FUEL CELLS

TECHNOLOGY DESCRIPTION

Fuel cells are electrochemical devices that are similar, in principle, to primary batteries, except that the fuel (eg hydrogen) and oxidant (eg oxygen) are stored externally. Fuel cells produce both electricity and heat directly, with individual cells typically generating a DC voltage of 0.7-0.8 volts and a power output of a few tens or hundreds of watts. Cells are assembled in modules known as stacks to provide a larger voltage and current. There are several types of fuel cell, usually categorised according to their electrolyte and operating temperature.

Main types of fuel cell

Type	Electrolyte	Operating temperature (°C)	Development status	Applications
Solid oxide fuel cells (SOFC)	A ceramic, solid oxide, zirconia	700-1000	Tubular systems available for demonstration; planar technology still under development	Commercial and residential CHP, power generation, ship propulsion, trains
Intermediate temperature SOFC (IT-SOFC)	A ceramic, solid oxide, ceria-gadolinia	650-750	Fundamental research still required	Commercial and residential CHP, power generation, ship propulsion, trains
Molten carbonate fuel cell (MCFC)	Molten lithium carbonate	630-650	250kW systems being demonstrated, also previously 2MW, but further R&D needed	CHP, power generation, ship propulsion, trains
Phosphoric acid fuel cell (PAFC)	Phosphoric acid	190-210	200kW systems offered for sale, but not commercially competitive in the UK	CHP, power generation
Alkaline fuel cell (AFC)	Potassium hydroxide	50-200	Fully developed for space systems Transport systems available for initial demonstrations	Space, transport
Solid polymer fuel cell (SPFC), also known as proton exchange membrane (PEM) fuel cell	Sulphonic acid incorporated into a solid polymer membrane	50-90	250kW CHP systems Several cars and buses being demonstrated, but not yet commercial	Commercial and residential CHP, distributed power, portable power, transport
Direct methanol fuel cell (DMFC)	Sulphonic acid incorporated into a solid polymer membrane or sulphuric acid solution	50-110	Still at R&D stage with much fundamental research still required	Portable power, possibly transport

MARKETS

The enormous global effort over the past ten years to develop fuel cells was initially driven by the prospect of improved electrical efficiency and better air quality in urban environments. Today, they are regarded as an important potential option for improving the sustainability of energy use, reducing greenhouse gas emissions and reducing the emissions associated with transport energy use.

Fuel cells can, potentially, be used for large and small-scale electricity generation, combined heat and power (CHP), transport of all types (both as a potential replacement for the internal combustion engine and to service auxiliary power requirements), and as a battery replacement for portable power applications such as power tools, laptop computers and mobile phones.

In general, the lower-temperature fuel cells are better suited to mobile and portable applications, whereas the high-temperature fuel cells are more suited to stationary power and CHP:

- The SPFC is a strong candidate for transport and portable power applications because of its high power density, rapid start-up and load-following characteristics: it is also a candidate for distributed power generation.

- The AFC has been developed as a range extender for battery-powered vehicles.

- The DMFC is a long-term option for transport, as it would remove the need for a reformer on board the vehicle: it is also of interest in niche markets for portable power applications.

- The PAFC has been demonstrated in both CHP and in buses.

- The high temperature SOFC and MCFC are best suited to stationary power and CHP applications, where rapid start-up and load-following are less important and where the waste heat can be effectively utilised. Depending on the scale of power generation required, the high temperature fuel cells would probably be used in combination with gas/steam turbines.

Although fuel cells have already been supplied to specific sectors (eg the space industry), and while demonstrations are either under way or planned in almost all market sectors, this level of activity does not, in any way, constitute a significant market penetration.

However, there is a strong and growing market pull for fuel cells, with initial market entry for applications that can stand a higher cost of energy.

For the time being, and for a variety of reasons, the main market pull is in North America. In California, for instance, 10% of new cars are required to have zero emissions by 2003. This has proved a powerful market driver, particularly for the SPFC. In Europe, some cities are restricting the use of cars in an attempt to reduce emissions and improve air quality. This, too, is providing a strong market pull for fuel cells, from public vehicles in general and particularly where there is a requirement for low emissions. Significant market penetration is expected, initially, in the bus sector where the application requirements are less demanding than in the car sector, and where it will be easier to establish suitable refuelling and maintenance regimes.

Cars currently represent the most substantial potential market for fuel cells, but the cost targets are very demanding and car manufacturers will need to make a significant investment commitment if the resources required for volume manufacturing are to be made available. Most car manufacturers are forecasting initial sales in around 2004, but significant sales are not expected until 2010. However, by 2025, the fuel-cell-powered car market could be worth as much as US$8 billion per year.

Distributed power generation and CHP have a weaker market pull than the automotive sectors, but the cost and performance requirements are less demanding. SPFC systems could find early commercial applications in these sectors, and sales to the distributed power generation sector have already begun. However, high temperature fuel cells are not expected to achieve significant market penetration for some time. Overall, the stationary heat and power markets are forecast to grow to around US$3 billion per year by 2020.

BENEFITS

Fuel cells offer the prospect of:

- high electrical efficiency
- significantly lower emissions of pollutants than conventional energy conversion technologies
- reduced greenhouse gas emissions (particularly when using hydrogen produced from renewable energy sources)
- improved air quality in urban and industrial areas
- quiet operation
- modular construction
- the facilitation of embedded generation
- high quality electricity.

TECHNOLOGY STATUS

Solid oxide fuel cells

The SOFC is one of the most promising fuel cell systems currently under development. A 100kW$_e$ unit that uses a tubular cell design has been demonstrated in the Netherlands. In California, a 220kW$_e$ SOFC/micro-gas-turbine hybrid system has achieved 60% efficiency (based on the lower heating value (LHV) of the fuel) in a 110-hour factory test prior to demonstration. There are further plans for demonstrating hybrid cycles of up to $2MW_e$.

In the longer term, planar designs are expected to offer greater prospects, largely because of their potential for lower-cost manufacture. However, at present, much work remains to be done in the development of such designs. Other design concepts are also being explored.

Solid polymer fuel cells

Because of a massive global effort to develop SPFC technology for automotive markets, considerable progress has been made in addressing the development issues, and manufacturing costs are falling rapidly. Most of the major car companies have demonstrated fuel-cell-powered cars, and fuel-cell-powered buses have been evaluated on commercial routes in North America and in Europe. In addition, stationary power systems capable of delivering $250kW_e$ are now becoming available, although the price of these demonstration units is still high at around US$6,000 per kW_e and they are still some way from being commercially competitive.

Alkaline fuel cells

The AFC is a relatively simple device that offers the prospect of low manufacturing costs. It was the first fuel cell technology to be developed, as part of the space programme. The AFC is usually limited to operation with pure hydrogen and air. However, because the concentrated potassium hydroxide electrolyte readily absorbs carbon dioxide (CO_2), which can severely degrade performance, any CO_2 in the air supply must be removed.

Although the hydroxide electrolyte can give excellent electrochemical performance, current designs (other than those for space applications) have a relatively low power density and have been developed primarily as on-board battery chargers for electric vehicles. However, the AFC could be suitable for depot-serviced vehicles, such as local delivery fleets, and it is likely to become more important if hydrogen becomes more widely available as a transport fuel.

Molten carbonate fuel cells

The need for CO_2 recycle and the resulting system complexity has meant that the development of MCFC technology has focused on large-scale applications. A $2MW_e$ plant has been demonstrated in the USA, but problems with the fuel cell stack have limited its operation: the plant achieved system electrical efficiencies of 48-53% (LHV). Smaller units have operated for periods of more than 5000 hours on simulated coal-derived fuel gas and natural gas.

Recent progress in system simplification suggests that the technology will be applicable down to a scale of ~$250kW_e$. Two $250kW_e$ systems have been demonstrated in the USA and Europe for periods of, respectively, more than 3000 hours and more than 1500 hours, and a series of four field demonstrations is planned for the near future. Early tests of two $250kW_e$ stacks in Japan indicate that an efficiency of 45% (LHV) is obtainable, together with a lifetime of 10,000 hours.

Phosphoric acid fuel cells

The PAFC is the most developed of the fuel cell types and is available commercially, though not yet at commercially competitive prices for its principal markets.

There have been more than 200 demonstrations of PAFC technology in stationary power applications, usually as a 200kW$_e$ packaged unit operating on natural gas. The plant has proved to be very reliable and, on natural gas, has achieved electrical efficiencies of ~40% (LHV). There is also significant PAFC development in Japan where more than 100 plants, ranging in size from 50kW$_e$ to 11MW$_e$, are operating in a range of applications.

Doubts remain over whether this technology will achieve the cost reduction necessary to be truly competitive in locations other than those where electricity costs are high and dispersed generation is preferred, eg Japan.

TARGETS FOR COMMERCIAL COMPETITIVENESS

Fuel cells are currently commercially competitive only in narrow "premium power" niches where reliability and quality of electricity are of primary concern or where no other technology is appropriate. Among the more mainstream markets, fuel cells are beginning to make minor inroads into the distributed power/CHP sector, again usually where no other technology is appropriate.

Irrespective of the market, fuel cells must be able to compete with conventional technologies in an environment where performance and value for money expectations are extremely high, and where lack of experience/familiarity is a significant barrier. They must, at least, be capable of matching the energy cost (a combination of capital and operating costs and lifetime) achieved by existing conventional technologies.

System capital cost targets are, typically, £30/kW$_e$ for passenger car and light commercial vehicle "engines" (more for auxiliary power units), £120/kW$_e$ for buses, £100/kW$_e$ for residential CHP, £500/kW$_e$ for distributed power and £800/kW$_e$ for commercial-scale CHP. System lifetime targets range from 5000 hours for passenger cars to 20,000 hours for buses and 100,000 hours for large stationary power applications.

RESEARCH AND DEVELOPMENT ISSUES

For all types of fuel cell, research is needed to develop and evaluate the materials and fuel cell systems components that offer the prospect of low-cost mass production while meeting the demanding targets for commercial competitiveness.

It is vital for components to be developed from an integrated systems perspective that is driven by the application requirements. Novel system concept design work should also be pursued.

In the case of road transport, fuel choice remains a source of great uncertainty, and there are many candidate fuels. Compact, responsive fuel processors are required for carbonaceous fuels. For hydrogen, fundamental R&D is needed into effective means of storing sufficient hydrogen on vehicles to give them an adequate range.

There is also a great need to gain experience in systems integration, installation, maintenance and operation, to establish system durability, and to demonstrate the potential benefits of fuel cells to operators and the public. Prototypes, demonstrations and field trials are required to provide essential information on the performance of fuel cell systems under conditions that are representative of commercial applications.

NON-TECHNICAL ISSUES

The widespread deployment of fuel cell systems would also require an effective framework of legislation, standards and codes of practice governing commercial manufacture, planning, and safe operation and maintenance.

UK INDUSTRY STRENGTHS

The UK has significant strengths in several key areas:

- materials and catalyst technology for fuel cells and reformers
- the design of fuel cell stacks
- the "balance of plant" (BoP) for stationary applications.

The UK also has strong capabilities in system design, packaging and systems integration, and production engineering. There are world-class power plant vendors with significant activity and manufacturing in the UK. Important opportunities are therefore likely to exist for UK industry in the design, manufacture, installation and maintenance of fuel cell systems, particularly for stationary power and CHP applications.

There are good quality research teams in UK Universities, with world-class expertise in key areas such as materials and catalysis. Equally important is the fact that many of the global energy companies (eg Shell, BP) have significant R&D capabilities in the UK.

A major difficulty in the car sector is the fact that the major car manufacturers' development programmes are located overseas. This reduces the opportunity for a DTI programme to make a significant contribution in the car sector, although some UK companies are important participants in these international initiatives.

In the bus sector, the UK has an excellent coach-building industry, although chassis and engines are largely supplied by companies whose development activities lie outside the UK. This again reduces opportunities for a DTI programme to work with key players.

RATIONALE FOR A DTI PROGRAMME

There has been a huge global effort to develop fuel cells in the last ten years, and major programmes are in place in the US, Japan and Europe. Although, initially, most of the funding for these programmes came from government, there has been a rapid growth in the level of industrial investment as the commercial prospects for fuel cells have become clearer.

This is particularly the case in the automotive sector, where the major car manufacturers all have significant development programmes.

The UK Department of Trade and Industry (DTI) initiated a research and development programme to assess the prospects for advanced fuel cells in April 1992. This programme, in collaboration with industry, aimed to tackle key development issues and reduce uncertainty. The results of its assessments of the prospects for fuel cells in the car, bus and CHP/distributed power sectors were published in 1999. The overall conclusion was that, although considerable further development was needed before fuel cells were a commercially competitive option, and although more field trials and demonstrations were required, there appeared to be no major show stoppers.

It follows from this that fuel cells could make a major contribution to the sustainability of energy use in the UK. They also present a significant potential opportunity for industry. However, while there is a growing national interest in their development and application, the commercial prospects are still unclear, while the timing and value of future markets, and the energy and environmental benefits that would result, remain uncertain.

Fuel cells offer the prospect of considerable environmental advantages – high efficiency, very low emissions levels for pollutants such as oxides of sulphur (SO_x) and nitrogen (NO_x), and reduced levels of CO_2 (on a well-to-wheels basis). The deployment of fuel cells could help the UK meet its greenhouse gas commitments, although they are unlikely to make a significant contribution prior to 2010. They could also contribute to a substantial improvement in air quality in urban and industrial areas.

The adoption of fuel cells in the UK can be expected to enhance the diversity and security of national energy supplies. Fuel cells are also a key enabling technology for a potential hydrogen economy based on renewable energy.

Fuel cells are an attractive potential option for many major and niche markets, although much work remains to be done before the commercial prospects are truly understood. Two things have already become clear:

- Substantial markets are developing for fuel cell technologies, systems and ancillary components.
- Fuel cells represent a rapid growth industry, and one that is unlikely to slow down for several decades.

From the point of view of the industry, there are significant and continuing technological and market uncertainties. The commercial risks are high and the commercial prospects uncertain. Without assistance, UK manufacturers are unable to commit to the large-scale and long-term investment that is necessary if they are to become major players in this field.

Similarly, the widespread adoption of fuel cell technology in the UK, whether for transport or for stationary power, is inconceivable until significant operating experience has been gained through demonstration programmes. UK demonstrations will not take place without government support.

Several conclusions can be drawn from this:

- A UK Programme is necessary to encourage greater investment in fuel cells, and particularly investment in longer-term development.

- A UK Programme could be a catalyst, encouraging innovation that might, in the longer term, give the UK a competitive advantage in this field. It could help to nurture ideas in all technology areas, facilitate the greater co-ordination of activities within the UK, support the generation of intellectual property rights (IPR), and help to exploit these IPR through manufacturing, joint-ventures or licensing agreements.

- A UK Programme could also provide a useful means of channelling the efforts of UK companies, ensuring that they take full advantage of European and international opportunities for collaboration.

TECHNOLOGY ROUTE MAP FOR THE DTI PROGRAMME

The suggested actions and targets are based on published benchmarks for major fuel cell development programmes around the world as well as in the UK. Achievement of these targets should give the UK a competitive position in certain fuel cell markets.

Activity	Target date
Construct and evaluate a novel SPFC stack with the following characteristics: • capacity: >50kW_e • power density: >1kW/litre • pressure: <2bar_g • CO-tolerant to at least 100ppm • performance degradation <1% over 1000 hours.	2003
Construct and evaluate a novel SPFC stack of ~1kW_e, with a power density of ~500W/litre and operating at ambient pressure.	2003
Construct and evaluate a ~20kW SOFC system operating on natural gas.	2003
Design, construct and evaluate a compact integrated auxiliary power unit (APU) of ~5kW, together with fuel reforming facilities.	2003
Identify in detail those component technologies in which the UK could gain market leadership and the most effective means of supporting the associated development.	2003
Ensure that the UK has clear permitting systems/approval frameworks in place for the operation of fuel cell vehicles and power plant. Achieve connection agreements for systems of ~1MW and a few kW.	2004
Identify and evaluate a range of possible market enablement measures that are likely to serve UK interests the most effectively.	2005
Construct and evaluate a novel, planar SOFC stack of ~20kW_e that internally reforms natural gas and delivers an efficiency of >50% (LHV). The stack should be capable of manufacture using a viable (if not yet proven) process, and with materials costs of less than US$300/kW.	2005
Build and evaluate a compact, integrated, self-sustaining system around a	2005

~50kW$_e$ SOFC stack, achieving an electrical efficiency of >40% (LHV).	
Design, construct and evaluate a compact, responsive, natural gas fuel processor, scaleable between ~1kW and ~50kW, and hence suitable for residential through to small commercial CHP systems. The system should achieve a power density of >1kW/litre, a performance degradation of <0.5% in 1000 hours, <10ppm CO output, and a 10,000-hour operating life.	2005
Design, construct and evaluate a compact, responsive, liquid-fuelled fuel processor, suitable for passenger cars, that achieves a power density of >1kW/litre, a performance degradation of <0.5% in 1000 hours, <10ppm CO output, and an operating life of 10,000 hours.	2005
Develop and evaluate a viable hydrogen storage system suitable for passenger cars.	2005
Review the prospects for MCFC, DMFC, IT-SOFC.	2005
Build and evaluate a pressurised SOFC stack of ~50kW$_e$, complete with immediate BoP and control system.	2006
Develop and demonstrate in the UK an integrated pressurised SOFC/gas turbine (GT) hybrid system of ~1MW$_e$, complete with BoP and control system and with well-optimised distribution between SOFC and GT.	2008
Evaluate a small fleet of fuel cell vehicles on commercial routes in the UK.	2010
Demonstrate a series of at least four fuel cell systems in commercial and residential applications for stationary power in the UK.	2010
Subject to the above targets being successfully met: • conduct extended field trials of passenger cars throughout the UK • conduct extended field trials of distributed power and CHP fuel cell systems throughout the UK.	Post 2010
Subject to the continued good progress of fuel cells towards commercial competitiveness and the provision of energy and environmental benefits, implement a market enablement scheme to encourage widespread market deployment in the UK.	Post 2010