Advances in Solid Oxide Fuel Cells VI

A Collection of Papers Presented at the 34th International Conference on Advanced Ceramics and Composites
January 24–29, 2010
Daytona Beach, Florida

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The Seventh International Symposium on Solid Oxide Fuel Cells (SOFC): Materials, Science, and Technology was held during the 34th International Conference and Exposition on Advanced Ceramics and Composites in Daytona Beach, FL, January 24 to 29, 2010. This symposium provided an international forum for scientists, engineers, and technologists to discuss and exchange state-of-the-art ideas, information, and technology on various aspects of solid oxide fuel cells. A total of 75 papers were presented in the form of oral and poster presentations, including ten invited lectures, indicating strong interest in the scientifically and technologically important field of solid oxide fuel cells. Authors from eleven countries (China, Denmark, Germany, India, Italy, Japan, Russia, South Korea, Taiwan, UK and U.S.A.) participated. The speakers represented universities, industries, and government research laboratories.

These proceedings contain contributions on various aspects of solid oxide fuel cells that were discussed at the symposium. Fifteen papers describing the current status of solid oxide fuel cells technology are included in this volume.

The editors wish to extend their gratitude and appreciation to all the authors for their contributions and cooperation, to all the participants and session chairs for their time and efforts, and to all the reviewers for their useful comments and suggestions. We hope that this volume will serve as a valuable reference for the engineers, scientists, researchers and others interested in the materials, science and technology of solid oxide fuel cells.

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Introduction

This CESP issue represents papers that were submitted and approved for the proceedings of the 34th International Conference on Advanced Ceramics and Composites (ICACC), held January 24-29, 2010 in Daytona Beach, Florida. ICACC is the most prominent international meeting in the area of advanced structural, functional, and nanoscopic ceramics, composites, and other emerging ceramic materials and technologies. This prestigious conference has been organized by The American Ceramic Society’s (ACerS) Engineering Ceramics Division (ECD) since 1977.

The conference was organized into the following symposia and focused sessions:

Symposium 1  Mechanical Behavior and Performance of Ceramics and Composites
Symposium 2  Advanced Ceramic Coatings for Structural, Environmental, and Functional Applications
Symposium 3  7th International Symposium on Solid Oxide Fuel Cells (SOFC): Materials, Science, and Technology
Symposium 4  Armor Ceramics
Symposium 5  Next Generation Bioceramics
Symposium 6  International Symposium on Ceramics for Electric Energy Generation, Storage, and Distribution
Symposium 7  4th International Symposium on Nanostructured Materials and Nanocomposites: Development and Applications
Symposium 8  4th International Symposium on Advanced Processing and Manufacturing Technologies (APMT) for Structural and Multifunctional Materials and Systems
Symposium 9  Porous Ceramics: Novel Developments and Applications
Symposium 10  Thermal Management Materials and Technologies
Symposium 11  Advanced Sensor Technology, Developments and Applications
Focused Session 1  Geopolymers and other Inorganic Polymers
Focused Session 2  Global Mineral Resources for Strategic and Emerging Technologies
Focused Session 3  Computational Design, Modeling, Simulation and Characterization of Ceramics and Composites
Focused Session 4  Nanolaminated Ternary Carbides and Nitrides (MAX Phases)

The conference proceedings are published into 9 issues of the 2010 Ceramic Engineering and Science Proceedings (CESP); Volume 31, Issues 2–10, 2010 as outlined below:

- Mechanical Properties and Performance of Engineering Ceramics and Composites V, CESP Volume 31, Issue 2 (includes papers from Symposium 1)
- Advanced Ceramic Coatings and Interfaces V, Volume 31, Issue 3 (includes papers from Symposium 2)
- Advances in Solid Oxide Fuel Cells VI, CESP Volume 31, Issue 4 (includes papers from Symposium 3)
- Advances in Ceramic Armor VI, CESP Volume 31, Issue 5 (includes papers from Symposium 4)
- Advances in Bioceramics and Porous Ceramics III, CESP Volume 31, Issue 6 (includes papers from Symposia 5 and 9)
- Nanostructured Materials and Nanotechnology IV, CESP Volume 31, Issue 7 (includes papers from Symposium 7)
- Advanced Processing and Manufacturing Technologies for Structural and Multifunctional Materials IV, CESP Volume 31, Issue 8 (includes papers from Symposium 8)
- Advanced Materials for Sustainable Developments, CESP Volume 31, Issue 9 (includes papers from Symposia 6, 10, and 11)
- Strategic Materials and Computational Design, CESP Volume 31, Issue 10 (includes papers from Focused Sessions 1, 3 and 4)

The organization of the Daytona Beach meeting and the publication of these proceedings were possible thanks to the professional staff of ACerS and the tireless dedication of many ECD members. We would especially like to express our sincere thanks to the symposia organizers, session chairs, presenters and conference attendees, for their efforts and enthusiastic participation in the vibrant and cutting-edge conference.


Sanjay Mathur and Tatsuki Ohji, Volume Editors
July 2010
SOLID OXIDE FUEL CELL (SOFC) BASED POWER SYSTEMS FOR MOBILE APPLICATIONS

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ABSTRACT
As the largest user of energy within the DoD, the USAF consumes approximately 2.8 billion gallons of fuel annually in support of both domestic and deployed operations. One solution being explored for reducing this energy need is to implement solid oxide fuel cell (SOFC)-based power systems. SOFCs can offer higher efficiencies when compared to conventional power generation approaches and greater compatibility with military logistic fuel than low temperature fuel cells. Efforts at AFRL are focused on increasing the power density of SOFC-based systems and on improving the operability of these systems on conventional battlefield fuels. Current SOFC-based activities are focused on developing a 2 kW compact, lightweight SOFC system for use in UAV prime power or vehicle APU applications. In addition, basic research efforts are also underway which seek to decrease the interfacial resistance and improve the operational flexibility of SOFCs. The objective of this paper is to present an overview of AFRL's activities which include SOFC system development and basic R&D activities focused on improving SOFC stack technology.

INTRODUCTION
Solid oxide fuel cell (SOFC)-based systems offer an attractive alternative for internal combustion engines as field power generators, ground vehicle auxiliary power units (APUs) and primary power units for small unmanned air vehicles (S-UAV). SOFC systems represent a compelling power system option due to their high efficiencies, fuel flexibility and low audible signature. Compared with other fuel cell approaches, the thermal environment and conductivity mechanism in SOFCs allow for a considerable improvement in fuel tolerance, providing a path forward for electrochemical logistic fuel operation.

Fuel cells are devices which electrochemically combine fuel and air to produce high quality electrical power. Because these systems do not generate power via combustion processes, they offer significantly lower specific fuel consumption rates relative to advanced heavy fuel engines or diesel power generators. Solid oxide fuel cells, in particular, offer the potential for fuel-flexible operation with the capability to operate off of hydrogen or reformate (containing hydrogen and carbon monoxide), supplied externally or produced internally via an onboard fuel reformer. Numerous fuel options exist including conventional or renewable hydrocarbon fuels such as standard gasoline or diesel, JP-8 (military diesel), ethanol, methanol, natural gas, propane, biodiesel, and Fisher-Tropsch synthesized fuels (e.g. dimethyl ether).

The Department of Energy (DoE) initiated the Solid State Energy Conversion Alliance (SECA) program in 1999 to promote the advancement of SOFC power systems for a variety of energy needs. However, the emphasis of this alliance is on stationary power generation as opposed to mobile auxiliary power which is the primary need of the Department of Defense (DoD). Even so, the DoD can leverage the extensive efforts of the SECA program and related international efforts which have developed the base technology and manufacturing capabilities required to move forward. However, unlike the DoE goals of extremely long-life (<4%/1000hr) and low cost (<$400USD/kW), the DoD has made investments to extend the operation of these systems to challenging military environments which include compact packaging as well as compatibility with fuels that may contain as much as 3000 ppm sulfur.

The objective of this paper is to present work performed at the Air Force Research Laboratory (AFRL) focused on the development of a SOFC-based power system for mobile applications. The
primary focus is on systems in the 1kW - 10kW range for UAV prime power or vehicle APU applications. In the coming section, a brief summary of the required goals and metrics needed to successfully produce a SOFC-based power system for mobile applications will be described. In addition, an overview of an ongoing cooperative development program between AFRL, the Army Tank Automotive Research, Development, and Engineering Center (TARDEC), and United Technologies Research Center (UTRC) will be reviewed. Lastly, efforts at AFRL focused on developing an improved SOFC stack for use in such a system are illustrated. These include exploring interfacial modification of SOFCs for increased performance and the exploration of alternate anode materials capable of operating in higher sulfur environments.

MOBILE SOFC SYSTEM DEVELOPMENT

The current AFRL system development program, jointly funded with Army TARDEC, is focused on the advancement of high power dense SOFC systems for use in UAV and silent watch APU applications. The ultimate objective of the program is to develop a power dense SOFC-based power system capable of operating on logistic fuels for mobile applications. The UTRC-led team has constructed a “packaged” bench top APU unit, which is shown in Figure 1. This unit is capable of producing 1.5 kW peak power while operating on S-8 (Fischer-Tropsch fuel derived from the Fischer-Tropsch process) fuel. S-8 was chosen as the initial fuel to remove issues pertaining to sulfur content in JP-8 and diesel fuel, allowing us to concentrate on issues related to increasing power density and reducing system size. Future iterations will look to expand upon the system design to incorporate desulfurization technologies or sulfur-tolerant stack technologies, such as those mentioned in the Sulfur-Tolerant Anode Materials section below.

The following sections will explore the motivation behind utilizing fuel cell-based power systems for mobile applications and give an overview of the current status of the AFRL mobile SOFC system development program.
System-Level Impact

When compared to traditional internal combustion-based approaches, fuel cell power systems offer higher efficiencies in the 1kW – 10 kW range of mobile power generators, but system power density is generally lower. In the case of stationary power systems, this trade is more acceptable due to the alternative advantages of fuel cell-based power systems such as quiet operation and reduced fuel consumption. However, for mobile applications such as vehicle mounted APUs, aircraft APUs and S-UAV prime power systems, the increased system weight can offset some of the advantages gained by the higher system efficiency. This is due to the fact that a larger APU or prime power system can increase the overall vehicle weight leading to increased fuel consumption or require the vehicle to carry a smaller payload. This is particularly true for aircrafts or UAVs where weight is a crucial factor in platform fuel consumption.

One method to compare the performance of an internal combustion (IC)-based system versus a fuel cell (FC)-based system is to look at the power system in terms of total mass, which includes the dry system mass and the fuel mass required to achieve a given level of endurance between refueling. Figure 2 compares the performance of a baseline IC system to a number of projected FC systems. The baseline IC system is sized assuming a power density of 1000 W/kg and a thermal efficiency of 15% (corresponding to a specific fuel consumption of ~ 1 lb/hp-hr for JP-8). The baseline FC system is sized to match the performance goals stated by United Technologies Research Center for their next generation mobile power system, which is a power density of > 100 W/kg with a thermal efficiency of ~ 30%. For a 2 kW system, the IC system has a dry weight of 2 kg while the FC system is an order of magnitude greater at 20 kg. Even with this difference, the increased efficiency of the FC system shows a cross over point at 33 hrs of operation. This crossover point represents the endurance at which the total mass (dry weight and fuel) of the IC system and FC system are equal. Therefore, from a purely mass-based point of view, for missions greater than 33 hrs between refueling the FC system is advantageous.

Figure 2. Total mass (system and fuel) as a function of endurance for a 2 kW representative internal combustion (IC)-based propulsion system and 2 kW representative fuel cell (FC)-based prime power systems.
Exploring the effect of increasing either the thermal efficiency (from 30% to 40%) or power density (from 100 W/kg to 150 W/kg) on the FC system, it can be seen that increasing the efficiency while holding the power density constant decreases the crossover point to 26 hrs while increasing the power density with a constant efficiency decreases the crossover point to 21 hrs of operation. This illustrates that at this size level, increases in power density provide the most impact on the total mass of the system. This is further illustrated in Figure 3, which shows plots of endurance as a function of power density or thermal efficiency, for a 2 kW system when the total mass is fixed at 25 kg. These plots illustrate that, for a given fixed overall mass, increases in power density from 100 W/kg to the range of 400 – 500 W/kg result in the system endurance being greater. This shows that initial FC system development for mobile applications should primarily focus on increasing power density while maintaining efficiency. Once power density levels >200 W/kg are achieved, then thermal efficiency increases will start to show greater system level payoffs.

System Development Status
UTRC has successfully built and tested a 1.5 kW bench top system capable of operation on S-8 fuel8,9. The schematic in Figure 4 illustrates the design of the system. It is a single pass configuration utilizing a catalytic partial oxidation (CPOx) reformer to break down the fuel into a hydrogen-rich stream to be feed into the SOFC anode. Excess hydrogen from the anode stream is combusted in the burner to provide heat to the system. The burner exhaust is routed through a heat exchanger to provide heat to the incoming air stream which is routed to the SOFC cathode and CPOx inlet. The hot section components, which include: the CPOx reformer, SOFC stack, burner, and high-temperature heat exchanger, are enclosed in an insulated “hot box” (the larger section to the left in Figure 1) to maintain the required stack operating temperature (~ 800°C). This allows for a compact system design, but requires care to be taken to maintain the required thermal balance between the components. The cold section components are housed in a separate enclosure (the smaller section to the right in Figure 1) and include the fuel pump, air blower, valves and control electronics. A simple single pass system design with a CPOx reformer was chosen to make the system less complex and more compact. Other alternative designs include utilizing an autothermal reformer (ATR) with an anode recycle stream, which would boost the system efficiency but at the expense of added complexity and possibly added weight. As noted above, the biggest initial system level gains for fuel cell-based power systems is in increasing the system power density, therefore any design changes focused on increasing the system efficiency would have to maintain the current system level power density.

This initial bench top system was able to achieve a 26% system efficiency on S-8 at a power density of >50 W/kg. The efficiency was lower than the initial design target of 30%, but illustrates a key point for a thermally integrated system, such as this. One component does not operate independently of the others. The lower than expected efficiency was due to a requirement to run the reformer at an air to fuel ratio which was outside of the original design specifications. This led to an inability to maintain the stack temperature at the level required for higher efficiency operation due to the coupled interactions of the components and gas streams. The ability to maintain the proper thermal balance between components is a major challenge for the design of a compact SOFC system and will continue to play a significant role in future design efforts.

The current focus of the program is to further decrease the weight and volume of the system in order to produce a system at >100 W/kg capable of producing ~2 kW net power while operating on S-8. This effort is underway, with a goal of developing a system for flight demonstration during the summer of 2010. One key aspect for increasing the system power density is to further push the SOFC stack technology. The bench top system utilizes an SOFC stack developed by Topsoe Fuel Cell based on their planar SOFC stack design for mobile applications10. The bench top system stack operates at
Solid Oxide Fuel Cell (SOFC) Based Power Systems for Mobile Applications

~200 W/kg, which corresponds to ~30% of the system weight for a 50 W/kg system. To reach the weight targets for the flight system at 100 W/kg requires a stack that can produce ~300 W/kg corresponding to a stack that is almost 40% of the total system weight. This illustrates how critical power dense SOFC technology is to developing future mobile SOFC systems. To reach the current goal of a system-level power density >200 W/kg, it is estimated that an SOFC stack with a power density of >500W/kg is required assuming that the stack remains ~40% of the overall system weight.

Figure 3. Plots illustrating the relationship between endurance and power density (top), thermal efficiency (bottom) for a 2 kW system with a fixed total mass (system and fuel) of 25 kg.
Advances in stack power density alone will likely not be sufficient to achieve the long term objective of >200W/kg operating on JP-8. To achieve JP-8 operation it will be necessary to mitigate SOFC stack degradation associated with the high sulfur content in JP-8, which can reach 3000 ppm in the liquid phase which corresponds to ~300 ppm in the gas phase (primarily as H$_2$S) after the fuel reformation process. Several approaches are under development which show promise for achieving sufficient sulfur tolerance through improvements in stack material sets, cell structural changes, or stack operating modes\cite{11,12,13}. These approaches, when combined with advanced reforming technologies, have the promise to enable JP-8 operation without the need for an additional, adsorption-based desulfurization system to remove the sulfur from the JP-8 fuel.

Figure 5. Power dense SOFC stacks developed to support AFRL/Army TARDEC effort to demonstrate compact, light weight SOFC systems for mobile applications.