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Fuel cell commercialization — beyond the 'Notice of Market Opportunity for Fuel Cells' (NOMO)

J. A. Serfass*
Fuel Cell Commercialization Group, 1101 Connecticut Ave, NW, Washington, DC 20036 (USA)

D. R. Glenn
Energy Research Corporation, 1627 K Street NW, Washington, DC 20007 (USA)

Abstract

The Notice of Market Opportunity for Fuel Cells (NOMO) was released in Oct. 1988 by the American Public Power Association. Its goal was to identify a manufacturer for commercializing a multi-megawatt fuel cell power plant with attractive cost and performance characteristics, supported by a realistic, yet aggressive commercialization plan, leading to mid-1990s application. Energy Research Corporation's program to commercialize its 2-MW internal-reforming carbonate fuel cell was selected. The program was refined in the development of the Principles and Framework for Commercializing Direct Fuel Cell Power Plants, which defines buyer responsibilities for promotion and coordination of information development, supplier responsibilities for meeting certain milestones and for sharing the results of success in a royalty agreement, and risk management features. Twenty-three electric and gas utilities in the US and Canada have joined the Fuel Cell Commercialization Group to support the buyers' obligations in this program. The City of Santa Clara, CA; Electric Power Research Institute; Los Angeles Department of Water and Power; Southern California Gas Company; Southern California Edison; National Rural Electric Cooperative Association; and Pacific Gas & Electric, have formed the Santa Clara Demonstration Group to build the first 2-MW power plant. The preliminary design for this demonstration is nearly complete. Integrated testing of a 20-kW stack with the complete balance-of-plant, has been successfully accomplished by Pacific Gas & Electric at its test facility in San Ramon, CA.

Introduction

In Oct. 1988, the American Public Power Association released an unusual market-oriented request for interest in supplying fuel cell power plants to the segment of the US utility industry represented by their members. The objective of this Notice of Market Opportunity for Fuel Cells (NOMO) was mid-1990s commercial availability of multi-megawatt fuel cell power plants with attractive performance and cost goals, and a realistic, yet aggressive, commercialization program. The NOMO invited responses from fuel cell developers worldwide, with the initial expectation of discussions and collaboration between the market and the developer, possibly to develop into a program conducted in 'partnership'. Additionally, the intent of the NOMO was to achieve

*Author to whom correspondence should be addressed.

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maximum market acceptance by communicating market needs and constraints, thereby influencing the prospective manufacturer's product design and commercialization strategy.

Five detailed responses to the NOMO were received from leading fuel cell developers in Japan, Europe and the US. Phosphoric acid, molten carbonate and solid oxide fuel cell technologies were each represented. The responses were evaluated by a twelve member Review Team comprised of managers from leading public power systems with a strong interest in the early commercial availability of these unique power plants. The Review Team was seeking a mutually beneficial program with one or more fuel cell developers that could lead to a product which met mature unit cost and performance goals outlined in the NOMO. The Review Team's formal criteria that guided the evaluation were:

- simplicity and reliability
- timing versus promise
- program requirements and funding
- performance standards and guarantees
- scope of supply
- capabilities and experience
- responsiveness

'The Principles' — a basis for cooperation

Energy Research Corporation's (ERC's) program to commercialize the internal-reforming carbonate fuel cell, initially in a 2-MW size fueled by natural gas, was selected. The program and objectives were negotiated, resulting in an agreement, the Principles and Framework for Commercializing Direct Fuel Cell Power Plants, which defines the buyer responsibilities for promotion and coordination of information development, as well as the supplier responsibilities for meeting certain milestones and for sharing the results of success through a royalty agreement. The Principles completely describe the commercialization plan, the risk management features that provide for sequentially deepening commitments by the buyers, and incentives for participation.

The Fuel Cell Commercialization Group (FCCG) was formed as an outgrowth of the NOMO activities. Representatives from all segments of the US and Canadian electric and gas utility industry formed this buyers group in June 1990 to support the buyers' obligations contained in the Principles and Framework. The FCCG is assisting ERC's marketing efforts by promoting the technology and urging support by other potential buyers and participants. FCCG members are expected to host one of the early demonstrations and to order in advance 40 MW (later extended to 63 MW) of the 100 MW required in the Early Production Unit (EPU) Phase of ERC's Commercialization Plan.

The Principles attempt to balance technical and financial risks and incentives between the developer and the utility participants. Before a 2-MW demonstration unit is built, the manufacturer is required to successfully achieve specified technology milestones and have letters of intent to purchase the early production units (EPUs). Carbonate fuel cell stack performance, endurance and manufacturability, technical success in smaller (100-kW) integrated systems and the 2-MW system demonstration must be accomplished as major milestones in the program. Early production unit advanced orders become 'firm' commitments and require payment of a deposit when:

- the prototype demonstration plant successfully achieves specified operational criteria
- ERC offers the EPUs and commercial units at agreed target prices with performance and operational warranties
- ERC commits to build the commercial fuel cell manufacturing facility to support EPU and commercial orders

A significant program feature (to FCCG members) is that early production unit advance orders require no down payment until the above items are satisfied. Other risk management measures include: technical and cost review of ERC's design, manufacturing and construction efforts by utility participants and the Electric Power Research Institute (EPRI); use of 'failure mode and effects analysis' and other proven design techniques to assess reliability, and fault isolation and maintenance; and documentation of demonstration plant experiences using a site 'engineer-of-record'.

ERC's commercialization program requires several 2-MW demonstration units, followed by ~50 early production units at a target installed price of $1500/kW* ($3 million each). The demonstration unit and the early production units are being offered at prices higher than their commercial value. The Principles address this issue by including financial incentives to early buyers in the form of royalties. The following guidelines were adopted:

- Early production units in the extended program should receive royalties as an incentive to early buyer commitments.
- No EPU should have a real cost (royalty considered) above the commercial target price of $1000/kW.
- Participants in Santa Clara's demonstration project, because of their greater risk, should receive the largest incentive and receive their royalty payments first.
- The real ($/kW) cost for the first participants to join the program should be lower than for later participants so as to recognize the greater risks of the buyers of the earlier units.
- Earlier buyers should receive their royalty payments before later buyers.

The royalty for the demonstration host utility and other utility demonstration participants will total (be capped at) two times their capital investment. The royalty for early production units has two stages. For the first 40 MW of EPUs, the incentive is equal to two times the capital cost 'premium' paid over the commercial unit price, repaid at $10/kW of gross fuel cell stack sales. As an example, for the commercial unit target price of $1000/kW, with early production units costs of $1500/kW, the royalty total is: 2×($1500–$1000) or $1000/kW or $2 million dollars per EPU. The program has been extended to cover an additional 13 EPUs (23 MW). The same EPU royalty methodology applies, except that the total royalty is 1.5 times the difference in price, not two times. The royalty payment scheme for the extended program also has a 'ratchet' feature that has the payment rate increase as a function of overall power plant sales. Royalties will also be indexed to account for inflation. With successful commercialization, the present cost of these 2-MW EPUs will be between $750 and $950/kW, depending on the position in the installation queue.

Other incentives for early participation include 'most favored nation' status with respect to future pricing, priority queuing for replacement fuel cell stacks, and the ability to influence the product design to satisfy buyer needs and applications.

The market-driven approach of this FCCG–ERC collaboration is unique in the power generation field. In an era of constrained budgets and relatively low growth, the introduction of new generating technologies faces severe hurdles. The sharing of

*All costs are in 1989$ (US).

risks and benefits between the market and supplier, as in this FCCG–ERC collaborative effort, may provide an example for the commercial introduction of other advanced power generation technologies.

The Fuel Cell Commercialization Group

The FCCG's twin roles are to promote the overall ERC commercialization initiative and to coordinate the development of buyer information in support of the program. These roles are implemented through FCCG technical committees covering design/engineering, licensing/permitting, system planning/evaluation, information transfer/promotion and EPU model contract development.

The twenty-three FCCG members and their geographical locations are shown in Fig. 1. Each of these members represents a potential buyer of early production and commercial units and/or a major financial participant in a demonstration. The Electric Power Research Institute, an Honorary FCCG Member, is also providing substantial assistance to the demonstration. FCCG membership is open to all potential buyers of fuel cells in North America.

The City of Santa Clara, CA, with FCCG endorsement, has been selected to host the first demonstration and will be providing the site. The Santa Clara Demonstration Group (SCDG) consists of seven major participants:

- City of Santa Clara Electric Department
- Electric Power Research Institute
- Los Angeles Department of Water and Power
- Pacific Gas & Electric Company
- Southern California Edison Company
- Southern California Gas Company
- United Power Association/National Rural Electric Cooperative Association

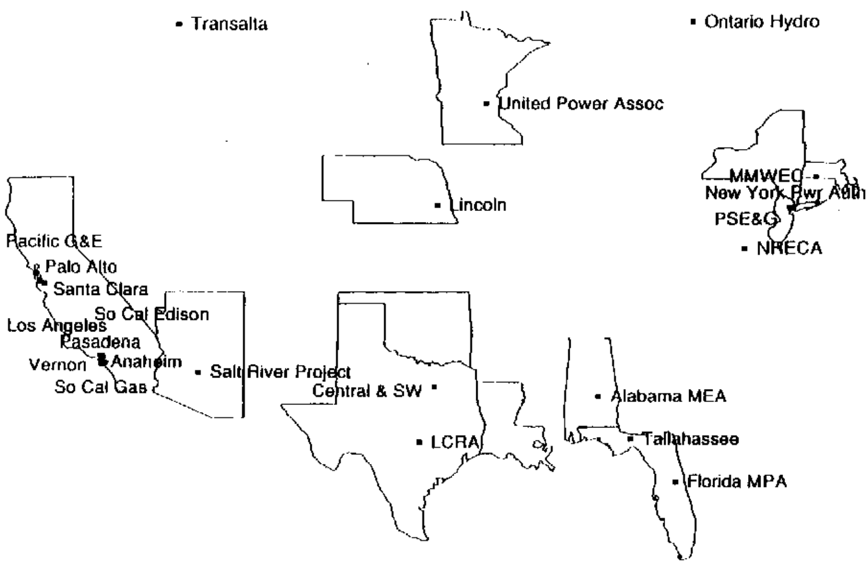


Fig. 1. Electric and gas utility members of the FCCG.

Other utilities and funding organization will be providing additional financial support for the demonstration through a sponsor program to be developed.

Direct fuel cells (DFC)

Research on ERC's version of molten carbonate fuel cells (MCFC) began in 1980, when the company attempted to integrate the reforming function directly with the anode reactions. In 1981, the Gas Research Institute (GRI) provided the first internal reforming MCFC contract to ERC. In the next ten years, the stack technology has been scaled to full height (under the sponsorship of EPRI and the US Department of Energy), two power plant systems have been synthesized, and preliminary plant performance and design specifications have been developed.

The direct fuel cell (DFC) power plant designs are the product of continuing system studies started by ERC and the Fluor Corporation in 1984. The plant capacity, at 2 MW, reflects the result of several market studies of the gas and electric utility sectors, as well as the rising popularity of the independent power producer sector responding to an increasing trend toward third-party generation (and co-generation) contracting. Moreover, the NOMO, on behalf of some 2000 municipal systems, pointed to this size as a likely candidate for their needs. It is largely due to ERC's selection by the NOMO Review Team and the successor organization, the FCCG, that the 2-MW DFC power plant has been selected as the market entry unit.

The DFC program represents a substantial combined private and public sector investment. The remaining steps, demonstration and the establishment of a major stack and systems production capability, are estimated to require an additional $220 million (US). Important support and promotional efforts are provided by the North American members of the FCCG and ERC's European partner, MBB.

The following sections describe the product offering and summarize the program's status, recent accomplishments, and major milestones that lie ahead.

The product: 2-MW DFC power plants

Two plant designs are to be offered; they are designated the Simplified System (S-S) and the Integrated System (I-S). These systems are diagrammed and explained in Fig. 2. The designs contain identical DFC Stack and Power Conditioning Sub-systems. The DFC Stack Sub-system consists of two pallets, each equipped with ten 100-kW DFC stacks arranged to simplify assembly, piping and ducting interconnections, and stack replacement, and to facilitate factory-to-site transportation. The balance-of-plant (BOP) is on two additional skids, the thermal management/gas handling module and the power conditioning module. The Power Conditioning Sub-system consists of state-of-the-art solid state equipment sized to handle the operating capacity envelope of generated power with appropriate real and reactive power quality control. The total installation is expected to occupy a footprint approximately equal to a conventional tennis court.

The plant designs were derived to resolve several buyer-instigated scenarios. The S-S provides a basic 2-MW DFC power plant, with the emphasis on simplicity, at some modest loss in capability. The I-S is the deluxe system and includes optimized thermal energy management, water self-sufficiency, and maximizes electric production efficiency. Table 1 summarizes the two plants' performance characteristics.

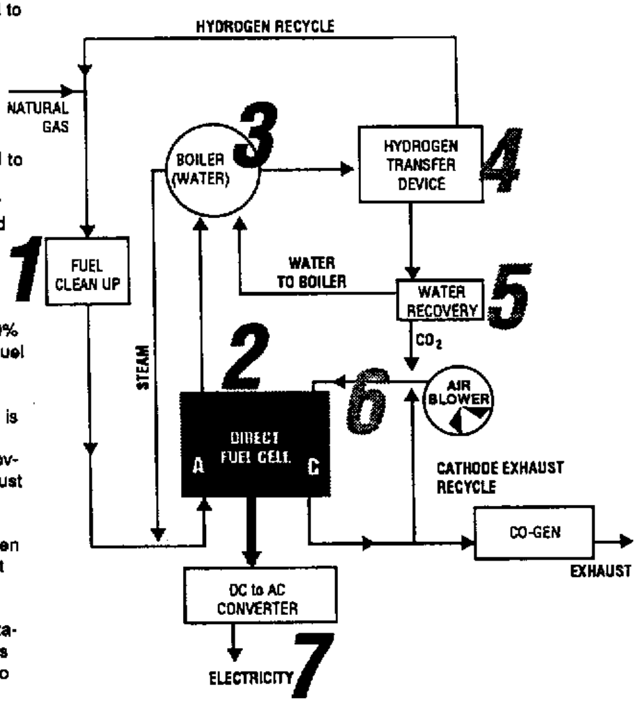
The diagram below "walks" you through the DFC Power Plant (Integrated System), from fuel to electricity:

1) Sulfur and other impurities are removed from the natural gas in a cleanup bed.

2) The fuel and steam are fed to the cell's anode (A) section. The fuel is reformed internally and electrochemically oxidized by carbonate ions which are formed at the cathode (C) by reacting with oxygen from the air and carbon dioxide. The DFC utilizes approximately 80% of the hydrogen entering the fuel cell.

3) The anode exhaust stream is cooled. The heat is used to preheat and vaporize the recovered water. The cooled exhaust is...

4) ...passed through a hydrogen transfer device where unspent anode hydrogen is separated and recycled back to the fuel cell for further utilization in electric generation, thus raising overall fuel utilization to about 90%.



5) The residual, consisting mainly of carbon dioxide and steam, is sent to a water recovery unit. The carbon dioxide is then fed to the fuel cell cathode section along with fresh air. The power plant is water self-sufficient at all load conditions.

6) Heat generated in the fuel cell is removed by recirculating the cathode exhaust mixed with incoming air. By-product thermal energy (approx. 20% of the inlet energy) is available at 620°F for cogeneration.

7) DC Power produced by the fuel cell section is conditioned by a high-efficiency inverter to meet user power quality requirements.

The electric efficiency of this integrated system is 60% equivalent to a heat rate of approximately 5700 BTU/kWh.

NOTE: The Simplified System design eliminates the water recovery, hydrogen transfer device and recycle steps (4-6). Several heat exchangers and control equipment are eliminated, thus simplifying the power plant as well as reducing the capital cost.

Fig. 2. DFC system functional diagram. These plants incorporate straightforward functional designs.

Both designs incorporate fuel cells with the ability to accept natural gas or other methane-containing gas fuels directly and interchangeably, hence the name direct fuel cell. The cells internally reform the natural gas into hydrogen and carbon dioxide, the reactants needed by the fuel cell to produce electricity. The integration of the reforming and anode reaction functions eliminates the need for an external fuel processor and heat exchangers. This results in a simpler system (lower costs, higher reliability) and an increase in electric efficiency of 5 to 8 percentage points compared to the efficiency of conventional molten carbonate fuel cell systems.

TABLE 1

2-MW DFC power plant features

Feature	Integrated system	Simplified system
Capacity (MW)		
Nominal	2.0	2.0
Minimum	0.45	0.45
Maximum	2.25	2.25
Cold start (h)	10	10
Efficiency/heat rate		
Full load	60/5700	54/6320
50% load	57/6000	45/7500
Footprint (ft.^{2})	5500	4500
Co-generation	optional	optional
Waste heat (BTU/kW h)	775@650 °F	1100@820 °F
Emissions (lb./MW h)		
SO_2	0.002	0.003
NO_x	0.0003	0.0004
Water requirement (gal./h)	0	110
Cost ($/kW) (1989$)	≈1300	<1000

Both designs offer attractive performance with high efficiencies and low pollution.

Future products: large capacity DFC plants

ERC has identified a 'phased capacity addition' strategy that capitalizes on the unique fuel flexibility feature of DFC plants. DFC stacks are able to accept both natural gas/methane and coal-gases containing methane fractions indiscriminantly. This suggests a generation expansion scenario where a utility adds, say, 10-MW blocks of natural gas/fuel cell capacity to match load growth until, eventually, the costs of natural gas may increase to the point that a coal gasification system is more economical.

ERC anticipates that natural gas-fueled DFC systems can compete economically right up to the crossover where coal-based gas systems are economically competitive. Only when it is certain that coal gasification is economical will the utility need to make the larger capital investment for the gasification system. When the gasification system is operational, the utility may switch from natural gas to the new coal-gas supply rather easily. No special plant adjustments are required. When the coal-gas system has a scheduled or preventative maintenance outage, the natural gas supply can be used with minimal disruption, as the DFC cluster remains operational during the changeover.

ERC, with support from Fluor-Daniel, under a US Department of Energy contract, analyzed numerous coal gasifier/carbonate fuel cell (CGCFC) systems. Table 2 presents the results of the cases studied, normalized to the reference size at 200 MW. Figure 3 shows an artist's concept of a 200-MW CGCFC plant with 150 MW provided by DFC power and 50 MW from a bottoming cycle.

Commercialization: key milestones and schedule

The US and ERC program strategy to develop the coal option is to validate the DFC technology on natural gas before proceeding to full scale testing on coal-derived

TABLE 2

Coal gasification carbonate fuel cell systems evaluation

	CGCFC systems			Competing systems		
	Entrained bed	Fixed bed	Fluid bed	IGCC	PC	AFBC
Performance						
Gross/net power (MW)	289/238	243/205	247/209	259/234	207/196	210/196
Heat rate (BTU/kW h)	7565	7379	7246	8420	10571	10780
Cost						
Capital cost ($/kW)	1928	1965	1802	1522	1745	1706
Capacity factor (%)	85	85	85	80	65	65
Cost of electricity (mills/kW h)	46.5	48.6	49.7	47.5	65.3	66.1
Emissions (lb./MW h)						
SO_x	0.03	0.25	0.003	0.08	3.95	4.0
NO_x	Trace	0.18	0.09	1.0	1.1	0.8
CO_2	1580	1540	1600	1860	2070	2107
Water requirements (gal./(W h)	173	169	186	268	274	228

IGCC = integrated gasification combined cycle, PC = pulverized coal, AFBC = atmospheric fluidized bed combustion.
Superior performance with fuel cells is obtainable using available gasifiers.

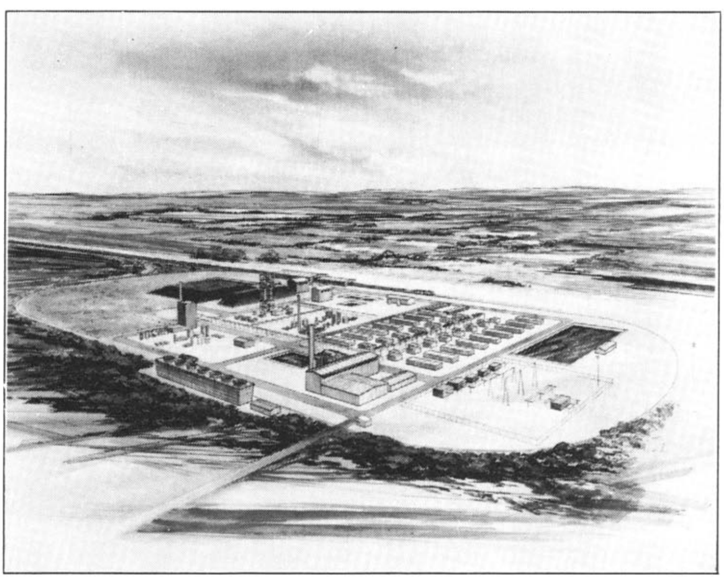


Fig. 3. Artist's concept: 200 MW CGCFC power plant — with phased capacity additions, capital investment tracks load growth.

gases with their more complex impurities. This strategy builds upon the expectation of a sizeable 2-MW natural gas DFC power plant market, utilizing the opportunity to establish a positive cash flow and establish a market position within the power production business. Concurrently, efforts are being directed to completing the development of coal gasification-carbonate fuel cell systems through numerous interrelated projects. Current activities emphasize hardware development and testing on natural gas and synthesis gas. Studies and experiments are also underway to identify and evaluate coal-gas contaminants and their effects on fuel cell materials — their survivability and life cycle expectations.

The aggressive program and schedule, shown in Fig. 4, was adopted because of the very encouraging stack scale-up test results over the past several years. The overall program includes the following elements:

Natural gas
- stack development and testing
- stack manufacture
- 2-MW power plants/dispersed generation
- phased capacity additions

Coal gas
- fuel cell materials contaminant resistance
- cold- or hot-gas clean-up
- gasification/carbonate fuel cell systems (conventional and advanced)
- clean coal technology demonstration

Coal gasification systems have been developed and demonstrated employing entrained, moving and fluidized beds, as well as slagging versions. However, their high

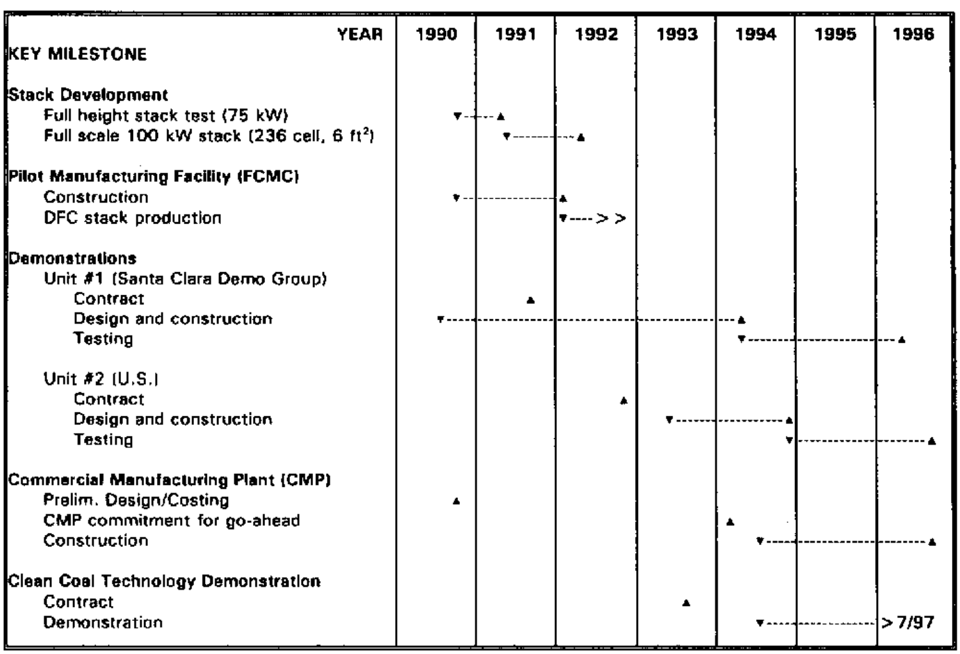


Fig. 4. DFC commercialization key milestones. An aggressive but manageable path to market entry is being implemented.

capital costs, siting issues and waste products, have retarded serious investment in new coal systems for power production. In the near term, integrated gasification combined cycle (IGCC) systems are likely to capture the attention of the market because of their commercial availability, improved efficiency (up to 45%, LHV) over other alternatives, moderate capital requirement, and reasonably clean exhaust products after clean-up.

CGCFC systems are close behind IGCC systems. Because coal gas trace contaminants can inhibit or incapacitate a fuel cell's electrochemical conversion capability, additional R&D in materials' contaminant resistance, impurity removal and/or neutralization techniques is needed before large scale CGCFC demonstrations are fielded. Single- and multi-cell testing has been underway for several years using simulated coal gas. Recent test runs of over 4000 h were successfully concluded, using 1 $ft.^2$ active area cells, with the simulated coal gas containing up to eight impurities. In 1992, the first system field test with an on-line gasifier is planned, using a sub-scale (20 kW) DFC stack fed from a slipstream. With continued success in these early tests, large CGCFC systems will be demonstrated in the late 1990s, possibly under the ongoing US Clean Coal Technology program. Commercial deliveries of these systems could begin shortly thereafter.

Status

Late in 1990, it was apparent that response to the initial fuel cell commercialization initiative was exceeding expectations. The FCCG had set a goal of placing 20 EPUs (20 members) by the end of 1990. By Feb. 1991, the FCCG's membership had reached 22, a membership level sufficient to secure 40 MW in commitments of 2-MW nominal (1.8-MW actual) EPUs, beating the Group's initial 1994 commitment goal by three years with additional interest in the wings. The combination of ERC's carbonate fuel cell design, its target prices, the incentives, and risk management features contained in the overall commercialization initiative, have obviously been sufficient to attract serious buyer interest.

In contemplating an expansion of commercialization responsibilities, FCCG felt than any extended program should retain the balance of incentives, costs and risks that had created the success of the 40-MW offering. On May 15, 1991, following discussions with ERC, the FCCG Board of Directors agreed to extend its commercialization responsibilities by 13 additional power plants for a total of 35 power plants, or 63 MW, with similar buyer incentives.

The Fuel Cell Engineering Corporation (FCEC), a joint venture between PG&E and ERC to provide power plant engineering and marketing, was established in early 1991. Also formed was ERC's wholly-owned subsidiary, the Fuel Cell Manufacturing Corporation (FCMC), which will supply DFC stacks for the demonstrations and commercial units.

Substantial progress in the first demonstration has been made. FCEC has nearly completed the detailed engineering design and costing for the unit. The Santa Clara Demonstration Group has contracted with Stone & Webster as their 'engineer-of-record', and has received significant technical support from the Los Angeles Department of Water and Power, a SCDG participant. Further, recognizing the importance of this new technology and the higher costs for this project, the US Department of Energy (DOE) has developed tentative plans to co-fund the early, higher risk portion of this effort. The SCDG and FCEC have begun negotiating terms and conditions of the anticipated contract with completion of the agreement expected by the end of 1991.

The DFC stack development program has seen dramatic progress in recent years and especially in 1991. ERC built and successfully tested a 60-cell, 20-kW stack in its Danbury, Connecticut R&D facility. The stack was then shipped by truck cross-country to the Pacific Gas & Electric Company's San Ramon, California R&D Center. PG&E, working with ERC staff over the last two years, has designed and built a 100-kW integrated systems test facility that includes the appropriately sized balance-of-plant to test full size DFC stacks. The 20-kW stack was installed and operated for over 400 h to qualify the new facility for its intended mission to test FCMC-supplied stacks. An earlier test was conducted at Elkraft's power station in Lyngby, Denmark. This 7-kW demonstration began in Oct. 1990 and ran continuously until May 1991. Both the PG&E and Elkraft demonstrations were natural gas-fueled and grid-connected.

With the formation of the Fuel Cell Manufacturing Corporation, ERC is providing corporate funds to equip the new plant with process machinery to reduce to manufacturing practice the laboratory-proven component fabrication, particularly the sintered anode and cathode electrodes, bipolar plate and electrolyte matrix. This plant can produce 20 DFC stacks annually, with an expansion potential of up to 50 stacks, or 5 MW/year. The plant is located in Torrington, Connecticut, about 40 miles from ERC's Danbury Headquarters. FCMC's plant is on schedule for commencing stack production in early 1992.

Conclusions

After several unsuccessful attempts by the US utility industry and developers to introduce fuel cell systems, ERC and the FCCG have embarked on a new collaborative program to manage the formidable technical and economic risks in commercializing a promising fuel cell technology. This arrangement is documented with both the supplier and the marked sharing in the challenges ahead, with appropriate safeguards to protect each party. A substantial set of obligations has been negotiated and is now being implemented. This paper reflects on the shared tasks — information transfer and market promotion.

Significant hardware progress continues to be made in the prototype DFC stack development power plant design, manufacturing and system test facilities, and the first 2-MW demonstration. A high expectation of success prevails despite the aggressive schedule. Plans call for the introduction of factory-assembled, truck transportable 2-MW DFC power plants, followed by larger generation modules, fueled with natural gas. With completion of coal-gas sensitivity studies and smaller scale (1 to 2 MW) tests, a large scale (>100 MW) design will be offered.

Interest in reducing regional air quality deterioration, concern for the impact of CO_2 and other emissions globally, controls on acid rain-causing emissions, objectives to improve the efficiency of power production from fossil energy resources, and the need to support continued growth in electric demand, make this technology a very attractive option for the future. This program provides the incentives and the risk management features that should lead to commercial success, serving the interests of both the buyers and the supplier.

Acknowledgements

The authors wish to recognize the Electric Power Research Institute and the US Department of Energy for their important technical and financial support of DFC technology R&D and power systems development; Pacific Gas & Electric Company for their early participation and active role in the overall program; and FCCG members for their precedent-setting example of the utility sector's ability to catalyze the commercialization of a needed technology to ensure a successful outcome.