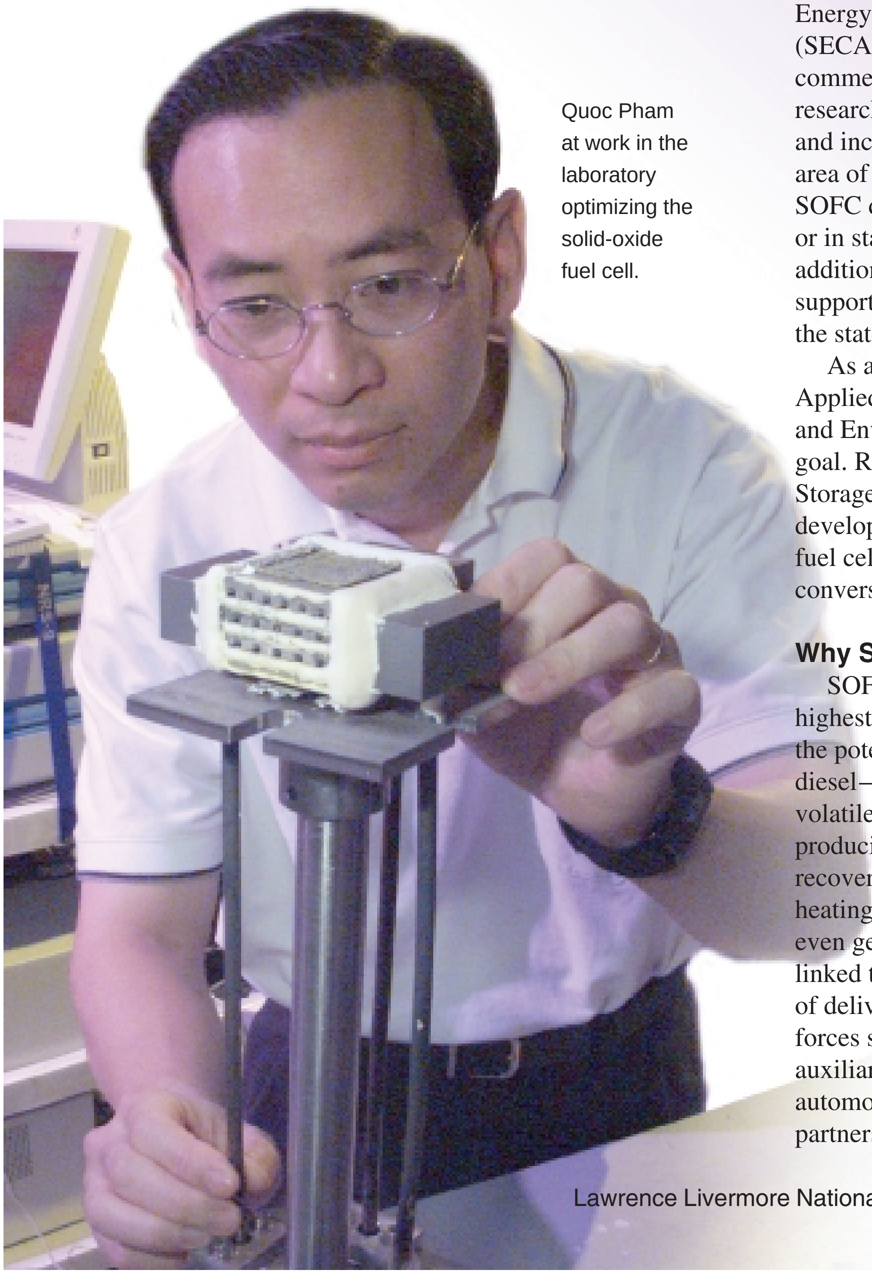
Solid-Oxide Fuel Cells Stack Up to Efficient, Clean Power

FOR a growing number of power generators and users, fuel cells are the key to the nation's energy future. Clean, quiet, efficient, and compact, fuel cells generate electricity through chemistry instead of combustion. (See the box on p. 19.) As they become more widely used, fuel cells promise to help reduce global warming, air pollution, and U.S. dependence on foreign oil. No wonder, then, that interest in the advanced development and commercialization of fuel cells is at an all-time high.



Quoc Pham at work in the laboratory optimizing the solid-oxide fuel cell.

Much of this interest is focused on four types of fuel cells—solid oxide, proton exchange membrane, molten carbonate, and alkaline. A major impediment to commercialization is the manufacturing cost. In the case of solid-oxide fuel cells (SOFCs), high manufacturing, or fabrication, costs translate into capital costs that run upwards of $5,000 per kilowatt. In comparison, energy produced by conventional power plants has a capital cost of about $500 per kilowatt.

Primarily because of these high costs, the Department of Energy formed the Solid State Energy Conversion Alliance (SECA) in 1999 to accelerate the development and commercialization of SOFCs. The alliance is helping researchers to discover ways to both lower fabrication costs and increase power density, that is, the power generated per area of fuel cell. SECA's goal is a modular, 3- to 10-kilowatt SOFC design that can be mass-produced and used individually or in stacks to provide power for a host of applications. In addition, the California Energy Commission (CEC) is strongly supporting the development and demonstration of fuel cells in the state.

As a committed developer of fuel cell technology, the Applied Energy Technologies Program in Livermore's Energy and Environment Directorate is helping SECA to reach its goal. Researchers in the program's Energy Conversion and Storage Technologies Group have extensive experience in developing several types of fuel cells, including the zinc–air fuel cell, the unitized regenerative fuel cell, the direct carbon conversion fuel cell, and the SOFC.

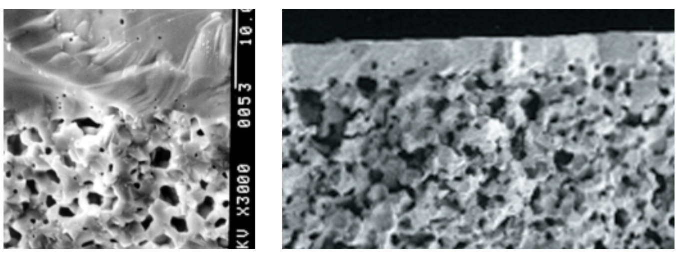
Why Solid-Oxide Fuel Cells?

SOFCs are particularly attractive because they have the highest efficiencies of any conventional fuel cell design and the potential to use many fuels—including gasoline and diesel—without expensive external reformers that create more volatile chemicals. SOFCs can operate at high temperatures, producing high-grade waste heat, or exhaust, which can be recovered and used for other applications, such as space heating and cooling, supplying homes with hot water, and even generating extra electricity by spinning a gas turbine linked to the unit. For the military, SOFCs offer the possibility of delivering quiet, clean, and uninterruptible energy to armed forces stationed in remote locations. SOFCs can also serve as auxiliary power units in motor vehicles, and leading automotive companies are already working with industrial partners to exploit their potential.

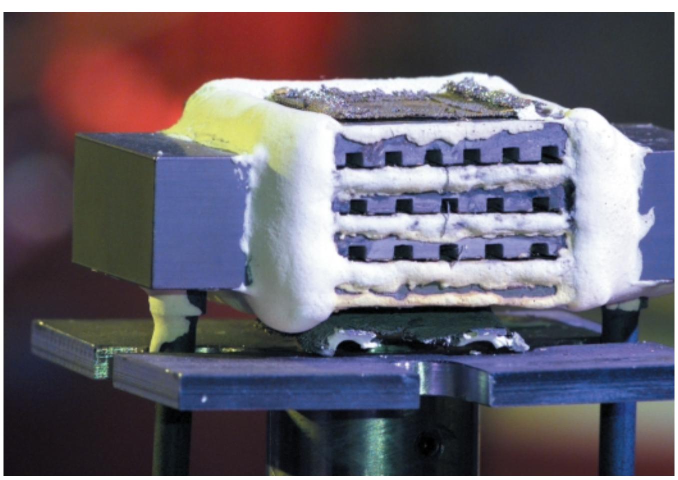
Before SOFCs can be fully commercialized, however, several technological breakthroughs are needed. A team of Livermore researchers led by materials scientist Quoc Pham is working to address the key technological challenges. Under Laboratory Directed Research and Development (LDRD) funding since 1998, the team has pursued the development of low-cost, high-power-density SOFCs that operate at temperatures below 800°C. The team's focus is developing low-cost thin-film processing techniques and optimizing materials and design to increase power density.

Lower Operating Temperatures, Higher Power Density

The current Livermore design is flat, or planar, as described in the box on p. 19. Some SOFCs were originally fashioned in a tubular design, but they proved to be too expensive and had little potential for increasing power density. Livermore researchers focused on a planar design because of its potential for both higher performance and lower costs. Because a single cell has a voltage of 1 volt or less, several cells must be connected in series using electrical interconnections to achieve higher voltages. The complete unit is called a fuel cell stack.



This cross section of yttria-stabilized zirconia electrolyte, imaged at different resolutions, is an example of a thin film that was deposited on a porous anode using colloidal spray deposition.



Livermore's first prototype fuel cell stack, consisting of three solid-oxide fuel cells, set a record for stack power density.

SOFCs traditionally operate at extremely high temperatures (around 1,000°C). As a result, the stacks' interconnections are made of ceramic materials that are expensive and difficult to manufacture. Thus, one way to cut the fabrication cost is to reduce the operating temperature by at least 200°C, so that inexpensive alloys can be used as interconnecting materials.

The initial challenge for Pham and his team was to lower the SOFC's operating temperature without compromising the power density. The researchers first made the electrolyte layer thinner, thereby lowering the amount of resistive energy lost during operation and increasing the efficiency. The team developed a low-cost, thin-film deposition technique called colloidal spray composition, which has since been patented. This simple technique produces high-quality thin films ranging from one to several hundred micrometers thick.

The team then turned its attention to optimizing the fuel cell components. They created a multilayer fuel cell structure that features different materials to enable the use of high-performance electrodes. The structure minimizes the stress generated by the difference in thermal expansion characteristics at the interface between the electrodes and the electrolyte materials, thereby achieving a significant decrease in electrical loss. When the researchers combined the multilayer design with their thin-film deposition technique, they improved the power density of a single cell to 1.4 watts per square centimeter, one of the highest values reported for power density at 800°C.

The team then set out to demonstrate this same high power density in a stack. A three-cell stack prototype generated 61 watts, exceeding the LDRD project goal of 50 watts. The power density of the stack was 1.05 watts per square centimeter (at 800°C using hydrogen fuel), a value at least 50 percent higher than any stack power density previously reported.

The latest Livermore SOFCs operate at 700°C, a dramatic improvement. The team has received funding from the CEC to lower the operating temperature even further and to make other improvements.

The Problem of Fuel

In a separate LDRD project, Pham and his colleagues focused on streamlining the SOFC's fuel supply. Hydrogen is the preferred fuel for SOFCs, but hydrogen's high production cost and complex storage issues have made hydrocarbons such as natural gas the preferred fuels. However, methane, the main constituent of natural gas, has low reactivity, so it must be converted to more reactive products, such as carbon monoxide and hydrogen gas.

To eliminate this conversion step, which is both expensive and complex, the Livermore team explored the possibility of directly oxidizing methane at the anode. Carbon deposition has been a major barrier to the direct oxidation of methane at SOFC anodes, but the team discovered that highly porous anodes permit direct oxidation.

Tackling Current Challenges

Although the team has addressed many SOFC issues, three major materials science challenges are preventing the commercialization of planar SOFCs. "The planar fuel cell is a difficult design because of sealing problems," says Pham. The biggest challenge is separating the air from the fuel, which requires that the edges of the ceramic plate be sealed.

The second challenge concerns the type of interconnection used in the fuel cell stack. Livermore's success in lowering the operating temperature made possible the switch from ceramic to metal interconnections. At lower temperatures (below 800°C), metallic interconnects are less subject to oxidation, which leads to a loss of conductivity.

Problems with the mechanical integrity of the fuel cell stack constitute the third challenge. When brought up to operating temperature and then back to room temperature, the fuel cell stack components experience dramatic thermal and mechanical stresses. Researchers must try to minimize these stresses by both attempting to match the thermal expansions of stack components as much as possible and developing engineering designs that can accommodate the inevitable level of mismatched thermal expansion.

With CEC funding, the Livermore team has already developed potential, patentable solutions to the problems of interconnection and mechanical integrity. In total, Pham's team has seven patents pending related to fuel cell technology.

Partnering for the Future

Once the remaining materials science problems are resolved, the team plans to construct and demonstrate a 100-watt, high-power-density SOFC, followed by construction of 500- and 1,000-watt prototypes. "After that, we can say we've solved the materials science issues, and our task evolves into an engineering project," says Pham.

The team has secured several sources of funding, including support from DOE's Fossil Energy Program. The Livermore technology is being licensed to Solid Oxide Systems, LLC (SOX), a private start-up company that is matching the CEC funding with a goal of demonstrating a 10-kilowatt system. By partnering with SOX, Pham and his colleagues hope to achieve the long-sought goal of commercializing solid-oxide fuel cell technology and fulfilling the promise of clean, highly efficient electric power at an affordable cost.

—Emmeline Chen

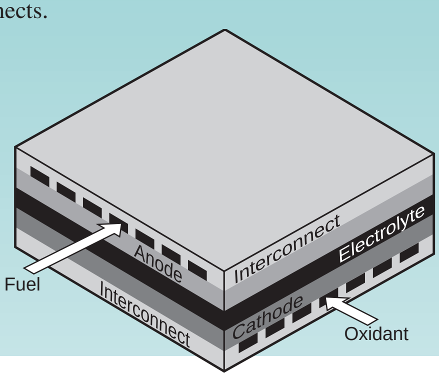
Solid-Oxide Fuel Cell Basics

Fuel cells are electrochemical energy conversion devices that generate electricity and heat by converting the chemical energy of fuels. Like batteries, fuel cells can be connected together in series to produce higher voltages. Fuel cells and batteries differ. A battery is an energy storage device that stores its fuel internally and that can supply only a fixed amount of energy. Reactants used in fuel cells are supplied externally, and a fuel cell has no fixed capacity—it will generate electricity as long as it is supplied with fuel and air.

Fuel cells can accept almost any kind of fuel, including natural gas, coal gas, gaseous fuels from biomass (plant materials and animal waste), and liquid fuels (gasoline, diesel), although some fuels may require preprocessing and purification. Once connected to a fuel supply, a fuel cell will produce electricity until its fuel supply is removed or exhausted.

Solid-oxide fuel cells (SOFCs) are made from solid-state materials, namely ceramic oxides. SOFCs consist of three components: a cathode, an anode, and an electrolyte sandwiched between the two. Oxygen from air is reduced at the cathode and is converted into negatively charged oxygen ions. These ions travel through the electrolyte to the anode, where they react with fuel that has been delivered to the anode. The fuel is oxidized by the oxygen ions and releases electrons to an external circuit, thereby producing electricity. The electrons then travel to the cathode, where they reduce oxygen from air, thus continuing the electricity-generating cycle. Individual cells can be stacked together in series to generate larger quantities of electricity. Within this unit, called a fuel cell stack, the cells are separated by bipolar separator planes, or interconnects.

The three components of a solid-oxide fuel cell form a modular unit that can be connected to other cells in a fuel cell stack.



Acknowledgments: The work described in this highlight was done by Quoc Pham (principal investigator), Brandon Chung, Jeff Haslam, Dave Lenz, and Ervin See.

Key Words: colloidal spray deposition, energy conversion, fuel cell, fuel cell stack, high power density, multilayer fuel cell, power generation, solid oxide, Solid State Energy Conversion Alliance (SECA), thin-film deposition.

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