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Planar solid oxide fuel cells: the Australian experience and outlook

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Abstract

Since 1992, Ceramic Fuel Cells (CFCL) has grown to what is now the largest focussed program globally for development of *planar* ceramic (solid oxide) fuel cell, SOFC, technology. A significant intellectual property position in know-how and patents has been developed, with over 80 people involved in the venture. Over $A60 million in funding for the activities of the company has been raised from private companies, government-owned corporations and government business-support programs, including from energy — particularly electricity — industry shareholders that can facilitate access to local markets for our products. CFCL has established state-of-the-art facilities for planar SOFC R&D, with their expansion and scaling-up to pilot manufacturing capability underway. We expect to achieve commercial introduction of our market-entry products in 2002, with prototype systems expected to be available from early 2001.

Keywords: Solid oxide fuel cells; Distributed generation; Electric generation systems

1. The company

The venture to develop and to bring to the market ceramic (solid oxide) fuel cell, SOFC, products based on Australian-owned and -developed technology was launched in November 1991. The interest of the initial, and subsequent, venture partners — Australian and New Zealand electricity businesses, Australian companies and government research and technology investment organisations — was driven by the:

- Potential market opportunities within the fast-growing distributed generation (DG) sector for clean, reliable and cost-competitive electricity supply systems based on the highest efficiency conversion technology known — SOFCs;
- Prospects for establishment of a major, new, Australian-based, high-technology manufacturing enterprise; and
- Credibility of the base technology (knowledge of zirconia ceramics and their application in high temperature fuel cells) and its promoters to achieve the technical goals of the venture.

To undertake the technology development, demonstration and commercialisation activities, the company — Ceramic Fuel Cells (CFCL) — was incorporated in July 1992. Since then CFCL has:

- Been recognised by its major peers as one of the top developers of SOFC technology worldwide;
- Developed significant intellectual property in know-how and patents;
- Built a strong track record of overcoming technical challenges and meeting milestones;
- Raised over $A60 million in cash and in-kind funding for the activities of the company from private companies, government-owned corporations and government business-support programs;
- Negotiated the transition from a corporate structure designed for the R&D phase to one that positions CFCL for commercialisation; and
- Attracted key shareholders, Board members and staff with the capabilities and experience in directly relevant technology commercialisation.

2. The market opportunity

Change is sweeping the electricity (and gas) industries on a global basis. As with banking and telecommunications, these energy sectors are being transformed through political, competitive and innovation pressures [1–3] (Fig. 1).

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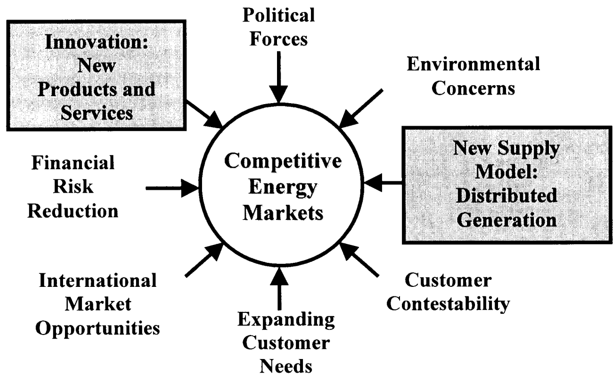

Fig. 1. Influences on competitive energy markets.

This worldwide change process is considered irreversible — notwithstanding that local setbacks and delays will continue to occur as a bulwark against globalisation and to appease vested local interests. In this competitive environment, customer retention is becoming of central importance to those participants in the value chain who deal with the energy end-users, particularly retailers and energy service companies (ESCos).

There is considerable financial risk associated with the traditional, centralised generation paradigm for electricity supply where large increments of generation, transmission and distribution capacity — requiring large capital outlays — are added. Community and political pressures to improve local and global environments are also driving a move to higher efficiency generation of electricity, particularly with natural gas as the fuel.

Further, ‘‘over the next five to seven years, a number of potential (technical) breakthroughs — all with the attractive features of small-scale efficiency and environmental cleanliness — could turn established utilities into so many buggy-whip companies’’ [3].

These unprecedented changes in and forces on industry sectors that enjoyed ‘‘natural’’ monopolies for some three generations provide many threats and opportunities to existing and new businesses that participate in the provision of energy services to customers. The centralised generation model of electricity supply is under challenge — and the alternate model is *distributed generations*, (defined as generation at or close to the end-user with smaller increments of capacity).

Finally, it should never be forgotten that in the non-OECD world, some two billion of the world’s population do not yet have access to electricity networks, and those that do often have to endure standards of service well below those provided in developed countries. In many of these underdeveloped markets, it is recognised that access to gas and electricity services would substantially improve economic conditions. Delivery of energy services by DG technologies may finally fulfil the needs of these markets in an economic manner.

3. The market’s characteristics

DG currently accounts for 26% (or 7.8 GW) of *new* capacity additions in USA and Western Europe. However, today a significant percentage of DG capacity operates only in stand-by or ‘‘back-up’’ mode. A crucial transformation that is forecast to occur is that *new* DG units will increasingly operate in a fully loaded mode, and thus take a much larger share of *energy* supply than currently is the case.

For DG sources to penetrate existing electricity markets to any significant extent, they will need to be cost-competitive *for the customer*. The challenge and the opportunity are for DG technologies to deliver a *lower* cost to customers *at their meter*.

The installed generation capacity in the USA and Europe is expected to grow in line with forecast demand growth of 2% per year to 2010, requiring 38 GW of new capacity additions per year. However, given the advanced age of many existing coal and nuclear plants, the expected retirement of some nuclear capacity and a lower utilisation of coal plants because of emissions controls and competition from combined cycle gas turbine and DG plant, coal and nuclear *capacity reductions* are expected to be 15 GW/year by 2010. The potential market for new generation plant is thus 53 GW/year by 2010.

For the purposes of forecasting market share, a historical extrapolation for DG would be overly conservative, and would represent only 12.9 GW/year of new capacity additions in 2010 — an annual increase over the period to 2010 of only 5%. However, given the emergence of new DG technologies that have the scope for substantially improved cost-competitiveness, DG’s market share is expected to increase significantly.

DG, therefore, is expected to gain a 40% share (or 21 GW/year) of the potential market for new generation plant by 2010 as its cost competitiveness improves and

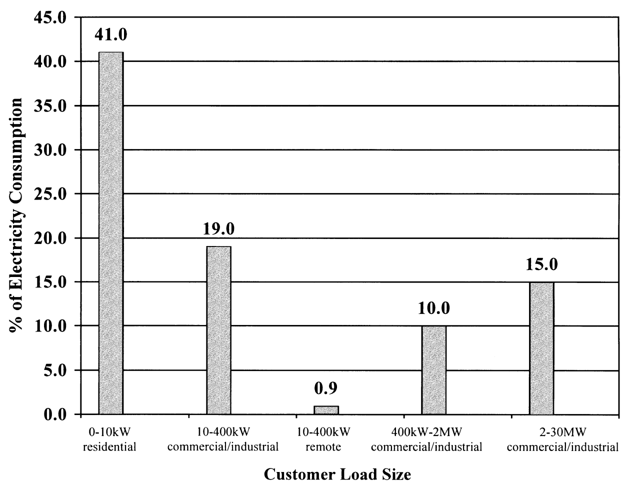

Fig. 2. Typical OECD country customer consumption profile.

environmental pressures facilitate more efficient generation and increased use of cogeneration. This represents an average growth rate of 8% per year to 2010.

CFCL has segmented the market based on customer size/type and geography. Given the confidentiality of detailed market information in today's competitive energy industries, customer information is scarce. However, research indicates that a typical OECD country would have a customer load size profile similar to Fig. 2.

4. CFCL's proposed product roll-out

CFCL's initial target market is expected to be the 400 kW to 2 MW customer segment, although this is continually being reassessed. This segment typically represents 10% of total electricity consumption, which in the USA today is in excess of 350 TW h out of a total of 3500 TW h — equivalent to the total consumption of New York, New Jersey and Pennsylvania combined. A total of approximately 56,000 customers in the US make up this segment, comprising medium size offices, hotels and industrial sites.

This target market segment is considered most prospective for CFCL because the:

- Segment comprises customers that have a commercial driver to achieve energy cost reductions;
- Segment has lesser buying power than larger end-users; and
- Residential segment will require more advanced technical and commercial solutions.

To service the 400 kW–2 MW target market segment, CFCL expects that a 200-kW SOFC unit will form the standard module. Total electricity needs of a customer will be met via a number of identical 200-kW modules connected in series and parallel.

At this stage, it is planned that market entry will occur in 2002. Once product performance is proven and market acceptance gained in a number of geographic markets, CFCL will consider moving down in product size for the following reasons:

- A large portion of the total consumption of electricity occurs at the lower end, with consumption by customers of size less than 400 kW representing 60% of the market;
- Acceptance of the 200-kW unit in the 400 kW to 2 MW range will demonstrate that CFCL's products can compete with grid-connected and other DG options;
- The substantial remote market is also in this lower end of the size range; and
- The size and characteristics of the unit required for the residential market mirror those of the power pack required for the auxiliaries in the passenger car market, thereby opening up greater market potential.

At the appropriate time, CFCL will also consider moving up in product size, to service the 2–30 MW customer load range with the highest efficiency unit available based on a 2 MW combined cycle module. It is expected that an approximately 1.4 MW fuel cell unit could be coupled with a microturbine (gas or steam) to produce a total output of 2 MW at an efficiency of 65% plus. If developed, *this product would essentially be the 21st century replacement for large power stations as these are retired, with the added benefit of being able to be positioned at distribution substations within the network*.

5. CFCL's proposed product features

Customers will purchase fuel cell systems principally, but not solely, on economic grounds. Low-cost production is therefore required quickly to provide a sustainable competitive advantage. To open up volume markets to fuel cell-based systems, various studies around the world suggest that a maximum system sales price of US$1500 per kW, and preferably US$1000 per kW, is required.

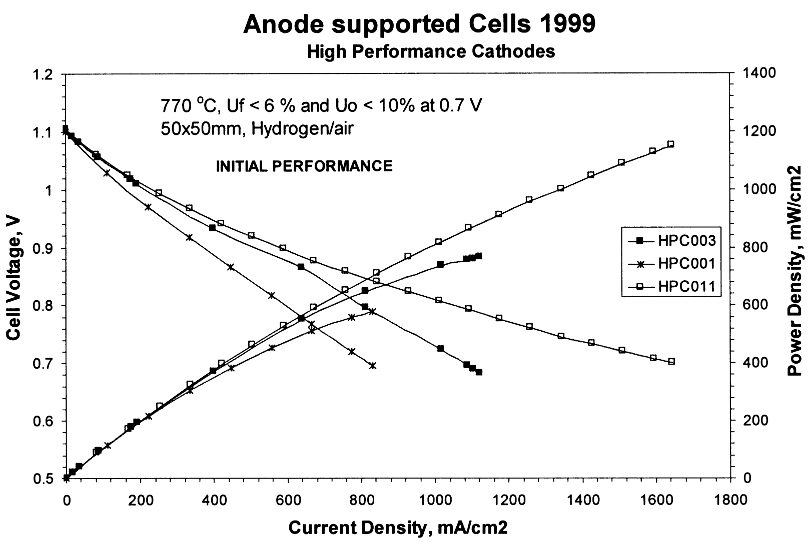

Fig. 3. Performance of CFCL's anode-supported cells.

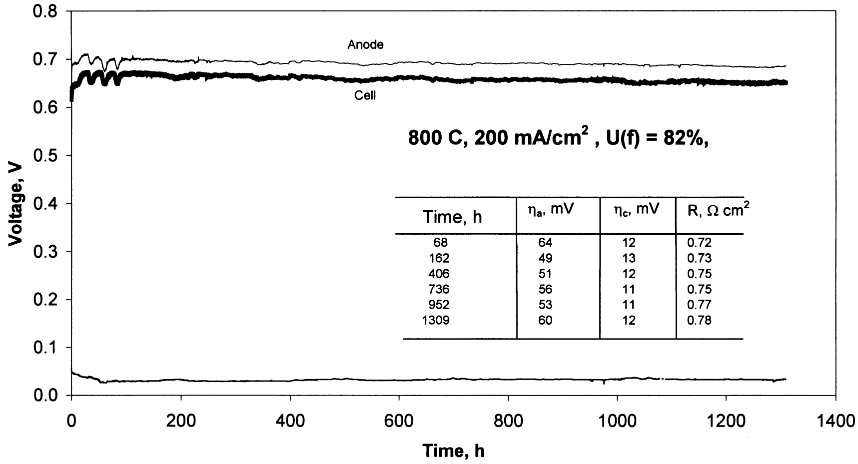

Fig. 4. Direct internal reforming results for methane.

To achieve competitiveness, CFCL believes the following aggressive performance and cost *targets* for its SOFC system products are possible:

- Unit selling price of \$A1000 per kW ($\approx$ US\$650 per kW) *in volume production*;
- Minimal installation and commissioning costs;
- Remote operation, dispatch and monitoring;
- Efficiency $\geq 50\%$ in open cycle;
- Low aging: $\leq 15\%$ stack voltage drop over 7 years; and
- Low operating and maintenance costs: < 0.5 cent/kW h over 20-year system life.

6. CFCL's technology base

6.1. Fuel cell stack technology

- Developed manufacturable tape casting and screen printing technology to fabricate *electrolyte-supported cells* with high performance electrodes and good cell stability ($< 1\%$ loss per 1000 h, after the first 1000 h)
- Developed manufacturable tape casting, lamination and screen printing technology to fabricate intermediate temperature cell technology based on *anode-supported cells* that have achieved > 1200 mW cm^{-2} at 770°C with 50 mm $\times$ 50 mm cells (Fig. 3)
- Developed stainless steel interconnect material and protective coating technology, including novel interconnect concepts that promise low-cost and long-life interconnect solutions
- Developed sealing technology for a number of different designs and temperature ranges, including seal concepts for easy assembly and mass fabrication
- Developed direct internal reforming technology for methane (CH_4) that has been demonstrated to be stable and non-coke forming in medium term tests (> 1500 h) at steam to carbon ratios of approximately 1.5:1 to 2.5:1, fuel utilisations of up to 85% and temperatures down to 700°C (Fig. 4)
- Established an extensive testing facility with over 20 test stations with in-built diagnostic facilities for testing single cells to array stacks with outputs up to 5 kW_e

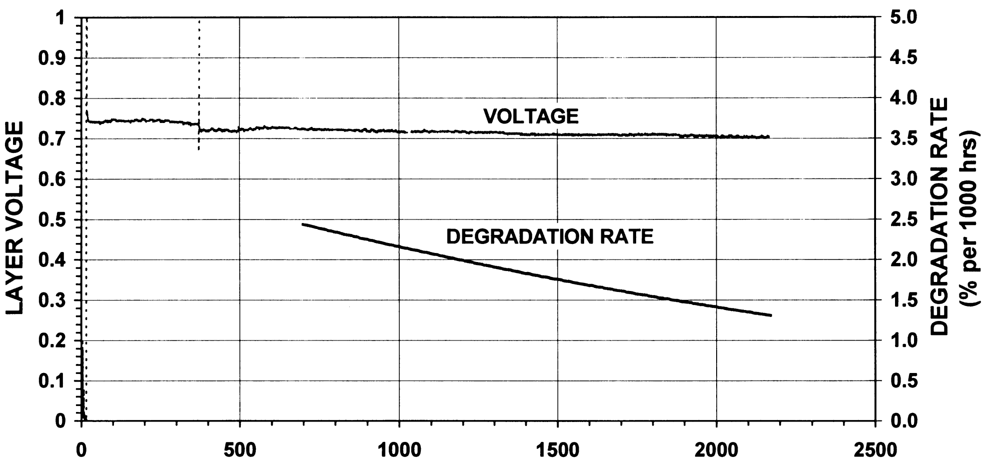

Fig. 5. Degradation of best layers in 400 W array test (820°C, moist H_2).

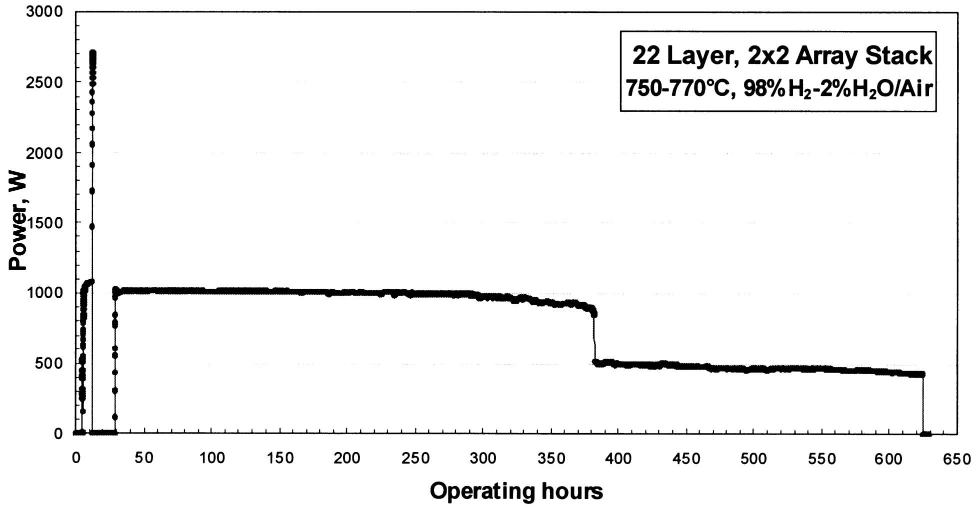

Fig. 6. History of operation of anode-supported cell 1 kW array stack.

6.2. Stack design and demonstration

- Tested a 4 × 2 array, 50-layer stack that utilised proprietary ferritic steel interconnects, and electrolyte-supported cells, and produced 5.5 kW output. It was run for some 400 h of operation at various power levels and generated approximately 720 kW h of electrical energy.
- Developed a stacking concept based on sheet metal interconnects that promises lower costs and better lifetime.
- A 10 layer 2 × 2 array stack utilising this sheet metal interconnect technology has been tested at an output of approximately 400 W at 820°C for around 3500 h and has generated about 1.3 MW h of electrical energy. Better performing layers achieved a degradation rate of only 1–2% per 1000 h (Fig. 5).
- Constructed and successfully tested a 22 layer, 2 × 2 array stack utilising *anode-supported cells* operating at 760°C in moist hydrogen. During an unfortunate failure of the load, it produced 2.7 kW of power for 20 min, which subsequently shortened the life of the stack to only a few hundred hours of operation. Stability of the stack was good and aging effects not noticeable (Fig. 6).

6.3. System design and demonstration

- Constructed a proof-of-concept system for natural gas use that will enable system component verification for up to 5 kW stacks
- Established economic models and stack and system modelling capability
- Constructing a 25 kW SOFC module (natural gas fuel in to AC electricity out) (Fig. 7)
- Developed stack/systems monitoring and control software
- Identified and demonstrated stack-control regimes and strategies

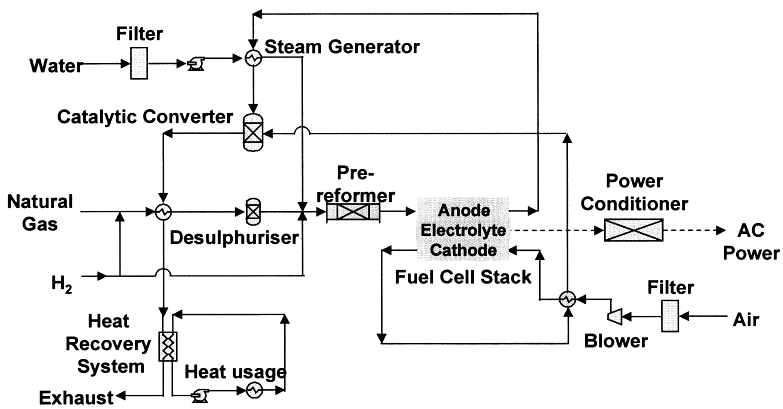

Fig. 7. Schematic diagram of basic system configuration.

7. Conclusion

Building a sustainable, growing business on a base of competitive, distributed-generation products — derived from planar (solid oxide) fuel cell, SOFC, technologies — is CFCL's goal. However, competitive positioning of planar SOFC technology in commercial markets will take significant commercial, financial and technical expertise. Market access and a good market-entry product are key to ramping production to volume levels quickly. Demonstrating prototype product and manufacturing capability is necessary to build market confidence. Having a technology base that can deliver the production cost and system reliability targets is the starting point.

Our experience to date suggests that CFCL is well on its way to achieving its business goal.

Acknowledgements

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