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Direct fuel cell power plants: the final steps to commercialization

Donald R. Glenn

Fuel Cell Engineering Corporation, Danbury, CT and Suite 900, 1634 I Street, N.W., Washington, DC 20006, USA

Abstract

Since the last paper presented at the Second Grove Fuel Cell Symposium, the Energy Research Corporation (ERC) has established two commercial subsidiaries, become a publically-held firm, expanded its facilities and has moved the direct fuel cell (DFC) technology and systems significantly closer to commercial readiness. The subsidiaries, the Fuel Cell Engineering Corporation (FCE) and Fuel Cell Manufacturing Corporation (FCMC) are perfecting their respective roles in the company's strategy to commercialize its DFC technology. FCE is the prime contractor for the Santa Clara Demonstration and is establishing the needed marketing, sales, engineering, and servicing functions. FCMC in addition to producing the stacks and stack modules for the Santa Clara demonstration plant is now upgrading its production capability and product yields, and retooling for the final stack scale-up for the commercial unit. ERC has built and operated the tallest and largest capacities-to-date carbonate fuel cell stacks as well as numerous short stacks. While most of these units were tested at ERC's Danbury, Connecticut (USA) R&D Center, others have been evaluated at other domestic and overseas facilities using a variety of fuels. ERC has supplied stacks to Elkraft and MTU for tests with natural gas, and RWE in Germany where coal-derived gas were used. Additional stack test activities have been performed by MELCO and Sanyo in Japan. Information from some of these activities is protected by ERC's license arrangements with these firms. However, permission for limited data releases will be requested to provide the Grove Conference with up-to-date results. Arguably the most dramatic demonstration of carbonate fuel cells is the utility-scale, 2 MW power plant demonstration unit, located in the City of Santa Clara, California. Construction of the unit's balance-of-plant (BOP) has been completed and the installed equipment has been operationally checked. Two of the four DFC stack sub-modules, each rated at 500 kW, are on-site and will be installed to the BOP upon completion of the BOP pretests now in the final stages. Full operation and commencement of the formal demonstration is to begin late this year. Now five years old, the Fuel Cell Commercialization Group (FCCG) has grown to include over 30 buyers. The Group's Committees have been actively working with FCE personnel to hone the plant's performance, configuration and cost/benefit trade-offs to assure a market-responsive unit results from the collaboration. A standard contract has been developed for use with the FCCG buyers to streamline the purchase agreement negotiations for the early units. These are essential steps to support a market entry for the 2.8 MW power plant in 1999. The paper details the program's progress and provides additional information on the current demonstration and stack test efforts, with comparisons to earlier test data. Recent accomplishments and planned efforts to affect market entry of the first production units is reviewed as well.

Keywords: Fuel cells; Commercialization

1. Introduction

The direct fuel cell (DFC) is a variant of molten carbonate fuel cell (MCFC) technology. There are three MCFC types of fuel cells external reforming/external manifolds, external reforming/internal manifolds and internal reforming/external manifolds. Because the operating temperature of MCFCs is about 1300 °F (700 °C), ERC thought it was possible to integrate the natural gas reforming functions with the electrochemical conversion processes that occur in the MCFC anode. These relationships are shown in Fig. 1. The thermochemical reactions synergistically combine with the electrochemical catalytic activity causing a favorable imbalance that never allows an equilibrium state to be reached. This imbal-

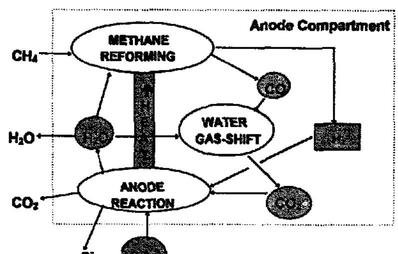

Fig. 1. Direct fuel cell concept.

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ance causes natural gas/methane reforming reactions to operate at a suppressed temperature compared with normal (external) reformer temperatures of over 1500 °F (815 °C). Moreover, the resulting conversion from methane to electricity is the highest attainable by any fuel cell or other single pass/simple cycle generation scheme.

In the early 1980s, ERC adopted the internal reforming MCFC for its baseline technology, and coined the name of direct fuel cell (DFC) for this approach. The major hardware advantages offered by this scheme includes the promise of a simpler overall system due to elimination of a major piece of equipment, the reformer, its interconnecting high temperature piping and electrical subsystems, and physical support structure. Since embarking on this as the company's technology baseline, ERC has built and tested over 50 stacks totalling over 100 000 h of testing at its Danbury, Connecticut R&D Center. The company has also supplied a number of stacks to outside agencies, domestic and foreign, in support of their test and evaluation programs, and as part of license agreements ERC maintains with Mitsubishi Electric Company and Sanyo Electric Company in Japan, and Deutsche Aerospace/MTU in Germany.

2. Commercialization

ERC's formal commercialization program [1] began in 1990 with the selection of the 2 MW DFC power plant by the American Public Power Association (APPA) for promotion to the over 2000 municipal utilities comprising APPA's segment of the utility sector. Since that beginning, the APPA core group expanded to be the Fuel Cell Commercialization Group (FCCG) to include representation from all markets, utilities and other power generation equipment buyers.

ERC is aggressively proceeding to commercialize DFC systems as soon as possible. To serve commercial customers, ERC established two subsidiaries, the Fuel Cell Manufacturing Corporation (FCMC) and the Fuel Cell Engineering Corporation (FCE). Over US $12 million of private sector financing has been raised to launch these two entities through an initial capital formation effort in support of ERC's fuel cell activities. Most of these funds have been applied to build and equip a now-operational manufacturing plant that is supplying DFC stacks and modules for the coming demonstration projects. Both of the new firms are establishing their respective commercial functions through contracts with the US Department of Energy (DOE) and the Santa Clara demonstration project.

Since being selected in February 1990, FCE/ERC and the FCCG have entered numerous cooperative efforts, all derived from the spirit of the collaborative initiative. ERC/FCE have shared technical data, test experiences and system design requirements with the group. Each of the buyers/members have executed confidentiality agreements to allow a free transfer of material allowing for a robust interchange to hone the 2 MW power plant to a market-acceptable product.

The FCCG–FCE collaboration is precedent-setting in that a buyer's group is actively participating in the design, demonstration and commercial introduction phases of a new technology product into a conservative, risk-averse industry. One approach to presenting the dynamics of this commercialization scheme is to describe the separate functions comprising the effort and how the parties are interacting in each to affect a positive outcome. The FCCG–ERC collaboration is now five years old with a highly interactive program that scopes the functions of information transfer, system planning, design and engineering, early production unit model contract and organizational cooperation at corporate executive levels. These activities are conducted through the following mechanisms: Committee meetings; Board of Director meetings; Executive Committee guidance; program trigger, and program reviews.

The past two years have seen this structure become increasingly vital to the technical, business and economic directions of the commercialization effort. ERC has prepared a commercialization plan defining the series of technical, business and financial paths for completion of product development, manufacturing, demonstration and production units, anticipated customers and markets and the implementation of a corporate organization.

3. Stack and plant demonstrations

3.1. DFC technology

ERC has built and tested stacks from the first 12″×12″ (1 ft^2 active area) short stack of 11 cells and rated at about 2 kW to the present 2′×4′ (8 ft^2 active area) cells, representing the commercial-sized components in short stacks. Table 1 depict ERC's stack construction and test history over the years. The stacks that were installed into a system that included a balance-of-plant (BOP) are highlighted. These are further explained for their importance in advancing the technology baseline, allowing the overall program to proceed to higher ordered systems and in configuring the first commercial product.

The interdependency of these programs is dynamic as research results are incorporated into the demonstration and commercial unit designs. A rapid pace is dictated by the very real expectation of foreign competition and the coincident high demand for replacement- and new-generation capacity from our nation's power providers and to meet the growing opportunities in the developing nations of the world. Some recent accomplishments are:

3.1.1. Santa Clara demonstration plant

At 2 MW, the Santa Clara demonstration plant (SCDP) is the world's largest carbonate fuel cell generator. The 2 MW SCDP is under construction at the Santa Clara site, the BOP is fully constructed with testing underway. The four 500 kW stack modules are being assembled at FCMC for shipment to

Table 1
Stacks tested at ERC facilities. Extensive stack design verifications are being demonstrated

Year	No. of cells	Power (kW)	Stack test at system conditions	Integrated system	Time (h)
1990	20	8	✓		1000 [a]
1990	54	20	✓		1300
1990	234	70	✓		400 [a]
1992	6	3	✓		6800
1992	54	20	✓		100
1993	246	120	✓	✓	250
1993	246	120	✓	✓	1800
1994	54	30	✓		2000
1994	258	130	✓	✓	2000
1994–1995	6	3	SCDP component life test		12000+

[a] Additional testing at customer sites.

the demo site this summer. Connected to a 60 kV distribution station, this unit consists of:

- four DFC stack submodules, each rated at 500 kW, containing four 125 kW stacks per submodule
- a heat recovery-thermal management module consisting of heat exchangers, the inlet cathode air blower and steam generator
- the catalytic burner for oxidizing unspent hydrogen exhaust from the anode
- natural gas and water clean-up equipment
- the d.c./a.c. inverter/power conditioner and plant control module
- switchgear and transformation equipment
- a multi-functional facility for plant control, visitor viewing, staff/operator training and meetings

The new technology part of the project is, of course, the DFC stacks. As noted earlier, four 125 kW stacks, each containing 258 cells, are packaged into each 500 kW submodule. Each stack is insulated to promote thermal uniformity within the envelope, then electrically and physically mounted into their respective bay in the enclosure. Fig. 2 shows this operation underway with the first submodule located in the shipping area at FCMC. Fig. 3 shows the package as it proceeds down a Connecticut highway enroute to Santa Clara.

Fig. 2. Loading the submodule onto the trailer.

Fig. 4 shows the SCDP site and some of the BOP equipment. At the time of preparing this paper, the BOP is undergoing full systems testing with spool pieces simulating the stacks to allow for a comprehensive checkout of the BOP, including the start-up and operation and shutdown sequences to be fully validated before the stack submodules are connected. It has been our experience that most problems with a new plant's first operation associates with the BOP. For this reason, FCE has built in a four-month window in the demonstration schedule for the BOP pretest phase.

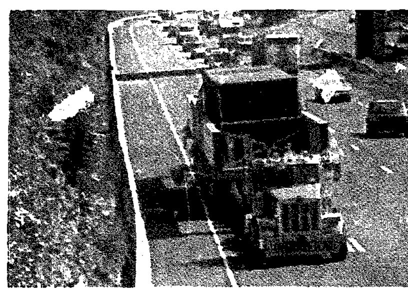

Fig. 3. The first submodule enroute to Santa Clara.

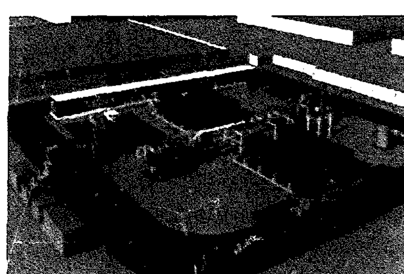

Fig. 4. Santa Clara demonstration project (SCDP) layout.

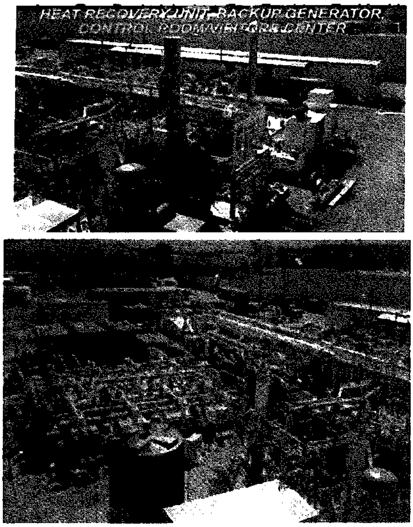

Fig. 5. Recent views of the 2 MW SCDP BOP and operations center.

3.1.2. Coal gasification experiment

In 1992, a 32 kW (2″×2″ active area) short stack successfully operated for over 4000 h on coal gas supplied from DOW/Destec's gasification facility located in Plaquamine, Louisiana (Figs. 5 and 6). As can be seen from the composite histogram of the test (Fig. 7), the frequency of BOP or the gasifier-side 'trips' confirmed our concerns to fully test the BOP to attain operational integrity. In fact, the facility 'trips' included events that were previously feared would compromise a DFC stack's survivability. Through operator error, water was admitted into the stack during one procedure, anode gas burner failures allowed for carbon admission into the cells and, most often, the gasifier itself shut down. In each of these instances, the fuel cell subsystem reverted to the hot stand-by mode and recovered to operate to within 5% of the performance results on natural gas obtained at ERC before shipment to the site, as corrected for the lower energy value of the syngas or a 26 mV/cell difference (Fig. 8). This was again confirmed when this stack ran on the facility natural gas supply with results equivalent to those obtained at ERC.

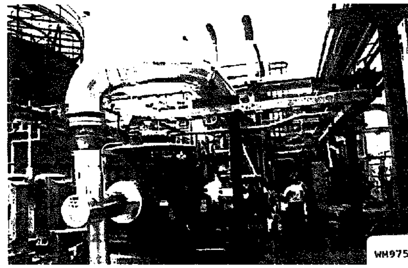

Fig. 6. Stack installed at the Destec stack/gasifier test facility.

This was the first stack manufactured and assembled at FCMC, ERC's commercial stack manufacturing subsidiary.

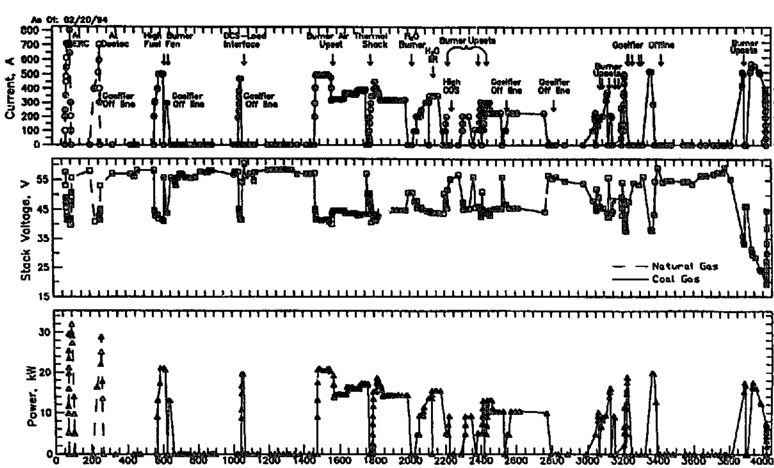

Fig. 7. Destec stack performance results. Irregular facility and BOP operation proved that stack is a robust.

Table 2
Customer site stack tests. Accumulated 50 000 operating hours on natural gas and coal gas

Year	Stack size (kW)	Customer	Fuel	Integrated system	Grid connected	Time (h)
1990	20 (54 cells)	PG&E	Natural gas	✓		300
1990	7 (20 cells)	Elkraft (Denmark)	Natural gas	✓	✓	4000
1992	70 (234 cells)	PG&E	Natural gas	✓	✓	1400
1993	3	DASA/MTU	Methane			4700
1993–1994	20 (54 cells)	Destec (LA)	Coal gas (DOW gasifier)	✓		3600
1993–1994	0.2–4 stacks	RWE (Germany)	Coal gas (simulated) wi/CGC and HGC			30000
Total						50500

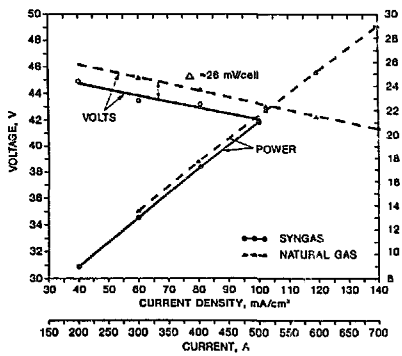

Fig. 8. Performance comparison of Destec stack with natural gas and syngas. Syngas operation results in a predicted 4.6% reduction in power output.

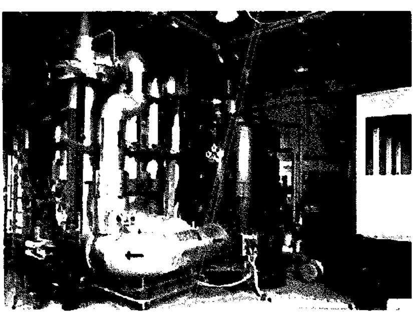
Fig. 9. ERC stack test facility.

Based on this stack having attaining state-of-the-art performance, FCMC was qualified as a fuel cell manufacturing facility for the SCDP stacks to follow.

3.1.3. Elkraft stack tests

In 1990 and 1994, ERC supplied two stacks to Elkraft for trials at their Kyndby, Denmark facility. The first, a 20 cell, 7 kW short stack operated for 4000 h. This was followed by an 8 kW package that incorporated added technology improvements and operated for 6500 h. Both were grid-connected, the latter producing 30 MWh of electricity.

3.1.4. Other customer-site tests

In addition to the Elkraft tests, in 1993–1994, a number of smaller stacks were shipped to ERC's clients, including DASA/MTU and RWE in Germany, for evaluation using methane and simulated coal gas fuels in systems that incorporated hot- and cold-gas clean-up and advanced BOP arrangements. These tests are summarized in Table 2.

3.1.5. Tall stacks

In the period of 1992–1994, ERC and FCMC have built and tested four 100 kW class tall stacks containing 234 to 258 cells. The first, a 70 kW stack with 4000 cm² active area cells was tested at PG&E's San Ramon, California test facility following pretesting at ERC where the unit was cured and run at full power for 600 h including two thermal cycles. The stack was then transported to California and operated in a grid-connected mode for over 1400 h reproducing essentially the same performance in a grid-connected test series. During this test series, 33 MWh were supplied to the grid. Three SCDP-class DFC stacks containing 246 to 258 6000 cm²

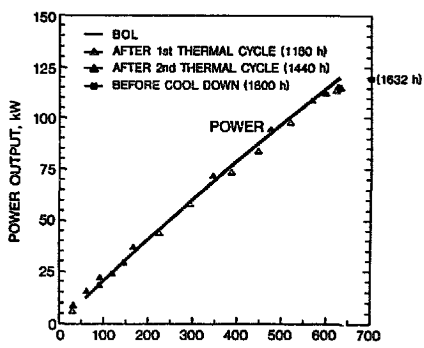

Fig. 10. Stack test results: AF 100-4.

Table 3
Other MCFC stack tests to 1995 [a,b] (US, European and Japanese programs are progressing)

Developer (MCFC type)	Power (kW)	Area (m^2)	No. of cells	Power density (mA/cm^2)	Time (h)
ERC (IIR/DIR) [b]	130	0.6	258	107	2000
MC-P (ER)	20	1.06	20	109	2500
Hitachi (ER)	100	1.2	88	109 [c]	5500
IHI (ER)	100	1.0	102	126 [c]	5100
MELCO (DIR)	30	0.5	62	106	10000
MELCO (IIR)	100	0.5	192	114	2300
ECN (ER)	10	0.34	33	125 [d]	2100

[a] Operated at 0.1 MPa except as noted. Gas compositions vary for different developers making power density comparisons difficult.
[b] IIR: indirect internal reforming; DIR: direct internal reforming; ER: external reforming.
[c] Operated at 0.7 MPa.
[d] Operated at 0.4 MPa.

active area cells were manufactured at FCMC and tested on pipeline natural gas in ERC's 130 kW test facility (Fig. 9).

Fig. 10 shows the test results of the last stack in this series. This stack incorporated improved manifold flow distribution and internal reformer designs yielding very uniform and stable thermal and electric stack performance over the planned 1200 h test including one thermal cycle. The open-circuit voltages (in 6-cell groups) shown in Fig. 11 indicated only a 0.2% variation over the 43 groups, demonstrating excellent manufacturing reproducibility. The stack produced 130 kW at 74% fuel utilization and a 55% conversion efficiency, the highest known to date. In addition, NO_2 and SO_x emissions were measured to be > 0.04 and 0.01 ppm, respectively, and noise generation at ≈ 60 dB at 10 m (excludes electric load) from this test system.

3.1.6. *Clean coal technology*

A 2.5 MW system was selected by the US DOE as part of the Clean Coal Technology Program's Fifth Round (March 1994). This unit, if completed, will be the first precommercial carbonate fuel cell/coal gas power plant demonstrated fueled by syngas from a commercial coal gasification system (an advanced Lurgi gasifier in this case).

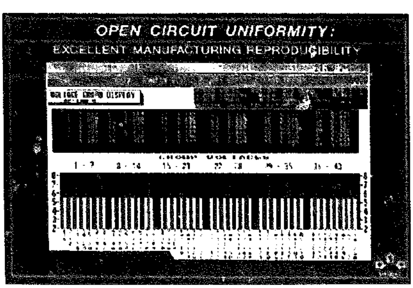

Fig. 11. Open-circuit voltages for AF 100-4, > 0.02% variation between all 6-cell groups verified manufacturing processes.

3.1.7. *Alternative fuels*

Exploitation of DFC multi-fuel flexibility is in-progress. Landfill gas, ethanol and other fuel sources are being tested in subscale stacks as a precursor to more substantial field experiments.

3.2. *Stack tests of other MCFC developers*

Japan and several European countries are sponsoring aggressive MCFC programs that may or may not be linked to one of the American initiatives. Not surprising, there is a dearth of detailed information or published data on the ongoing technical progress of these efforts. However, some materials have been assembled and form the information contained in Table 3. While the data is topically organized into logical categories, differences in fuel utilizations, current densities and system conditions would suggest using caution in attempting any comparisons. Therefore, the values shown should be reviewed mindful of these limitations.

4. A worldwide network

ERC has entered an agreement with a European consortium led by Deutsche Aerospace AG and comprised of a number of well-respected companies interested in coal- and natural gas-fueled applications using FCMC-supplied DFC stacks and stack modules. Through this arrangement, the Europeans are investing significant funds into R&D areas that complement the ERC program. Both organizations are sharing their respective findings with full disclosure of all advances, a major benefit to all parties.

In addition, ERC's direct fuel cell technology has been licensed to several overseas corporations. These licensees are also investing in technology development with mutually beneficial, full disclosure as part of our agreements. In this manner, the participants share the results from their respective programs while ERC receives some income for corporate investment in product developments, offsetting funding that would otherwise be needed from other sources.

Acknowledgements

There are many supporters who have contributed immeasurably to this effort. Their relationship to the many steps involved for DFC technology and systems to reach the present status is as critical to the eventual success of this endeavor as the technology itself. The organizations are now familiar to all who follow ERC's program; they include:

Organization	Areas of impact
Department of Energy–Morgantown ETC	MCFC technology and systems R&D, policy support
Electric Power Research Institute	MCFC systems/BOP and applications
Fuel Cell Commercialization Group	Utility/buyers interests in ERC's commercialization plan and products
National Rural Electric Cooperative Association	Demonstrations and alternative fuels
Santa Clara Demonstration Project	World's first MW class DFC unit
ERC Board and Stockholders	Corporate development: structure and resources
Deutsche Aerospace/MELCO/Sanyo	Complementary R&D with technology exchange, license income
US Congress	Funding/confidence in DFC R&D success

The aggregate influence of the named entities in terms of patience, cooperative team attitude, and professional guidance have each their own ways shaped the picture represented in this paper. The true conclusion is just ahead and with it, the hopes of many dedicated to the realization of the promise of fuel cell power in our time.

References

[1] J. Serfass and D.R. Glenn, *J. Power Sources*, *37* (1992) 63–74.