Advances in the Design of Solid-Oxide Fuel Cells Addresses Needs of Intermittent Operations

The Pitch

A novel solid-oxide fuel cell (SOFC) architecture has been developed that enables a broad range of applications where intermittent operations such as stand-by or back-up power are required, such as in fuel-cell-powered hybrid automobile engines that need to be totally shut down when parked. Developed at the Lawrence Berkeley National Laboratory (LBNL), this SOFC is robust and has survived hundreds of rapid thermal cycles. All non-stationary applications must be both rugged and able to withstand unlimited thermal cycling and rapid start-ups.

The LBNL patent-pending advances address several practical problems for SOFCs: high processing and materials costs, reduced electrode performance at temperatures below 750°C, limited cell durability, and failure from thermal cycling. LBNL's technology makes it possible to lower the system cost significantly and, together with the advantage of fuel flexibility for SOFCs, to use the fuel cells for applications where intermittent operation is desirable or inherent. Early applications are envisioned in mobile systems that have power demands as high as 10 kW. The market potential for such systems has been the subject of numerous analyses and can be projected to range from several hundred million dollars for smaller units to several billion dollars for automotive auxiliary power units and the fuel cell hybrid electric vehicle markets.

The Technology

LBNL's technology permits heating and cooling rates of planar fuel cells to be as high as 1000°C/min. This cell design, shown in part in Figure 1, relies on the assembly of small, 5–20 W Chipcell™ (LBNL's name for the SOFC) units in series and parallel arrangements. For example, one such cell with a membrane size of 5.08 cm × 5.08 cm (2 in. × 2 in.) delivers approximately 10–15 W at 0.7 V and 700°C.

The stability of such cells under extreme thermal cycling can be seen in Figure 1. Heating rates of over 1000°C/min were sustained without damage to the cells after hundreds of cycles. The 2–3-mm-thick Chipcells can be arranged in compact units with a projected power density of up to 1000 W/l in sizes from just a few watts to several kilowatts.

Lower operating temperatures enable the modification of the anodes and cathodes of the SOFC by exploiting methods for catalyst infiltration that offer enhanced stability and performance. An example of the electrode structure resulting from a novel catalyst infiltration method is shown in Figure 2, where the nanoparticulate catalysts are positioned on the pore walls of a conventional lanthanum strontium manganate porous cathode. Such infiltration procedures typically enhance the cell power density by 50–75% at constant cell voltage and temperatures around 700°C.

As early as 1994, LBNL researchers pioneered the use of anode- or cathode-supported thin-film, solid-electrolyte fuel cells, reporting a record specific power density of 2 W/cm^2 at 800°C. They use a variety of colloidal deposition methods together with controlled cofiring of the various layers that compose the fuel cell membrane. The subsequent development trend has been in the direction of supported thin-film SOFCs to reduce the operating temperatures further, to the 650–750°C range, with the aim of broadening compatible, durable, and economical materials choices. Cell durability has been enhanced by substituting, where functionally permitted, low-cost metallic alloys for ceramics. Significant progress has been made by the development of novel structures that allow very rapid thermal cycling, infiltration methods that expand the choice of catalysts, and high-temperature alloy brazes for metal/ceramic sealing that match the thermal expansion characteristics of the membrane materials and show stability in anode and cathode atmospheres up to at least 800°C.

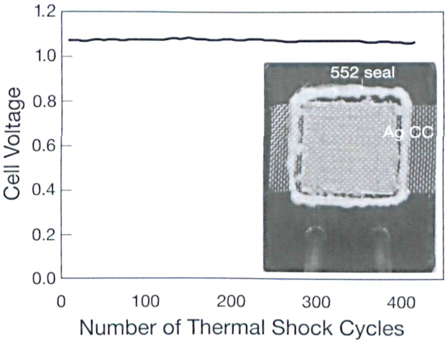

Figure 1. Cell voltage stability during several hundred rapid thermal cycles for a Chipcell of the type shown in the inset (the side-to-side measurements of this Chipcell is 4 cm × 4 cm; the active area is about 2.5 cm × 2.5 cm).

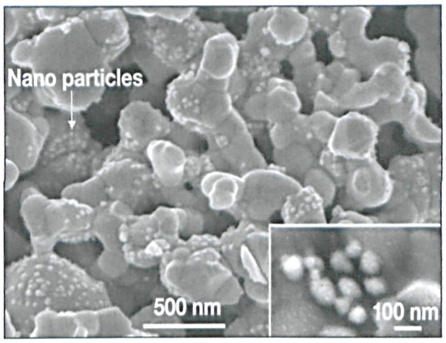

Figure 2. Samarium, strontium, and cobalt oxide ($Sm_{0.6}Sr_{0.4}CoO_{3-\delta}$) nanoparticles incorporated into a lanthanum strontium manganate/zirconia cathode by a novel infiltration process.

Opportunities

The researchers and LBNL are seeking development partners and licensees for their SOFC technologies.

Sources: For technical information: Craig P. Jacobson, Building 62, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA; tel. 510-486-7053 and e-mail cpjacobson@lbl.gov. For licensing: Viviana Wolinsky, LBNL Technology Transfer Department, 90R1070, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA; tel. 510-486-6463 and e-mail VIWolinsky@lbl.gov. For development partners: Lutgard C. De Jonghe, e-mail bfcdejonghe@aol.com.

TECHNOLOGY ADVANCES seeks materials developments on the threshold of commercialization. Send suggestions to Renée G. Ford, Renford Communications, renford@comcast.net.

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Carbon Nanomaterials Provide Unique Properties

The Pitch

Both biomedical and materials science applications are expected to benefit from recently discovered carbon nanomaterials that have spherical shells containing up to 80 carbon atoms enclosing a trimetallic nitride cluster (shown in Figure 1) with the formula $M_3N@C_{80}$ (M represents lanthanide or the Group IIIB metals: Sc, Y, and Lu). The discoverers at Virginia Tech and the developers at Luna nanoWorks said that these carbon nanomaterials, which they have named Trimetasphere™, have the potential for providing optical, electronic, and magnetic properties resulting from the combination of the carbon sphere plus the internal metals.

A large global market for new nanomaterials is anticipated as nanotechnology is expected to have an impact on almost every industry. (According to a May 2006 report by Lux Research: "In 2014, Lux Research projects that $2.6 trillion in global manufactured goods will incorporate nanotech, or about 15 percent of total output.") Luna nanoWorks is focusing on two main applications for these nanomaterials: imaging agents and photovoltaic devices.

Magnetic resonance imaging (MRI), a noninvasive technique, is one of the most powerful diagnostic tools available for imaging soft tissues within the body, including the brain, spinal cord, ligaments, and cartilage in the joints. However, MRI can only distinguish specific conditions. There are many potential applications that would be markedly improved if the signal-to-noise ratio were increased, enabling the radiologist to see pathological conditions that are currently not visible. Trimetasphere-enhanced medical imaging agents may be able to improve the quality of the imaging safely.

Organic photovoltaic devices are also under development. Luna's scandium Trimetaspheres ($Sc_3N@C_{80}$) have unique electron transport properties that could improve organic solar panel performance. Organic solar cells are lightweight, flexible, and less expensive than inorganic solar cells but have not been widely used because they do not convert as much of the sun's radiation into electrical energy as do inorganic ones. Trimetasphere-based electron carriers are under development that could more than double the output of organic solar cells at lower cost.

The Technology

Trimetasphere carbon nanomaterials are produced by electric-arc synthesis. Electrodes made from graphite containing metal catalysts are used to create a carbon arc plasma in the presence of nitrogen gas, thereby providing the conditions for producing this unique carbon-and-metal hybrid material. Because the chemical yield of these endohedral (fullerene) trimetallic nitride compounds is relatively high, the company expects to be able to produce them cost-effectively in commercial quantities.

These novel carbon nanomaterials are extracted from soot and purified by proprietary separation methods. The three metals encapsulated inside the C_{80} cage can be the same or different, selected from the periodic Group IIIB and the lanthanide series. The company projects that more than a thousand different combinations could potentially be created, each differing with respect to electronic bandgap, magnetic, and optical properties; this would enable fine-tuning of the control of optical and electronic characteristics on the nanoscale.

The properties of these carbon nanomaterials can be modified chemically by the controlled addition of functional groups to the cage surface, making them water-soluble, introducing ligands that bind to biological macromolecules, or improving their processing into polymers for solar cells. Some Trimetasphere derivatives show improved performance over currently used materials for optical and novel electrochemical responses.

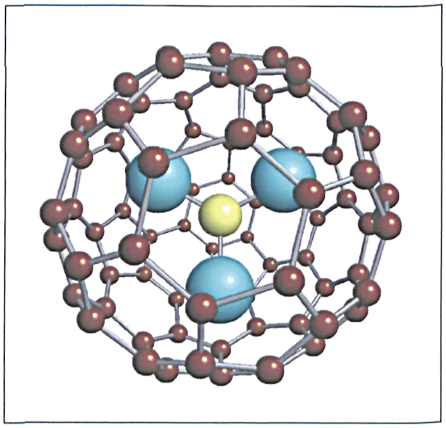

Figure 1. Trimetasphere™ carbon nanomaterials are a novel composition of matter providing unique physical, chemical, thermal, magnetic, biological, optical, and electronic properties. The center atom is nitrogen; the three large atoms are metals.

Opportunities

Luna nanoWorks is seeking investments, collaborations, and contracts to further expand its manufacturing facility and accelerate research and development progress.

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Shape Memory Stainless Steels Show Promise for Large-Scale Construction Applications

The Pitch

According to researcher Chenxu Zhao of the Taiyuan No. 6 Professional School in Shanxi, China, shape memory stainless steels (SMSS) have both a good shape-memory effect (SME) and good mechanical properties as well as machinability, weldability, and corrosion resistance. In addition, their costs, which are roughly equivalent to that of conventional austenitic stainless steels, are expected to increase industrial interest in shape memory stainless steels.

At present, pipe couplings appear to be the most practical application for SMSS. The advantages of SMSS couplings over traditional pipe-joining techniques such as welding, brazing, and threading are ease of installation, reliable performance, and the capability to join many materials, including those not readily welded. In welding, the inner lining of pipes can be severely damaged by the high temperature. In addition, the heat-affected zones near the welds become annealed, which markedly decreases their localized corrosion resistance and mechanical properties, such as strength. However, when SMSS couplings are used to connect pipelines, they only require heating to a level considerably below the welding temperature, thus the corrosion resistance and mechanical properties of the pipe materials are maintained. Consequently, this process is both safe and reliable. In addition, due to their high corrosion resistance, SMSS couplings can also be used in marine environments.

Stainless steel piping systems are becoming increasingly important in both civil and industrial applications such as oil and gas fields, chemical plants, water distribution systems, and urban construction. Their uses continue to expand globally as lower maintenance costs become a top priority. In order to function properly, each pipe needs to be reliably connected with others. SMSS couplings are expected to find applications in these areas, and the quantity that will be needed is clearly very large. For example, about 100 million feet of high performance stainless steel condenser tubing have been installed from 1975 to 2002. Moreover, their use may lower overall construction costs because, compared with traditional joining methods, they can be installed quickly using less skilled labor and are easy to clean and maintain.

The Technology

When an external force is applied to an alloy, the alloy deforms first elastically then plastically. For a conventional alloy, the plastic deformation is permanent and the alloy cannot revert to its original shape when the force is removed. However, a shape-memory alloy (SMA) can return to its original shape when heated above a certain temperature. This phenomenon is defined as the shape-memory effect (SME). The SME in shape memory stainless steels (SMSS) is associated with the stress-induced transformation of austenite (a solid solution of carbon in fcc iron) to ε-martensite (a hcp structure) and its reverse on heating.

In SMSS pipe couplings, the original inner diameter of the SMSS coupling is slightly smaller than the outer diameter of the pipe to be connected. After expansion to the designed size by inserting a mandrel or by bulging with liquid pressure, the SMSS couplings can be readily installed. When heated above their recovery temperature by using induction devices, the SMSS couplings will shrink to their original diameter and the two pipes can be tightly fastened together.

The most widely used materials by volume are construction materials, with concrete dominating (~1 m^3 per person annually). Concrete is usually reinforced with carbon steel bars (rebars) to obtain the required mechanical properties. However, carbon steel corrodes, and the rust weakens the bond between the concrete and the bars, which causes the concrete to crack. Extensive maintenance may be required within as little as 15 to 20 years. Consequently, stainless steels are now replacing carbon steel as rebars. For example, concrete structures built in marine environments using austenitic stainless steel rebars have been known to last more than 60 years. The resulting maintenance-free period justifies the higher initial cost of using stainless steel.

SMSS can be used as rebars in concrete structures. In addition to reinforcement, they could provide other beneficial effects to the concrete structures due to their unique SME. The SMSS is first tensile-deformed at room temperature to transform the austenite to martensite. Then the concrete structure is made with the deformed SMSS as reinforcing bars. When heated above their recovery temperature, the SMSS bars shrink during the reverse transformation to austenite, thereby gradually generating internal compressive stress in the surrounding concrete matrix. The residual stress is the key factor in increasing the tensile yield stress of the overall concrete structure.

Damage in concrete structures involves the generation of microcracks in the matrix and their propagation. The existence of an internal compressive stress could have the effect of closing the microcracks and suppressing their propagation. Other properties, such as damping capacity, fracture toughness, and fatigue and wear resistance could also be improved. The strength and durability of the SMSS–concrete interface are of particular importance. This concept has been verified in TiNi SMA fiber-reinforced metal composites, the so-called smart/intelligent materials. The relatively low cost of SMSS-reinforced concrete structures is expected to be promising for commercial industrial applications. However, their development is still in the concept stage. More detailed investigation and systematic evaluation are needed. Considering their huge potential market, such research and development (R&D) are well warranted.

Opportunities

Chenxu Zhao invites academic and industrial interactions for collaborative basic and applied R&D projects for the joint commercialization of SMSS products.

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Focus Issue: Multiferroics

Ferroelectricity, ferromagnetism, and ferroelasticity are the well known ferroic properties that have received extensive research efforts over the decades, resulting in a significant understanding. New ideas and concepts have arisen in recent times, particularly with regard to the inter-relationship between these ferroic properties. The coupling between ferroelectricity and ferroelasticity is well established but the coupling between ferromagnetism and ferroelectricity is a more recent discovery. Faced with this new challenge, researchers started analyzing the inter-relationships among the ferroic properties and their associated phenomena such as piezoelectricity, magnetostriction, magnetoresistance, and thermoelectricity. The term "multiferroics" was created to refer to materials that exhibit at least two ferroic properties simultaneously. Interestingly, some multiferroics exhibit polarization interactions. For example, a magnetic field applied to a multiferroic can induce an electric polarization; besides the expected magnetic ordering, a cross polarization of the two ordering phenomena exists. Such materials are called magnetoelectric materials. In developing multiferroic materials researchers seek to enhance the weak properties while retaining the dominant property. Researchers may also examine composites or multilayer films where each phase exhibits a strong polarization of distinct ferroic properties.

A host of factors have driven the current spate of interest in multiferroics. Demands in applications such as in transducers and data storage devices are a common example. Increased interest in spintronics has also fueled research interest.

Scientists theoretically analyzing the inter-relationships in multiferroics have come up with several proposals to explain them. An important path pursued by theoreticians is fundamental principles computational modeling. This powerful technique, if cleverly exploited, could give valuable insight to the material behavior and could also provide strong support to the experimentalists.

A focus issue on multiferroics presents an excellent opportunity for all physicists, materials scientists, and materials engineers to pause for a moment and examine the advancements made by other researchers. *Journal Materials Research* will publish a focus issue in August 2007 to examine recent developments in multiferroics in the following areas:

- Design, synthesis, and developments in material systems, including monolithic and composite materials: single crystals, ceramics, thin films and nanostructures
- Structure- property- composition relationships
- Characterization issues of multiferroics
- Local properties of multiferroics: effects of surfaces, interfaces and grain boundaries
- Interactions and couplings: magneto-electric, magneto-capacitive, magneto-dielectric, magneto-resistive and magneto-optic
- First principles computational modeling applied to multiferroic materials and materials design based on computation and modeling
- Functional devices based on multiferroics
- Emerging applications and technology development
- New characterization methods

Guest Editors

Mohammed Es-Souni, Kiel University of Applied Sciences (Germany), S. Pamir Alpay, University of Connecticut (USA), Thirumany Sritharan, Nanyang Technological University (Singapore), Wilfrid Prellier, Laboratoir CRISMAT, CNRS UMR (France), and Umesh V. Waghmare, J. Nehru Centre for Adv. Sci. Res. (India) will serve as the Focus Issue co-editors.

Manuscript Submission

To be considered for this issue, new and previously unpublished results significant to the development of this field should be presented. The manuscripts must be submitted via the JMR electronic submission system by December 19, 2006. Manuscripts submitted after this deadline will not be considered for the issue due to time constraints on the review process.

Submission instructions may be found at http://www.mrs.org/jmr_instructions. Please select "Focus Issue: Multiferroics" as the manuscript type so that it may be routed to the Focus Issue co-editors. All manuscripts will be reviewed in a normal but expedited fashion. Papers submitted by the deadline and subsequently accepted will be published in the August 2007 Focus Issue. Other manuscripts that are acceptable but cannot be included in the August 2007 issue will be scheduled for publication in a subsequent issue of JMR.

Please contact **jmr@mrs.org** with questions.

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