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Assessment of commercial prospects of molten carbonate fuel cells

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Abstract

The commercial prospects of molten carbonate fuel cells have been evaluated. Market applications, and the commercial criteria that the MCFC will need to satisfy for these applications, were identified through interviews with leading MCFC developers. Strengths, weaknesses, opportunities and threats (SWOT) analyses were carried out to critically evaluate the prospects for commercialisation. There are many competing technologies, but it is anticipated that MCFCs can make significant penetration into markets where their attributes, such as quality of power, low emissions and availability, give them a leading position in comparison with, for example, engine and turbine-based power generation systems. Analysis suggests that choosing the size for MCFC plant is more important than the target market sector/niche. Opportunities will exist in many market sectors, though the commercial market would be easier to penetrate initially. Developers are optimistic about the commercial prospects for the MCFC. Most believe that early commercial MCFC plants may start to appear in the first decade of the next century, the earliest date suggested for initial market entry being 2002.

Keywords: Molten carbonate fuel cells; Commercial; Market applications

1. Introduction

Molten carbonate fuel cells are approaching the early stages of commercialisation, having been under study and development for more than 40 years. Contemporary research into MCFCs started in 1950 by Ketelaar and Broers and much progress in terms of improving the materials, the performance and manufacturing techniques have been made since then. Scale up of MCFC stacks has now reached the position that systems as large as 250 kW to 2 MW have been constructed and demonstrated.

Carbonate fuel cells can operate on a number of fuels from hydrogen to CO-containing gases, including gasified coal and reformed natural gas. MCFCs are high-temperature fuel cells, which makes them suitable for combined heat and power applications (CHP). They also benefit from a relatively high efficiency (typically 50% HHV, for electricity production), and are deemed suitable also for large-scale power plants.

The high operating temperature of MCFCs offers the prospect of being able to internally reform fuels such as natural gas. The internal reforming concept simplifies the design of the MCFC plant in comparison with systems that employ fuel cells operating at lower temperature (e.g. the Phosphoric Acid Fuel Cell, PAFC). High temperatures do present a few design problems. Long start-up times are implied, expensive materials are needed, and a number of design challenges are encountered due to leakage, corrosion, and loss through vaporisation of the electrolyte.

The present study was undertaken for the DTI to review MCFC technology and to critically assess its status and the prospects for true commercialisation, in the context of the other fuel cell types and competing technologies.

2. Methodology

Questionnaires were prepared and sent to leading developers of MCFCs and supporting organisations. The questionnaires were aimed at obtaining developer's views on the following:

- size of application for which MCFC would be suitable
- the type of fuel that MCFC developers envisaged using
- geographical location
- prospective markets
- commercial requirements for the MCFC in each particular market and the relative importance of each market

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- commercial criteria that the MCFC would need to satisfy
- present development status of their technology
- technical and non-technical barriers to commercialisation
- present and projected costs of the systems and stacks
- present and projected environmental performance of the system
- external factors which will accelerate the commercialisation.

2.1. Strengths, weaknesses, opportunities and threats (SWOT) analysis

An analysis of market applications carried out by BG Technology showed that there are many criteria that are important for the intended applications. In addition, commercial feasibility also depends on the competitiveness of the technology compared with more conventional power generation technologies, and other fuel cell types. In evaluating the prospects for the commercialisation of MCFC technology, technological progress, the business environment (deregulation, liberalisation of energy markets, unbundling of energy business, etc.) and the advancement of competing technologies have to be considered.

The process for evaluating these criteria for the MCFC is termed SWOT analysis. In this, developers are asked to rank the relative importance of attributes of the technology to the customer (opportunities and threats), and compare these attributes with the relative strengths and weaknesses of the technology. Thus, the SWOT analysis is undertaken according to the following basis:

- *Strengths* are taken as being positive characteristics of MCFC technology that can be exploited to achieve the strategic performance goals.
- *Weaknesses* are taken as being those characteristics of MCFC technology that may inhibit or restrict market penetration.
- *Opportunities* are characteristics of the external environment that have the potential to help MCFC technology to achieve or exceed the strategic goals.
- *Threats* are characteristics of the external environment that may prevent attainment of the strategic goals.

SWOT analysis has been applied to the results from the questionnaires to analyse the strengths and weaknesses of MCFC technology for all stationary applications identified by the developers.

3. Results

The response rate was approximately 64%, though most of the main industrial developers replied. The responses from the questionnaire are discussed in the following sections.

3.1. Size of applications

The size of possible applications at which MCFCs could be aimed is generally thought to be from 100 kW to 10 MW, although the Japanese have interests in larger power stations of the order of 100 MW.

Combined cycle is expected to dominate power generation above 10 MW. There is some merit in MCFC combined cycle, since integrating MCFC with gas turbine bottoming cycles in hybrid power plants can achieve LHV electrical efficiencies of the order of 70%. However, it should be noted that it is generally more difficult to integrate a turbine with an MCFC than with an SOFC because the MCFC presents more difficulties in operating at elevated pressures as compared with the SOFC.

In the USA and Europe, the main markets are in the medium to large commercial 250 kW–3 MW range. There is general agreement that, below 250 kW, the market will be dominated by reciprocating engines and PEMs. The main competitors in the lower end of the co-generation market are gas engines, turbines and central power/steam boiler systems. There is a lot of interest in MCFC applications in the 250–400 kW range. Industrial parks, electroplating and commercial applications such as hospitals and shopping malls are being considered for MCFC deployment. Theoretically, 250 kW should be their minimum size. However, in the early stages of commercialisation, 500 kW seems to be the minimum economic size.

3.2. Choice of fuel

MCFC developers consider natural gas to be the fuel of choice for commercial systems. There is, however, much interest in coal gasification in Japan and Europe. Other fuels such as water digester gases, waste gas, landfill, biogas, petroleum refinery off-gas and methanol are also being considered for MCFC projects. For example, Ansaldo have an interest in using landfill gas and continue to work on gas clean-up for landfill gas applications.

There are likely to be considerable waste gas applications, particularly in the near term. Waste gases allow for higher capital cost of fuel cell plant given the presumed low cost of the fuel. High capital plant costs may also be justifiable because the costs of cleaning up waste gases prior to release into the environment can be avoided.

Some years ago, BCN considered coupling development of a 250-kW MCFC demonstration unit with a coal gasifier. More recently, BCN considered using a biogasifier product gas in an MCFC. MTU's interest in coal gas has been demonstrated through collaborative work with the German electric utility, RWE. They have run laboratory stacks of five cells on simulated coal gas. MTU have also considered using anaerobic digestor gas. In addition, ERC have run two stack tests on the side-stream of a gasifier at Danbury USA and a 20-kW plant on diesel fuel, using a gas processing system designed by Haldor Topsoe. ERC recognize that fuel flexibility of fuel cells drives new applications. Fuels like LNG and propane could be used with very little adjustment to the system. Fuels like coal gas, landfill gas, and digester gas can all be used after modifying the fuel processing system to handle their specific impurities.

In Japan, CRIEPI suggests that LNG will be used for 10-MW MCFC combined cycle applications and coal gasification gas for applications above 100 MW. LNG is the present fuel of choice, with coal gasification the preferred long-term option.

3.3. Commercialisation and markets

Developers were asked what parts of the world the commercialisation of their technology is being channelled towards. Some of the commercial ventures are subject to exploitation agreements between major developers.

ERC are initially targeting North America and Europe (through MTU) for early market entry, high value applications, but they recognise that very large markets exist elsewhere in the world. In some cases, a lack of a developed grid system drives the need for distributed generation even more than in North America and Europe.

IHI and Hitachi are presently working together on a 1-MW MCFC demonstration under the NEDO programme. For commercialisation, IHI are targeting Japan, Asia and then other parts of the World. Hitachi are aiming at the electric power business using gas derived from coal gasification.

The prospective markets for MCFC power plants are very difficult to quantify, with a wide range of estimates offered by developers and institutions. A common theme emerging from questionnaire returns was that there are large markets in the range 500 kW–1 MW and 1–10 MW in most countries including Japan, United States, Southeast Asia and Latin America.

3.3.1. United states

Edward Gillis predicted that US installed capacity per year in the first 5 years of market entry of MCFC will be 750 MW with 400 MW in the 100–500 kW range, 50 MW in the 500 kW–1 MW range and 300 MW in the 1–10 MW range. In subsequent years 5–10, with capital cost reduction expected to be $300/kW, the 100 kW–1 MW market is estimated to increase sixfold. The 1–10 MW market may increase by three times.

Ignoring market penetration, MC-Power estimated that the minimum total US markets for the 500 kW–1 MW range could be 739 MW in 2002, and 2801 MW installed power generation by 2008.

ERC estimate that the North American market for distributed power generation might grow from 2700 MW/year in 2001 to 6700 MW/year in 2008. The European market could grow from 2700 MW/year to 4300 MW/year over the same period. The Asian market is significant: China alone is expected to add over twice the US projected additions in this period. The sizes of applications, which will be important in these countries were thought to be:

- commercial self-generation of co-generation applications 250 to 3000 kW
- industrial self-generation of co-generation 1 to 10 MW
- large industrial and distributed generation > 10 MW

ERC predict that the commercial and smaller industrial (< 10 MW) sizes will be more important during the market entry period, whilst public acceptance is being fostered.

3.3.2. Europe

A.D. Little carried out a study that was funded by the Groupe European des Recherches Gazieres in 1990 of MCFC market penetration in Europe. More recently, MTU funded an extension of this work. These figures are a conservative assessment of the market for units above 100 kW. Since that report was published (1991), the figures will have changed as a result of German government 'green' taxes, as well as other factors such as the deregulation of the electricity supply industry.

The current consensus in Germany is that there is a possible market of 60 MW/year for stationary fuel cells in the 300 kW–2 MW range.

3.3.3. Japan

Japan has a very different market structure from the USA or Europe. There are fewer sites for sub-MW size CHP facilities; opportunities such as in the hotel market are already fully saturated with natural gas driven CHP plants that are unlikely to be replaced in the short term [1]. Hattori [2] from CRIEPI predicts that the residential and commercial sectors will be two of the most important driving forces in the investment of new power technologies in the near future. The annual rate of increase in the residential/commercial sector will exceed 3.5% until 2005 and then remain steady at 2% until 2010. However, there is a strong possibility that nuclear power generation may steal the market presently being targeted for the MCFC. Japan has a strongly regulated power industry, which has heavily invested in conventional power and nuclear power generation. The Japanese government's target of reducing the CO_2 emission volumes per capita in 2000 to the level of 1990 will be assisted by increasing the amount of nuclear power plant.

The prospective market for MCFC in Japan and Asia is predicted as distributed power plant (200 kW to 10 MW) and centralised power plant (10 MW). In Japan, IHI predict 20 MW/year with 10 plants in the 100–500 kW range and initially two plants in the 1–10 MW range.

3.4. Commercial requirements

In the questionnaires sent to MCFC organisations, the following commercial requirements were considered:

- modularity
- heat/power ratio
- efficiency
- lifetime of stack
- lifetime of plant
- weight
- footprint
- reliability
- cost/kW_e
- reliability/availability
- flexible heat to power ratio
- steam production
- emissions
- part-load characteristics.

For each application, the developer was asked to rank the relative importance for that particular application. The applications considered in this exercise included hospitals, shopping centres, remote military camps, power stations, industrial works, commercial locations, offices, and leisure centres. Most of the responses favoured applications in the range 100–1000 kW.

The results from the questionnaire were compiled in a bar chart as shown in Fig. 1. It can be seen that the most important requirements determined by the replies to the questionnaire were:

- efficiency
- plant lifetime
- reliability
- reliability/availability.

The least important commercial requirements were considered to be:

- weight
- footprint
- steam production
- part-load characteristics.

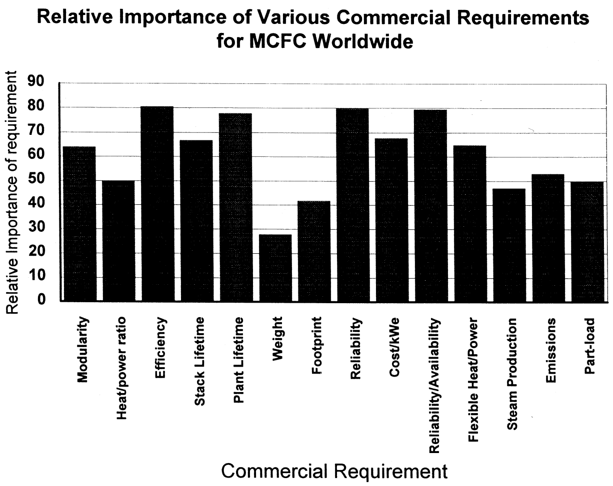

Fig. 1. Relative importance of commercial requirements.

The flexibility of the heat/power ratio was considered important in some applications where the high temperature of the MCFC was considered an advantage.

An additional requirement, suggested by MTU, is the ease of obtaining authorisation for use. The MCFC's intrinsic attributes of low noise, low NO_x, low sulphur associated with environmental acceptance may make it easier to obtain planning permission and safety authorisation. Developers and customers want turnkey systems, otherwise installation procedures can be long, tedious and too costly.

3.5. Commercial criteria that MCFC would need to satisfy

Fig. 2 summarises the strengths and weaknesses (SWOT analysis) of MCFC plant for all stationary power applications identified by the developers. These technical, as well as non-technical, barriers to commercialisation were averaged from the 18 responses, with suitable weightings being applied. In addition to those listed as commercial requirements in the previous section, noise was also considered as this was believed to be a possible barrier. The relative importance of this factor, together with all of the others considered, is shown.

Cost saving was the main issue raised by respondents; this applies in most circumstances, although, it cannot be considered in isolation.

The cost/kWh and the reliability of the fuel cell system have to be rationalised against the competing technologies before successful market penetration can occur. A capital cost of \$800–1200/kW_e for a fuel cell system is acceptable for most European markets. Fuel cell systems have significantly lower emissions than the competing technologies. This may be rewarded by various financial incentives for clean power such as CO_2 tax (climate change levy) and green credits.

For the USA, MC Power claim that the appropriate criterion is the delivered cost of electricity; variations in fuel costs, efficiency and stack replacement assumptions can make a \$1200/kW unit uneconomic and a \$2500/kW unit quite competitive when compared with retail alternatives. There are examples in the USA where a power installation was economically justifiable at nearly \$30,000/kW; the fuel cells involved represented \$14,000/kW with four units placed in parallel. MC Power are building a 1-MW unit for a waste water treatment utility. The utility chose a fuel cell unit because of the low emissions.

There is a consensus that capital cost is only one of the several key economic drivers for buyers and users of power systems. The total cost of energy produced and/or the value of energy received over the project's life, which should be at least 10 years, needs to be considered. This should include its form, availability and reliability. The primary components in the cost of energy include capital

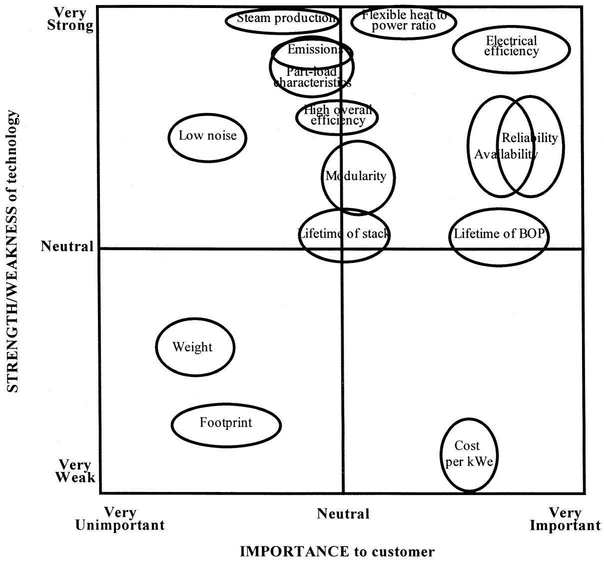

Fig. 2. Profile of the strengths and weaknesses for MCFC in commercial applications.

cost, operation, maintenance and fuel costs. Once capital costs are reduced, the cost of electricity generated by fuel cells is far more sensitive to installation, operation, fuel and maintenance costs.

Although power quality is not yet an issue in Germany, where customers are used to high quality, stable and secure electricity supplies, MTU proposed that deregulation in the electricity market may disrupt supply. At this point, fuel cell power quality may become important. MTU do not consider environmental performance to be a commercial driver. The ability to provide premium power will, however, be significant in early market.

3.5.1. Power station and distributed power plant applications

For applications above 1 MW, the cost of electricity produced by the MCFC plant would have to be lower than wholesale costs from existing power plants. Higher costs may be acceptable if offset with siting or environmental advantages. MCFC would have to have better load following capability, equal reliability, superior environmental performance with a footprint equal or less than existing power plants. MCFC will have to demonstrate power quality equal to or better than that of the grid.

An availability of 95%, including forced and planned outages, has been requested by ERC's buyer's group (FCCG) and this is typical of that required by others.

The environmental emissions must be below regulatory limits, especially in high cost applications where good environmental performance is part of the value of the fuel cell package. For example, negligible NO_x and SO_x emissions, and low CO_2 emission per kWh arising from high efficiency operation, is required. Other commercial criteria demanded may include low noise, unattended operation for smaller plants and an inherently safe design.

3.5.2. Hospitals

For a hospital application, high efficiency and a minimum of 5 years lifetime are required, with an initial stack life of 3 years. Hospitals also have a compelling requirement for steam. Low emissions are attractive, but few are prepared to pay the premium. Regarding load following, there should be a balance between the customer requirement and stack requirement. The MCFC stack cannot load-follow very well because the stack responds only slowly to changes in gas flows and compositions.

The cost of MCFC installations in hospitals will be based on an installed cost basis. Simple payback is not applicable, however, as any apparent savings should be amortised over a long period, typically 10 years. MC-Power are aiming for a Balance of Plant lifetime of 20 years.

3.6. Technical barriers and non-technical barriers to commercialisation of the MCFC

The following possible barriers to the commercialisation of the MCFC were considered:

Non-technical Barriers:	Technical Barriers:
energy costs	lifetime of stack
market dynamics	lifetime of balance of plant
	efficiency
	environmental issues including emissions and noise
	safety
	availability
	quality of power
	load following
	weight
	footprint
	heat/power ratio

The most important barrier to commercialisation of the MCFC was considered to be the energy cost. Capital costs and stack lifetime are also very important barriers, which have to be overcome. The relative risks of these barriers to commercialisation are illustrated below:

High Risk ***Low Risk***
<--->
Non-Technical Barriers
energy costs *market dynamics*

Technical Barriers
capital costs

3.6.1. Non-technical barriers

A view shared by most developers from Japan, US and Europe is that energy costs represent the main non-technical barrier for MCFC. Energy costs are presently too low and this makes investment in more efficient systems unattractive. It was suggested that energy costs may need to rise to greater than \$0.08/kWh to make MCFCs attractive.

ERC are more optimistic and suggest that present energy costs do not offer a barrier to MCFC commercialisation and that an increase in energy costs could accelerate commercialisation due to the MCFC's high efficiency.

There were concerns in the USA and Europe over market dynamics following deregulation, with great uncertainties apparent for future energy costs. Energy costs are becoming increasingly difficult to predict. For example, deregulation of the electricity market in Sweden has had the effect of reducing the price of electricity. Companies are now able to buy relatively cheap hydro-power from Norway. This is so competitive that producers in Sweden no longer want to operate base-load plant and prefer to buy the electricity from Norway.

Liberalisation of the energy markets tends to result in lower prices for both electricity and gas by different degrees in different countries. Regional variations may result in new opportunities for distributed power. There may be locations where MCFC can be economic.

The prospect of automotive fuel cells heralds a cheaper alternative to high temperature fuel cells. It should be noted that MCFC will also have to compete with alternative technologies that are fast advancing such as Stirling engines and small (micro-) turbines.

3.6.2. Technical barriers

3.6.2.1. Capital costs and operation and maintenance costs. Capital costs may hinder initial market entry for MCFC plant. To be competitive, figures of system costs < \$1000/kW and installed costs < \$1500/kW are commonly quoted. It has been suggested that the size of the market is inversely proportional to the installed capital cost of the system. Hence, even at \$3000/kW, a relatively small market could exist consisting of niche applications involving opportunistic fuels or premium power.

Operation and maintenance costs are expected to be low for MCFC plant. A figure of < \$0.02/kWh for operation and maintenance costs, including stack lease/replacement, has been suggested.

3.6.2.2. Efficiency, environmental issues and safety. Efficiency was not considered a barrier to commercialisation, the electrical efficiency for the MCFC being higher than most fuel cells except the SOFC.

Environmentally, the MCFC was also seen as having an advantage over most other technologies. This would, however, need to be demonstrated in long-term commercial field trials.

Most developers have decided that safety is not a barrier to market entry, though in the USA, steam plant normally requires attended operation. This is thought to be an unnecessary requirement for the MCFC and, therefore, MCFC plant should be exempted from local codes for attended operation. Developers are aware that there is a perception problem associated with hydrogen and possibly a regulatory code issue.

3.6.2.3. Stack lifetime. It is generally agreed that to achieve commercial credibility, the lifetime of the stack would have to be a minimum of 40,000 h with 8000 h of uninterrupted power at > 80% of rated power output. Lifetime could still be an issue for some components such as the cell matrix. The balance of plant should have a lifetime of 25 years.

3.6.2.4. Availability and quality of power. Availability is defined as the time during which useable power is generated and expressed as a percentage of total time, including downtime and start-up time. Availability should be at least 90%, but greater than 95% is preferred. There is little data so far on availability/reliability of MCFC technology, and this will be an issue until MCFC plants have been operated for long periods. Power quality is also a consideration, as with all fuel cell systems that use inverters.

3.6.2.5. Load-following. Load-following is seen as a market segment limitation rather than a barrier to commercialisation. Their high electrical efficiency and low emissions make MCFC plant best suited to base-load applications.

3.6.2.6. Weight. Weight was similarly viewed as a market segment limitation, though it may relate more to capital cost. For example, it could be an issue for transport, or if the application was to be used on the top of buildings.

3.6.2.7. Footprint. Footprint was thought to be a factor in some applications, but not a barrier. Competing technologies such as stationary PEM may have smaller footprints. More important than the footprint is transportability. The MTU hot module and BCN advanced system have been designed for transporting in standard European road haulage containers.

3.7. Present and projected costs of stacks and systems

Costs are a particularly difficult area to obtain accurate figures for and most developers were understandably reluctant to disclose current costs. The projected figures that developers were willing to provide were in the range \$1250–1470/kW for installed systems and stacks.

The first commercial MCFC units are expected to be available from US and European developers by 2002 at the earliest. Most developers predict that true commercialisation will not occur until the next decade, i.e., from 2002–2010.

Production rates in the first year, worldwide, were predicted to be 12–75 MW of installed capacity with a gradual increase depending on demand.

3.8. Present and projected environmental performance

Environmental performance has been considered as one of the advantages that MCFC technology has to offer over conventional technology. Three replies regarding environmental data were received from MC-Power, ERC and IHI. Table 1 shows estimated emissions quoted by one developer. The figures are similar from all three developers.

3.9. External factors which will accelerate commercialisation

The speed of regional deregulation and concern over emissions could affect the pace of commercialisation of MCFC. For example, with the advent of the Kyoto protocol, in which the developed nations agreed to limit their greenhouse gas emissions relative to levels emitted in 1990, the United States has agreed to reduce emissions from 1990 levels by 7% during the period 2008 to 2012. Such factors may have a significant influence on the development of efficient technologies such as MCFC. With localised environmental concerns, governments could encourage the move towards low emission, high efficiency energy generation systems through tax credits and subsidies.

On the political level, Germany is taking a lead in environmental issues, and may offer bonuses for clean power generation systems. In the USA, the Department of Energy has a buy-down program to reduce the cost to customers of early commercial units.

Higher energy costs and more stringent environmental drivers are confidently predicted. Present MCFC systems have noise levels of 60–70 dB(A), but developers project that this can be reduced to around 45 dB(A) in the future.

If the cost of energy or fuel increased for any unforseen reason, this could also affect commercialisation significantly. In Japan, for example, it is suggested that if a high demand for coal gasification arose, this could also benefit MCFC commercialisation.

Table 1
MC Power's estimated emissions using their MCFC technology for 500 kW units

Composition (vol.%)	Projected emissions for year 2005
CO_2	4.8
N_2	63.4
CO	< 5.0 ppmv
H_2O	23.4
O_2	7.6
Ar	0.8
HC	< 10 ppmv
NO_x	< 1 ppmv
SO_x	< 0.01 ppmv
Particulates	0
Noise at 20 ft	65 dB(A)

Perceived advantages of MCFC over conventional technologies may be limited. If an economically important application was found in which MCFC has unique advantages, this could accelerate commercialisation. An example would be a biogas application of MCFC. In such an application, the MCFC is tolerant to changes in the gas composition, and is able to generate power from very low heating value gases. In contrast, gas turbines and gas engines are much more critically dependent upon fuel composition and heating value.

3.10. Future prospects for the commercialisation of MCFCS

All replies to the questionnaire were positive and optimistic. It is generally believed that all technical and non-technical barriers to commercialisation can be overcome.

The next stage for the commercialisation of the MCFC requires the successful prototype power plant demonstrations to convince buyers of their durability and favourable operating cost. Satisfactory demonstrations at the MW scale, defined in terms of average percentage of rated capacity over a pre-set lifetime and full-scale operation, would encourage buyers to invest in MCFC. However, it is acknowledged by developers, that the cost of large demonstrations is very difficult to bear without further consolidation of BOP and system variants.

4. Conclusions

The general conclusion from this study is that the main developers of MCFC are committed to moving into the early stages of commercialisation. There are many competing technologies, but it is anticipated that MCFC can make significant penetration into markets where their attributes such as quality of power, low emissions, availability, etc., give them a leading position in comparison with, for example, engine- and turbine-based power generation systems.

Analysis, by BG Technology and others, suggests that choosing the size for MCFC power plant is more important, selecting a specific target market sector/niche. Opportunities will exist in many market sectors, though the commercial market would seem more accessible initially, especially hospitals, and perhaps hotels. On balance, it might be best to target a size of 300–400 kW_e for initial market entry. Further consideration should be given to the economies of mass production compared to economies of scale. Consideration should be given to the possible costs of combining units to give a larger system.

The study concludes that the main commercial requirements are high efficiency, long plant lifetime and reliability/availability for MCFC applications in the 100–1000 kW range. The major technical and non-technical barriers to MCFC commercialisation are energy costs, capital costs and lifetime of stack. Most organisations believe that these barriers can be overcome and that early commercial MCFC plants may start to appear in the first decade of the next century, the earliest date suggested for initial market entry being 2002.

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