13 - Fuel Cells

The promise of endless, cheap electricity that is too inexpensive to meter is the dream of many advocates of fuel cell technology. The view held by those working in this technology is much more subdued. Fuel cells are commercially available but this technology has not reached levels that are competitive with coal-fired power stations.

Fuel cells operate through a chemical reaction that releases heat, direct-current electricity and some emissions. In this sense, fuel cells can be thought of as a battery that is recharged with a chemical rather than electricity. Fuel cells operate at low or high temperatures and are best at providing a steady supply of power rather than varying demands or surges.

The more popular types of fuel cells use hydrogen as the energy source with a range of electrolytes used for the electrochemical reactions. The attraction of fuel cells is that they produce no harmful exhausts and have high efficiencies. If the hydrogen fuel is produced using renewable energy sources, such as electrolysis from photovoltaic cells, the entire energy conversion system produces no harmful waste.

However the challenges facing the widespread adoption of fuel cells are:

- Hydrogen is comparatively expensive to produce and difficult to compress;
- Hydrogen distribution systems need to be developed for use by the transport industry or in distributed generation; and,
- Fuel cell technology requires much more research and development to reduce cost of generation.

Issues Relating to Commercialisation

There are major, subsidised programs in Japan, Europe, the United States and Canada. In 2002 Japan committed $330m for research into fuel cells for transport and stationary power applications. The European Commission allocated $3,450m to be spent over the next four years after having spent $213m between 1999 and 2002.[1]

The United States announced in February 2003 that $2,800m would be spent on fuel cell technology including the FreedomCAR and FreedomFUEL initiatives.[2] Canada has Ballard Fuel Systems as a domestic company that has been working with DaimlerChrysler and the Ford Motor Company who have invested over $800m in the company and DaimlerChrysler intends to invest a further $1,670m over the next four years. In Australia, the CSIRO is working with Ceramic Fuel Cells to develop fuel cell prototypes and received $15m from the Department of Industry, Science and Resources in 1998.[3]

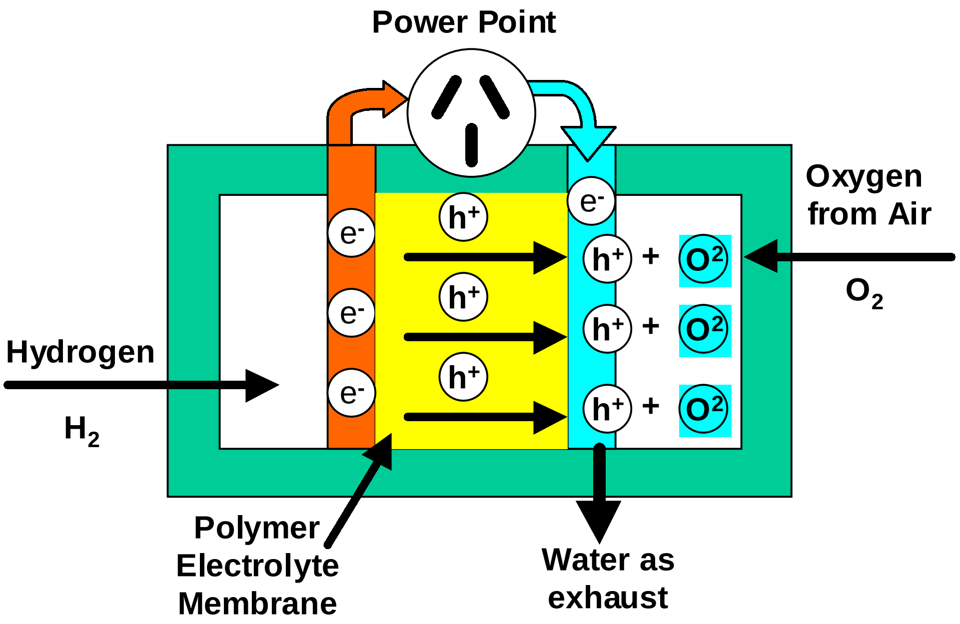
Throughout the world over the next four years some $7.85 billion will be spent on fuel cell technology. This represents a significant investment and some hope that new innovations will come from research in this emergent technology area. An increase in the economies associated with mass production can provide for a much lower cost of manufacture.[4]

How a Fuel Cell Works

The first fuel cell was developed by the British physicist William Robert Grove in 1839. The device he created was able to reverse the electrolytic process to covert hydrogen and oxygen back into water. As electrolysis uses electricity to separate the two elements from water, a fuel cell combines the two elements thereby creating electricity, heat and water.

The main component of a fuel cell is a catalyst-coated electrolyte that is placed between two plates (an anode and a cathode). On one side is preferably pure hydrogen and on the other side is oxygen in the form of normal atmospheric air. The hydrogen permeates the electrolyte and recombines with the oxygen to form water. However during the process, the hydrogen atom releases an electron when it passes through the electrolyte. This electron is left on the hydrogen-side anode and is transferred to the oxygen-side cathode by means of a connector. It is at this point that there is a direct-current energy flow that is able to be used.[5]

Figure 13.1 – Fuel Cell Process



The process is clean and is scalable with additional plates being added to increase the amount of power to be produced. However, hydrogen is not easily obtained and must be formed by electrolysis or be derived from fossil fuels such as reforming natural gas or through a "clean" coal process.[6]

Types of fuel cells

The application of fuel cells can be divided into three main areas. These are:

- Stationary power – commercial or domestic generation systems
- Transport – for use in vehicles
- Portable – to power mobile devices such as radios, information technology equipment
- Micro – to power mobile telephones and personal digital assistants

There are around seven popular types of fuel cells. The most commercialised is a Phosphoric Acid (PAFC) fuel cell and is primarily used in stationary generation. The Proton Exchange Membrane (PEM or PEMFC) is primarily used in transport applications. For portable applications, there are a number being trialed and includes Zinc-Air (ZAFC), Direct Methanol (DMFC) and the Proton Exchange Membrane (PEM).[7]

Other types of fuel cells include the Molten Carbonate (MCFC), Solid Oxide (SOFC), and Alkaline (AFC). A review of the composition of a fuel cell, the operating performance, the chemical basis and efficiencies would be fairly lengthy and are not included in this report. There are a number of reference materials available for further study.[8] Table 13.1 – Fuel Cell Attributes outlines some of the more salient aspects of each of these technologies.

Table 13.1 – Fuel Cell Attributes [9]

Type	Fuel	Electrolyte	Operating Temperature Celsius	Efficiency Percentage
Phosphoric Acid	non-pure hydrogen	liquid phosphoric acid	150-200	40
Proton Exchange Membrane	pure hydrogen	poly-perflouro-sulfonic acid	80	30
Molten Carbonate	wide range of fuels	lithium, sodium, or potassium	650	60
Solid Oxide	wide range of fuels	zirconium oxide	700 - 1000	60
Direct Methanol	methanol	poly-perflouro-sulfonic acid	50-100	40
Alkaline	Pure hydrogen	alkaline potassium hydroxide	300-400	70

High temperature fuel cells are able to be used in a cogeneration or indirect heating system. This can raise the overall efficiency of the fuel cell to around 80 per cent. Some fuel cells such as Molten Carbonate and Solid Oxide are able to use not only hydrogen but carbon monoxide, natural gas, and propane.

Fuel production, storage and distribution

Production

While hydrogen is available throughout the world in seemingly limitless quantities, hydrogen is difficult to store and transport. Ideally, hydrogen could be produced by using photovoltaic produced electricity to form hydrogen and oxygen through electrolysis. This process would create no emissions what so ever. Unfortunately this is currently the most expensive way to produce hydrogen.[10]

A less expensive way to produce hydrogen is through a steam reforming process using a fossil fuel. As these fuels can be easily transported and reformed near the fuel cell, this is becoming the preferred method of manufacture. However during this reforming process carbon dioxide is released and therefore the process contributes to greenhouse gas emissions.

The CSIRO is working on a process where natural gas is reformed using a solar concentration dish to separate the natural gas into hydrogen and carbon dioxide.[11] This process and others are not the ultimate goal but can be viewed as a transitional path towards the development of a hydrogen economy. This allows the fuel to become available to feed the fuel cells while technological advancements can be made.

Another important goal is for the hydrogen to be pure of contaminants. Ideally, fuel cells will operate best if the fuel used is without other elements or molecules as the electrolyte is designed to remove only an hydrogen electron from the atom and allow it to pass through.

However if there are other molecules in the gas, these molecules will remain on the electrolyte and reduce its efficiency. Methane from land fill sites often contains impurities from the range of decomposing materials buried. When the electrolyte is contaminated it requires replacing at a substantial cost. The goal within the research and development of fuel cells is for this to occur every five years of operation using clean fuels.[12]

Storage

Hydrogen does not easily compress however methanol is able to be handled in a similar way to petrol. Hydrogen tanks are usually engineered to contain hydrogen at around 350 atmospheres and there are some prototype tanks at 700 atmospheres. Interestingly in transport applications, a personal automobile will require only around three kilograms of hydrogen to travel 200 kilometres.[13] The tank to contain the hydrogen will weigh several times more.

There is a tremendous amount of work being undertaken to find methods of storing hydrogen at relatively high temperatures and in light-weight containers. One possible method is to compress hydrogen and water at very high pressures and comparatively high temperature (-24 degrees Celsius) until the hydrogen is trapped in the ice crystals as a clathrate. As water freezes, it expands and can form a “cage” of ice in which another molecule such as hydrogen can be trapped. This process occurs naturally with methane in permafrost conditions but can also be created using various temperatures and pressures. This clathrate can then be stored at low pressures using liquid nitrogen as a coolant.[14]

Other methods of storing hydrogen use a solution of sodium borohydride and water at the same temperature and pressure as petrol[15] or encapsulating hydrogen in sodium hydride pellets that release hydrogen when mixed with water.[16]

Distribution

The distribution of hydrogen is currently very expensive. As liquid hydrogen needs to be kept at a high pressure, a tanker is able to carry only around 3,600 kg of hydrogen. A petrol tanker by comparison can carry 30,000 kg of fuel. Hydrogen in a liquid form (and therefore more compact) needs to be stored at -253 degrees Celsius and this requires additional energy.[17] Therefore the reforming of fossil fuels on site or in the vehicle are appearing to be the most efficient methods of utilising hydrogen for fuel cells.

Applications

Stationary

The Phosphoric Acid fuel cell in the late 1990s was the dominant technology for stationary generation. There are estimates of around 530 systems built and operated recent years with Solid Oxide and Molten Carbonate systems increasing.[18] Some of these systems operate at levels as high as 200 kW and while the demonstrated reliability is between 10,000 and 20,000 operation hours, the costs of generation are very high. The cost per kW can be between $6,500 to $20,000. At this price, the technology will only have application in premium energy situations and will need to fall to a price comparable with other renewable energy sources.[19]

Transport

Road transport in Australia consumes around 79 per cent of transport energy resources of which two-thirds is consumed by passenger vehicles. The primary fuel is petroleum and the world's primary energy resource, oil, is a finite resource. Australia is facing an increasing imbalance in fuel consumption and oil discovery. This is likely to lead to a $7 billion balance of payment short fall with 60 per cent of Australia's oil being imported by 2010.[20] The development of alternative fuels should be a priority.

Commercial

Fuel cells have been trialed in busses in Europe for a number of years. The primary producer is DaimlerChrylser in conjunction with Ballard Power Systems using a Proton Exchange Membrane (PEM) as this fuel cell is able to provide for high power requirements that would be used during acceleration. There is currently planned a trial of some 33 busses worldwide with Perth, Western Australia included.[21] These busses are able to travel around 200 kilometres on a tank of hydrogen with 70 passengers.[22]

Some of the difficulties encountered in this context is the need to carry the fuel with the vehicle. The fuel, hydrogen, in a liquid form is relatively light for its energy capacity. However to liquefy hydrogen, high pressures of around 350 atmospheres are required and this requires very strong tank. These tanks have an aluminum internal liner to contain the hydrogen and a strong carbon-fibre cover. For large vehicles the weight of the tanks and fuel cell does not present a problem.

This type of technology is able to be readily used by public transport or fleet vehicles as these vehicles would (or could) return to a depot for refuelling. The return to a single point is necessary as the infrastructure for the distribution of hydrogen would need to be built. Additionally the "exhaust" for these urban vehicles would only be water and therefore have no impact on air quality. The water could be stored but more likely released onto the street. While this does not present a problem for Australia, it will cause difficulties in the northern hemisphere where freezing temperatures are common thus causing a potential hazard with frozen water on the roadway.

Industrial

Prototype fuel cell vehicles for industry have not been developed at the same rate as stationary generators. At this time of this research there were very few available. One application is in the mining industry where a battery-powered locomotive has been refitted with a fuel cell.

The advantages of this is that the refuelling of the fuel cell requires one hour compared to the eight hours required for the lead acid battery. The locomotive is also lighter and runs more quietly.[23] The application of large fuel cell powered load, haul, dump (LHD) would avoid the need for large ventilation systems in long-hole mining operations as there would be no emissions.

Private vehicles
A number of automotive manufacturers are producing fuel cell prototypes. These include DaimlerChrysler's NECAR5, Honda's FCX, Nissan's X-Trail FCV, Toyota's FCHV-5, General Motor's AUTOnomy and Ford's Focus FCV. In all, around $13 billion has been spent by motor vehicle manufacturers worldwide on fuel cell technology.[24]

The US Department of Energy believes the full commercialisation of fuel cell private vehicles will not occur until around 2020.[25] While fuel distribution issues have been discussed above, motorists will need to be more patient with fuel cell powered vehicles as the refuelling process is expected to take at least twice as long.[26] A transitional approach has been recommended where fuels such as methanol (which is as manageable as petrol) is used with reforming taking place on-board. The use of methanol avoids the need to create a hydrogen distribution system and is less expensive to install but difficulties remain in meeting high energy requirements for acceleration.[27]

Portable Fuel Cells

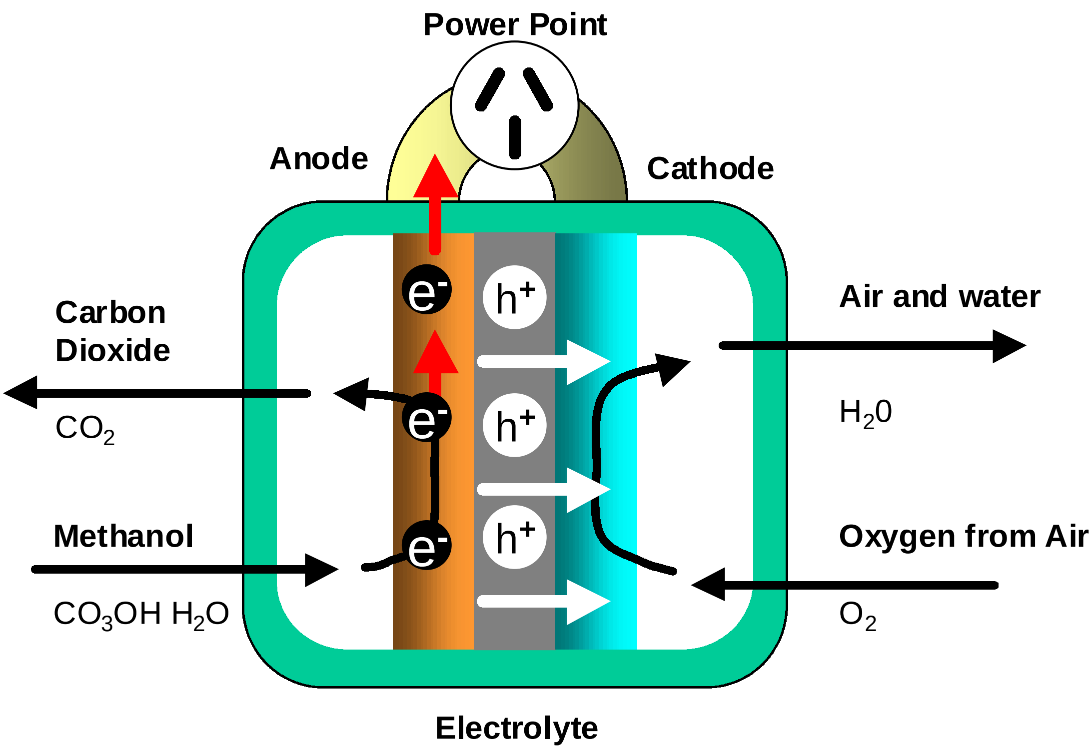
Portable fuel cells have been in use by the U.S. military for a number of years. While some fuel cells are termed "portable", a vehicle is required to transport the fuel cell. In this section, a portable fuel cell is defined as a device that can be carried by a human being. In this range there are around 1,700 systems that have been built and operated worldwide with power ranges between 1 watt to 1.5 kW.[28] These systems are usually Proton Exchange Membrane (PEM) or Direct Methanol (DMFC).

Zinc-Air fuel cells have been used by the military. These systems work on the electrochemical oxidation of metallic zinc with atmospheric oxygen. As this technology does not use a volatile fuel (zinc reacts with oxygen rather than using hydrogen) it is safe to use should it be struck with a projectile. In one test by the developers the fuel cell was struck with two rounds of gun fire and continued to work without igniting.[29]

Micro Fuel Cells

This area will see the first wide-spread use of fuel cell technology. While the popularly used lithium-ion batteries are lighter and more powerful than previous technologies, these batteries are not sufficient for wireless, always-on Internet connections. As a result, these devices have limited 'talk-time' and need to be recharged on a regular basis. Fuel cells are able to provide for around ten-times the power-to-weight ratio as lithium-ion batteries and can be carried by the user on a belt or contained within clothing. Due to issues of heat and safety, the preferred fuel cell technology is the Direct Methanol Fuel Cell (DMFC).[30]

Figure 13.2 – Direct Methanol Fuel Cell Operation



There are around 25 companies currently working on micro-fuel cells.[31] Toshiba is planning to launch a fuel cell powered notebook in 2004 along with Casio Computers.[32] The Smart Fuel Cell company is actively working on this technology. The Smart Fuel Cell product weighs around two kilograms, is about the size of half a brick and provides 40 watts of power for eight hours on a single 175 millilitre ampoule of methanol. An even smaller fuel cell is being developed by Case Western Reserve University in Ohio that is just one centimetre square and a few millimetres thick. This fuel cell is able provide low levels of power for around ten hours. [33]

These types of fuel cells will be able to achieve high levels of manufacturing production and provide for decreasing prices as product acceptance increases . Simplicity of use and easy refuelling will be a core requirement. However, safety issues still need to be resolved as methanol is a highly flammable material. Additionally the idea of having this type of equipment in an aircraft cabin for powering notebook computers may be viewed as a safety hazard.

Implications for the Shared Technology Industries

Automotive

Beginning in 2004, Australia will be testing fuel cell busses. While there may be some proto-typing of private vehicles, the first genuine applications will most likely be in premium power locations such as long-hole mining equipment. Passenger vehicles and transport will continue with traditional engines within the time period that this report covers.

Building and Construction

Few applications of fuel cells are likely for distributed generation and no additional skills will be required in this area.

Electrical

While no large scale installations are planned, portable fuel cells will become more popular and will require maintenance. Technical operatives in this area will need to become more familiar with the concepts used in this technology.

Electronics

Some applications in power electronics will be necessary to utilise this technology. Growing use of power-hungry consumer devices will see micro fuel cells become more popular. Electronics technicians will be called upon to maintain this equipment as they do with computing and communications equipment. The first sales of this equipment will be by computer and mobile telephone handset manufacturers.

Engineering

Few applications planned for this industry in the time period that this report covers.

Information technology

Apart from use as a battery recharging device, few new skills will need to be learned in this industry. Important safety issues will emerge and will need to be addressed.

Telecommunications

Apart from use as a battery recharging device, few new skills will need to be learned in this industry.

[1] Energy Efficiency and Renewable Energy. (2003). *Fuel cell report to congress: (ESECS EE-1973)*. Washington, DC: U.S. Department of Energy. Available: http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/fc_report_congress_feb_2003.pdf Accessed: 12 April, 2003.

[2] Fuel Cell Today. (2003). Bush pushed fuel cell support to $1.7 billion over next five years. *Fuel Cell Today*, March 2003. Available: http://www.fuelcelltoday.com Accessed: 11 April, 2003.

[3] Energy Efficiency and Renewable Energy. (2003). *Fuel cell report to congress: (ESECS EE-1973)*. Washington, DC: U.S. Department of Energy. Available: http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/fc_report_congress_feb_2003.pdf Accessed: 12 April, 2003.

[4] Department of Industry, Tourism and Resources. *Renewable energy technology roadmap*. Canberra: Commonwealth of Australia. Available: http://www.industry.gov.au/retr Accessed: 22 November, 2002.

[5] Freedman, D. H. (2002). Fuel cells vs. the grid: Road to a true hydrogen economy is proving pave the way to a fuel. *Technology Review*, *105*(1), pp. 40-48.

[6] Williams, A. (2002). *Energy and transport sector: Outlook to 2020*. North Ryde: CSIRO Energy Technology. Available: http://www.det.csiro.au/PDFfiles/Energy_Transport_Sector_Outlook_2020.pdf Accessed 22 March, 2003.

[7] Jollie, D. (2003). *Fuel cell market development: History and future*. Fuel Cell Today. Available: http://www.fuelcelltoday.com Accessed: 11 April, 2003.

[8] See especially Fuel Cells 2000. *Types of fuel cells*. Available: http://www.fuelcells.org Accessed: 12 April, 2003. Also see Fuel Cell Today. Available: http://www.fuelcelltoday.com Accessed: 11 April, 2003.

[9] Adapted from Fuel Cells 2000. *Types of fuel cells*. Washington, DC: Author. Available: http://www.fuelcells.org/fctypes.htm Accessed: 12 April, 2003.

[10] The Economist. (2003). These fuelish things. *The Economist*, 13 February, 2003. Available: http://www.economist.com/science/displaystory.cfm?story_id=1576453 Accessed: 13 April, 2003.

[11] Benito, R. *et al* (2002). *CSIRO's advanced power generation technology using solar thermal – fossil energy hybrid systems*. Lucas Heights, NSW: CSIRO Energy Technology. Available: http://www.rite.or.jp/GHGT6/pdf/REP1.pdf Accessed: 22 March, 2003.

[12] Energy Efficiency and Renewable Energy. (2003). *Fuel cell report to congress: (ESECS EE-1973)*. p. 25. Washington, DC: U.S. Department of Energy. Available: http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/fc_report_congress_feb_2003.pdf Accessed: 12 April, 2003.

[13] Energy Efficiency and Renewable Energy. (2002). *National hydrogen energy roadmap*. p. 22. Washington, DC: U.S. Department of Energy. Available: http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf Accessed: 11 April, 2003.

[14] Chandler, D. L. (2002). Hydrogen utopia comes two steps closer. *New Scientist*, 5 October, 2002, p. 14.

[15] Millennium Cell (2003). *The hydrogen on demand system*. Author. Available: http://www.millenniumcell.com/solutions/white_hydrogen.html Accessed: 13 April, 2003.

16 Powerball Corporation. (2003). *Innovative technology for the storage and transportation of hydrogen.* Author. Available: http://www.powerball.net/business/description.html Accessed: 13 April, 2003.

17 Geiger, S. (2003). *Automotive hydrogen infrastructure – On the way to a hydrogen economy.* Fuel Cell Today. Available: http://www.fuelcelltoday.com Accessed: 11 April, 2003.

18 Jollie, D. (2003). *Fuel cell market development: History and future*. Fuel Cell Today. Available: http://www.fuelcelltoday.com Accessed: 11 April, 2003.

19 Energy Efficiency and Renewable Energy. (2003). *Fuel cell report to congress: (ESECS EE-1973).* p. 23. Washington, DC: U.S. Department of Energy. Available: http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/fc_report_congress_feb_2003.pdf Accessed: 12 April, 2003.

20 Williams, A. (2002). *Energy and transport sector: Outlook to 2020.* pp. 11-12. North Ryde: CSIRO Energy Technology. Available: http://www.det.csiro.au/PDFfiles/Energy_Transport_Sector_Outlook_2020.pdf Accessed 22 March, 2003.

21 Department for Planning and Infrastructure. (2002). *Sustainable transport energy for Perth hydrogen fuel cell bus trial.* Perth, WA: Author. Available: http://www.dpi.wa.gov.au/fuelcells Accessed: 28 December, 2002.

22 DaimlerChrysler. (2002). *Driving test period now starts for the first Citaro bus with fuel cell power system*. Stuttgart, Germany: Author. Available: http://www.daimlerchrysler.com/news/top/2002/t20204a_e.htm Accessed: 12 April, 2003.

23 Miller, A. R., & Barnes, D. L. (2002). *Advanced underground vehicle power and control fuelcell mine locomotive.* Denver, CO: Vehicle Projects LLC. Available: http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/32405a30.pdf Accessed: 22 November, 2002.

24 Geiger, S. (2003). *Automotive hydrogen infrastructure – On the way to a hydrogen economy.* Fuel Cell Today. Available: http://www.fuelcelltoday.com Accessed: 11 April, 2003.

25 Energy Efficiency and Renewable Energy. (2003). *Fuel cell report to congress: (ESECS EE-1973).* p. 2. Washington, DC: U.S. Department of Energy. Available: http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/fc_report_congress_feb_2003.pdf Accessed: 12 April, 2003.

26 Energy Efficiency and Renewable Energy. (2002). *National hydrogen energy roadmap*. Washington, DC: U.S. Department of Energy. Available: http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf Accessed: 11 April, 2003.

27 Geiger, S. (2003). *Automotive hydrogen infrastructure – On the way to a hydrogen economy.* Fuel Cell Today. Available: http://www.fuelcelltoday.com Accessed: 11 April, 2003.

28 Copper, M. (2002). *Fuel cell market survey: Portable applications.* Fuel Cell Today. Available: http://www.fuelcelltoday.com Accessed 22 November, 2002.

29 Putt, R., Naimer, N., & Koretz, B. (2000). *Zinc-air batteries for the dismounted warfighter*. Auburn, AL: Electric Fuel Corporation. Available: www.electric-fuel.com/defense/ps40.pdf Accessed: 13 April, 2003.

30 Tully, J., & Ball, R. (2002). *Micro fuel cells power mobile devices*. Gartner. Research Note Number: T-18-6478.

31 Fuel Cells 2000 (2002). *Micro fuel cells – technical info.* Available: http://www.fuelcells.org/MicroTechnical.pdf Accessed: 13 April, 2003

[32] Tanokura, Y. (2002). More fuel cells to mounted on mobile devices. *Fuel Cell Works*, 22 July, 2002. Available: http://fuelcellsworks.com/Supppage138.html Accessed 4 March 2003.

[33] Cohen, D. (2002). Batteries not included. *New Scientist*, 19 October, 2002, pp. 40-42.