO_{3-\delta}$ (M = Co, Fe) Hetero-interface on Oxygen Surface Exchange Kinetics and Stability

Massachusetts Institute of Technology-Oak Ridge National Laboratory
Dongkyu Lee,[1] Yueh-Lin Lee,[1] Wesley T. Hong,[1] Michael D. Biegalski,[2] and Yang Shao-Horn[1]
[1]Massachusetts Institute of Technology and [2]Oak Ridge National Lab
e-mail: shaohorn@mit.edu phone: (617) 253-2259

Oxide heterostructure interfaces of the form (A_2BO_4/ABO_3) are a new approach to design highly active and stable cathode materials for solid oxide fuel cells (SOFCs). Using epitaxial thin films deposited on (001)-oriented yttria-stabilized zirconia (YSZ), we demonstrate that $(La_{0.5}Sr_{0.5})_2CoO_{4\pm\delta}$ (LSC_{214}) surface decoration leads to distinct influence on surface chemistry, oxygen surface exchange kinetics, and the time-dependent surface stability of $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$ ($LSCF_{113}$) and $La_{0.8}Sr_{0.2}Co_{O3-\delta}$ (LSC_{113}). The surface exchange coefficients (k^q) of the LSC_{113} measured within the first 70 hours were dramatically enhanced by LSC_{214} decoration, in contrast to the LSC_{214}-covered-$LSCF_{113}$ vs. undecorated $LSCF_{113}$ films. Auger electron spectroscopy (AES) showed that LSC_{214} decoration can modulate the surfaces of LSC_{113} differently from $LSCF_{113}$ by enhancing surface Sr content of the LSC_{113} to a greater extent than the $LSCF_{113}$, which may be responsible for distinct k^q enhancement of the LSC_{214} decorated vs. the undecorated films. Six hours of annealing led to formation of Sr-enriched particles on the surface of the LSC_{113} film while no such particles were observed on the $LSCF_{113}$ film surface. In addition, LSC_{214} decoration suppressed the formation of these Sr-enriched secondary particles on the surface of the LSC_{113} but did not impact the Sr segregation on the $LSCF_{113}$ surface. Our findings provide new insights into material design of surfaces and heterostructure interfaces for highly active and stable electrocatalysts of intermediate temperature oxygen electrocatalysis.

Effects of Sr Doping on the Oxygen Reduction Reaction Kinetics of $La_2NiO_{4+\delta}$ Cathode for Solid Oxide Fuel Cells

West Virginia University
Bo Guan, Hui Zhang, Wenyuan Li, and Xingbo Liu
Mechanical & Aerospace Engineering Department, West Virginia University
e-mail: Xingbo.liu@mail.wvu.edu phone: (304) 293-3339

Sr doped lanthanum nickelates, $La_{2-x}Sr_xNiO_{4+\delta}$ ($0 \leq x \leq 0.4$), have been prepared and investigated as cathode candidates for solid oxide fuel cells (SOFCs). The oxygen reduction reaction (ORR) kinetics of lanthanum nickelates after Sr doping is evaluated via electrochemical impedance spectroscopy (EIS) with the symmetric cell configuration. The polarization resistances of doped samples increase with Sr level. EIS analysis indicates that surface oxygen exchange and bulk ionic diffusion co-control the ORR kinetics. With high Sr content (x=0.3, 0.4), oxygen ion transfer resistance between nickelate/electrolyte is observed. The oxygen incorporation process is identified as the rate-limiting step (RLS) of surface reaction according to the reaction orders. The role of interstitial oxygen in such process has been discussed and a possible relationship between interstitial oxygen and the surface exchange kinetics has been proposed. In this proposal, increasing the amount of interstitial oxygen will affect the activation energies for the forward and backward reactions in ways that the rate constant for the forward reaction is accelerated so significantly that the drawback due to the loss of interstitial vacancy sites is offset, rendering a greater oxygen exchange flux in turn. It is suggested that Sr doping decreases both the ionic conductivity and the oxygen surface exchange rate of $La_2NiO_{4+\delta}$ by depleting the interstitial oxygen.

Solid Oxide Fuel Cell Application to Unconventional Oil and Gas Recovery from Oil Shale

Delphi and Independent Energy Partners Technology
R. Kerr, J. Bonadies, and M. Wall

Delphi, with support from the U.S. Department of Energy's SECA program, is developing solid oxide fuel cell (SOFC) technology for potential application in a variety of markets. One potential market is the recovery of unconventional oil and gas from oil shale in the U.S. The U.S. has estimated oil shale reserves that exceed 1.5 trillion barrels of oil, but extraction of oil from oil shale is not an easy task. In-situ recovery of oil involves heating the oil shale in-place to pyrolyze the kerogen into condensable and non-condensable gas which flows to central wells for extraction and collection. Solid oxide fuel cells are well suited to provide the heat required for this in-situ oil and gas recovery.

The Geothermic Fuel Cell (GFC) is the SOFC-powered heater unit that Delphi and IEP Technology (IEPT) are developing for in-situ oil and gas recovery from oil shale. This poster describes the oil shale market and updates progress by the Delphi/IEPT team on demonstrating the GFC technology and achievements toward commercialization in the application of unconventional oil recovery.

Pressurized Operation of Solid Oxide Fuel Cell Stacks

Naval Undersea Warfare Center
John R. Izzo Jr. and Louis G. Carreiro Jr.
e-mail: john.r.izzo.@navy.mil phone: (401) 832-6116

Increased efficiency can be achieved by operating solid oxide fuel cell (SOFC) stacks at elevated pressure; however, sealing in planar solid oxide fuel cell (SOFC) stacks is challenging. Gas leakage can occur due to small pressure differentials (2-3 psi) between the process flows and external atmosphere, and this adversely affects fuel cell performance and lifetime. A 10-cell, planar SOFC stack was operated up to 45 psia with the pressure differentials minimized by containing the stack in a pressure vessel and regulating back-pressure for each of the three zones (anode, cathode, and vessel). The absolute efficiency increase was shown to be 1.7% and 2.4% for air and oxygen, respectively, which is in agreement with other recent studies on pressurized planar SOFC stacks. Both Nernstian and kinetic effects were found to be responsible for enhanced fuel cell performance at elevated pressure.

Carbon-based Solid Oxide Fuel Cells

The University of Akron, Department of Polymer Science
Steven S.C. Chuang, A. Rismanchian, S. A. Modjtahedi, J. Mirzababaei, and N. Hedayat
e-mail: schuang@uakron.edu phone: (330) 972-6993

The operating principle of the carbon-based solid oxide fuel cell involves the direct electrochemical oxidation of carbon on the surface of the anode to produce electricity with CO and CO_2. This poster presentation reports the results of studies on anode catalysts, design of a fuel cell stack, and cost analysis of a fuel cell system. Faradaic resistances of the cells operated with carbon are compared with those operated with CH_4 and CO_2. Mechanistic studies revealed that the addition of CO_2 into the feed to the anode chamber enhanced the fuel cell performance by promoting the reaction of CO_2 with carbon to produce CO which is then further electrochemically oxidized at the anode interlayer. This presentation will also present the results of cost analysis based on various feeds including carbon, carbon/CO_2, and carbon/H_2O.

Long-Term Degradation of LSM-Based SOFC Cathodes: Use of a Proven Accelerated Test Regimen

Case Western Reserve University-LG Fuel Cell Systems Inc.
Mark R. De Guire,[1*] Arthur H. Heuer,[1] and Zhien Liu[2]
[1]Case Western Reserve University and [2]LG Fuel Cell Systems Inc.
e-mail: mrd2@case.edu[*] phone: (216) 368-4221

One of the most difficult challenges associated with bringing solid oxide fuel cell (SOFC) technology into wider use is the need to understand and mitigate the processes that lead to loss of power output over operating lifetimes of five years (40,000 h) or more. The overall goals of this program are to understand the microstructural basis of performance loss in cathodes based on lanthanum strontium manganite (LSM, $(La_{1-x}Sr_x)_{1-y}MnO_{3\pm\delta}$), and to develop strategies for optimizing the long-term performance of LSM-based cathodes for commercial fuel cell systems.
This program will implement an accelerated testing protocol, developed and validated by LGFCS, to gather performance data at CWRU in time frames of e.g. 500 h that are relevant to much longer-term normal cell operation (≥ 5,000 h), and compare these findings to results from tests carried out under non-accelerated conditions. We will then conduct detailed microstructural and microanalytical studies (TEM, STEM, HRTEM, EDXS, EELS, FIB-SEM, 3-D reconstruction) on tested cells, focusing on the following phenomena:

- Changes in phase fraction and their distribution across the cathode, particularly densification/loss of porosity near the cathode-electrolyte interface;
- Changes in (active) triple-phase boundary (TPB) density;
- Formation of free manganese oxides (Mn_xO_y);
- Interfacial chemistry, particularly LSM/YSZ at the cathode/electrolyte interface and in the composite cathode.

We will utilize the performance histories, the microstructural results, and computational thermodynamic analysis to develop design rules for improving the long-term stability and performance of LSM-based cathodes. We will iteratively refine the proposed design rules, with a view to identifying and quantifying the mechanisms that lead to loss of performance in LSM-based cathodes.

Development and Characterization of High Performance and Robust Mixed Conducting Cathodes Supportive of Lower Cost SOFCs

University of South Carolina and LG Fuel Cell Systems
Xiao-Dong Zhou,[1] Hwa-Young Jung,[2] Zhengliang Xing,[2] Zhien Liu,[2] and Rich Goettler[2]
[1]University of South Carolina
[2]LG Fuel Cell Systems
e-mail: zhox@cec.sc.edu phone: 803-777-7540

The objective of the poster is to present recent advances, rationales, and activities to research and develop mixed electronic and ionic conducting cathode materials for durable and robust low cost solid oxide fuel cells (SOFCs). The specific aims are to (1) Improve phase stability and performance durability over the entire operational temperature range (550 to 900°C) by using mixed ionic and electronic conducting doped $(Pr,Nd)_2NiO_4$-based cathodes on a dense barrier layer, and compare their performance with LSCF6428. (2) Deconvolute electrochemical and physical processes to pinpoint the location of degradation of doped $(Pr,Nd)_2NiO_4$ and LSCF6428 with respect to changes of the microstructural and electrocatalytic activity at both anode and cathode sides, and (3) Apply an accelerated testing method to screen mixed conducting cathodes with the presence of 1-3% moisture level and volatile Cr species.

Durable, Impermeable Brazes for Solid Oxide Fuel Cells

Michigan State University-Delphi Corporation
Yue Qi, Thomas R. Bieler, Stephanie Surface, Rick Kerr, and Jason D. Nicholas*
e-mail: *jdn@msu.edu phone: (517) 355-1615

One of the most daunting obstacles to the commercialization of planar SOFCs is a lack of durable, impermeable brazes. While the Ag/CuO based brazes used today have good oxidation resistance, high strength, and melting temperatures compatible with current SOFC manufacturing/operating temperatures, pores caused by poor braze wetting, the hydrogen-induced reduction of copper oxide, and water vapor formation in the braze interior lead to braze joint mechanical and hermetic seal failure. This poster summarizes a combined computational-experimental approach to identify new, SOFC-compatible, silver-free brazes forming durable, oxygen and hydrogen impermeable protective surface scales.

SOFC Quality Control and the Role of Manufacturing Defects on Stack Longevity

Acumentrics SOFC, Inc
Neil Fernandes, Wensheng Wang, and Michael Ulsh
e-mail: nfernandes@acumentrics.com phone: (781) 461-8251 x388

Abstract: Acumentrics SOFC, Inc has successfully developed solid oxide fuel cells in the 250W-10kW power range with the help of both DOE and DOD funding. Our commercial fleet has been deployed in various remote power applications since 2010 and has now accrued well over one million operating hours. Widespread SOFC commercial application requires that the life cycle cost of the fuel cell be able to be supported throughout the private sector. While this can be achieved through reductions in manufacturing costs and increased product reliability, such avenues are generally at odds with each other. It is accepted, for instance, that a single cell's demise can hasten stack degradation in a snowball effect. Thus, cell quality cannot be compromised at the expense of cost reductions. The question at large then is what is the quality threshold that optimizes lifecycle cost? Commercial success requires an answer. SOFC manufacturing is still a nascent industry and cell manufacturing flaws need to be quantitatively connected to performance and degradation in order to obtain optimized yields and acceptable stack reliability.

Acumentrics will partner with the Fuel Cell Manufacturing R&D project team at NREL to further this understanding. Combining high throughput machine vision methods for imperfection detection with a rigorous rule set for cell rejection is a logical step for improving lifecycle cost. The immediate project aims are 1) to develop minimally invasive, automatable techniques for the detection of cell imperfections; and 2) to instigate a cell testing program at cell area scales of 1 cm^2 to 1000cm^2 with the purpose of ranking the imperfection types relative to their effects on performance, degradation and reliability of both cells and stacks.

Materials and Approaches for the Mitigation of SOFC Cathode Degradation in SOFC Power Systems

University of Connecticut, Dept. of Materials Science and Engineering
Prabhakar Singh, Manoj Mahapatra, Boxun Hu, and Rampi Ram Prasad

The research program (DE-FE0023385) focuses on the development and validation of cost effective and reliable approaches for minimizing/mitigating SOFC cathode (Strontium doped lanthanum manganite (LSM) and Lanthanum strontium cobalt ferrite (LSCF) degradation through the incorporation of reliable materials and architectures to inhibit long term detrimental solid-solid and solid-gas interactions.

DFT calculation for screening suitable dopants combined with experimental validation will be performed to minimize the detrimental effects of moisture and chromium in 'real world' cathode atmosphere. Select materials will either be synthesized or procured, if available, from commercial vendors. In-situ and in-operando high temperature techniques such as X-ray diffraction (XRD), scanning electron microscope (SEM),thermo-analytical techniques such as thermogravimetric analysis and differential scanning calorimeter (TGA, DSC, dilatometer, and electrical conductivity measurement techniques will be utilized for the evaluation and screening of the developed materials prior to electrochemical testing (EIS).

Commercial-viability of the developed materials and methods will be determined in consultation with DOE program managers and the developers of stationary SOFC systems.

Mitigation of Chromium Impurity Effects and Degradation in Solid Oxide Fuel Cells: Understanding Transport and Thermodynamics

Boston University
Soumendra Basu, Uday Pal, Emily Ryan, and Srikanth Gopalan
e-mail: sgopalan@bu.edu phone: (617) 358- 2297

The formation of ternary phases such as chromates and chromites at the interfaces degrades the performance of solid oxide fuel cells. The chromates form due to the reaction of the chromium oxide scale on the surface of the interconnect, which then migrates to the triple phase boundaries (TPBs) and deposit there, effectively killing the electrochemical activity of the TPBs and thereby increasing the activation polarization of the cell leading to performance degradation and cascading failure of the cell. Other important sources of chromium in the stack arise from the hot balance of plant components, particularly the hot cathode side heat exchangers. The chromate formation reaction at the TPBs is driven by reactive transport and thermodynamics. However, these different factors contributing to compound formation in the cathode often predict different compositions and locations within the cathode where the compound formation occurs. It is thus important to consider all of these factors simultaneously to understand the effect of chromium impurities in the cathode. In the proposed project we separately consider the role of reactive transport and thermodynamics in the formation of compounds in the cathode in the presence of chromium impurities. We suggest a systematic procedure to elucidate the role of each and their interactions and finally suggest mitigation strategies we might consider.

Scalable and Cost-effective Barrier Layer Coating to Improve Stability and Performance of SOFC Cathode

West Virginia University-Northwestern University
Xingbo Liu[1] and Scott Barnett[2]
[1]Mechanical & Aerospace Engineering Department, West Virginia University
e-mail: Xingbo.liu@mail.wvu.edu phone: (304) 293-3339
[2]Materials Science & Engineering Department, Northwestern University
e-mail: s-barnett@northwestern.edu phone: (847) 491-2447

The overall objectives of this project are (1) to develop a scalable and cost-effective coating process by means of electrophoretic deposition (EPD) to achieve a dense barrier layer (i.e. one with low or no porosity) between a YSZ electrolyte and LSM or LSCF cathode that can significantly improve both stability and performance of SOFC cathodes; and (2) to systematically investigate the interaction between doped ceria barrier layers in SOFC cathodes and the effect on oxygen reduction reaction (ORR) kinetics, electrochemical performance, and long-term stability to thus identify the optimal barrier layer composition and thickness.

Cost-effective Manufacturing and Morphological Stabilization of Nanostructured Cathodes for Commercial SOFCs

University of Pennsylvania-University of South Carolina-FuelCell Energy
Anthony Yu, R. J. Gorte, J. M. Vohs, K. Huang, and H. Ghezel-Ayagh
e-mail: gorte@seas.upenn.edu phone: (215) 898-4439

The primary goals of the work that will be carried out in this program will be to develop (1) simple, cost-effective processes to manufacture nanostructured cathodes and (2) unique surface functionalization to stabilize nanostructured cathodes under SOFC operating conditions. Fundamental studies and characterization will be carried out to complement the development. The developed processes will ultimately be applied to industrial-scale cells and validated by FuelCell Energy.

One promising approach that has been developed to take full advantage of the high ORR activity of LSCF while avoiding the deleterious solid-state reactions and thermal expansion mismatch within the cell is the synthesis of composite electrodes by infiltration, i.e. adding LSCF nanoparticles or precursor salts into a preformed, porous, and ionically-conducting electrode scaffold (generally composed of the electrolyte material) at low temperatures. However, broad adoption of infiltration-derived nanostructured cathodes/promoters in commercial SOFCs has been impeded by two major issues: manufacturability and stability. This poster will describe past work using Atomic Layer Deposition (ALD) to promote and stabilize SOFC cathodes prepared by infiltration. While ALD with various oxides is found to decrease performance in most cases (R. Küngas, A. S. Yu, J. Levine, J. M. Vohs, R. J. Gorte, J. Electrochem. Soc., 160 (2013) F205-11), ALD layers of ZrO_2 (Y. Gong, R. L. Patel, X. Liang, D. Palacio, X. Song, J. B. Goodenough, and K. Huang, Chem. Matls., 25 (2013) 4224) were shown to stabilize the performance over time by stabilizing the surface area.

Novel Nanostructure Tailored Highly Active and Stable Electro-Catalytic Architecture on Surface of Cathode of SOFCs

Department of Mechanical and Aerospace Engineering, West Virginia University
Xueyan Song and Yun Chen
e-mail: xueyan.song@mail.wvu.edu phone: (304) 293-3269

One of the critical challenges facing the development of a new-generation SOFC, with improved reliability, robustness and endurance, is to design and create a highly active and stable cathode. This research herein focuses on improving the power density and durability of commercial cells through tailoring the nanostructure of the surface of cathodes that possess complex three-dimensional topographies. The target material systems are commercial LSM/YSZ and LSCF/SDC composite electrodes, and emphasis will be towards applications at temperatures of 650-800°C. The formation of the designed nano- architecture/scaffold on the surface of SOFC cathode will be achieved through morphological control. The formation of the engineered nano-scale architecture/scaffold on the surface of SOFC cathode, their effect on overall cell performance, and resultant electrochemical reaction mechanism of cathodes will be investigated through full cell electrochemical performance testing, as well as nanostructure and chemistry characterization by advanced analytical transmission electron microscopy. With optimized design of the surface nanostructure, the technical achievement is expected to be 50% greater power density for commercial operation throughout the entire SOFC operation temperature range of 650-800°C, as well as the increased durability for long term operation.