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Short communication

Distributed generation—Molten carbonate fuel cells

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Abstract

High efficiency and ultra-clean molten carbonate fuel cell (MCFC) technology development by FuelCell Energy, with support from the U.S. Department of Energy (DOE), has progressed to commercial power plants for stationary applications such as distributed generation. Lessons learned from this development will also be valuable to DOE for the ongoing Solid State Energy Conversion Alliance (SECA) solid oxide fuel cell (SOFC) development and cost reduction, for fuel cell turbine hybrids, and for hydrogen economy development with FutureGen.

Keywords: Molten carbonate fuel cell (MCFC); Distributed generation; Solid State Energy Conversion Alliance (SECA); Solid oxide fuel cell (SOFC); Fuel cell turbine hybrids

1. Introduction

A high efficiency and ultra-clean MCFC commercialization is based on FuelCell Energy's (FCE) Direct FuelCell® (DFC) technology that has matured from a laboratory experiment 30 years ago to commercial power plants for stationary applications. The DFC technology was developed from the beginning to end in a private–public sector partnership with the company and the DOE. DOE-sponsored development activities started with proof-of-concept 0.0003 m^2 single cell testing and culminated in the design and verification of commercial design power plants using 0.9 m^2 cells (see Fig. 1). In this collaboration, the high performance components and stack technology were developed in the 1980s, and the scale-up and proof-of-concept pilot systems were tested in the 1990s. Based on these early successes, the company was able to raise equity in the public markets in the early part of the current decade to fund market development and product field tests. FCE has raised over $ 400 million from the market to support the R&D and commercialization efforts.

The DOEs National Energy Technology Laboratory (NETL) has provided technical guidance all through the development phase and has conducted due diligence exercises annually as the products approached commercialization stage. From its humble production of 1 W of power nearly 30 years ago to its generation of nearly 2 million watts or 2 MW today, the DFC technology is shaping the production of ultra-clean electricity at a fraction of its former cost. In fact, the recently completed 10-year agreement between NETL and FCE slashed fuel cell costs to less than one-third of what they were a decade ago [1].

The successful partnership between DOE and FCE in developing DFC products goes a long way toward the expected hydrogen economy of the future. By using hydrogen as a basis for electric production, virtually no pollutants are emitted into the atmosphere, thereby reducing greenhouse gases and meeting the goals of the President's Clear Skies and Global Climate Change initiatives [2]. The lessons learned from this project will also be valuable for DOEs ongoing Solid State Energy Conversion Alliance (SECA) for solid oxide fuel cell (SOFC) development and cost reduction.

DOE investment and market competition have produced a remarkable technology and manufacturing capability. The market down selected among MCFC developers to choose FCE. FCE success will help introduce all other fuel cells. The MCFC has outstanding efficiency attributes needed today more than ever. FCE is delivering commercial products now with advanced DFC technology, has established strong commercial relationships with major distributors in the U.S., Germany, Japan and Korea, and is the number one high temperature stationary fuel cell manufacturer and developer including carbonate and solid oxide applications. FCE has been a leading fuel cell technology developer for over 30 years and has a strong balance sheet with more than $ 210 million at April 30, 2005.

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Fig. 1. Full-size stack completed at the FCE manufacturing facility: ~350–400 cell stack.

1.1. Distributed generation and manufacturing development

Distributed generation (DG) is power production at or near the customer site. Rastler [3] has reported that at the end of 2003, there was an estimated 234 GW of installed DG in the U.S., with DG defined as generation less than 60 MW in size. However, almost all of it was not interconnected with the electrical transmission and distribution (T&D) system. DG capacity that functions as part of the grid (grid-connected) was estimated at 30 GW, which accounts for only 3% of the U.S. electric grid capability of 953 GW. Among distributed generation (DG) technology types, reciprocating engines dominate the current capacity landscape at 86%, and combustion turbines are a distant second at 7%. As regards application, emergency/standby applications lead the field with 81%, while combined heat and power (CHP) is a distant second at 9%.

Fuel cell commercialization and cost reduction by FCE and the SECA program should significantly alter these percentages. Moreover, escalating fossil fuel prices are putting an unprecedented premium on system efficiency, which favors high-temperature fuel cells. Poor grid reliability is also inhibiting growth in all economic sectors, including information technology, and the base load profiles of these industrial sectors favor high temperature fuel cells.

There needs to be a commensurate growth in manufacturing capacity with incentives to support manufacturing development through production and employment retention grants, other loans and grants, rebates and price incentives, net metering, and tax incentives, including tax-exempt financing and property tax exemptions. A Department of Commerce SECA Manufacturing Summit planned for the end of 2005.

Some states have clearly taken an aggressive and competitive initiative to be the manufacturing and employment base for fuel cell technology. For example, Ohio leads the way with its fuel cell grant and loan programs and its renewable energy program. The Ohio Fuel Cell Grant Program is a $ 103 million, 3-year initiative to invest in research, project demonstration and job creation. This includes $ 75 million in financing to make strategic capital investments that will create and retain jobs, $ 25 million for fuel cell research, development and demonstration, and $ 3 million for worker training. The Ohio Fuel Cell Loan Program provides $ 15 million to finance traditional economic development investments for expansion of Ohio's fuel cell industry through low-interest loans and guarantees, with a maximum loan per company of $ 5 million. Additionally, the Ohio Department of Development has set aside $ 60 million for tax-exempt financing of qualified projects. And under Ohio's Renewable Energy Program, 11 banks provide reduced interest rates, by approximately half, on loans for those qualifying Ohio residents and businesses for energy efficient technologies, renewable energy and fuel cells.

If you wanted to estimate the dollar amount of state incentives authorized or appropriated for fuel cell incentives, it would have to exceed $ 150 million per year. Much of this goes underutilized, and we are unaware of any state fuel cell incentive program that has met its cap. A complete listing of all state and federal incentives for fuel cell technologies can be found at http://www.dsireusa.org.

2. FCE products

FCE is developing high temperature, high efficiency MCFC power plants for base load commercial and industrial applications capable of high value waste heat by-product for cogeneration [1]. FCE has completed certifications for product safety, interconnection, performance and installation. FCEs power plants are state certified to meet California Air Resources Board's (CARB) stringent new distributed generation emissions standards for 2007. By meeting these standards, the company's power plants are categorized as an 'ultra-clean' technology, exempting them from air pollution control or air quality district permitting requirements by CARB.

FCEs DFC power plant provides greater electrical fuel efficiency (45–48%) than low temperature fuel cell systems (30–40%) such as proton exchange membrane and phosphoric acid. This is because the DFC power plant creates the hydrogen it needs directly from readily available hydrocarbon fuels, such as natural gas and wastewater treatment gas, within the fuel cell module. Pure hydrogen from external processing equipment is not needed. In addition, FCEs DFC products provide a useable waste heat by-product and depending on the application, location and load size, can achieve an overall thermal energy efficiency of up to 70–80%.

The DFC development and commercialization effort has culminated in product offerings with warranties, performance guarantees and extended service agreements. FCE is currently offering three products for commercial and industrial customers: DFC300A and DFC300MA—nominal rating of 250 kW, DFC1500—nominal rating of 1000 kW, and DFC3000—nominal rating of 2000 kW (see Fig. 2).

DFC® 300A **DFC® 1500** **DFC® 3000**

Fig. 2. Three DFC products currently offered for stationary applications.

2.1. *FCE field test program*

FCE commenced a Field-Follow program in 2003 with its 250 kW DFC300A power plant. To date, over 40 units have been installed at customer locations throughout the world in the following vertical market segments that offer the opportunities for repeatable business: breweries, industrial and municipal waste water treatment facilities, hotels, universities, manufacturing, mission critical/data communication centers, government, grid support, hospitals/clinics and prisons. A 1 MW power plant has been operation at King County Waste Water Treatment Facility. A view of the plant is shown in Fig. 3. Cumulative output at customer sites has doubled from 35 million kWh in the second quarter of 2004 to 70 million kWh in the second quarter of 2005.

The data generated in the Field-Follow program are analysed to identify areas/subsystem affecting availability. Through April 2005, resolving these issues has increased the availability of FCEs fleet to 89%. Additionally, conditioning and test times have been reduced by 25% and the start-up cycle time of the DFC power plants at customer sites has been reduced by over 80%. FCE expects continued improvement of its fleet's availability and product performance as additional operating hours at customer sites are achieved.

In parallel with Field-Follow program, the company launched a value-engineering cost-out program in mid-2003 with annual cost reduction targets of 20–25% at nominal volume. This is focused on all areas contributing to cost, including initial capital cost of the product as well as testing, conditioning and installation, operation and maintenance expenses. In parallel, performance improvement is sought to increase power output, availability and stack life. For its sub-MW product, costs have declined from approximately $ 8000/kW at January 1, 2004 to $ 6000/kW at January 1, 2005. Furthermore, the company expects the cost of its sub-MW product to decline to $ 4800/kW by January 1, 2006.

Fig. 3. King County DFC1500 fuel cell power plant: the plant operates on digester gas and on natural gas when digester gas is not available.

3. Current DOE fuel cell program directions

Funding for fuel cells in the U.S. DOE Fossil Energy (FE) DG program is at its highest level ever in fiscal 2005, including a $ 54.2 million budget for SECA, $ 12.2 million for advanced research at the High Temperature Electrochemistry Center (HiTEC) at PNNL, and $ 5 million for hybrid coal-based central systems.

The mission of the DG program is to ensure the widespread deployment of clean distributed generation fuel cells, hybrids and novel generation technologies. In the fuel cell area specifically, the mission is to reduce costs and improve reliability so that fuel cells can be widely deployed in stationary applications from DG to central stations. The program goals are to achieve a 10-fold cost reduction to $ 400/kW with 40–60% efficiency by 2010, to undergo advanced technology slipstream testing at the FutureGen Site by 2012–2015, and to develop a hybrid fuel cell applicable to 60% efficient coal-based power systems by 2020.

3.1. *SECA*

NETLs SECA program is playing a crucial role in reaching these objectives [4–6]. SECA is an alliance of industry groups who individually plan to commercialize SOFC systems for predefined markets; research and development institutions involved in solid-state development activities; and government organizations that provide funding and management for the program. The SECA alliance was formed in 1999 to accelerate the commercial readiness of SOFCs in the 3–10 kW range for use in stationary, transportation and military applications. Recently, a number of advances achieved through SECA have helped push SOFCs closer to commercialization.

Within SECA, several industry teams are working toward developing SOFC system prototypes with a net power output of 3–10 kW. Each industry team is expected to: (1) propose a SOFC design for a target market; (2) coordinate the process of refining the design elements that will contribute to a high-power-density SOFC that can be mass-produced, with end-users and manufacturers; (3) communicate their R&D gaps with SECAs Core Technology Program—a group composed of universities, national labs and other research institutions.

The industry teams are independent and therefore compete with each other; however, all are committed to the concept of mass customization as the pathway to reducing the cost of fuel cell systems. The teams are targeting a wide variety of markets, including DG, to attain high volumes. As the industry teams develop and refine their SOFC designs, any R&D gaps are identified and given to the Core Technology Program participants to research. This allows the industry teams to continue their SOFC development process, while the Core Technology Program participants are developing and researching much-needed breakthrough technologies.

Each industry team project is structured in three phases over 10 years and follows the minimum requirements established by SECA. At the end of each phase, the prototype is tested according to these minimum requirements. All of the SECA industry teams are making excellent progress in Phase I using their proprietary and patent positions towards developing alternatives.

FCE brings its long history of fuel cell development to a teaming relationship with Versa Power Systems (VPS) as one of the SECA industry teams. VPS progress has been significantly accelerated with the incorporation of FCEs global thermoelectric technology and manufacturing capability of 5 MW per year and over 25,000 h of testing experience on their RP-2, 2 kW units. FCE acquired an equity position in VPS in November 2004 and transferred Global's SOFC development team and assets to the company, a joint venture of the Gas Technology Institute, Electric Power Research Institute, Materials and Systems Research Inc., the University of Utah, and now FCE.

The Core Technology Program is providing the collaborative system design improvements and technology transfer that will help to meet the Phase I cost and performance targets outlined in the industry teams' solicitations. CTP transferred technology is helping to solve problems with seals, interconnects, electrodes, fuel processing and other issues.

3.2. *Fuel cell turbine (FCT) hybrids*

NETL and FCE are working collaboratively to do large-scale expedient testing of an atmospheric Direct FuelCell/Turbine (DFC/T) hybrid system. To date, the R&D efforts have resulted in significant progress in validating the DFC/T cycle concept. FCE has completed successful proof-of-concept testing of a DFC/T power plant based on a 250 kW DFC integrated initially with a Capstone 30 kW and then a 60 kW modified microturbine as shown in Fig. 4. The results of the sub-MW system tests have accumulated over 6800 h of successful operation with an efficiency of 52%.

The Hybrid Power Generation Systems Division of GE is collaborating with NETL to develop SOFC/gas turbine hybrid systems as intermediate products for DG power applications. The objectives for this project are to analyze and evaluate planar SOFC/gas turbine system concepts. Technical barriers in pressurization and scale-up of preliminary design concepts will be resolved for both the feasibility demonstration system and the conceptual system. A preliminary design for high-temperature heat exchangers for hybrid system applications has been developed, and pressurized operation of planar SOFC stacks has been demonstrated. The SOFC is based on the SECA thin-film electrolyte technology fabricated with the tape calendaring method and thin-foil metallic interconnects leading to a low-cost, high-performance, compact planar SOFC. The gas turbine is based on commercial products. The proposed hybrid system has a potential for efficiency greater than 65%.

Fig. 4. Direct FuelCell/turbine hybrid system.

Researchers in the Combustion and Engine Dynamics Division within the Office of Science and Technology at NETL have completed shakedown of an experimental facility capable of physically simulating the dynamic operation of a FCT hybrid system [7]. The objective of the Hybrid Performance (Hyper) project at NETL is to conceptualize, simulate, analyze and demonstrate critical operability issues inherent in hybrid fuel cell systems. The hardware-in-the-loop simulation facility enables researchers to identify dynamic issues related to the interdependencies of fuel cell and turbine technology integration without risk to expensive fuel cell stacks [8].

3.3. *FutureGen*

FutureGen [9], the Integrated Hydrogen, Electric Power Production and Carbon Sequestration Research Initiative, is a partnership to design, build and operate a nearly emission-free, coal-fired electric and hydrogen production plant. No coal-to-gas plant in the world today is configured to optimize hydrogen production or to capture carbon. The FutureGen prototype plant would be the world's first. The 275 MW prototype plant will serve as a large scale engineering laboratory for testing new clean power, carbon capture, and coal-to-hydrogen technologies. It will pioneer advanced hydrogen production from coal, as well as capture and permanently sequester carbon dioxide.

The future production of hydrogen from fossil fuels requires advances in membranes and fuel cells. Wachsman and Williams [10] discuss the importance and potential of ion conducting ceramics in SOFCs and ceramic membranes to hydrogen production, and their ultimate integration in a coal-based FutureGen plant. SOFCs, oxygen and hydrogen separation membranes

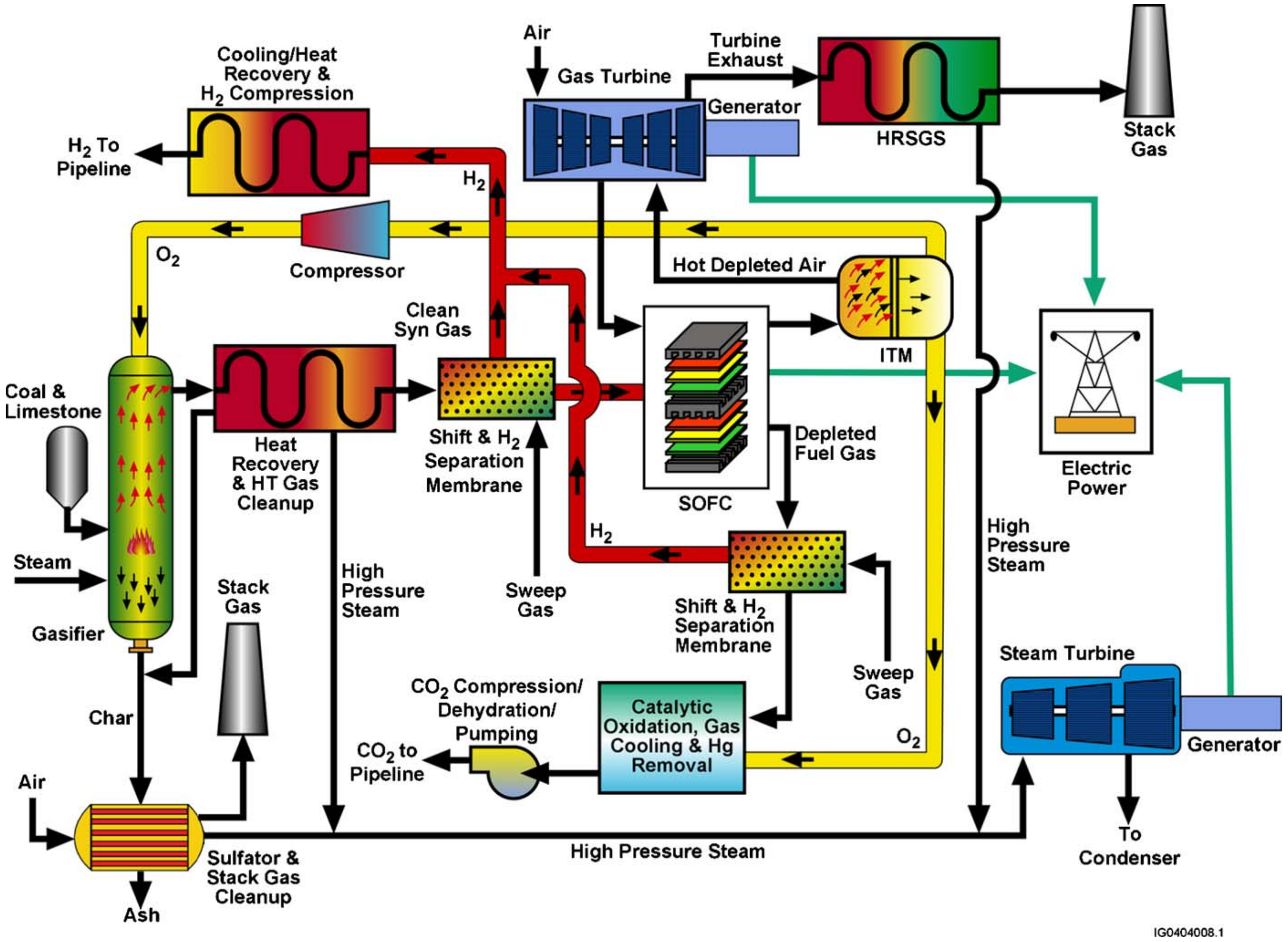

Fig. 5. FutureGen simplified process flow diagram.

are based on high temperature ion conducting ceramics. These ceramics are metal oxides with typically a perovskite or fluorite structure.

The FCT hybrid is a key part of the FutureGen plant to produce hydrogen from coal. The highly efficient SOFC hybrid plant, with its SECA fuel cells, will produce low-cost electric power and other parts of the plant could produce hydrogen and sequester CO_2. The hydrogen produced can be used in fuel cell cars and for SOFC DG applications (Fig. 5).

4. Conclusion

The DFC power plants are suitable for highly efficient electricity or CHP for stationary applications. Over 40 units ranging in 250 kW–1 MW size have been in field operation worldwide. These units have shown 45–48% LHV electrical conversion efficiencies and overall thermal efficiency approaching 80% in CHP applications. The plant emissions are ultra-clean. These attributes and the various incentives available for high efficiency, ultra clean power generation technologies are helping market entry of the product in stationary applications. As the technology matures and the cost is lowered through cost-out efforts, the product is expected to capture broader commercial acceptance, paving the way for larger multi-megawatt systems and for other fuel cell products.

References

[1] M. Farooque, S. Katikaneni, H. Maru, in: R. Selman (Ed.), Proceedings of the Fifth International Symposium of the Electrochemical Society, vol. 99, no. 20, 1999, pp. 47–55.
[2] National Energy Technology Laboratory TechNews, July 19, 2005.
[3] D. Rastler, EPRI Report 1008415, Palo Alto, CA, 2004.
[4] M.C. Williams, S. Singhal, Proceedings of the 15th World Hydrogen Conference, Yokohama, Japan, 2004 (pending).
[5] M. Williams, J. Strakey, W. Surdoval, in: S. Singhal (Ed.), Proceedings of the Ninth International Symposium on Solid Oxide Fuel Cells (SOFC-IX), Electrochemical Society, 2005, pp. 1–10.
[6] M.C. Williams, J. Strakey, W. Surdoval, J. Power Sources 143 (2005) 191–196.
[7] M.C. Williams, Proceedings of the Colloquium on Environmentally Preferred Advanced Power Systems (ICEPAG), 2005 (pending).
[8] M.C. Williams, R. Gemmen, D. Tucker, Turbomach. Int. 3 (2004) 2–3.
[9] Report to Congress, FutureGen Integrated Hydrogen, Electric Power Production and Carbon Sequestration Research Initiative, U.S. DOE, Office of Fossil Energy, March, 2004.
[10] E.D. Wachsman, M.C. Williams, Interface 13 (2004) 27–32.