STATUS OF SOLID OXIDE FUEL CELL DEVELOPMENT AND COMMERCIALIZATION IN THE U.S.

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ABSTRACT

Solid Oxide Fuel Cell (SOFC) powerplants are expected to impact the natural gas stationary power distributed generation (DG) market -- 300-kilowatt (kW) to multi-megawatt (MW) -- the portable power market, the specialty applications (commercial and military) market, and transportation markets. Siemens Westinghouse is the leader in tubular SOFC technology. Several completely packaged and self-contained power plants, up to nominal 100-kW size, have been manufactured and tested by them. A manufacturing facility currently produces these power plants. In the U.S. several planar designs are also under development. Organizations developing planar designs include the Institute of Gas Technology, Ceramatec, Ztek, Technology Management Incorporated, and Allied Signal Aerospace Corporation. The high-efficiency, fuel cell-turbine hybrid, with and without networking or staging of fuel cells, represents the most efficient power plant type ever conceived. Siemens Westinghouse is planning the first test of a 60 percent efficient 250-kW fuel cell turbine hybrid in 1999.

INTRODUCTION

SOFC power plants offer the potential for ultra-high energy conversion efficiency levels and ultra-low emissions levels -- a combination attractive in energy markets worldwide. Because of this, organizations in the U.S. such as the Department of Energy (DOE) Federal Energy Technology Center (FETC), the National Institute of Standards and Technology, the Department of Defense, the Gas Research Institute and the Electric Power Research Institute are funding the SOFC technology. DOE FETC currently funds only one solid oxide fuel cell developer -- the Siemens Westinghouse tubular solid oxide developer. Siemens Westinghouse has the technical lead in solid oxide fuel cells, broad cost share support, and is the closest solid oxide developer to commercialization. Long term, DOE is interested in realizing the full potential of the fuel cell technology. It is considering a 21st Century Fuel Cell Program to develop fuel cells whose advanced design meets the strategic goals of a 21st Century Fuel Cell Program, including cost goals of < $100/kW for the fuel cell stack and $400-600/kW for the fuel cell system and efficiency goal of up to 70 to 80 percent by 2015. Possible fuel cells meeting the goals include solid oxide fuel cells.
SOLID OXIDE FUEL CELLS STATUS

In the U.S. several SOFC technology configurations are being developed. Since the SOFC may be operated over a wide range of temperatures, several lower temperature configurations with alternative materials are being considered. While interest in a wide range of alternative electrolytes and electrodes are being investigated, the standard SOFC consists of the 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 character of the SOFC electrolyte means there are few constraints on design.

Power densities for SOFCs are very promising. Power density possibilities of almost 2.0 watts per square centimeter on hydrogen at 800 to 1,000 EC have been reported for SOFCs by the Lawrence Berkeley Laboratory (2). The high-power density with thin-layered components could make the SOFC the fuel cell with the highest potential power density.

Siemens Westinghouse Power Corporation (SWPC), is the leader in tubular SOFC technology. The SWPC tubular configuration is shown in Figure 1. Several completely packaged and self-contained power plants, up to nominal 100-kW size, have been manufactured and tested by SWPC. A 4-MW/year 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 cell is now supported by the air electrode. The SWPC technology has been validated to a far greater extent than any other SOFC technology. Multiple cell tests have been successfully conducted for almost 70,000 hours, with less than 1 percent per 1,000 hours degradation. Pressurized

Solid Oxide Fuel Cell Tubular Design

Figure 1. SWPC Design
operation to 15 atmospheres of the tubular SOFC has recently been demonstrated at Ontario-Hydro. This pressurization testing is a key aspect of the eventual integration of the SOFC with the gas turbine. A 100-kW test in the Netherlands is underway (3).

The testing of the first SWPC 250-kilowatt pressurized fuel cell turbine hybrid at the National Fuel Cell Research Center in Irvine is planned for 1999. This unit promises to be the most efficient power plant ever built at its size.

Several planar designs are also under development. Organizations developing planar designs include the Institute of Gas Technology, 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.

HYBRID, SOFC-GAS TURBINE POWER PLANTS

Over the last several years, fuel cell and gas turbine combined cycle systems, or hybrid systems, have been analyzed and studied by the DOE and industry (4-12). Fuel cells and gas turbines are two of the enabling technologies for proposed Vision 21 systems (13). Because of their high efficiency and reduced level of pollutant emissions, hybrid systems can serve as a next generation advanced power device. In addition, hybrids are a means of getting to lower power plant capital costs faster.

Although developing hybrid power cycles will be a formidable task, the basic building blocks needed are already becoming available. These building blocks, including advanced turbine systems and fuel cells, are the subsystems being developed by partnerships between FETC and U.S. industry. The fuel cell's electrical energy conversion efficiency ranges from 40 to 60 percent of the fuel's lower heating value (LHV). Combined with a gas turbine, efficiencies of 60 to 80 percent LHV are possible. By carefully integrating these subsystems or modules, and solving the remaining technical challenges, hybrid power cycles with efficiencies of 60 percent (near term), 70 percent (mid term), and 80 percent (long term) that meet the required emissions and cost criteria can be realized.

Hybrid cycles may configure a fuel cell and a gas turbine in several different fashions. As shown in Figure 2, one concept, a 70 percent LHV hybrid, includes one or more natural gas-fired fuel cells bottomed with one or more gas turbines, in a combined-cycle process. Heated fuel and air streams pass into the anode or cathode compartments, respectively, of the fuel cell where electrochemical reactions take place. Fuel cell exhaust gases are mixed and burned, raising the turbine inlet temperature. Expansion of the combustor exhaust gases through the gas turbine provide an inexpensive means for recovery of the fuel cell waste heat. It is the effective utilization of this heat that provides the high cycle efficiency.

Several cycle configurations have been presented or patented for hybrid systems. Many of these systems show tremendous promise for ultra-high efficiency. However,
feasibility assessment and analysis is needed to determine which cycles are the best candidates for various Vision 21 markets and applications (13).

Near- and mid-term hybrid systems are targeted for distributed generation at below 20 MW size range at 60 to 70 percent efficiency (LHV). FETC envisions hybrids to be available for demonstration by the year 2003 and commercially available by the year 2007.

A long-term hybrid concept, the UltraFuelCell (shown in the Figure 3), includes a turbine bottomed by one or more fuel cells. New long-term concepts such as this promise efficiencies of over 80 percent. Fuel cells may be networked, placed in series as well as in parallel, further increasing the overall system efficiency. In this sense, a fuel cell can be bottomed by another fuel cell to increase efficiency. Table I shows the potential efficiency advantages of such a system.

|                      | LHV Efficiency | SIZE           | STATUS        |
|----------------------|----------------|----------------|---------------|
| UltraFuelCell        | 80%+           | 200 kW through MW | Conceptual    |
| Near- and Mid-Term   | 60-70%         | 200 kW through MW | Conceptual    |
| Fuel Cell/Turbine Hybrids |        |                |               |
| Advanced Turbines    | 60%            | 400 MW         | Developing    |
| Modern Large Turbines| 42%            | 50 MW          | Commercial    |
| Average Grid Technology | 35%        | Wide range     | Commercial    |
| Micro Turbine        | 25%            | 28 kW          | Developing    |

Table I. Comparison of UltraFuelCell with Competing Power Generation Systems
DISTRIBUTED GENERATION (DG) MARKET

Deregulation of the electric industry should result in greater opportunity for fuel cells, greater competition, lower prices, and the introduction of a number of energy alternatives. The creation and growth of DG markets could accompany deregulation which will be occurring over the next decade. No other force would change the electricity industry more than the explosive growth of distributed generation, accounting for perhaps 20 percent of all new domestic power generation capacity additions through 2010 -- some 10 gigawatt per year in the U.S. and Europe.

Deregulation is expected to eventually lead to the merger of many former utilities, gas companies, etc. in a few full service energy providers. These providers should be able to respond to customer choice with a full range of energy alternatives, including distributed generation technology alternatives. The opportunity for DG is for the following size ranges: small residential and commercial, less than 500 kW; medium commercial and industrial, 0.5 to 5 MW; and large industrial, 5 to 50 MW.

The building segment of the commercial and industrial market is potentially important for fuel cells. A specific example of a good fuel cell application would be power for a new hospital, hotel or prison, i.e., a building with beds, requiring heat, electricity and a uninterruptable power supply, in an area with no transmission and distribution infrastructure, so credit could be given for deferment of a substation upgrade. In this example, the fuel cell would be owned and operated by an energy service entity having a distributorship taking credits for environmental benefits.
OTHER MARKETS AND THE LONG-TERM POTENTIAL OF SOLID OXIDE FUEL CELLS

The SOFC is being considered for a multitude of applications in addition to stationary power. Defense applications in portable power, propulsion, ancillary power, shipboard power, battery replacement, etc., have been identified. The transportation application for SOFC is especially interesting due to the high power densities and efficiencies projected for the technology. Table II shows the long-term potential of solid oxide fuel cells as established in various laboratories (2,14). DOE is considering a 21st Century Fuel Cell Program to develop fuel cells whose advanced design and low costs will provide even deeper and wider market penetration into a multitude of applications.

| Feature          | Projection   |
|------------------|--------------|
| Operating temperature | 600-800°C    |
| Start-up         | Less than 2 minutes |
| Cell power density | 2 W/cm²       |
| Stack power density | 1 W/cm²      |
| Stack power per volume | 2 kW/l        |
| Stack power per mass | 2 kW/l       |

CONCLUSIONS

The future of the fossil-energy based systems is the intense subject of interest. The solid oxide fuel cell technology is certain to be a part of our energy future. Hybrid power systems based on fuel cells, gas turbines, and heat engines provide tremendous opportunity to reduce emissions, costs, and fuel use associated with energy conversion to heat and power. In the long term, hybrids are viable candidates to provide the high efficiency power modules for future power systems such as Vision 21 and new emerging markets for distributed generation and transportation.

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