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U.S. distributed generation fuel cell program

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Abstract

The Department of Energy (DOE) is the largest funder of fuel cell technology in the U.S. The Department of Energy—Office of Fossil Energy (FE) is developing high temperature fuel cells for distributed generation. It has funded the development of tubular solid oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC) power systems operating at up to 60% efficiency on natural gas. The remarkable environmental performance of these fuel cells makes them likely candidates to help mitigate pollution. DOE is now pursuing more widely applicable solid oxide fuel cells for 2010 and beyond. DOE estimates that a 5 kW solid oxide fuel cell system can reach $400 per kW at reasonable manufacturing volumes. SECA—the Solid State Energy Conversion Alliance—was formed by the National Energy Technology Laboratory (NETL) and the Pacific Northwest National Laboratory (PNNL) to accelerate the commercial readiness of planar and other solid oxide fuel cell systems utilizing 3–10 kW size modules by taking advantage of the projected economies of production from a “mass customization” approach. In addition, if the modular 3–10 kW size units can be “ganged” or “scaled-up” to larger sizes with no increase in cost, then commercial, microgrid, and other distributed generation markets will become attainable. Further scale-up and hybridization of SECA SOFCs with gas turbines could result in penetration of the bulk power market. This paper reviews the current status of the solid oxide and molten carbonate fuel cells in the U.S.

Keywords: Stationary power; Distributed generation; Cogeneration; Solid oxide fuel cell; Molten carbonate fuel cell; Hybrids

1. Introduction

Fuel cells have high efficiency, low environmental impact, potential low-cost even in small size units, and are easy to site. Because of these factors, together with the interest for distributed power generation, the U.S. Department of Energy—Office of Fossil Energy (FE) is funding several major programs for the development of fuel cell-based power generation systems [1]. These programs include both solid oxide and molten carbonate fuel cells, and can be categorized as follows:

- Solid oxide fuel cells (SOFCs):
  - Siemens Westinghouse Power Corporation Tubular SOFC Program
  - Solid State Energy Conversion Alliance (SECA) Programs
- Molten carbonate fuel cells (MCFCs):
  - FuelCell Energy (FCE), Inc. Direct Fuel Cell (DFC) Program.

In addition, a new concept termed FutureGen was initiated early this year to produce electricity and hydrogen from coal in a virtually emission-free plant; this concept will also employ fuel cells. This paper discusses the status of the various fuel cell programs.

2. Solid oxide fuel cells (SOFCs)

2.1. Siemens Westinghouse Power Corporation’s Tubular SOFC Program

Siemens Westinghouse (formerly Westinghouse Electric Corporation) has been developing tubular solid oxide fuel cells since late 1970s. In their latest tubular design, the cell components are deposited in the form of thin layers on a cathode (air electrode) tube, closed at one end [2]. Fig. 1 schematically illustrates the design of the Siemens Westinghouse tubular cell [3,4]. The lanthanum manganite-based cathode tube (2.2 cm diameter, 2.2 mm wall thickness, about 180 cm length) is fabricated by extrusion followed by sintering to obtain about 30–35% porosity. Electrolyte, zirconia doped with about 10 mol% yttria (YSZ), is deposited in the form of about 40 μm thick layer by an electrochemical vapor

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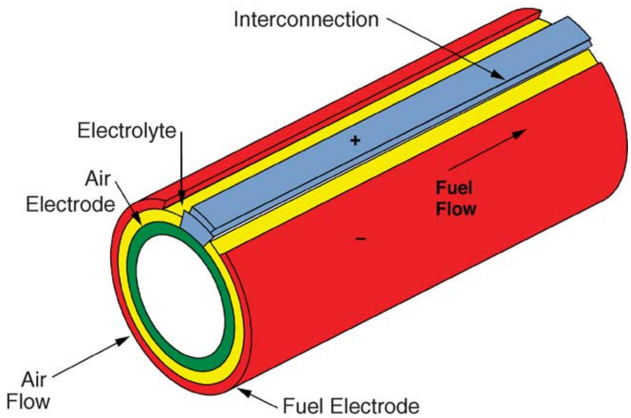

Fig. 1. Schematic illustration of a Siemens Westinghouse tubular SOFC [3].

deposition (EVD) process [5,6]. In this process, chlorides of zirconium and yttrium are volatilized in a predetermined ratio and passed along with hydrogen and argon over the outer surface of the porous air electrode tube. Oxygen mixed with steam is passed inside the cathode tube. In the first stage of the reaction, molecular diffusion of oxygen, steam, metal chlorides, and hydrogen occurs through the porous cathode and these react to fill the pores in the cathode with the yttria-stabilized zirconia. During the second stage of the reaction after the pores in the air electrode are closed, electrochemical transport of oxide ions occurs through the already deposited yttria-stabilized zirconia in the pores from the high oxygen partial pressure side (oxygen/steam) to the low oxygen partial pressure side (chlorides). The oxide ions, upon reaching the low oxygen partial pressure side, react with the metal chlorides and the electrolyte film grows in thickness. The ratio of yttrium chloride to zirconium chloride is so chosen that the electrolyte deposited contains about 10 mol% yttria.

The EVD technique deposits a very high quality, 100% dense, uniformly thick electrolyte film. However, this technique to deposit the electrolyte is complex, capital-cost intensive, and requires vacuum equipment that makes scaling it up to a cost-effective, continuous manufacturing process for high-volume SOFC production difficult. Fabrication of the YSZ electrolyte films by a more cost-effective non-EVD technique, such as plasma spraying followed by sintering, is presently being investigated to reduce cell manufacturing cost.

The Ni/YSZ anode, 100–150 μm thick, is deposited over the electrolyte by a two-step process. In the first step, nickel powder slurry is applied over the electrolyte. In the second step, YSZ is grown around the nickel particles by the same EVD process as used for depositing the electrolyte. Deposition of a Ni–YSZ slurry over the electrolyte followed by sintering has also yielded anodes that are equivalent in performance to those fabricated by the EVD process. Deposition of the anode by a thermal spraying method is also being investigated. Use of these non-EVD processes should result in a substantial reduction in the cost of manufacturing SOFCs.

Doped lanthanum chromite interconnection is deposited in the form of about 85 μm thick, 9 mm wide strip along the air electrode tube length by plasma spraying followed by densification sintering [7].

The cell tube is closed at one end. For cell operation, oxidant (air or oxygen) is introduced through an alumina injector tube positioned inside the cell. The oxidant is discharged near the closed end of the cell and flows through the annular space formed by the cell and the coaxial injector tube. Fuel flows on the outside of the cell from the closed end and is electrochemically oxidized while flowing to the open end of the cell generating electricity. At the open end of the cell, the oxygen-depleted air exits the cell and is combusted with the partially depleted fuel. Typically, 50–90% of the fuel is utilized in the electrochemical cell reaction. Part of the depleted fuel is recirculated in the fuel stream and the rest combusted to preheat incoming air and/or fuel.

A large number of tubular cells have been electrically tested over the years, some for times as long as 8 years; typical performance of these cells is illustrated in Fig. 2. These cells perform satisfactorily for extended periods of time under a variety of operating conditions with less than 0.1% per 1000 h performance degradation [3]. The tubular SOFCs have also shown the ability to be thermally cycled to room temperature from 1000 °C over 100 times without any mechanical damage or electrical performance loss. This ability to sustain thermal cycles is essential for any SOFC generator to be commercially viable.

To construct an electric generator, individual cells are connected in both electrical parallel and series to form a semi-rigid bundle that becomes the basic building block of a generator [3]. Nickel felt is used to provide soft, mechanically compliant, low electrical resistance connections between the cells. This material bonds to the nickel particles in the fuel electrode and the nickel plating on the interconnection for the series connection, and to the two adjacent cell fuel electrodes for the parallel connection; such a series–parallel arrangement provides improved generator reliability. A three-in-parallel by eight-in-series cell bundle is shown in Fig. 3. The individual cell bundles are arrayed in series to build voltage and form generator modules.

Since 1984, Siemens Westinghouse has designed, built and tested almost a dozen fully-integrated power systems of successively increasing sizes. More recently, a 100 kW size atmospheric pressure power system, employing 1152 tubular cells in 48 bundles of 24 cells each, was built as shown in Fig. 4. It operated very successfully for over 20,000 h in the Netherlands and Germany on natural gas at an efficiency of 46% with no detectable performance degradation. Such atmospheric systems are ideal for combined heat and power generation (CHP) in distributed applications.

A scaled-up 250 kW size atmospheric pressure system, shown in Fig. 5, employing 2292 tubular cells, with heat extraction (CHP), has also been built and is now operating

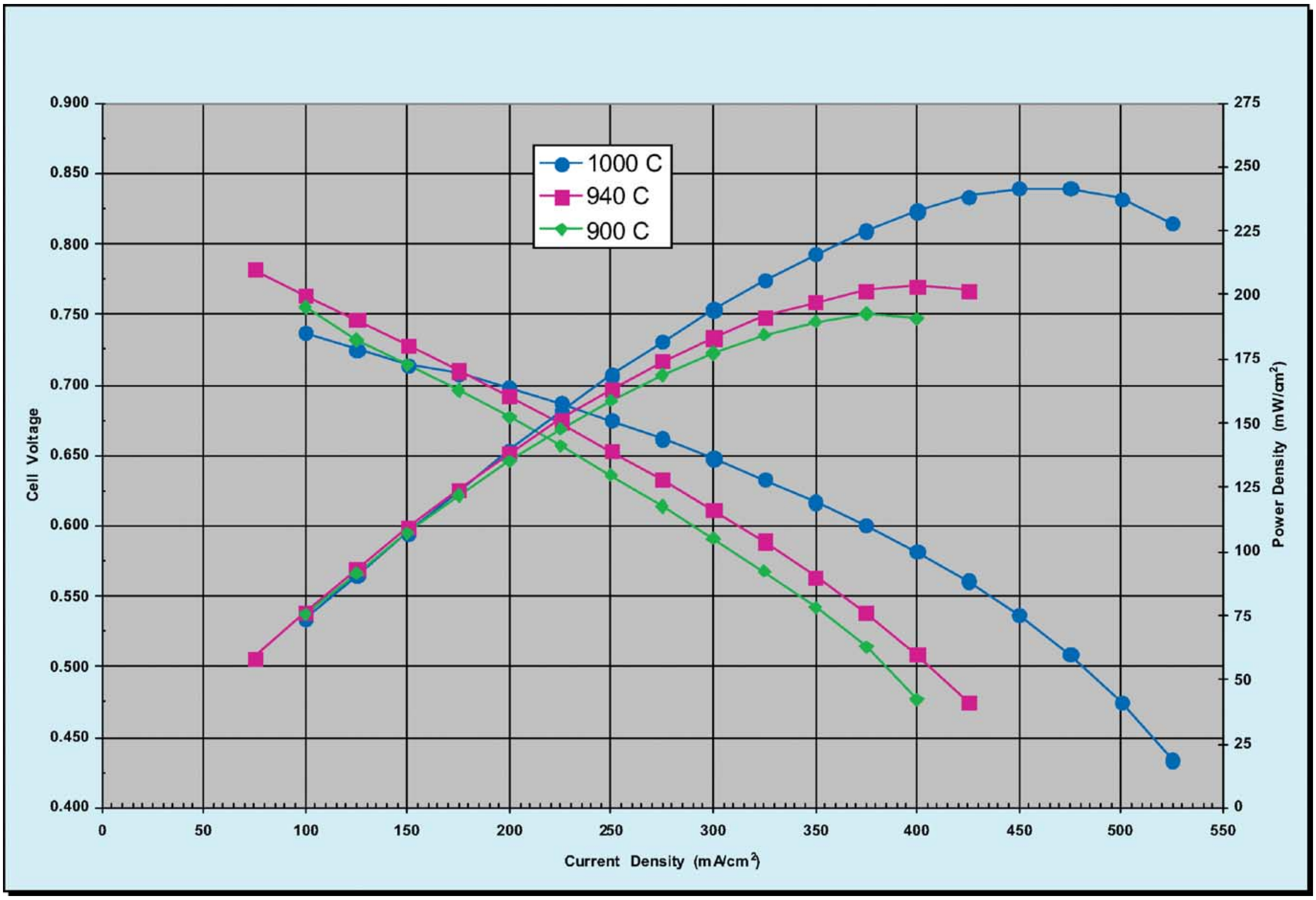

Fig. 2. Voltage–current density and power–current density plots of a commercial prototypical tubular SOFC (courtesy of Siemens Westinghouse Power Corporation).

at a Kinetrics Facility in Toronto, Canada. Similar 250 kW size systems are planned for operation in 2004 at Stadwerke Hannover in Germany and at BP America in Alaska. Such atmospheric CHP products with electrical efficiencies in the 45–50% range are expected to be the Siemens Westinghouse's initial commercial offering commencing in 2006.

Siemens Westinghouse has also tested tubular SOFCs at pressures up to 15 atm on hydrogen and natural gas fuels [3]. Fig. 6 shows the effect of pressure on cell power output for a 2.2 cm diameter, 150 cm active length cell at 1000 °C. Operation at elevated pressures yields a higher cell power at any current density due to increased Nernst potential and reduced cathode polarization, and thereby permits higher

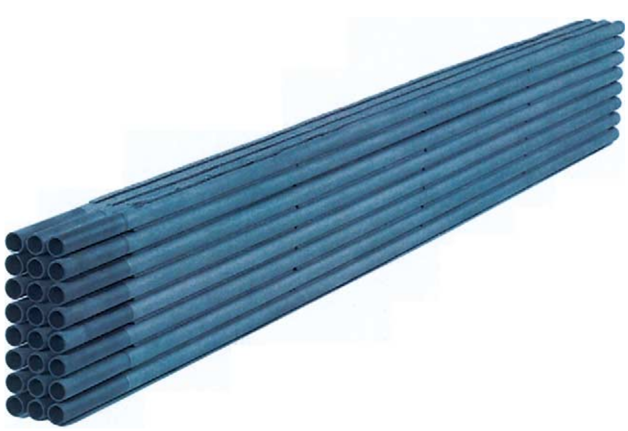

Fig. 3. A three-in-parallel by eight-in-series tubular cell bundle [3].

Fig. 4. Siemens Westinghouse's 100 kW size atmospheric pressure CHP system.

Fig. 5. Siemens Westinghouse's 250 kW size atmospheric pressure CHP system.

stack efficiency and greater power output. With pressurized operation, SOFCs can be successfully used as replacements for combustors in gas turbines for SOFC/turbine hybrid systems.

Siemens Westinghouse has designed, fabricated and tested a pressurized SOFC/gas turbine hybrid system for enhanced efficiency. The initial 200 kW hybrid system (PH200), shown in Fig. 7, underwent proof-of-concept testing at the National Fuel Cell Research Center in Irvine, CA, for about 3000 h, and the unit achieved 52% electrical efficiency. This first-of-a-kind system provided many useful lessons and demonstrated excellent emissions and efficiency performance. It demonstrated that SOFC/turbine hybrid systems are feasible, with promise of unparalleled efficiency, but stack and gas turbine development, system capacity scale-up, and validation must occur before commercialization. A scaled-up 330 kW size hybrid system (PH300) (Fig. 8) is presently undergoing factory test in Pittsburgh, PA, before its eventual shipment to a German utility, RWE, in Essen, Germany. This system is expected to achieve an electrical efficiency of 58%. Further demonstrations of hybrid systems in coming years are planned at utilities in U.S., Germany, and Italy.

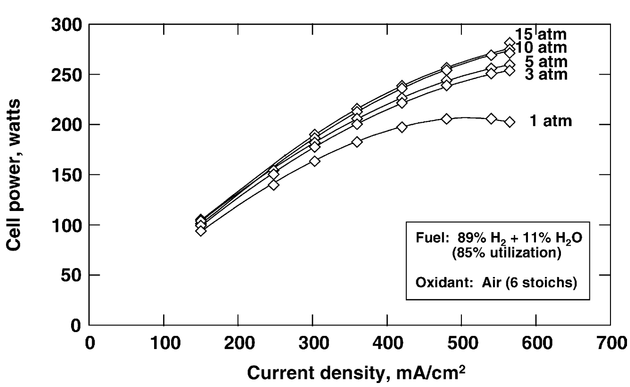

Fig. 6. Effect of pressure on the power of a tubular SOFC [3].

Fig. 7. Siemens Westinghouse's 200 kW pressurized SOFC/gas turbine hybrid system.

Siemens Westinghouse's efforts are now focused on reducing the cost of SOFC power systems. A manufacturing facility with a production capacity of 15 MW per year has been built for start-up in late 2004; this facility will provide information on the rate of reduction in the cost of SOFC power systems as production volume increases.

Siemens Westinghouse Power Corporation's Department of Energy (DOE) program is scheduled to wind down in FY2004. It is in a sense the precursor program to the SECA program. It was through the tubular SOFC program that many of the attributes of solid oxide fuel cells have been first demonstrated.

2.2. Solid State Energy Conversion Alliance (SECA) SOFC Programs

The SECA program is the main thrust of the Department of Energy—Fossil Energy's distributed generation fuel cell program. SECA SOFC program supports Climate Change, FutureGen, Clear Skies, and Homeland Security initiatives. SECA is also recognized as part of the overall U.S. Hydrogen

Fig. 8. Siemens Westinghouse 330 kW pressurized SOFC/turbine hybrid system for RWE, Germany.

program. Achieving SECA goals should result in the wide deployment of SOFC technology in high-volume markets. This means that benefits to the nation are large but the cost must be low. This is the SECA goal—less expensive materials, simple stack and system design, and high-volume markets. These criteria must be met to compete in today's energy market. Near-zero emissions, fuel flexibility, high efficiency, and simple CO_2 capture will provide a national payoff that gets bigger as these markets get larger.

The SECA program is dedicated to developing innovative, effective, low-cost ways to commercialize solid oxide fuel cells [8]. The program is designed to move fuel cells out of limited niche markets into widespread market applications by making them available at a cost of $400 per kW or less by 2010 through the mass customization of common SOFC modules. SECA fuel cells will operate on today's conventional fuels such as natural gas, gasoline and diesel, as well as the fuels of tomorrow—coal gas and hydrogen. The program will provide a bridge to the hydrogen economy beginning with the introduction of SECA fuel cells for stationary (for both central station and distributed power generation applications) and transportation's auxiliary power applications.

The SECA program is currently structured to include competing industry teams supported by a cross-cutting core technology program. SECA has six industry teams working on designs that can be mass-produced at costs that are almost 10-fold less than current costs. The SECA core technology program is made up of researchers from industrial suppliers and manufacturers as well as from universities and national laboratories, all working towards addressing key science and technology gaps to provide breakthrough solutions to critical issues facing solid oxide fuel cells.

The SECA industry teams collectively are making very good progress. Delphi, in partnership with Battelle, is developing a compact, gasoline-fueled, 5 kW unit utilizing planar anode-supported SOFCs operating at 700–800 °C for distributed generation and auxiliary power unit (APU) markets. Their first prototype APU, shown in Fig. 9, was installed in the trunk of a luxury automobile and tested successfully [9,10]. Delphi is expert at system integration and high-volume manufacturing and cost reduction. They are focused on making a very compact and light-weight system suitable for auxiliary power generation in transportation applications.

General Electric (GE) is initially developing a natural gas-fueled 5 kW system, also utilizing planar, anode-supported SOFCs, for residential power markets. GE is evaluating several stack designs and is especially interested in extending planar SOFCs to large hybrid systems. Presently, they are working on a radial design that can simplify packaging by minimizing the need for seals. GE has made good progress in achieving high fuel utilization with improved anode performance using standard materials.

Cummins and SOFCo team is developing a 10 kW product initially for recreational vehicles (RVs) that would run on propane using a catalytic partial oxidation (CPOX) reformer. The team has produced a conceptual design for a multilayer SOFC stack assembled from low-cost "building blocks." A thin electrolyte layer (50–75 μm) is fabricated by tape casting. Anode ink is screen-printed onto the one side of the electrolyte tape, and cathode ink onto the other. The printed cell is sandwiched between layers of a dense ceramic that accommodates reactant gas flow and electrical conduction. The assembly is then co-fired to form a single repeat unit.

Siemens Westinghouse, in addition to its ongoing tubular SOFC program for larger systems, is developing smaller, 5–10 kW size products in the SECA program to satisfy multiple markets. They have developed a new flattened, ribbed cell design for these smaller units that retains all

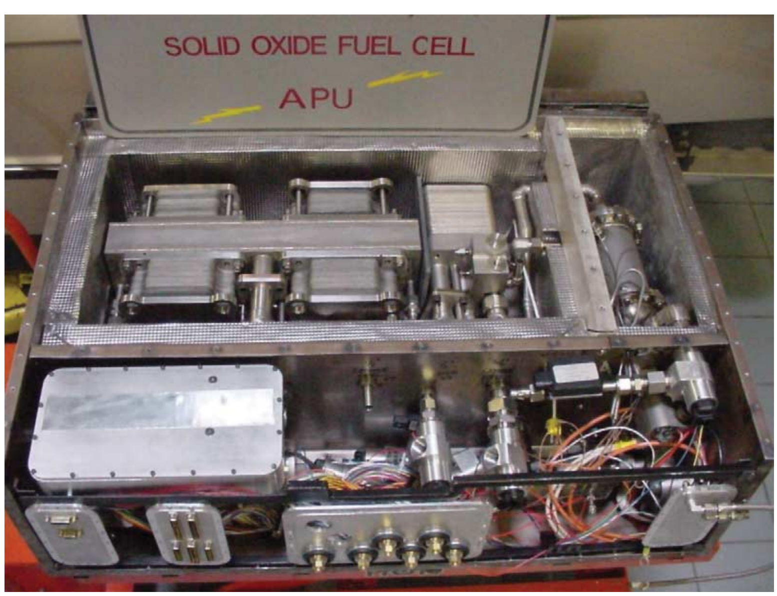

Fig. 9. Delphi/Battelle 5 kW auxiliary power unit [9,10].

the advantages of the cylindrical, cells such as not requiring seals, yet provides higher power density. These cells also make possible more efficient manufacturing, bundle assembly, and provide higher volumetric power density. These cells will be initially incorporated in 5 kW size systems being developed by Fuel Cell Technologies of Canada for residential and other distributed power applications.

Two additional industry teams, one led by FuelCell Energy and the other by Acumentrics, recently initiated work under the SECA program. FuelCell Energy will utilize lower-temperature planar anode-supported cells for distributed power systems, whereas Acumentrics plans to use microtubular cells for fast-starting small systems. Overall, the six industry teams are pursuing several design alternatives that enhance the prospects of success of SECA fuel cells for a broader market.

Fig. 11. FuelCell Energy's DFC/Turbine hybrid system.

3. Molten carbonate fuel cells (MCFCs)

Department of Energy—Office of Fossil Energy has been funding molten carbonate-based Direct FuelCell® (DFC®) development at FuelCell Energy, Inc. for stationary power plant applications. FCE, Danbury, CT, is a world-recognized leader for the development and commercialization of high efficiency fuel cells that can generate clean electricity at power stations or in distributed locations near the customer, including hospitals, schools, universities, hotels and other commercial and industrial applications. FCE has designed and is beginning to commercialize three different fuel cell power plant models (DFC300, DFC1500, and DFC3000). Rated output and footprint of these plants are provided in Fig. 10.

These power plants offer significant advantages compared to existing power generation technology—higher fuel efficiency, significantly lower emissions, quieter operation, flexible siting and permitting requirements, and scalability. Also, the exhaust heat can be used for cogeneration applications such as high-pressure steam, district heating, and air conditioning. Because hydrogen is generated directly within the fuel cell module from readily available fuels such as natural gas and waste water treatment gas, DFC power plants are ready today and do not require the creation of a hydrogen infrastructure.

FCE's products are based on its patented Direct FuelCell technology [11,12]. Several DFC sub-megawatt power plants are currently operating in Europe, Japan, and the U.S. Accomplishments to date include over 17 million kWh generated with 12 million kWh at customer sites. FCE has also developed manufacturing and testing capabilities to produce 50 MW per year. Additional DFC power plants are scheduled for delivery in Europe, Japan, and the U.S. over the next 12 months, including its first DFC1500 and DFC3000 units. In parallel, FCE is also developing technology for coal gas, logistic fuels, and other fossil and renewable fuels such as coal mine methane gas and anaerobic digester gas from municipal and industrial wastewater treatment facilities.

FuelCell Energy is also developing a ultra-high efficiency hybrid system, the patented Direct FuelCell/Turbine® (DFC/T®), a power plant designed to use the heat generated by the fuel cell to drive a unfired gas turbine for additional electricity [13]. During 2002, FCE completed successful proof-of-concept testing of a DFC/T power plant (Fig. 11) based on a 250 kW DFC integrated with a 30 kW modified microturbine. This proof-of-concept demonstration has provided information for the continued design of a 40 MW

Fig. 10. FuelCell Energy's DFC power plants for stationary application.

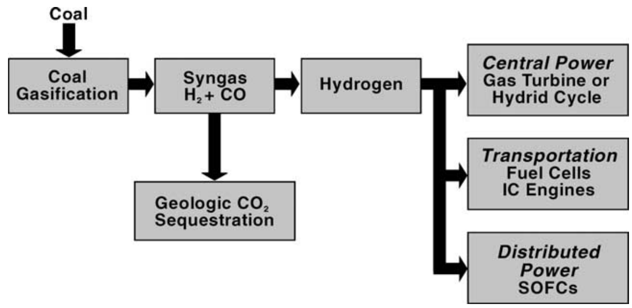

Fig. 12. Schematic illustration of the FutureGen concept.

DFC/T power plant that is expected to approach 75% efficiency, as well as to serve as a platform for high efficiency DFC/T systems in smaller sizes. FCE is currently continuing its proof-of-concept testing of the DFC/T power plant with a 60 kW microturbine.

4. FutureGen

FutureGen is a major new Presidential initiative to produce electricity and hydrogen from coal. It is a $1 billion government/industry partnership to design, build and operate a nearly emission-free, coal-fired electricity and hydrogen production plant. The 275 MW prototype plant will serve as a large-scale engineering laboratory for testing new clean power generation, carbon capture, and coal-to-hydrogen technologies, and will establish the technical and economic feasibility of producing hydrogen and electricity from coal, the lowest cost and most abundant domestic energy resource. It will be the cleanest fossil fuel-fired power plant in the world. Virtually every aspect of the prototype plant will employ cutting-edge technology. As shown schematically in Fig. 12, rather than using traditional coal combustion technology, the plant will be based on coal gasification which produces synthesis gas consisting of hydrogen and carbon monoxide. Advanced technology will be used to react the synthesis gas with steam to produce hydrogen and a concentrated stream of CO_2. Initially, the hydrogen will be used as a clean fuel for electricity production either in turbines, fuel cells, or fuel cell/turbine hybrids. The hydrogen could also be supplied as a feedstock for refineries. Later on, the plant could be a source of transportation-grade hydrogen fuel.

The captured CO_2 will be separated from the hydrogen, perhaps by novel membranes currently under development. It would then be permanently sequestered in a geologic formation.

The project will require 10 years to complete and will be led by an industrial consortium representing the coal and power industries.

5. Summary

U.S. Department of Energy—Office of Fossil Energy is funding several major programs for clean and efficient power generation; these include high temperature solid oxide and molten carbonate fuel cells and the combinations of these with gas turbines in highly efficient hybrids. Significant progress has been made in these programs and 250 kW to few MW size systems are nearing commercialization. The biggest hurdle to large-scale commercialization is their rather high cost and the manufacturers are now concentrating on reducing the cost of fuel cell-based power systems. The SECA program is expected to provide SOFC systems that cost about $400 per kW by 2010. Beyond 2010, SECA solid oxide fuel cells are expected to be incorporated in the FutureGen type plants to produce electricity and hydrogen in a virtually emission-free plant.

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