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SOLID OXIDE FUEL CELL COMMERCIALIZATION IN THE UNITED STATES

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INTRODUCTION

This paper discusses aspects of solid oxide fuel cell (SOFC) technology commercialization in the U.S. It provides the status of the major SOFC developments occurring in the U.S. by addressing both intermediate- and high-temperature SOFC's, several SOFC designs, including both planar and tubular, and SOFC system configurations. This paper begins with general characteristics, proceeds with designs and system configurations, and finishes with a discussion of commercialization, funding, and policies. The U.S. Department of Energy's (DOE) Morgantown Energy Technology Center (METC) is the lead U.S. DOE center for the implementation of a Research, Development, and Demonstration program to develop fuel cells for stationary power. METC's stakeholders include the electric power and gas industries, as well as fuel cell developers and others. This paper offers some new perspectives on SOFC development and commercialization which come from the broad consideration of the commercialization efforts of the entire fuel cell industry.

SOFC CHARACTERISTICS

Some general characteristics appear to be shared by many of the SOFC technologies being developed. While there is variability in materials being used for various components, the SOFC is an oxygen-ion conducting, solid-state device composed of a nickel-zirconia cermet anode, yttria-stabilized zirconia electrolyte, a strontium-doped lanthanum manganite cathode, and a doped lanthanum chromite interconnect (1). The solid-state electrolyte of yttria-stabilized zirconia oxide is characterized by ionic conduction. The solid-state (non-liquidus) character of the SOFC electrolyte means there are few constraints on design. There is no problem of electrolyte containment, although electronic conduction path-length is an issue. Hence, the flexibility and the wide variety of designs or forms being pursued.

The flexible SOFC may be operated over a wide range of temperatures. The theoretical thermodynamic efficiency (73 percent based on the hydrogen oxidation reaction at 927 °C) is slightly lower for the SOFC than for the molten carbonate fuel cell (MCFC), the phosphoric acid fuel cell (PAFC) and the Polymer Electrolyte

Membrane (PEM). However, the overall efficiencies of SOFC systems are more than PAFC and PEM and certainly rival those of MCFC system configurations.

Power densities for SOFC's are promising. Power densities of 0.91 watts per square centimeter (more than 800 watts per square foot) on hydrogen at 1000 °C have been reported for SOFC's. Higher densities appear possible. The high-power density with thin-layered components could make the SOFC an attractive power plant alternative. However, packaging and cost reduction will be required to make the SOFC promise a reality.

The high-temperature (1000°C) SOFC can provide greater fuel flexibility than lower temperature fuel cells, since the reforming reaction is favored at higher temperatures. Reforming heat requirements with low-temperature fuel cells, such as the PEM fuel cell, can actually lower overall system efficiency. Reforming is an important system consideration which will remain important in the absence of a hydrogen economy. In addition, a higher quality heat produced by the high-temperature SOFC's results in better bottoming cycle performance in some system configurations.

The fuel flexibility of the SOFC means it can operate on a wide variety of fuels. These fuels sometimes contain contaminants. Sensitivity of the SOFC to hydrogen sulfide in the fuel appears to be a minor issue, and sensitivity to ammonia and hydrogen chloride does not appear to be a problem (1,2,3).

The characteristics of the SOFC need to be fully exploited in system configurations as development proceeds. In an integrated commercialization activity, it is at the discretion of SOFC development teams and manufacturers how to advertise and exploit SOFC technology advantages.

DEVELOPMENTAL DESIGNS

While all SOFC share the same general characteristics, the unit designs or forms being developed offer advantages and disadvantages from various perspectives. There are many SOFC designs being developed, some of which are quite similar. Many companies and organizations have publicly announced that they are pursuing the technology. Other companies, which shall not be named, are pursuing the technology privately.

The funding for the SOFC development and commercialization effort is provided by a variety of sources, including DOE, Department of Transportation, the Advanced Research Projects Agency of the Department of Defense, the Electric Power Research Institute (EPRI), the Gas Research Institute (GRI), and private industry as well. DOE cooperates closely with both EPRI and GRI in coordinating the U.S. SOFC program. Currently, METC supports one SOFC developer, Westinghouse Electric.

Westinghouse Electric is the acknowledged world-leader in SOFC technology. The Westinghouse Electric tubular configuration is shown in Figure 1. Several completely packaged and self-contained generators, up to nominal 25-kilowatt size, have been manufactured and tested by Westinghouse Electric. A pre-pilot manufacturing facility currently produces the cells (tubes), bundles, and generators. The length of the tubes has been scaled-up to a nominal 2 meters in length. The porous air-support tube has recently been eliminated. The cell is now supported by the air electrode. The Westinghouse Electric technology has been validated to a far greater extent than any other SOFC technology. Multiple tube tests have been successfully conducted for more than 50,000 hours with less than 1 percent per 1000 hours degradation. Pressurized operation of the tubular SOFC has recently been demonstrated at Ontario-Hydro. Testing of 25-kilowatt systems at Southern California Edison and in Japan is expected to continue through 1996. A 100-kilowatt generator test, at a to-be-determined location, is also planned for the 1995-1996 timeframe. Westinghouse Electric, a large, integrated corporation, has a well-developed development, demonstration, and commercialization program (4,5,6).

METC is not currently funding a planar SOFC developer. Several planar designs are under development. Organizations developing plannar designs include the Institute of Gas Technology (IGT), Ceramatec, Ztek, Technology Management Incorporated, and Allied Signal Aerospace Corporation. These developers hold strong patent positions on cell designs, which is essential for low-cost manufacturing.

IGT is developing an 800 °C, intermediate-temperature, internally manifolded planar design. This trilayer IGT design, shown in Figure 2, has, according to IGT, the advantages of more effective gas flow patterns, more compact design and cell stacking, more efficient current and voltage transfer from cell to cell, and more cost-effective manufacture (7). The IGT design is an internally manifolded fuel cell design using pressed metallic plates called IMHEX^R. Because the IMHEX^R design has no external gaskets and seals, only compression seals are necessary to obtain good sealing. The ceramic bipolar separator plates in the SOFC's currently under development are the single most expensive component. These make up more than 80 percent of the total materials and fabrication costs of the cell components (8). IGT replaces the ceramic separator plates with nickel-based metallic separator plates, thus lowering cost significantly. Since at 800 °C the zirconia electrolyte will have high-internal resistance losses, IGT is using the provskite gadolinium-doped barium cerium oxide. IGT will partner with Argonne National Laboratory (ANL) to develop glass/ceramic composites which, they hope, will sidestep most of the problems associated with glass-only or cement-only manifold seals. IGT plans scale-up from single cell to the 1-kilowatt size within the next 5 years.

The Ceramatec design, **CPn**^{R}, consists of stacks and fuel processor, and places some cells in a series rather than in parallel to obtain greater efficiency. Ceramatec has attained a power density of 0.18 watts per centimeter square (167 watts per square foot) and a current density of 250 milliamperes per square centimeter (230 amperes per square foot). Ceramatec has tested a 1.4-kilowatt module and has recently announced a limited partnership with Babcock and Wilcox (9) for the commercialization of the technology. Ztek uses a radial design stacked into two-stack modules which are then combined into arrays. Ztek, along with EPRI and Tennessee Valley Authority, is testing a 1-kilowatt stack. A 25-kilowatt stack test is also planned (10). Technology Management Incorporated uses an Interscience Radial Flow design in which each cell is made up of four layers, with sealing being achieved through the use of rings which also form the internal fuel and air manifolds. Small stack testing from one to ten cell stacks has been performed. Power densities around 0.08 watts per square centimeter (75 watts per square foot) have been attained (11). Allied Signal Aerospace Corporation is developing the monolithic and flat planar designs and is now using tape-calendering to produce a thin-electrolyte, reduced-temperature fuel cell with a potentially low manufacturing cost (12).

It is often difficult to determine if the SOFC materials and their electrochemical and physical properties, per se, or if the individual SOFC designs contribute more to performance, as measured by power density, efficiency, longevity (or durability), cost, packagability, and system integrability. A variety of both material and design-related issues are being addressed by the ANL, Pacific National Laboratories, University of Missouri-Rolla, and others in support of SOFC development and commercialization.

Various SOFC stack components, such as interconnects and seals, are under general development through METC. Lower cost and more compatible interconnect materials are being considered. The development of a lower, intermediate-temperature SOFC design, such as the IGT design, may sidestep or postpone issues such as the interconnect development. However, the SOFC performance and system configuration may be impacted.

Sealing, a major issue in planar SOFC development, is being pursued by ANL and others. It is not surprising that sealing, in externally manifolded planar designs, has been a significant issue in other fuel cell development (13). Material corrosion--changes in composition, porosity, density, phase, etc., over time--is of continuing concern for all SOFC developers. The capability to deposit thin layers of materials with time-invariant physical and electrochemical properties is a basic challenge in the development of low-cost SOFC's.

SYSTEM CONFIGURATIONS

As previously mentioned, the high-temperature SOFC exhaust and inlet temperatures are near 1000 °C. The SOFC efficiency (and fuel utilization), temperature, and pressure are the chief variables which influence the way it is configured with other power generation and ancillary equipment into a system configuration. A higher quality heat produced by the high-temperature SOFC's results in better bottoming cycle performance in some system configurations. The SOFC exhaust temperature is also compatible with gas combustion turbine inlet temperatures.

Pressurization is an important issue to be addressed in the commercialization of any fuel cell and has been an issue with other fuel cells (14,15). It is generally believed that pressurization lowers footprint and balance-of-plant costs. As was indicated, pressurized operation has already been demonstrated for the tubular SOFC. Since gas turbines generally operate from 10-30 atmospheres, it may be possible to integrate the pressurized, tubular SOFC with gas turbines. System configurations of interest include the use of the SOFC as a topper in a fuel cell/turbine system. Perhaps integration of a fuel cell into a turbine system may eliminate some balance-of-plant development.

Power plant size is an important consideration that affects both cost and marketability. For the SOFC, it may be that several large power plant demonstrations will be required to establish manufacturing capability and lower power plant dollar per kilowatt costs. In Japan, where there is a high population density and where transmission and distribution distances are small, large power plants may be preferred. Westinghouse Electric has developed a conceptual design for a 300-megawatt coal gasification SOFC power plant, 2- to 5-megawatt natural gas fueled power plants for commercial (office building) applications, and 20-megawatt liquified natural gas fueled power plants for distributed power (16).

As SOFC stacks increase in size, a level is reached where multiple stacks are more economical. At this point, the decision as to whether to place the stacks in parallel or in series networks will become important (17). Ceramatec is evaluating this series-parallel issue in its **CPn**^{R} SOFC design. The benefits of increased efficiency and potential for fuel conditioning may make networking alternatives economically attractive.

DEVELOPMENT AND COMMERCIALIZATION AS AN INTEGRATED ACTIVITY

The state of development and commercialization varies among the various SOFC design developers. Some developers are small entities, while others are large, integrated companies. However, for any SOFC developer, the focus cannot remain on just SOFC technology developmental issues--technology development cannot proceed in a vacuum. From the beginning, cost requirements, manufacturing process requirements, and performance specifications must be coordinated and mutually developed. Making something work--demonstrating technical feasibility--is not enough.

Development and commercialization is an integrated activity. At the development stage, where basic choices in materials and designs are being made and validated, decisions must incorporate the considerations of system cost, system integrability, manufacturability, and marketability. Packaging and system integration must begin early. Value engineering, which simplifies and combines component functions, is critical. Organizational commitment to packaging may be a cornerstone of success.

Product improvement is an ongoing activity. Once over the hurdle of feasibility, material selection for improved designs must continually be made with low-cost manufacturing processes and materials in mind. Manufacturing processes which are more conventional, such as tape-casting, tape-calendering, etc., need to be considered where possible. High-fabrication cost is primarily due to the large numbers of costly steps which must be performed under controlled conditions. Fabrication processes requiring fewer and less complex steps and less expensive equipment used for component fabrication need to be considered. The combination of manufacturing steps through the use, for example, of lamination and co-sintering needs to be considered. Capital will also be required at the proper time to build up manufacturing capability to exploit economy-of-manufacture and lower power plant costs.

For small corporations, strategic alliances, which provide a presence in the small or large stationary power market or other target market, are valuable assets for the SOFC commercialization team. The primary application of the SOFC is currently stationary power generation, but a variety of other potential applications, such as vehicular transportation, may be possible. SOFC's for vehicular transportation must deal with more demanding requirements, such as mechanical shock, low-cost targets, and even smaller footprints than stationary power applications. Capability of the commercialization team to quantify both the U.S. and international markets and the possession of the appropriate marketing, sales, and service infrastructure is desirable.

Product definition and customer focus are crucial. Product definition is a developmental-long activity. From the beginning, cost requirements, manufacturing process requirements, and performance specifications (product definition) must be kept in mind. End-user input must be surveyed and translated into marketable designs. In this regard, commercialization groups, advisory groups, EPRI, GRI, and DOE can provide valuable service(s).

FUNDING AND POLICY IMPACTS

There are two important questions in regard to SOFC development: (1) how many developers does the U.S. need to create a viable and internationally competitive SOFC industry and (2) how many developers can the Government and utility industry sponsors afford. All Government-funded programs are subject to additional scrutiny as the result of the recent changes in Congress. Research for research sake is no longer valued. The DOE strategically plans for fuel cell development and commercialization (18,19) and funds integrated programs where basic research and development supports commercialization. Only the most broadly supported, electric utility and other end-user backed, market-responsive SOFC programs can expect to be supported.

It is important, now more than ever, for sponsors and developers to keep the real goal in mind. The larger goal is not development of a particular SOFC design, per se, but SOFC commercialization. From the DOE policy perspective, commercialization is the activity that promotes economic competitiveness and job formation, that is, industrialization.

In the future, the demands on all sponsors' budgets for fuel cells will probably become greater. Furthermore, in the electric utility industry, deregulation, unbundling, and wholesale wheeling are expected to result in lower costs of electricity and lower industry-wide profit margins. A leaner electric utility industry may mean fewer dollars for SOFC commercialization.

In a more competitive electric utility industry, the SOFC developer must get to the market at the right time and at the right dollar/kilowatt. The costs must be low enough to effectively compete against existing power generation technologies. If the SOFC market is in the larger rather than smaller power plant sizes, the challenge may be how to jump from the small size immediately to a larger size where most applications are expected to present opportunities for sustained industry growth. The problem is whether or not the Government and other funding agencies, manufacturers, or end-user industries can afford multiple large demonstrations for single, let alone multiple developers.

SUMMARY

The SOFC could represent an attractive power plant alternative. However, the challenges facing many SOFC developers are significant. Once over the hurdle of feasibility, the activities of SOFC development and commercialization must be integrated and coordinated at all levels. Only the most broadly supported electric utility and other end-user-backed, market-responsive SOFC programs can expect to be supported. Organizational commitment to packaging, product definition, and continuous product improvement may be a cornerstone of success.

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Solid Oxide Fuel Cell Tubular Design

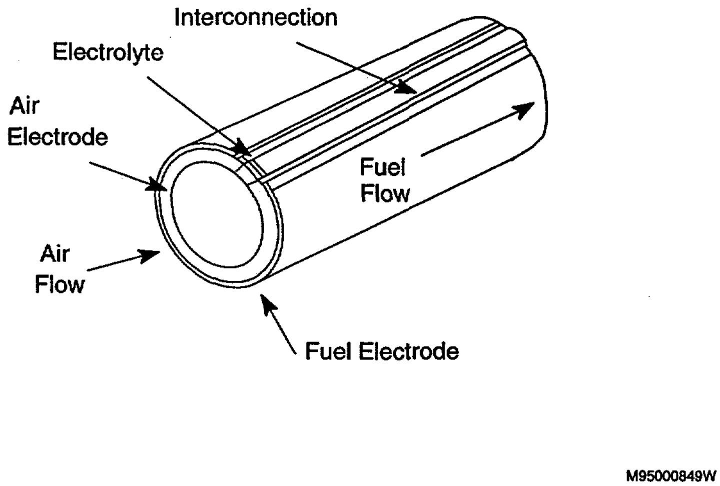

Figure 1

Schematic of Active Component Tri-Layer of IMHEX SOFC

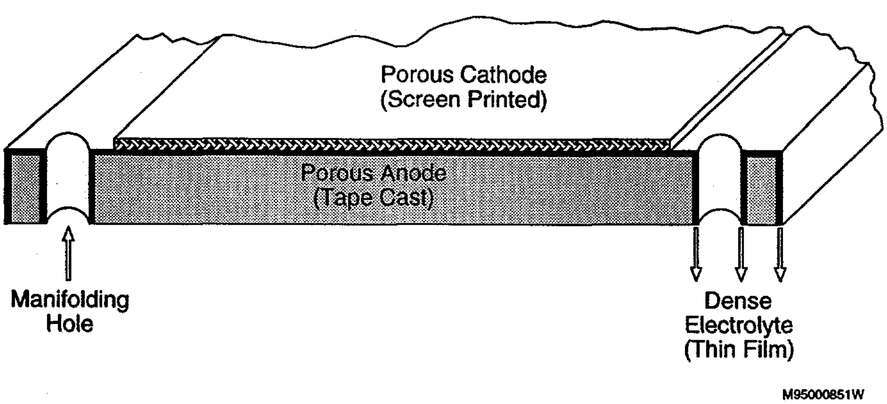

Figure 2