

Ceramics in CLEAN TECH

John Olenick, Dr. Viswanathan Venkateswaran, Gregory Korbut, James Newkirk

**ENrG Incorporated
155 Rano Street, Suite 300
Buffalo, NY 14207**

Abstract

The role of ceramic materials and processes are becoming increasingly important in the Clean Technology (Clean Tech) market space and its multitudes of applications. Clean Tech in the past several years has garnered a tremendous increase in funding and venture capital attention. In some cases the key system component, such as solid oxide fuel cell stacks, are nearly entirely composed of ceramic materials and would not function without these materials. In other cases, a critical single component in the system, such as a ceramic insulation material might be all that inhibits the system from entering a runaway condition. The functions provided by ceramics include ion transport, thermal management, catalysis of gases or liquids, generation and or storage of power and energy, storage and release of hydrogen, generation of light, and the generation of energy from waste. This list is no where near complete.

This paper focuses on the use of varying amounts of porosity, to modify membrane and catalysis coating characteristics in fuel cell, gas separation membrane, and insulation packaging applications. These applications differ in the amount of porosity used in the key separation membrane, the yttria stabilized zirconia electrolyte in the fuel cell, the ceramic support structure in gas separation member, and the near total porosity fiber structure of ceramic insulation.

Key Words: Clean Tech, Porosity, Fuel Cell, Ceramic Multilayer



Markets and Applications

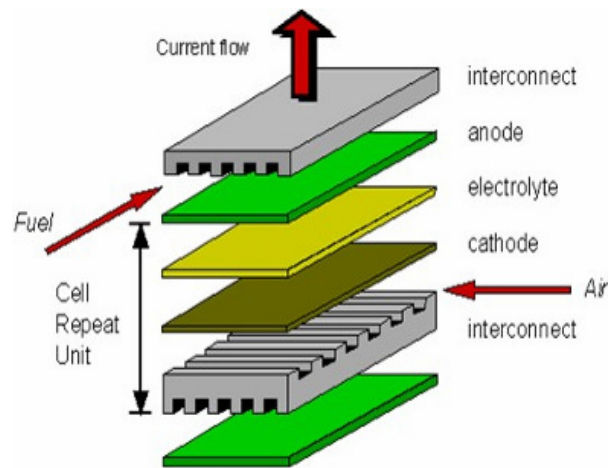
The applications and markets are as varied as the roles for the ceramic components and materials. Ceramic technologies are critical in advanced nuclear technologies, air pollution control, biofuels, carbon sequestration, coal gasification, environmental

remediation, fuel cells, green building technologies, high capacity energy storage, hydrogen generation along with storage and delivery, silicon solar technology, solid-state lighting, thermoelectrics, thin-film solar, tidal power, waste-to-energy, water purification, and wind power. How we generate and utilize energy and how we remediate our environmental effluent in the next three decades will be significantly different than it is today. It has to be. Regardless of what side of the global warming debate you are on, it is imperative that we manage our resources better, continue to clean up our environment and provide for better energy security and reliability.

The companies focused on Clean Tech are also as varied. There are hundreds of companies working in this exciting energy market space. Large well established companies such as CoorsTek and brand new startups such as Lilliputian, working to put solid oxide fuel cell technology on a chip, along with our company ENrG Inc. now six years old, all see a very bright future in developing and supplying

ceramic technologies for Clean Tech systems. As with the ceramic role in electronic systems and the manufacturer of these systems, the expansion of the Clean Tech market segment will create a growing technological demand of the ceramic product base and the engineering teams that support the development and manufacture of these components.

Solid Oxide Fuel Cells

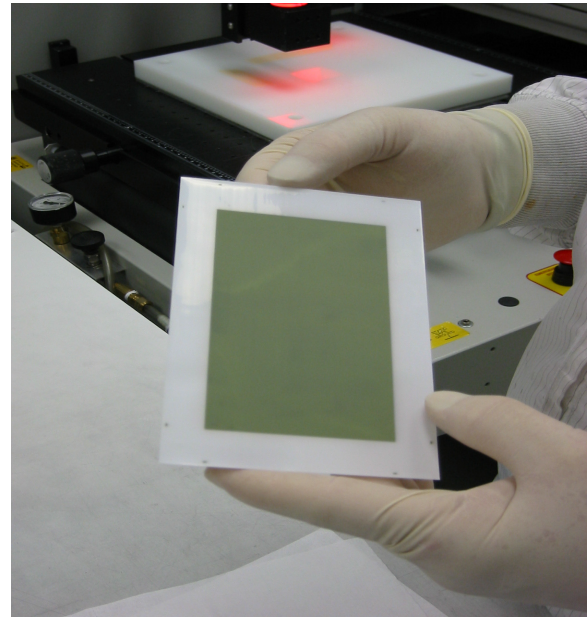


Solid oxide fuel cell (SOFC) systems are forecast to achieve excellent energy efficiency and performance targets, and to be able to achieve commercially viable economics through the next decade. SOFC systems in large volumes are forecast to reach cost targets that are $<\$800/\text{kW}$ this decade with 2010 targets of $<\$400/\text{kW}$. The Department of Energy's Solid State Energy Conversion Alliance (SECA) has been leading the effort to attain these goals. The drive for low cost resulted in a technology approach that created several other performance issues that present significant roadblocks in meeting the overall goals. Applications such as aeronautic and military have a contrary list of priorities. Cost, while being on the list, is last in priority. Another difference is that SECA measures power density based on area (mW/cm^2), while the military is interested in minimizing weight (mW/kg) and volume (mW/l). The aeronautic and military reliability requirements are also much different compared to SECA.

This difference in goal targets has created two distinct trends in SOFC technology. The first trend to meet commercial and large utility system requirements is the goal for ceramic cell (trilayer of electrolyte and the two electrodes, anode and cathode) technology to increase in surface area from

standards today of 100 cm^2 to something greater than 500 cm^2 . The second trend for aeronautic and military applications is to maximize the power per weight or volume of the stack technology, maximum specific power.

Trilayer Cells and Setters



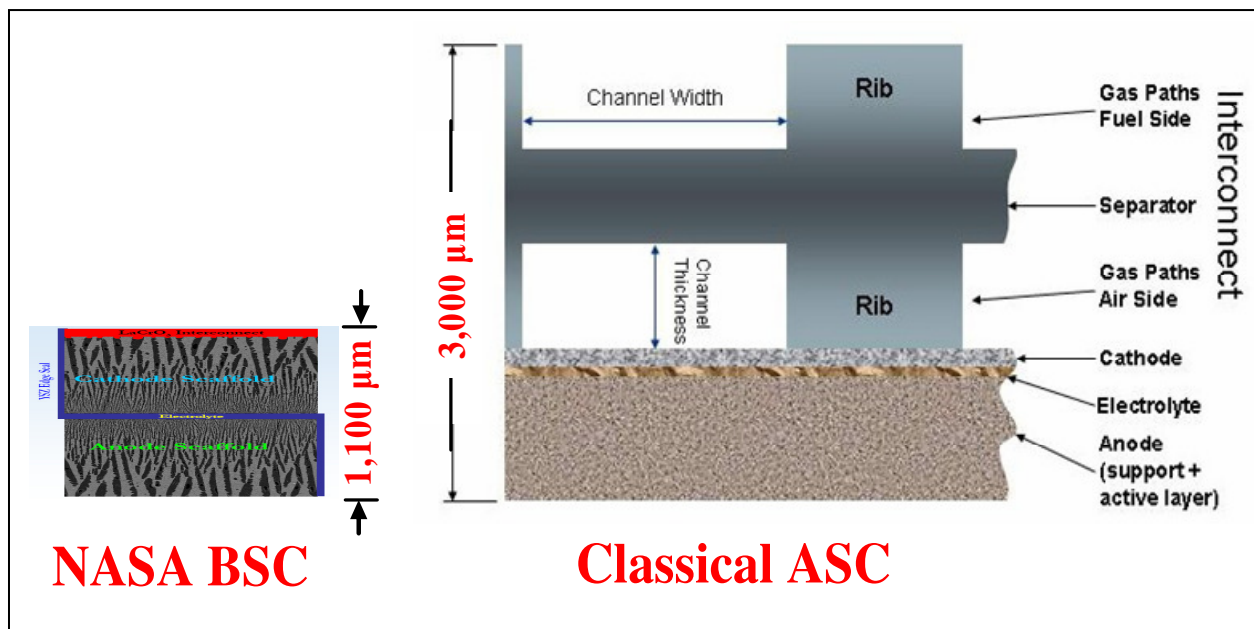
Standard cell technology as shown in the figure here, involves the tape casting of thin yttria stabilized zirconia membranes, firing of those membranes at greater than 1400°C , and then screen printing of anode and cathode compounds on alternate sides with subsequent firing steps after each printing. The electrolyte here is processed to be pinhole free, as thin as possible, and typically is greater than 98% dense. As shown, the anode is a nickel compound and the cathode which is not shown is a lanthanum strontium manganate (LSM) compound. Other compounds are in use by many companies that are variations of these standards, and many companies have moved to other element containing electrodes, such as LSF (lanthanum strontium iron) for better performance levels.

While cells are commonly produced in $100\text{--}200 \text{ cm}^2$ active area format, it is uncommon to make cells $>500 \text{ cm}^2$. Since the base support of cells is a thin ceramic membrane, cells of this size or larger are difficult to work with and process without breaking. With SECA's shift in focus to utilization of SOFC technology in combined cycle utility plants using clean coal technology as the fuel feed, a need exists to produce cells in larger formats. ENrG Inc. has installed equipment and a full clean room facility

capable of printing electrolyte supported cells with active areas reaching and exceeding 1000 cm^2 .

To process cells through the firing cycles, you must use non-contaminating setters usually produced from either alumina or zirconia, and possibly coated. If the cells are the cookies, one can think of the setters as the cookie sheets. The right level of strength and porosity are issues here as the setter will need to see many 10's of firings and the porosity is necessary to allow evolution of gases during the firing cycle. ENrG Inc. produces a series of setters compatible with cell sizes up to 500 cm^2 and with the respective firings of electrolyte, anode or cathode.

hermetic sealing is required between the ceramic cells and metal interconnects. From both a performance and safety perspective, the gases (fuel and air) can not be allowed to combine except when the oxygen ions flow through the electrolyte. When the layers are assembled a hermetic seal, typically ceramic-to-metal braze, must be created around the edge where the interconnect contacts the anode/electrolyte/cathode assembly. Due to the problems the industry has encountered creating robust seals, SECA has identified this as a leading issue in improving the reliability of the SOFC systems.



High Specific Power Stacks

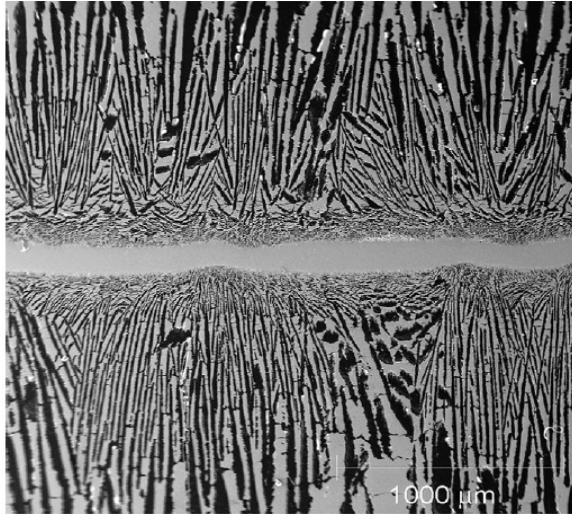
The NASA Glenn Research Center (GRC) has been working on SOFC for the aeronautics' industry for several years and their approach is significantly different than the SECA companies. The NASA Bi-Electrode Supported Cell (BSC) SOFC technology has the potential to provide a 500% increase in power performance per weight (mW/kg) and increased reliability of the fuel cell stack. ENrG Inc. has agreed with NASA GRC to co-develop and license the BSC SOFC technology. ENrG Inc. has incorporated the BSC production process into its current membrane facilities, further advancing the processes and manufacturing techniques.

In standard Anode Supported Cell (ASC) SOFC technology where cells are interleaved with metallic flow fields as shown in the schematic,

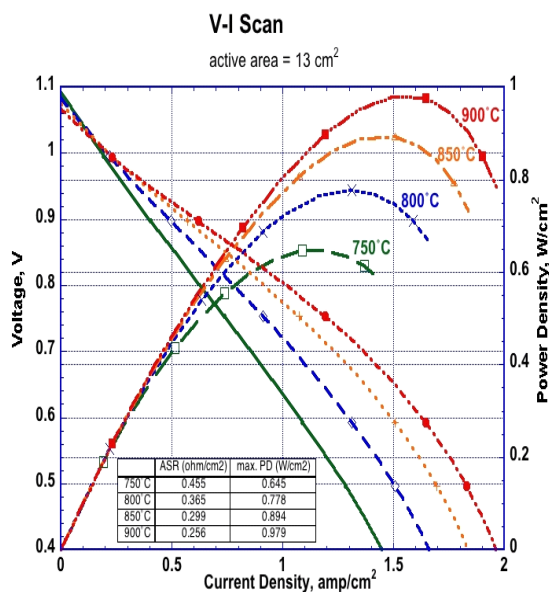
NASA's patent-pending Bi-Electrode Supported Cell (BSC) design uses yttrium stabilized zirconia (YSZ) for the electrolyte, electrode (both anode and cathode) and sealing components. In addition, innovative structural aspects of the design allows for thin ceramic (non-YSZ) interconnects based on well known conductive lanthanum chromite (LaCrO_3) ceramic to replace the metallic electrical interconnect. The figure compares the height of BSC ($1,100 \mu\text{m}$) versus a classical anode-supported cell (ASC) cell ($3,000 \mu\text{m}$). This reduction in thickness and weight of the various materials are part of the reason for the increased specific power density.

The backbone of this process is ceramic freeze casting technology. Here the ceramic tape made using the freeze casting process is used as the scaffold to hold the electrode material. Two layers of freeze cast tapes are laminated with a dense

electrolyte layer to form the trilayer structure for the fuel cell as shown in the figure below. Later the necessary catalysts are infiltrated into the scaffold structure to complete the fuel cell.



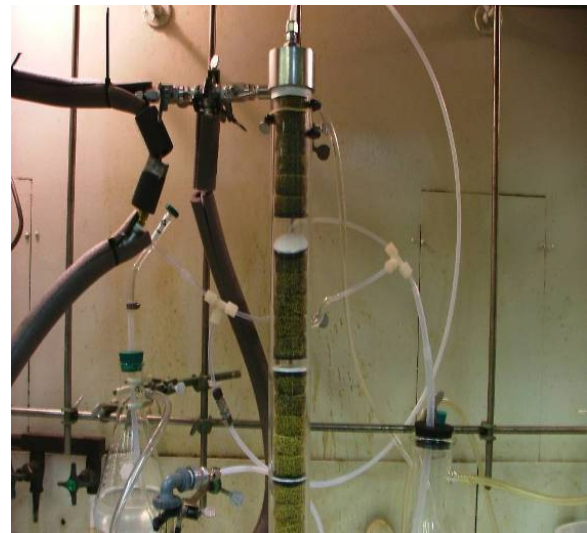
A majority of the SOFC processes currently under development are designed to operate at temperatures where metal interconnects can be safely used. This translates to very low specific power densities - kW/kg. SOFCs for aircraft application require an order of magnitude increase in specific power density to that currently achievable via metallic interconnect route. The approach pursued here consisting of an all ceramic design lends itself to meeting the specific power density target since it can operate at higher temperatures with greater efficiency.



The replacement of the metallic interconnect with a ceramic allows the operating temperature to increase up to 900°C. NASA test results (shown in the preceding figure) demonstrate the advantage of higher temperature. NASA achieved a power density of 0.95 mW/cm² for 0.7 volts at 900°C compared to 0.60 mW/cm² at 750°C. The lower power output is similar to results reported by other SECA team companies which use metal interconnects and therefore must operate at a lower temperature. The combination of increased operating temperature and reduced size together combine to enable the BSC to potentially achieve a 5X improvement in power density.

Gas Separation Membranes

Gas separation membranes have varied applications and gases that are processed. One common gas, methane, a very potent greenhouse chemical, is the primary constituent of landfill gas at about 50% of the composition. Reducing emissions by capturing and beneficiating this landfill gas to greater than 90% methane produces a burnable fuel. The remaining constituents of landfill gas are carbon dioxide and hydrogen sulfide. Carbon dioxide can be captured through many known processes. Hydrogen sulfide capture is one area where ceramic membranes can be used.



Globally, landfills are the third largest anthropogenic emissions source, amounting to about 13 percent of global methane emissions. While early adopters have begun to use this landfill biogas, in combination with distributed generation technologies such as small generators, broader adoption of the

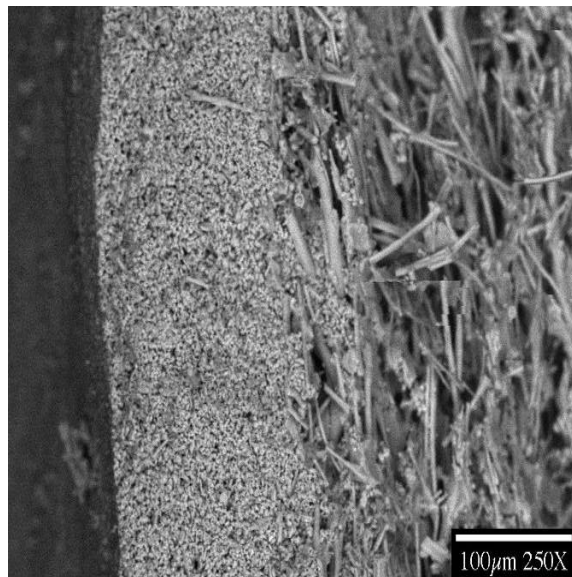
beneficial use of landfill gas for energy production has been limited in part by its low BTU content per unit volume.

Hydrogen sulfide removal can be achieved by a number of methods and materials. Use of metal oxides, hydroxides, and carbonates are effective, but often require high temperatures for efficiency. Room temperature sorbents, oxides and hydroxides of iron and copper fall into this category, were deposited on inert foams as shown in the figure. The figure shows that capture of hydrogen sulfide is ongoing as the foam cores change color from the top of the reactor column to the bottom.

Insulation Packaging

SOFC auxiliary power units (APUs) are being designed and developed to provide the heating and electric power currently provided to a truck's cab by the main vehicle engine but at much lower fuel consumption and emission level. By using an on-board diesel fuel reformer to provide hydrogen and carbon monoxide as the fuel, the SOFC APU will help support the hydrogen economy, significantly reducing/eliminating the current idling emission levels. It will also support the DOE 21st Century Truck Initiative by reducing overall diesel fuel consumption. If all overnight trucks were equipped with SOFC APUs, DOE estimates an annual savings of >600 million gallons of diesel fuel.

The compactness of SOFC APUs has driven the need for an insulation package that exceeds the state-of-art. Off-the-shelf insulation technology is not designed to meet the requirements of the APU application driven by the transportation sector.



Based on ENrG's setter work where the operating temperature is significantly higher than the operating temperature of a SOFC system, technology has been developed to manufacture non-contaminating insulation as shown in the preceding photomicrograph. Insulation packages with porosity nearing 60% have been designed to withstand the operating temperature of SOFCs and fuel reformers. They were also designed to provide a low thermal mass and are based on products that have excellent insulative properties without causing any contamination either through chemical or particle transference which is extremely important for transportation applications.

Summary

Ceramics play a key role in the successful performance of new alternative energy system in the Clean Tech market space. Different ceramic materials, along with catalysis compounds and porosity make for materials systems that can be tailored to many different functions and applications. This growing market space will be a key component of future systems work for IMAPs.

ENrG continues to add capabilities within our ceramic processing. Ceramic isopressed (CIP) electrode and electrolyte tubes are being produced for the Clean Tech market, along with oxygen transport membranes in planar and tubular formats for clean coal technology.

With the Global Economy so sensitive to the value of fossil fuels, ceramics will continue to play a key and very valuable role as key components in new energy producing systems albeit to either improve efficiency of current systems or an entirely new source of power.

About ENrG Inc.

ENrG Incorporated develops and manufactures critical ceramic components required for clean energy generation. ENrG sells its components to product development groups working to design and manufacture clean energy systems. ENrG personnel are specialists in ceramic membrane technologies and ENrG is diversifying its ceramic membrane based technologies into many energy segments. We are currently working on ceramic technologies for fuel cells, gas separation membranes, battery charging, and process enablers such as ceramic setters and kiln furniture. ENrG Inc. is located in Buffalo, NY. ENrG Inc. is a member of New Energy New York and the Ohio Fuel Cell Coalition.

About John A. Olenick, Dr. Venkateswaran, James Newkirk, and Gregory Korbut

John Olenick is President of ENrG Inc. and with 5 other principals, started the company in 2003 to focus on fuel cell technologies. John has been a member of IMAPs since 1984 and has worked at Westinghouse, Mobay Corporation, Rogers Corporation, Eastman Kodak, and Tyco Electronics. John graduated from Pennsylvania State University with a B.S. in Ceramic Science and Engineering. He has also studied business administration at both Johns Hopkins and the University of Connecticut. John is a graduate of the 2004 class at the Center for Entrepreneurial Leadership of University of Buffalo's School of Management. He has published 20 papers and holds 7 patents.

Dr. Viswanathan (Venkat) Venkateswaran is the Technical/Development Manager for ENrG Inc. Dr. Venkat is currently the ENrG project manager working on the feasibility of new electrode materials for SOFCs. Prior to ENrG, Venkat worked for Tyco Electronics, where he was project manager for SOFC ceramic interconnect manufacturing. He has 26 years of experience working in ceramic industries, 17 of those years with the Carborundum Company. Venkat graduated from the Indian Institute of Science, India with a B.E. degree in Metallurgical Engineering. He obtained his M.A.Sc and Ph.D in Metallurgical Engineering from the University of British Columbia, Vancouver, Canada. He has taken an executive management course at Penn State University, published 10 papers, and holds 8 U. S. Patents.

James Newkirk is the General Manager – Fuel Cell Systems for ENrG Inc. James is currently leading the development effort for the NASA BSC technology. Prior to joining ENrG Inc. in January 2006, Mr. Newkirk worked for 37 years at Eastman Kodak Company. While at Kodak, his areas of responsibility included materials and electronic packaging research and development. Mr. Newkirk was responsible for the coordination of many development and commercialization projects with external partners including international activities, and he worked in new business development. Mr. Newkirk helped in the formation of the National Electronic Manufacturing Initiative (NEMI) now called iNEMI and was selected to be the Director of Technical Planning and the Co-Chair of the Technical Committee. He graduated from the Rochester Institute of Technology with a B.S. degree in Chemistry. He currently holds 12 U.S. patents.

Gregory P. Korbut is a Senior Process Engineer for ENrG Inc. Greg has been in the electronic ceramic industry for nearly 10 years with a focus on material processing and fabrication of multi-layer ceramic (MLC) structures and devices. He currently supports ENrG's NYSERDA program efforts on slurry and tape development across a number of programs. Mr. Korbut graduated from the NYS College of Ceramics and Material Science at Alfred University with a B.S. degree in Ceramic Engineering.