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Short communication

Large stationary fuel cell systems: Status and dynamic requirements

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Abstract

Molten carbonate fuel cell demonstrations to-date, have been able to show the highest fuel-to-electricity conversion efficiencies (>50%) of any stand-alone fuel cell type.

The primary developer of this type of fuel cell in United States is Fuel Cell Energy Corporation (FCE), the developer and manufacturer of the Direct FuelCell™ concept. FCE and MTU CFC Solutions in Germany, a licensee of FCE have demonstrated carbonate fuel cells from 10 kW to 2 MW of electrical output on a variety of fuels. IHI in Japan are also developing carbonate fuel cells for stationary power and have recently successfully demonstrated the technology in Kawagoe, Japan. In Italy, Ansaldo fuel cell have demonstrated a 100 kW carbonate fuel cell in Milan. In Korea, the Ministry of Commerce, Industry and Energy has committed to install 300 fuel cell units, sized 250 kW to 1 MW, for distributed power generation by 2012.

Carbonate fuel cell technology is more fuel flexible than lower temperature fuel cell technologies and is well suited for on-site stationary CHP applications as well as to marine, military, and traction applications.

The present paper gives an overview about the commercialisation efforts for the molten carbonate fuel cell technology.

Keywords: Molten carbonate fuel cells; Commercialisation; Field tests

1. Introduction

Increasing demand for reliable power worldwide, supplemented by air pollution concerns caused by older, combustion power generation, and unreliable electrical grid delivery systems present significant market opportunities for distributed generation products. Fuel cell power plants electrochemically produce electricity directly from readily available hydrocarbon fuels, such as natural gas and waste-water treatment gas. Especially high temperature fuel cells offer significant advantages compared to other power generation technologies, including:

- High fuel efficiency;
- Ultra-clean emissions;
- Improved reliability;
- Quiet operation;
- Flexible siting and permitting requirements;
- Scalability;
- Ability to provide electricity and heat for cogeneration applications, such as district heating, process steam, hot water and absorption chilling for air conditioning;
- Potentially lower operating, maintenance and generation costs than alternative distributed power generation technologies;
- Since fuel cell power plants produce hydrogen from readily available fuels such as natural gas and waste-water treatment gas, they can be used to cost-effectively co-generate hydrogen as well as electricity and heat.

The carbonate fuel cell, often referred to as the molten carbonate fuel cell (MCFC), is one of the fuel cell technologies that has proven efficiency and environmental performance. In addition, significant reductions in carbonate fuel cell capital cost are expected in the next few years. In particular, the use of carbonate fuel cells in the distributed power market could offer an ideal solution to increased energy demands with concurrent expectations for reliability and environmental sensitivity. The carbonate fuel cell concept involves conduction of carbonate ions ($CO_3^{=}$) within an immobilized mixture of molten carbonate salts. Other cell components are based on nickel and stainless steels, which contribute to initial capital cost, but, are significantly less expensive than the precious metal catalysts used in lower temperature fuel cells.

Since the charge carrier is an oxidant, several fuel species can be oxidized within the anode compartment leading to inherently greater fuel flexibility. To-date, carbonate fuel cells have been

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operated on hydrogen, carbon monoxide, natural gas, propane, landfill gas, marine diesel, and simulated coal gasification products.

The typical operating temperature of a carbonate fuel cell is around 650 °C. This temperature is almost ideal from the system perspective, since it allows higher Nernst potential compared to SOFC operating at around 800–1000 °C (ideal Nernst potential increases with decreasing temperature) while still providing high temperature thermal energy sufficient to sustain and support reformation chemistry. Thus, carbonate fuel cell system designs typically contain an internal reformer.

The high temperature thermal effluent of a carbonate fuel cell allows significant cogeneration and/or integration with a heat engine cycle, typically called a “hybrid”. Several carbonate fuel cell hybrid systems with fuel-to-electricity efficiencies greater than 70% have been conceptualized with some under development today. The system currently in development by Fuel Cell Energy and Capstone Turbine in Danbury, Connecticut is the prime example.

The high efficiency, low emissions, and fuel flexibility features of carbonate fuel cells together with recent demonstrations of robust and reliable operation, and the potential for dramatic cost reductions make carbonate fuel cells a key emerging technology for meeting future energy demands.

2. MCFC development and commercialization in Asia

Two countries in Asia are involved in the development and commercialisation of molten carbonate fuel cells, namely Japan and Korea.

Development of MCFC in Japan was started as a “Moonlight Programme” by the Agency of Industrial Science and Technology of the former Ministry of International Trade and Industry (MITI) in 1981. It was then taken over by a “New Sunshine Programme” of MITI and a Phase III Program started as a 5-year program in 2000.

As a highlight of the “New Sunshine Programme” two companies, Hitachi and Ishikawajima-Harima Heavy Industry (IHI), were strongly involved in developing and building a 1000 kW MCFC power plant. The plant was erected in Kawagoe and each company supplied 500 kW stack capacity. IHI was additionally in charge of the overall design and the control system of the plant. The test was executed successfully in 1999/2000 over 5000 h, the first time that a MCFC MW-System was operated under pressurized conditions.

Based on the experience gained with the MCFC test plant operation, development of MCFC systems has entered a new stage to supply the emerging market for MCFC plants in the Phase III Program. The NEDO target is now the development of a “Pressurized Compact Power Generation System”. In a first step, a 300 kW class pressurized generation system was developed (Fig. 1). The characteristic of the system are the combination of a MCFC with a gas turbine to form a hybrid system, external reforming and pressurized operation. To commercialize the system it was planned to introduce it first in several hundred kW and several MW distributed cogeneration systems.

Fig. 1. A 300 kW compact system in Kawagoe.

A further plan foresees the development of a 7 MW power plant for large-scale cogeneration systems. This plant will be equipped with 8 modules with two 250-cell stacks each and a reformer in a pressure vessel and a gas turbine operated at 1.1 MPa. The designed gross output is 7.1 MW that will be generated by the stack and the gas turbine with 5.8 and 1.3 MW, respectively. The designed net output is 6.8 MW and net efficiency is 57% (LHV). This system has an anode gas recycle with an adiabatic reformer to improve the reforming ratio caused by higher pressurized operation.

To design the higher pressurized system, it is need to have evidence that the system can be operated stably in pressurized condition at 1.1 MPa. The Phase III Program has a plan to estimate the stability and performance of the module in the pressurized condition.

In Korea, the Molten Carbonate Fuel Cell is regarded as a technology with high potential in future electric power generation market by its own outstanding characteristic [1]. Recognizing this high potential, the Korean Electric Power Research Institute (KEPRI) started the first phase MCFC system development program in 1993 and successfully completed this phase by developing a 2 kW stack by 1996. The second phase of the program aiming at a 100 kW system development has been carried out since 1997. As an interim target prior to the 100 kW system development, a 25 kW MCFC system was built and tested to verify scale-up technology (Fig. 2).

On the basis of the experience of 25 kW system operation, the design of a 100 kW system has been executed. Along with the system development, the fabrication process of cell components has been optimized, too. A 250 kW packaged prototype will be developed by 2008 if the 100 kW system test proofs to be successful. KEPRI has a plan of introducing a 250 kW-class MCFC plant as a distributed source to the market in 2010.

3. MCFC development and commercialization in USA

Fuel Cell Energy, Inc. Danbury, Conn., is a world-recognized leader for the development and commercialization of a high effi-

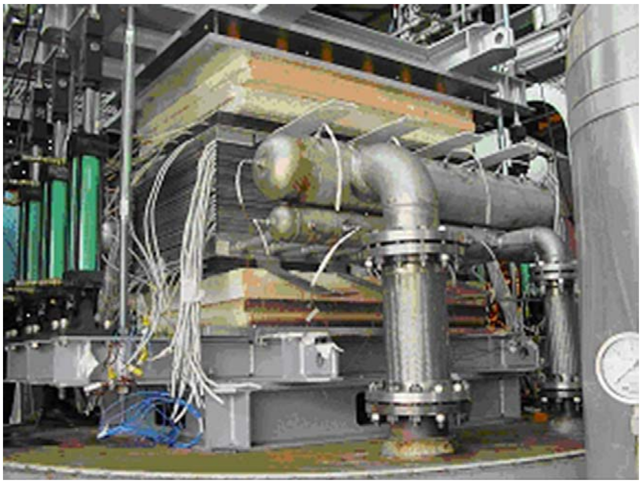

Fig. 2. A 25 kW stack in Korea.

ciency carbonate fuel cell for electric power generation. The FCE carbonate fuel cell, known as the Direct FuelCell®, is so named because of its ability to generate electricity directly from a hydrocarbon fuel, such as natural gas, by reforming the fuel inside the fuel cell to produce hydrogen (Fig. 3). This "one-step" process results in a simpler, more efficient and cost-effective energy conversion system compared with external reforming fuel cells. This internal reforming reduces capital cost and increases electrical efficiency. FCE is developing its patented Direct FuelCell® technology for stationary power plants that can generate clean electricity at power stations or in distributed locations near the customer, including hospitals, schools, universities and other commercial and industrial applications.

Fuel Cell Energy, Inc. entry commercial products will be rated at 250 kW, 1 and 2 MW in capacity (Fig. 4). The company expects commercial products to mature to three configurations [2]: 300 kW, 1.5 and 3 MW. The products output power and efficiency at different levels of maturity are described in Fig. 5. The FCE products are targeted for utility, commercial and industrial customers in the growing distributed generation market for applications up to 10 MW. All three products will offer the capability for co-generation where the heat by-product is suitable for

Fig. 3. DFC® unit in Tuscaloosa, Alabama.

Fig. 4. A 250 kW DFC/T® power plant in operation at FCE's headquarters, Danbury, CT.

high-pressure steam, district heating and air conditioning. FCE is also developing new products, based on company's existing power plant design, for applications in the 10–50 MW range.

The sub-megawatt class product is a skid-mounted, compact power plant that could be used to power a light industrial or commercial facility, 100 home subdivision or other similar sized applications. Additional units could subsequently be added to meet incremental demand growth. The company expects to begin delivering commercial sub-megawatt class product to the market in calendar year 2002.

Customers with larger power requirements will look to the megawatt-class power plants that combine several fuel cell stacks to provide increased power output. The megawatt class products are designed to meet the power requirements of customers such as industrial facilities, data centers, shopping centers, waste-water treatment plants, office buildings, hospitals and hotels. The company expects to bring megawatt class products to market also in calendar year 2002.

FCE is targeting initial commercialization efforts for the following stationary power applications:

- customers in regions where air pollution requirements are particularly strict;
- those seeking to address electric grid distribution or transmission shortages or congestion;
- industrial and commercial customers who can make use of high quality heat by-product for co-generation;
- customers with opportunity fuels such as waste-water treatment gas or other waste gases from municipal and industrial processes;
- utility and non-utility power producers who want to improve their knowledge of fuel cell technology;
- customers who possess several of the above characteristics.

	Field Trial	Market Entry	Mature Product
kW (Net AC)	250	250	300
Efficiency (LHV) %	47	49	54
kW (Net AC)	1000	1200	1500
Efficiency (LHV) %	49	51	56
kW (Net AC)	2000	2500	3000
Efficiency (LHV) %	50	52	57

Fig. 5. FCE Direct FuelCell® electric/cogen products.

FCE commercialization efforts after these initial applications will largely depend on how the distributed generation market develops as well as on company's ability to lower the cost of the products. FCE is focusing on energy service providers, specialty distributors and original equipment manufacturers (OEMs) as potential buyers and distributors of the products. Utilities are also potential customers, as they will need to add generating capacity to meet increasing demand.

FCE is also designing a 40 MW ultra-high efficiency power system that will combine its Direct FuelCell® and a gas turbine that will compete for applications between 10 and 50 MW in the distributed generation market [3].

In addition, because of the ability to operate on a variety of hydrocarbon fuels, FCE currently developing in conjunction with the U.S. Navy, a Direct FuelCell® power plant to provide power to ships using diesel fuel [4]. An additional, related market would be the cruise ship industry, which FCE believes has substantial "hotel" power needs. All the power required by a cruise ship, except for propulsion, could be provided by a diesel-powered Direct FuelCell® power plant. Many island communities that have limited natural gas or similar resources and rely on the use of diesel fuel for the generation of electricity could also use a diesel-powered fuel cell.

FCE plans on being the first to provide high quality, low-cost sub-megawatt and megawatt class fuel cell power plants to the distributed generation market. FCE plans to manufacture its proprietary fuel cell stack components and to purchase balance of plant equipment from suppliers as modularized packages that will either be delivered to the power plant site for assembly with company's fuel cell stack components or be assembled at company's manufacturing facility for delivery to the power plant site.

4. MCFC development and commercialization in Europe

In Europe two companies, namely Ansaldo fuel cell in Italy and MTU CFC Solutions in Germany, are working on the commercialization of the MCFC technology Ansaldo fuel cells S.p.A. (AFCo) is a company recently demerged from Ansaldo Ricerche S.r.l. from which it inherited all fuel cell related technologies, patents, rights and key personnel. AFCo mission is the industrial production and commercialisation of fuel cells and particularly Molten Carbonate fuel cells power plants in the middle size range (0.2–30 MW). To this aim, AFCo is finalising an experience coming from over 20 years of investments and development activity in the fuel cell field, which leaded to the successful construction and experimental operation, for over 7 months in 1998–1999, of a 100 kW_{el} co-generation plant including the whole realisation of the relevant MCFC stack [5]. The plant has been erected at an ENEL Ricerche's experimental site in Segrate, near Milan, and ran in parallel with ENEL main grid according to national Standards CEI 11/20. The main fallout of such experience has been the detailed definition of the "Series 500" as the AFCo's market entry unit, which uses an original, improved configuration closely matching the stacks (TWINSTACK®) and the reformer (Modular Integrated Reformer, MIR). A full-area stack based on the new design has been constructed and successfully tested in 1999 showing performance consistent with the main targets planned for the stacks to be used in the "Series 500".

AFCo regards MCFCs as being among the best primary continuous power sources in mid-sized stationary distributed generation systems (from several 100 kW to the multi-megawatt class). Applications include high quality/reliable on-site gen-

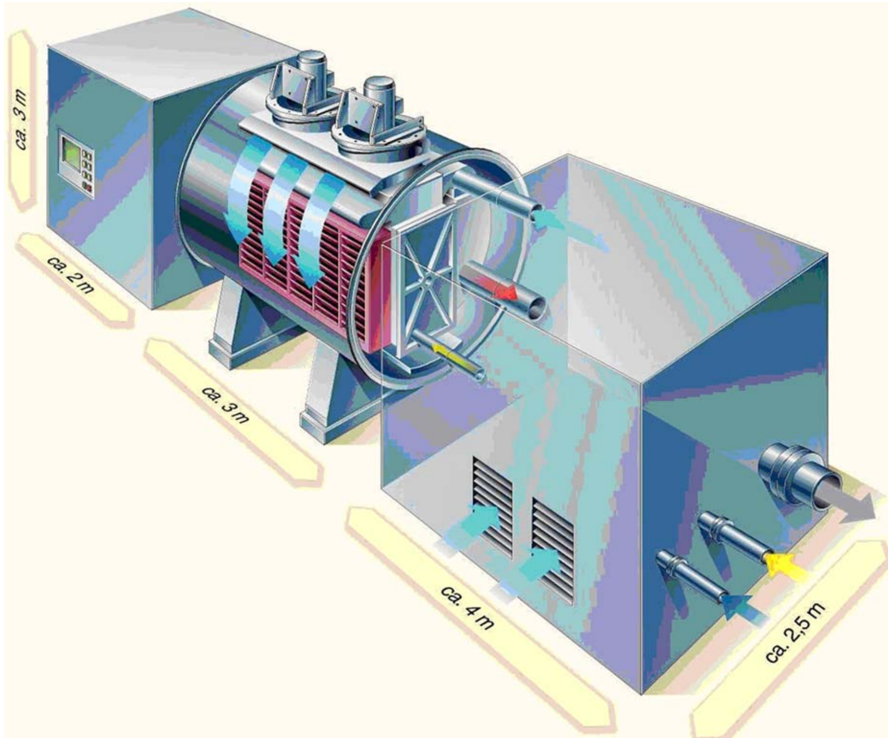

Fig. 6. Hot module system, developed by MTU CFC Solutions.

eration, clean and quiet power stations or a variety of marine applications. In fact, in addition to on-site and distributed co-generation with natural gas fed plants, which represent the reference sector for the market of MCFC systems, the multi-fuel capability of the "Series 500" allows its application to a wide field of market opportunities.

The possibility of using, without any modification to the AFCo's stack design, a variety of fuels with methane contents in the range from about 50% to zero, as coming from primary fuels like landfill-gas, diesel-oil, biomass gasification, bio-fuels, coal gasification, renewable sources, hydrogen, etc., through proper pre-treatment devices, will open in the short term several interesting market niches. Moreover, MCFCs could achieve significant penetration of the market for large ship engines due to their inherent efficiency advantage over the diesel engines.

By combining these main fields of application, a wider market opening is expected in the medium-long term.

In addition, a special market niche presently under evaluation for these plants with minor adjustments to AFCo's system configuration, is offered by their possible use as active separators of carbon dioxide from combustion exhaust streams.

AFCo's mission is the industrial production and commercialisation of Molten Carbonate fuel cells power plants in the mid-size range (0.2–30 MW). Focus will be initially concentrated on the "Series 500" unit, which has been designed as a market entry with power up to 500 kW. The company expects to invest significantly during the demonstration phase and plans additional investments for the scale up of the initial production capacity to meet initial commercial sales expected to begin by 2005.

Commercialisation plans also include industrial/commercial agreements with present and/or new partners/vendors to exploit all synergy opportunities both of technological and geographical nature.

The Hot Module system developed by MTU CFC Solutions in Germany (Fig. 6) is an innovative, compact solution for high temperature fuel cells. Patents have been filed in a number of countries [6]. The system combines the fuel cell itself and the hot peripheral equipment in a common, thermally isolated housing, which serves not only as a protective case and transport container but also provides for internal gas flow. Pipelines are largely avoided.

The Hot Module system has been tested in a number of pre-commercial Field Test Units at key applications in industrial and commercial co-generation. Altogether 12 field test units have been installed so far in hospitals, industrial enterprises and telecom installations. Those applications have been proven to be specifically suitable to demonstrate the benefits of high temperature fuel cells. In addition, Hot Modules have been tested in US in projects implemented in cooperation with FCE. Further units in Europe and in the US are planned, paving the way for the introduction of series produced power plants from 2006/2007 on.

The combination of the Fuel Cell Hot Module Cogeneration Plant with highly efficient absorption cooling devices or steam injection cooling systems opens an important perspective to create a system with a broad application range in the market of air conditioning and cooling. Due to the fact, that the COE (coefficient of power) for lithium bromide based absorption cooling systems can be increased up to 1.5–1.7 using higher temperatures for the separation process at the hot end of the absorption cooler, the overall efficiency of such kind of system is substantially higher in comparison with conventional air conditioning systems. The same is valid for steam injection coolers. Additionally, such combinations will increase the annual operation time of the plant substantially and sustainable due to the overlapping of annual thermal energy and cooling power demand. Annual operational times of up to 8.000 h per year are predicted for such systems compared with 2.500–4.000 h for electrical power and heat producing systems only. This shortens the pay back period of the investment cost considerably.

Additionally, projects concerning the test of the MTU Fuel Cell Hot Module operating on biogas, landfill gas and other hydrocarbon opportunity fuels are underway. The driving force for the application of biogas technologies is not in the first place the production of electricity and heat but the possibility of waste material management and disposal avoiding deposition or other environmental pollutant techniques.

In favorable cases, high temperature cogeneration plants can be economical with investment costs around 1500 per EUR/kW. According to consistent results of studies, a large market will open up at prices below 1200 EUR/kW for electrical outputs below 1 MW.

Again according to consistent results of studies about one-third of the costs of mature fuel cell plants will be accounted for by the cells and about two-thirds by the peripheral equipment. Thanks to the considerable simplification of the periphery in the Hot Module design, the target costs for the peripheral subsystems should be approached at a production volume of approximately 10 MW per annum. According to the current state of technology, the target costs for the cell components will be achieved at a production volume of 40–50 MW per annum. It is the overriding goal of the joint efforts of MTU CFC Solution and FCE to achieve more rapid reduction of cell costs with the help of further technological measures. In addition, a longer service life, the technologically achieved cost reduction will be the driving forces behind cell technology development in the coming years.

5. Conclusions

Most of the technical problems affecting MCFC have been solved, but some of the solutions applied are still too expensive. Therefore, R&D programs aiming to find cheaper processes and/or products as well as to improve cell, stack and system performance are still need.

All the players have, more or less, developed products suitable for market entry, but to make products really cheap and commercial, there is a strong need to stimulate the market.

EU and National policies should make further steps promoting fuel cell market through:

- Subsidy policy (incentives and support to field test demos), strong support to projects aimed to increase use of renewable and secondary fuels in MCFC systems (creation of a large niche market that will enable mass production and technological improvements);
- Support R&D activities aimed to improve the whole system;
- Environmental policy (i.e. lowering emission limits).

The MCFC developers' short and medium term objectives for the successful commercialisation of this technology should be:

- standardise the commercial products;
- meet the needs of the market: cost, operability, reliability;
- have programs aimed to develop systems (MCFC, gas clean up, reformer/catalysts, gasifier) suitable for the utilisation of gases from renewable energy sources;
- have R&D programs aimed to keep improving their products.

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