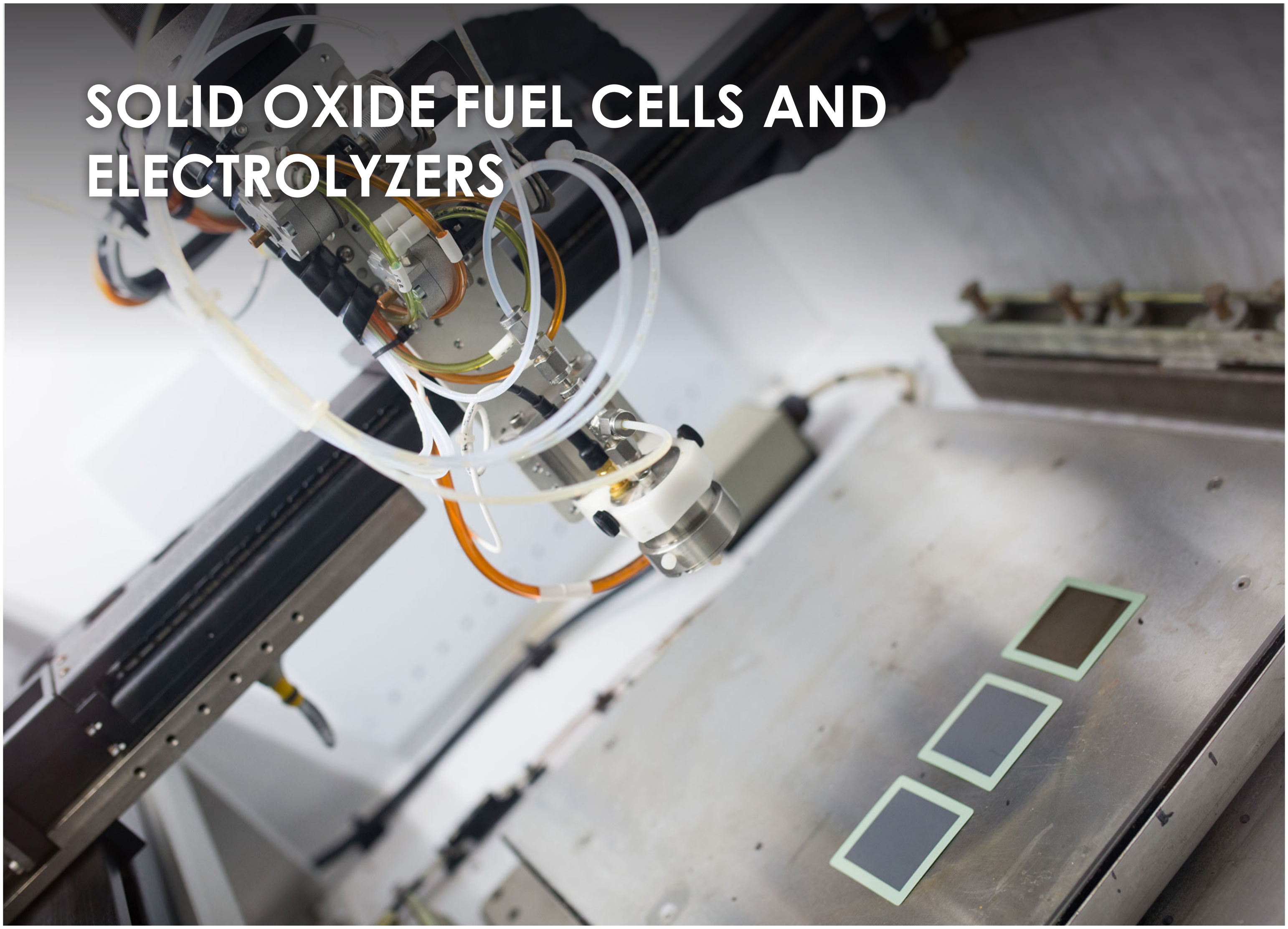

SOLID OXIDE FUEL CELLS AND ELECTROLYZERS

R&D182, December 2024

NATIONAL ENERGY TECHNOLOGY LABORATORY

The National Energy Technology Laboratory (NETL) Solid Oxide Cell (SOC) Team performs fundamental high-temperature fuel cell and electrolyzer technology evaluation, enhances existing technology and develops advanced solid oxide fuel cell/solid oxide electrolyzer cell (SOFC/SOEC) concepts in support of the U.S. Department of Energy's R-SOFC Program and the Hydrogen and Fuel Cell Technologies Office (HFTO). Research efforts are designed to meet critical technology needs broadly focused on investigation of cell and stack degradation, electrode engineering, and system analysis. The research approach is targeted to address R-SOFC program technology development goals, especially reducing stack costs, increasing cell efficiency and increasing cell reliability and robustness. The intended consequence of these research and development efforts is to transfer technology that facilitates commercial acceptance of SOFC/SOEC technology. This is done through close collaboration with SOFC/SOEC commercial developers, national laboratories and academic institutions throughout the country. The research portfolio is broken into three efforts, which are described in the subsequent sections.

ADVANCED FUEL SOLID OXIDE CELL RESEARCH AT NETL

SYSTEMS ENGINEERING AND ANALYSIS — The Systems Engineering and Analysis directorate within the Research and Innovation Center at NETL provides techno-economic analyses of critical baseline and future commercial plant configurations. Previously completed techno-economic analyses of SOFC power and SOEC hydrogen production plants have shown that the reduction of cell and stack degradation and an increase in cell performance are vital toward the commercialization of cost-competitive SOFC and SOEC technology. Such analyses provide crucial, quantitative information to guide research and development, ensuring that effort is placed where it will have a significant impact on the technology as well as to ensure that program goals and objectives are relevant and achievable.

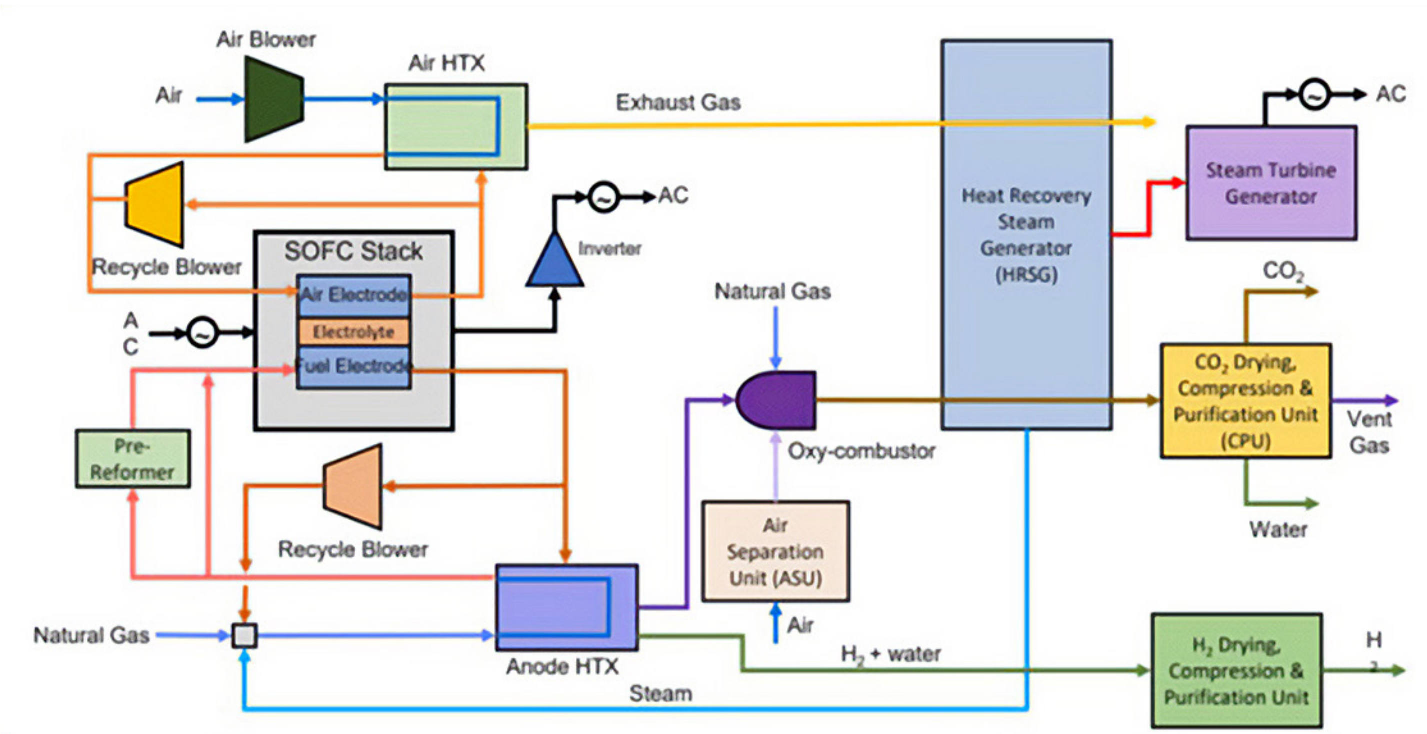

Figure 1: Block flow diagram of reversible fuel cell power plant that can produce electricity from natural gas (or H_2) or H_2 from steam. Analysis of various configurations informs developers of an optimum arrangement and operating conditions to minimize the cost of electricity (for SOFC operation) and cost of hydrogen (for SOEC operation) for the plant. We also identify market prices for electricity and H_2 that would determine when to operate in fuel cell mode and when to operate in electrolysis mode.

CELL DEGRADATION CHARACTERIZATION AND MODELING — To support accurate lifetime system model analysis, the cell and stack degradation effort focuses on the development of characterization tools and predictive models to compile a complete knowledge of prominent degradation modes in SOFC and SOEC components. This effort builds upon knowledge gained previously to inform a comprehensive, predictive model to be distributed for public consumption. Through the development of the predictive model, several individual toolsets are being made available to commercial developers that will aid in the advancement of their technology. Advanced electrode reconstruction techniques that pinpoint changes in the electrode microstructure at high resolution are being developed and can be used by commercial developers to evaluate their own technologies in detail. Advanced electrochemical impedance spectroscopy analysis techniques are being developed to help understand when and where degradation modes are occurring. These and several other techniques are being combined to evaluate a wide range of operating conditions relevant to commercial SOFC and SOEC operation.

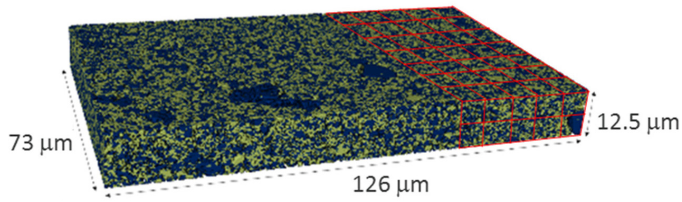

Figure 2: Depiction of a high-resolution cathode reconstruction completed with plasma-focused ion beam technology by research collaborators at Carnegie Mellon University. The volume of this 3D reconstruction is an order of magnitude larger than high-resolution 3D data collected by more accessible techniques. The larger volume allows NETL a greater sample size to evaluate the heterogeneity in electrode microstructures from conventional cells, as evidenced by the larger aggregates (larger blue particles). These heterogeneities lower cell performance and can accelerate some degradation modes.

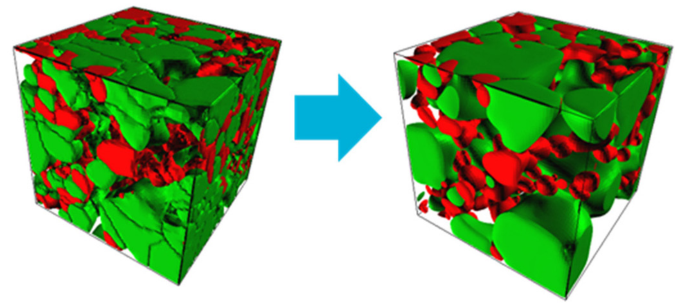

Figure 3: Depiction of particle coarsening of a sub-volume of an SOFC cathode structure. Particle coarsening occurs over long durations and is one known mode of performance degradation as the coarsening results in loss of active areas for electrochemical reactions.

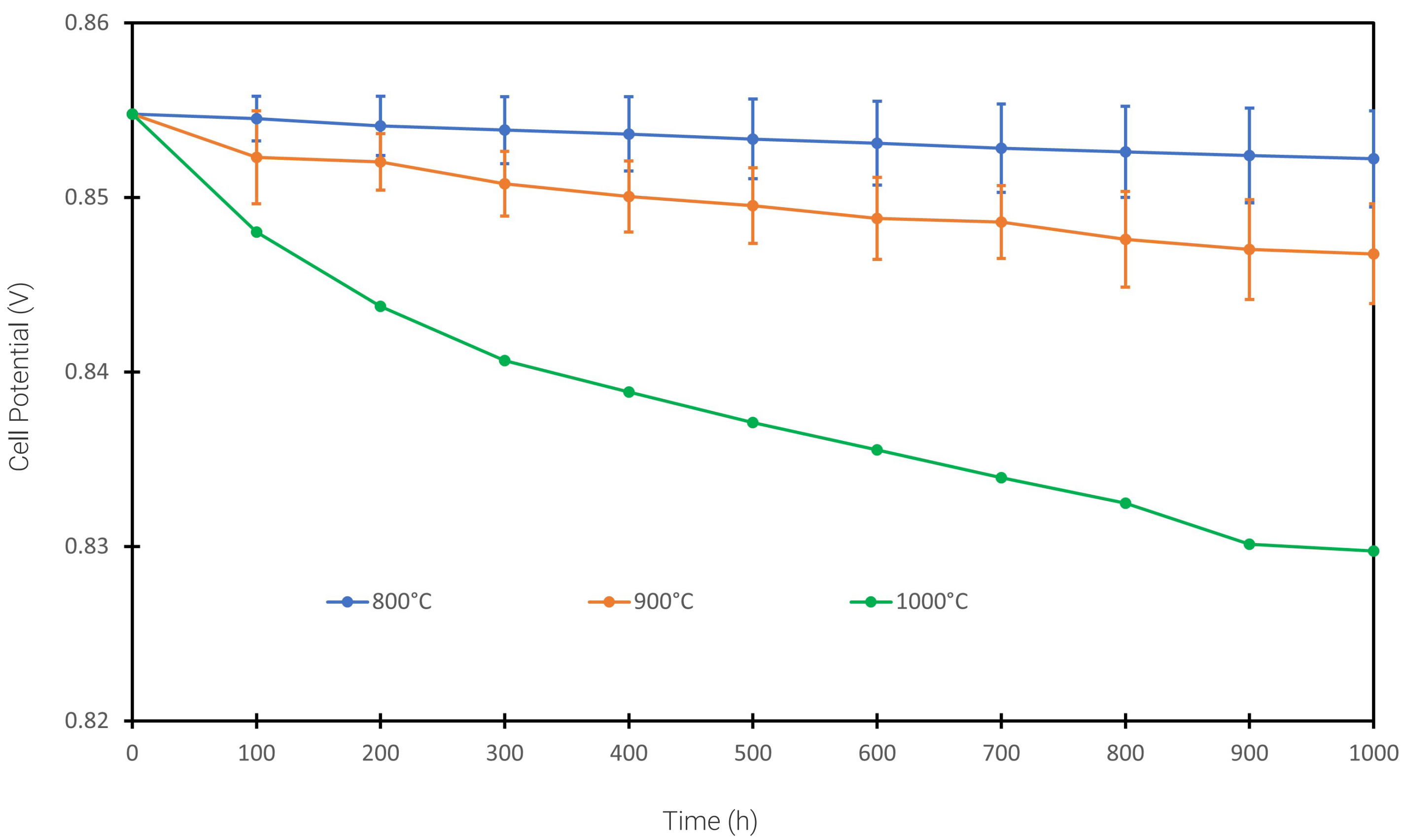

Figure 4: Performance simulations showing the decay in SOFC operating voltage for an example cell undergoing particle coarsening in the electrodes while operating at 800, 900, or 1000°C. Coarsening occurs more quickly at higher temperatures, resulting in more degradation. The simulations were carried out using NETL's inhouse SOC multiphysics performance degradation modeling code.

ADVANCED ELECTRODE ENGINEERING — Building upon the identification of degradation modes from the predictive model, electrode engineering methods are being developed to boost performance and mitigate degradation, thereby reducing costs and improving the life of commercial SOFC products. NETL works directly with commercial developers to improve their state-of-the-art technology performance and degradation rates. With NETL's patented electrode infiltration process, a commercial cell is analyzed via detailed characterization techniques and a novel formulation of nano-catalyst is applied through an ultrasonic spray coating method. NETL has shown success on several commercially developed cells and is currently investigating alternate uses for the technology such as reduced-temperature operation catalysts, materials to promote reversible SOC operation and materials to alleviate stresses caused by redox cycling in nickel-based anodes. Successful technologies are actively transferred to industry. While electrode infiltration is NETL's most mature SOC technology, NETL is also creating next-generation, advanced electrodes through developing new techniques such as (1) atomic layer deposition for even more controlled and uniform infiltrated electrode coatings, (2) additive manufacturing to create 3D gradients in electrode composition and microstructure, and (3) computationally guided electrode materials design using computational chemistry and machine learning methods

The SOC research group at NETL has a tight integration between its modeling and experimental research capabilities, using theoretical predictions to design new cell structures and pushing the creativity of our experimental efforts to fabricate, test and scale-up those new structures. These research efforts improve overall electrode performance, resulting in increased cell efficiency and, ultimately, a lower system cost and extended lifetime, requirements for realistic SOFC and SOEC commercialization.

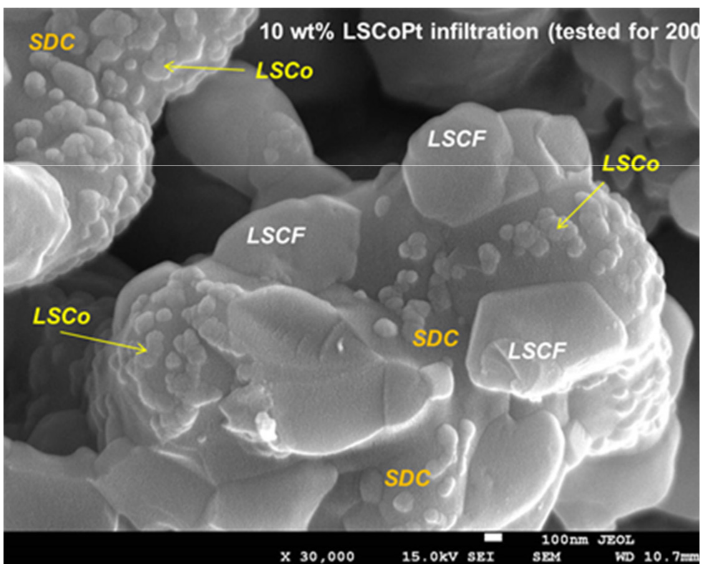

Figure 5: Scanning electrode micrograph of LSCo-Pt nano-catalyst deposited on an LSFC-SDC based air electrode material. The catalyst increases the activity and active surface area of the backbone electrode.

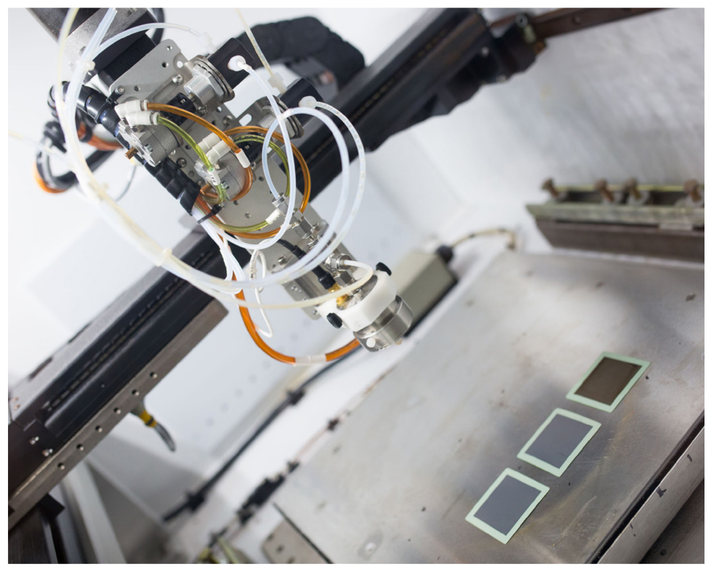

Figure 6: The automated ultrasonic spray nozzle used to apply NETL's patented electrode infiltration solution to an industrial partner's SOFC.

NETL is a U.S. Department of Energy (DOE) national laboratory dedicated to advancing the nation's energy future by creating innovative solutions that strengthen the security, affordability and reliability of energy systems and natural resources. With laboratories in Albany, Oregon; Morgantown, West Virginia; and Pittsburgh, Pennsylvania, NETL creates advanced energy technologies that support DOE's mission while fostering collaborations that will lead to a resilient and abundant energy future for the nation.

Research Partners

Leidos Research Support Team (LRST) | Carnegie Mellon University | Clemson University | Georgia Southern University | Idaho National Laboratory | Lawrence Berkley National Laboratory | Lawrence Livermore National Laboratory | National Renewable Energy Laboratory | Northwestern University | OxEon | Pacific Northwest National Laboratory | University of Wisconsin-Madison | West Virginia University

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