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FUEL CELLS

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FUEL CELLS

INTRODUCTION

As the world continues its rapid industrialization, the production and consumption of energy continues to keep pace. Without major technological innovation, the consequential increase in fossil fuel use will dramatically affect both the quality and sustainability of life on Earth. One of the technologies that offers great potential to provide a clean and efficient alternative means of energy production is the fuel cell. In 2000, the Battelle Memorial Institute predicted that fuel cells would be one of the top ten energy innovations for 2010.(1) Fuel cells offer ultra-low emissions of NO_x, SO_x, CO and hydrocarbons at their point of use, along with high levels of efficiency to help offset the adverse effects of meeting increasing energy demands. They do require fuel, however, and the production of that fuel will produce emissions.

Fuel cells are being developed at an increasingly rapid rate for a variety of applications, most of which can be divided into two distinct categories: *stationary* applications, specifically electricity production facilities; and *mobile* applications, such as automobiles. Together, the electricity generation and transportation sectors account for more than 50% of Canada's greenhouse gas emissions.(2) This explains why fuel cell technology, with its potential to cut pollution in these sectors, is attracting so much attention.

This paper:

- explains the basics of how fuel cells work and how they are fuelled;
- describes the various types of fuel cells in use and under development;
- describes the mobile and stationary applications of fuel cell technology that are currently available and emerging; and

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(1) Battelle, *Battelle Experts Forecast the Top Ten Energy Innovations for 2010*, News Release, http://www.battelle.org/News/00/07-26-00ENERGY.stm.

(2) Analysis and Modelling Group, National Climate Change Group, *Canada's Emissions Outlook: An Update*, December 1999.

- reviews the barriers that the technology must still overcome before its full potential can be realized.

WHAT IS A FUEL CELL AND HOW DOES IT WORK?

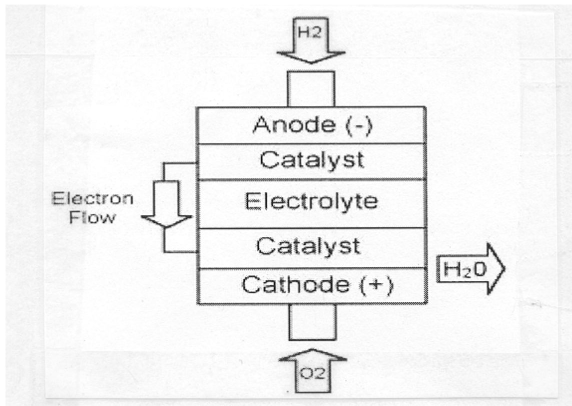
A fuel cell is an electrochemical device that efficiently converts a fuel's chemical energy directly into electrical energy. It produces electricity by chemically combing hydrogen ions drawn from a hydrogen-containing fuel with oxygen atoms, without combustion, thereby doing away with the inefficiencies and the pollution that accompany traditional, thermal electricity production. With no moving parts and very few to no pollutants emitted at the point of use, the fuel cell offers an appealing alternative to the current methods of producing electricity.

All fuel cells, regardless of the fuel or the electrolyte they use, operate on similar principles. A typical fuel cell consists of two electrodes – one negatively charged (anode) and the other positively charged (cathodes) – separated by an electrolyte. In most types of fuel cells, oxygen atoms – either purified or as contained in air – are passed over the cathode and hydrogen is passed over the anode. Both electrodes are coated with a catalyst such as platinum that promotes chemical reactions. At the anode, the hydrogen is split into its two constituent parts: one proton (positively charged), and one electron (negatively charged).

The protons and the electrons take a different route through the fuel cell (see Figure 1).

- *The electrons* are "collected" and passed through an external circuit to the cathode. The flow of electrons through such a circuit is called an electrical current and it can be used to power a motor, light a lightbulb, or heat water.
- *The protons*, on the other hand, pass through the electrolyte to the cathode side of the cell, attracted by its opposite charge. At the cathode, the protons are "reunited" with the electrons that went via the outside circuit and together, they combine with the oxygen atoms circulated past the cathode to produce water (H_2O) and waste heat.

Figure 1: Simplified Fuel Cell Diagram



Source: Fuel Cells 2000, *What Is a Fuel Cell?* February 2000.

The power that can be produced by any individual fuel cell is limited to a few volts per electrode pair. Therefore, in order to provide enough power for most applications, a number of cells are stacked together. These fuel cell stacks can then be put together in a module of the appropriate size for any application. The modular nature of fuel cells is one of their advantages; this offers the ability to match the size of the production unit to the demand.

FUEL FOR FUEL CELLS

As the foregoing description of a fuel cell indicates, these devices produce electricity without combustion, fuelled by hydrogen and oxygen. The only by-product of this chemical reaction is water. The oxygen used in fuel cells is obtained from air. Providing the hydrogen fuel is a more complicated, and polluting, procedure. On earth, hydrogen is always found in combination with another element or elements. For example, water (H_2O) is a compound of hydrogen and oxygen, and natural gas (CH_4 or methane) is a compound of hydrogen and carbon. To obtain pure hydrogen, energy must be spent to separate it from the other elements in the compound. Consequently, although the end use of hydrogen in a vehicle or other application may be free of pollution, the full life cycle of hydrogen is not. This is why hydrogen should not be referred to as an energy source, but rather as an energy carrier or energy currency.

There is an ongoing race to determine what will become the fuel of choice for hydrogen production and hence, for fuel cells. The choice will also determine which form of supply infrastructure will be needed. Hydrogen can be produced commercially from fossil fuels (such as natural gas, or gasoline), chemical intermediates (such as refinery products), biomass (such as wood chips), biogas (such as ammonia), waste materials, and by the electrolysis of water. In the future, methods used to obtain hydrogen may also include the use of green algae grown in anaerobic conditions, or its chemical extraction from glucose.

Clearly, there are a number of different methods for producing hydrogen, and the method chosen will have a direct bearing on the amount of pollution associated with the full life cycle. Many of today's leading, commercially available methods involve stripping hydrogen from fossil fuels. This process – known as steam reformation – involves heating a mixture of water and natural gas, crude oil or methanol to separate the pure hydrogen. Providing the heat for the process produces pollution. In addition, various forms of carbon are produced as waste products when the hydrogen is stripped from a hydrocarbon mixture (fossil fuel).

Hydrogen can also be produced commercially by the process of electrolysis in which an electrical current is used to split the hydrogen and oxygen atoms in water (the reverse of the reaction that takes place in a fuel cell). In this case, the fuel used to produce the electricity will determine the level of emissions associated with the full life cycle of the process. If the electricity has been produced using wind, solar or other clean, renewable source, greenhouse gas emissions can be virtually eliminated from the cycle. As noted above, in the future it may be feasible to produce pure, renewable hydrogen using a new method of growing green algae.

A 2000 study by the David Suzuki Foundation and the Alberta-based Pembina Institute provides an instructive comparison of carbon dioxide emissions using a variety of technologies. The study looked at the amount of carbon dioxide produced when a vehicle (in this case, a Mercedes-Benz A-Class car) travelled 1,000 kilometres using six different fossil-fuel-based fuelling systems. The results are summarized in Table 1.

Table 1: Carbon Dioxide Emissions for 1,000 Km of Travel

Fuelling System	Emissions (kg)
1. Standard car with internal combustion engine using gasoline	248
2. Fuel cell car using hydrogen generated by electric power plant (fossil fuel)	237
3. Fuel cell car using hydrogen generated on-board the car from gasoline	193
4. Fuel cell car using hydrogen generated on-board the car from methanol	162
5. Fuel cell car using hydrogen generated at service station from natural gas	80
6. Fuel cell car using hydrogen generated at large plant from natural gas	70

Source: "Fuel Cells; A Green Revolution?" Executive Summary, David Suzuki Foundation and The Pembina Institute, March 2000.

This study did not include all possible fuel/fuel cell combinations but it does clearly illustrate the impact that the choice of fuelling infrastructure will have on the emissions from vehicles powered by fuel cells.

TYPES OF FUEL CELLS

A number of different types of fuel cells are being developed; they are generally characterized by the electrolyte material that they use. The electrolyte is the substance between the anode and the cathode that serves as the medium for ion exchange. Each type of fuel cell exhibits very different characteristics such as operating temperature, available heat, power density (amount of power produced by a fuel cell of a given size and weight), and tolerance to fuel impurities. These differences make each cell suitable for particular applications. They are also at very different stages of development. To date, most research and development has focused on five main types of fuel cells: alkaline fuel cells (AFCs); phosphoric acid fuel cells (PAFCs); molten carbonate fuel cells (MCFCs); solid oxide fuel cells (SOFCs); and proton exchange membrane fuel cells (PEMFCs). More recently, several new types have been the subject of research and development efforts. These include Direct Methanol Fuel Cells

(DMFCs) and Regenerative Fuel Cells (RFCs). This section of the paper briefly describes each type of cell and its unique characteristics.

A. Alkaline Fuel Cells

The Alkaline Fuel Cell (AFC) was one of the first modern fuel cells to be developed and has long been used by NASA on space missions including the Apollo mission to the moon and on the Space Shuttle, to produce both electricity and water. As the name implies, these devices use a liquid alkaline (potassium hydroxide) as the electrolyte.(3) They operate at low temperature (80°C) and are very efficient, reaching generating efficiencies of up to 70%. However, their high cost has, until recently, restricted their application to niche markets such as the space program, where the by-product water is a valuable commodity. A number of companies are working on ways to reduce the overall cost of AFCs, hoping to find a larger market in the future.(4)

B. Phosphoric Acid Fuel Cells

In the Phosphoric Acid Fuel Cell (PAFC), which operates at more than 40% efficiency, phosphoric acid is the electrolyte. By comparison, the most efficient internal combustion engines operate at about 30% efficiency. Because PAFCs operate at the relatively high temperature of about 200°C, they provide an opportunity for co-generation. If the steam produced by the fuel cell is also used, the overall efficiency can rise as high as 85%.(5)

The PAFC – the first commercially developed fuel cell type – is already used in stationary applications, producing electricity (and sometimes, heat as well) for hospitals, nursing homes, hotels, office buildings, schools, utility power plants and airport terminals.(6) These fuel cells could also be used in larger vehicles, such as buses and trains, where their large size and higher operating temperatures could be tolerated.

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(3) National Fuel Cell Research Centre, *Fuel Cell Technology Comes of Age*, 2 May 2000, http://www.nfcrc.uci.edu/journal/article/fcarticleE/index.htm.

(4) "Types of Fuel Cells," *Fuel Cells 2000*, http://216.51.18.233/fctypes.html.

(5) *Ibid.*

(6) *Ibid.*

C. Molten Carbonate Fuel Cells

The Molten Carbonate Fuel Cell (MCFC) uses a slightly more complicated chemical reaction than do many of today's other fuel cells. In the case of MCFCs, carbonate ions – rather than hydrogen ions – are transferred through the electrolyte, which is a carbonate that becomes molten at the operating temperature of the cell (650°C). In the early years of its development, some critics of this technology pointed to the use of highly corrosive carbonate salts as the electrolyte, calling it a potentially serious problem with respect to the design and maintenance of such units.(7) However, advances in materials science have addressed most of the outstanding problems over the past four to five years.

The "Fuel for Fuel Cells" section of this paper explained that standard, hydrogen-rich fuels – such as natural gas, methanol, gas from coal mines or digesters, or liquid hydrocarbons such as gasoline – must first be "reformed" or chemically changed to extract the hydrogen for fuelling the fuel cells. Heat is required for this process.

Because MCFCs operate at such high temperatures, it has been possible to design and build a molten carbonate fuel cell system in which the fuel reformation and the electricity generation take place in the same unit. It is called a direct fuel cell for this reason. The heat from the fuel cell operation is used to produce steam, which in turn is used in the reformation of natural gas (or other fuel). When the steam reforming takes place in the fuel cell stack, a small amount of CO_2 is produced along with electricity, water vapour and heat. The MCFC has a cost advantage over most other fuel cells currently under development because it uses nickel, rather than (the more expensive) platinum, as the catalyst.

D. Solid Oxide Fuel Cells

The Solid Oxide Fuel Cell (SOFC) has been developed more recently than any of the other types discussed so far, but appears to be gaining ground. This type of fuel cell uses a solid metal oxide, in the form of a ceramic material, as the electrolyte. The use of a ceramic electrolyte allows the system to be operated at even higher temperatures than the MCFC, typically up to 1000°C.

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(7) Tim Beardsley, "Beyond Batteries," *Scientific American*, December 1996, www.sciam.com/explorations/122396explorations.html.

Operating at these temperatures allows the reformation of fuel on-site – in the fuel cell stack – as can also be done in a molten carbonate system. Solid oxide fuel cells have been demonstrated to reach generation efficiencies of over 60%. The high efficiency rating is partly attributable to the fact that, in addition to electricity, SOFCs produce high-grade waste heat, which can be harnessed as part of a co-generation system. The heat could also be used in a district heating system, again improving the overall system efficiency. One company also uses the hot, pressurized gases from a series of SOFC fuel cells to drive a microturbine generator, adding more electricity production to that obtained in the cells themselves. Again, system efficiency can be greatly improved by such designs.(8)

In the United States, SOFCs are the subject of a great deal of research at the moment, and advances in their design and operation are moving them quickly towards commercialization. The latest SOFCs operate like a hydrogen fuel cell in reverse. Oxygen picks up electrons coming into the cell via the cathode, creating negatively charged oxygen ions. These ions then migrate across a solid, ceramic membrane (made of substances such as yttria-stabilized zirconia). At the anode, the oxygen reacts with the hydrocarbon fuel to produce electricity, water and carbon dioxide.(9) This design avoids the necessity of reforming, or converting the hydrocarbons inside the cells. However, some problems relating to the bonding of carbon on the nickel anode at high temperatures have had to be addressed. Work is continuing, and advanced SOFCs appear to offer great potential for stationary applications.

E. Proton Exchange Membrane Fuel Cells

Instead of a liquid or a heavy solid electrolyte, the Proton Exchange Membrane Fuel Cell (PEMFC) has as its electrolyte a thin membrane made from a solid polymer. As a result, PEMFCs are much lighter than other types and therefore better suited to mobile applications such as automobiles.

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(8) “New Tigers in the Fuel Cell Tank,” *Science*, Vol. 288, 16 June 2000, p. 1956.

(9) *Ibid.*

PEMFCs operate at low temperatures (80°C) and have a high power density. They are also capable of quickly varying their output to match shifts in power demand. This feature also makes them well suited to the demands of automobile operation, where quick start-up is necessary.(10) The world's leading company in development and commercialization of PEMFCs is a Canadian company.

F. Other Fuel Cells

In addition to the principal fuel cell systems described above, research is also underway on a number of new technologies. Among the most promising are the Direct Methanol Fuel Cell (DMFC) and the Regenerative Fuel Cell (RFC).

The DMFC is similar to the PEM technology in that it uses a polymer membrane as the electrolyte. In the DMFC, however, the catalyst on the anode draws the hydrogen directly from liquid methanol fuel, removing the need for an external fuel reformer. The elimination of the reformer increases the DMFC's efficiency to about 40% and the cell operates at between 50° and 90°C.

Regenerative Fuel Cells are still at the early stage of development but offer promise. RFCs have a closed-loop power generation option. Water is fed into the system where it is separated into hydrogen and oxygen by means of solar-powered electrolysis. The hydrogen and oxygen pass through the cell as described above, generating electricity, heat and water. The water that is produced is then recycled back to the solar-powered electrolyser and the process starts again. In the United States, NASA is involved in RFC research, because a closed-loop system powered by the sun has obvious appeal for use in space.(11) To date, however, the cost of this type of fuel cell limits its likely terrestrial application.

Table 2 provides a comparison of the generating efficiencies of the various types of fuel cells discussed above (with the exception of RFCs).

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(10) *Ibid.*

(11) *Ibid.*

Table 2: A Comparison of Fuel Cell System Generating Efficiencies

Fuel Cell Type	Maximum Generating Efficiency (%)	Maximum Generating Efficiency When Including Co-generation (%)	Maximum Operating Temperature (°C)
Alkaline (AFCs)	70[a]	Not applicable	70[b]
Phosphoric Acid (PAFCs)	37-42[c]	Nearly 85[d]	200[e]
Molten Carbonate (MCFCs)	55[f]	80[g]	650[h]
Solid Oxide (SOFCs)	55[i]	60-80[j]	980[k]
Proton Exchange Membrane (PEMFCs)	40-60[l]	Not applicable	70-80[m]
Direct Methanol (DMFCs)	40[n]	Not applicable	50-90[o]

a “Types of Fuel Cells,” *Fuel Cells 2000*, November 2000.

b C. Padro and V. Putche, Survey of Economics of Hydrogen Technologies, National Renewable Energy Laboratory, Midwest Research Institute, Golden, Colorado, September 1999.

c *Ibid.*

d “Types of Fuel Cells,” *Fuel Cells 2000*, November 2000.

e *Ibid*.

f Tim Beardsley, “Beyond Batteries,” *Scientific American*, December 1996, www.sciam.com/explorations/122396explorations.html.

g *Ibid.*

h *Ibid.*

i *Ibid.*

j *Ibid.*

k “Types of Fuel Cells,” *Fuel Cells 2000*, November 2000.

l C. Padro and V. Putche, Survey of Economics of Hydrogen Technologies, National Renewable Energy Laboratory, Midwest Research Institute, Golden, Colorado, September 1999.

m “Detroit Auto Show: Ballard Announces Production-Ready Fuel Cell Module, Hints at Factory Plans,” *Hydrogen and Fuel Cell Letter*, February 2000, www.hfcletter.com/letter/february00/feature.html

n “Types of Fuel Cells,” *Fuel Cells 2000*, November 2000.

o *Ibid.*

FUEL CELL APPLICATIONS

A. Stationary

Stationary fuel cell applications, chiefly commercial power plants, are becoming established in the mainstream prior to the mobile (automobile) applications of the technology because they present fewer design challenges, such as size and weight restrictions. In fact, fuel cell generators of various sizes are already entering the marketing stage of development. Fuel cell systems can supply electricity to areas with no access to primary grid power, thereby delaying, if not eliminating, the necessity of grid connections. This situation will be found commonly in remote locations in industrialized countries, as well as in many developing countries. The possibility of designing a fuel cell system that can be converted to work both in grid-connected and non-grid-connected mode is also being explored.(12)

Fuel cell generating plants offer very significant advantages over conventional electricity generation systems.

- They are virtually pollution free at the point of end use. This allows their use in locations such as densely populated urban areas, where conventional systems would not meet low emission requirements.
- Because fuel cells are made up of individual cells stacked together, any size unit can be constructed. They thus offer the flexibility of matching electricity supply with electricity demand, whereas conventional generation usually requires the construction of very large plants to realize economies of scale. This flexibility will become more beneficial as electricity generation is gradually deregulated in the United States, Canada and other industrialized countries.

Governments around the world have long recognized the potential of fuel cell technology, at times providing financial incentives to the industry. In Canada, the CANMET Energy Technology Centre (CETC) of Natural Resources Canada has been working on making fuel cells marketable since 1983. To date, the federal government has contributed more than $73 million to fuel cell development. For example, in British Columbia, CETC has worked with Ballard Power Systems developing their world-leading PEM fuel cells. In Ontario, CETC has been involved with Hydrogenics Corporation in their research and development efforts relating

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(12) National Fuel Cell Research Centre, *supra*, note 3.

to natural gas-fired fuel cell generators. In March 2001, an additional $2 million in federal funding for the company's R&D (research and development) was announced. Of this amount, $1.6 million will come from the Technology Early Action Measures (TEAM) component of the Climate Change Action Fund (CCAF); the other $400,000 will come from Natural Resources Canada. These combined efforts have led, and will continue to lead, to advances in stationary fuel cell technologies that allow power generation to take place under extreme temperatures. Hydrogenics has modified fuel cells to operate at temperatures as low as -40°C, to be used in Arctic applications. The company currently is investigating further modifications to allow for desert use of their fuel cells. The systems being developed are aimed at providing power for multi-dwelling clusters and small commercial buildings.(13)

The U.S. government has also been a long-term supporter of fuel cell research. For example, in July 2000, the U.S. Department of Energy (DOE) awarded a $40 million increase and a three-year extension to FuelCell Energy Inc. under their Carbonate Fuel Cell Co-operative Program. Funding since the beginning of the program in 1994 has totalled approximately $144 million, including FuelCell Energy's share. The funds have been directed at enabling delivery of clean, efficient, non-centralized, commercial fuel cell power plants in the 2001-2002 time frame. Ongoing work will focus on cost reduction, extended life testing, and design update based on field trials. This technology – which is geared for the stationary market and uses natural gas directly as a fuel – will serve hospitals, schools, data centres and other commercial and industrial facilities. Field trials of a full-size 250kW plant have successfully powered the company's own facilities for some time. The commercial systems now available include 300kW, 1.5MW and 3.0MW models.(14)

Governments also assist with commercialization of fuel cell technology by providing an early product market, and by offering a variety of fiscal incentives. The U.S. Government has been a leader in purchasing the new technology, operating 30 co-generation units and, under the Climate Change Fuel Cell Program, providing grants of $1,000 per kilowatt to purchasers of fuel cell power plants. Canada, Japan and Germany are supporting early

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(13) Hydrogenics Corporation, News Release, *Hydrogenics Receives Project Funding of Two Million Dollars From the Government of Canada*, 26 March 2001.

(14) U.S. Department of Energy, *FuelCell Energy Inc. Receives DOE Award of $40 Million Increase and Three-Year Extension to DFC-r-Product Design Improvement Program*, Press Release, July 2000, http://fuelcellenergy.com/site/investor/press/releases/2000/07_13_00.html and http://www.ercc.com/site/products/products.html.

purchases and attempting to drive down the technology costs through tax credits, low-interest loans and grants. Ballard Power, for example, received $30 million from the Government of Canada and has since teamed up with a subsidiary of a New Jersey-based electric company to assist in commercializing its stationary co-generation units.(15)

Government support is not limited to stationary fuel cell applications, but also includes mobile applications, which are discussed later in this paper. In Canada, the fuel cell industry has been growing over the past decade, and in 1999 the federal government launched the National Fuel Cell Research and Innovation Initiative. Natural Resources Canada (NRCan), the National Research Council (NRC), and the Natural Sciences and Engineering Research Council (NSERC) are collaborating in this program which has been set up in response to requests from the industry for strategic and operational R&D help. The various parts of the fuel cell industry have also come together and formed an industry association, Fuel Cells Canada, to work with the government to promote the industry's overall development. Under the terms of the Initiative, the government has committed to a five-year program that will see the establishment of a Fuel Cells Technology Centre in Vancouver and a Fuel Cell Technology Deployment Program. In addition, NSERC and NRCan have set up a $14 million Partnership Fund targeted to fuel cells.(16)

Many companies are now in the fuel cell business and the race is on to gain commercial acceptance. The announcement of new projects is occurring at least on a monthly basis, making it difficult to keep up with the latest developments. Several examples are presented here to illustrate the interest that stationary fuel cell applications are creating.

Siemens Westinghouse Power Corporation and Southern California Edison have already successfully tested the world's first combination of a pressurized solid oxide fuel cell and a microturbine generator. In-factory testing of the hybrid produced enough energy to power a hotel or strip mall – 164 kW from the SOFC and 21 kW from the microturbine.

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(15) "What is a Fuel Cell," *Fuel Cells 2000*, http://216.51.18.233/whatis.html.

(16) Further details can be found in the following document: Rod McMillan, Director, NRC Fuel Cells Program, *NRC/NRCan/NSERC Fuel Cell Research and Innovation Initiative: An Opportunity*, Presentation to the 10th Canadian Hydrogen Conference, Quebec, May 2000.

Siemens Westinghouse has also signed an agreement with Ontario Power Generation (OPG) to construct a demonstration model of its 250kW SOFC co-generation system, which will be fueled by natural gas.(17) The OPG project is a model of partnerships in action. The April 2000 announcement of the project by OPG noted that Ontario Power Generation, in cooperation with the Government of Canada, would build the world's largest, pre-commercial SOFC heat and power plant. The U.S. Department of Energy and Siemens Westinghouse Power Corporation are also helping to fund the $18 million project. OPG is contributing $3.7 million to the project. The Canadian government is investing more than $2 million in the prototype: $1.1 million from the Technology Early Action Measures (TEAM) component of the Climate Change Action Fund, $373,000 from Natural Resources Canada, and additional funding from the National Research Council (NRC), under the National Fuel Cell Research and Innovation Initiative. The project is under construction and the system is expected to start operation in late 2001 or early 2002.

In addition to power plant applications, companies are now beginning to look at the use of fuel cells in the residential sector. The first U.S. application of fuel cell technology in a residence was in 1998. The company conducting the test, Plug Power, expects to be manufacturing the product commercially in the near future, at a cost of approximately US$4,000 per residence. The United States Department of Energy, which contributed some funding for the experiment, has said that it expects thousands of homes will be powered by fuel cells in the near future.(18) As a further step towards the commercialization of its residential fuel cells, Plug Power has undertaken a US$7 million program with the Long Island Power Authority (LIPA) of New York to connect 75 fuel cells to its electricity grid. The program, which is part of LIPA's Clean Energy Initiative, will help identify and develop measures to eventually allow widespread use of clean, distributed fuel-cell technology to supplement conventional electricity generation in this urban area.

The energy crisis in California in 2001 provides a golden opportunity for the residential fuel cell industry to expand its market. After suffering brown outs and black outs, consumers there are less trusting of the electricity grid and therefore more likely to be interested in having their own fuel cell generator.

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(17) "Stationary Power," *Fuel Cell Technology Update*, 2000, http://www.fuelcells.org/tu2000.htm#April00.

(18) *New York Times*, 17 June 1998.

Although residential use of fuel cells is reaching commercialization in the United States, Canada and Europe, Japan is expected to embrace this technology in advance of the rest of the developed world, given its lower electricity demand per household than in the Western Hemisphere. Ballard Power Systems, the Canadian leader in PEMFC technology, has recognized the value of this potential market and has teamed with Matsushita Electric Works to adapt its portable one-kilowatt unit (originally designed for emergency services such as police and fire department field use), for use in cottages and residential (emergency and leisure) settings.(19) Ballard has already sold over $1 million worth of its Mark 900 PEMFC to Matsushita for the project. The proposed system will be able to provide enough electricity to supply the average Japanese home with power, heat and hot water during off-peak hours, or during emergencies. The unit will be augmented during peak periods by conventional electricity from Japan's power grid.(20) The above-noted companies are just two of the many now moving towards the commercialization phase of stationary fuel cell applications.

B. Mobile

Mobile applications make use of the flexibility in size and design offered by fuel cell technology; and, as the cost of production decreases, more widespread applications will be discovered. Due to concerns over urban pollution and global warming, automobiles are a particularly important market for fuel cell technology.

Fuel cell powered vehicles will offer numerous advantages over vehicles powered by conventional internal combustion engines. For example, they offer much higher fuel efficiency, longer lifetimes, and lower maintenance costs. The challenge is no longer one of proving the feasibility of using fuel cells in mobile applications, but of creating demand through creative integration of the technology into the transportation industry at a reasonable cost.

A study by Allied Business Intelligence predicts that automotive fuel cells will have captured a vehicle market share of about 4% by 2010. The study further claims that PEM

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(19) Matsushita Electric Works Ltd., *Worlds First Portable Fuel Cell Generator Fuelled by LPG Cassette Cylinders*, Company Brochure, March 2000.

(20) "Fuel-cell generator developed for Japanese market," *Ottawa Citizen*, January 2000.

fuel cells (such as those produced by Ballard Power Systems) will dominate the market constituting 80% of all automotive fuel cells.[21]

Indeed, a level of technological maturity has been reached for mobile uses of fuel cells. The early assumption that heavy-duty vehicles would break into the market prior to light-duty passenger vehicles has proven true. The Chicago and Vancouver Transit authorities have each been involved in extensive demonstration projects of fuel cell powered buses, using Ballard's PEM fuel cell technology. Each of the cities has now purchased three of the buses.

Building on this experience, Daimler-Chrysler has emerged as the first company to offer commercial fuel cell buses for sale abroad to transit agencies. Ballard PEM fuel cell engines run their buses. Daimler-Chrysler announced that it planned to build 30 fuel cell city buses for transport operating companies, with delivery set for 2002. After the announcement was made, orders poured in. Orders have already been received from 17 European cities with demand quickly outstripping the supply. Only ten of the orders, of three buses each, can be filled unless the company can boost its anticipated production.

Other companies will have to step up production to meet the growing demand. In February 2001, the United Nations announced that it has given the go-ahead to a demonstration project involving fuel cell powered city buses. Using funds from the Global Environment Facility Fund (an arm of the United Nations Development Program), between 40 and 50 fuel cell buses will be deployed between 2002 and 2003 in major cities and capitals with some of the world's worst air pollution levels. The $130 million project will see this technology brought to Brazil, Mexico, Egypt, India and China.

Currently, a great deal of progress is being made in the development of fuel cell powered cars and light trucks. It has been predicted that, at the current rate of development, more than 100,000 fuel cell powered vehicles will be in use internationally by 2004.

All of the major automobile manufacturers are now developing prototypes.[22] Ballard Power Systems has forged strategic alliances with many of them, and the PEM technology appears to be the fuel cell of choice for automobile applications. For example, Ballard is now supplying fuel cell engines to Daimler-Chrysler, Daimler-Benz, the Ford Motor Company, General Motors, Nissan, Honda, Volkswagen, and Volvo. In Japan, Mitsubishi

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(21) *Fuel Cell Technology Update*, June 2000, http://www.fuelcells.org/tu2000.htm#June00.

(22) National Fuel Cell Research Centre, *supra*, note 3.

Electric and Fuji Heavy Industry (Subaru Research Division) are also involved in PEM development. They will be testing their new flat-type polymer electrolyte fuel cell in the Subaru Samber light truck.(23) In July 2001, Toyota announced its intention to introduce a commercial fuel cell vehicle in 2003. The fuel will be high-pressure hydrogen.(24)

Fuel cell engines, based on the Ballard PEM fuel cell and other PEM cells, will be comparable to conventional engines in size, weight, operating life, safety, acceleration and speed, range, and refuelling time. Ballard continues to improve the power density, fuel efficiency, environmental compliance, and reliability. The company is now focusing on cost reduction and developing volume for the manufacturing process. In fact, the company announced early in 2000 that it would construct a high-volume production facility for its latest model fuel cell stack and power module, the Mark 900.(25) Plant One, as it is known, is now in operation and the company is gaining valuable experience in the commercial manufacturing of fuel cells.

The fuel cell itself is not the only technology that must be developed before fuel cell vehicles break into the market. The question of fuel infrastructure is still being debated. As previously noted, the level of pollution associated with fuel cell use will be determined by how the hydrogen is produced. Some are advocating the use of pure hydrogen, produced in centralized plants that either reform natural gas, methanol or other fuel, or electrolytically produced hydrogen from water. Hydrogen would then have to be stored on-board the vehicle. This raises concern by some people regarding safety. However, tests show that technologies for storing hydrogen on-board vehicles are safer than those for typical gasoline storage tanks. The hydrogen dissipates faster than gasoline, so the risk of explosion is reduced. In addition, automatic switches are used to cut off the flow of hydrogen and electricity, thus avoiding fire hazard. In fact, the carbon fibre wrapped tanks have been designed only to leak hydrogen rather than explode, when punctured by gunfire or other means, and to remain intact during collisions.

Others are pursuing technology that will allow the fuel (gasoline or natural gas, for example) to be reformed on-board the vehicle. They feel that such an approach offers the

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(23) *Fuel Cell Technology Update*, May 2000.

(24) "Toyota Plans to Start Selling Fuel Cell Cars in 2003 in Japan, Announces New FC bus," *Hydrogen and Fuel Cell Letter*, July 2001.

(25) "Detroit Auto Show: Ballard Announces Production-Ready Fuel Cell Module, Hints at Factory Plans," *Hydrogen and Fuel Cell Letter*, February 2000, http://www.hfcletter.com/letter/february00/feature.html.

advantage of using the existing fuel supply infrastructure, and therefore making fuel cell vehicles more cost-competitive.

Numerous partnerships between fuel cell manufacturers, energy producers and automobile manufacturers are evolving to address the fuelling issue. For example, Ballard has joined forces with Methanex, the world's largest promoter of methanol products, to ensure that barriers to the use of methanol are removed. Ford and Mobil Corporation have been working together to develop a new, on-board gasoline reformer that is smaller, lighter and less expensive than existing reformers.(26) In August 2000, General Motors and ExxonMobil Corporation announced a major breakthrough in gasoline reforming technology. Their processor operates at over 80% efficiency. Work is now underway to integrate it into a fuel cell vehicle.(27)

As part of its Action Plan 2000 on Climate Change, the Canadian government will be investing $23 million in the Canadian Transportation Fuel Cell Alliance (CTFCA) program to evaluate and demonstrate a variety of fueling options for fuel cell vehicles.(28)

CONCLUSION

Fuel cell technology has come of age. New applications, new demonstration projects and new development plans are being announced daily. The speed and diversity of this evolving technology are reflected in the monthly editions of *Fuel Cell Technology Update* published by Fuel Cells 2000. Every month, it takes from six to ten pages just to list and very briefly describe the most recent advances. Power stations operating on fuel cells are appearing in many communities, fuel cell powered buses are taking to the streets of cities world-wide, and fuel cell powered cars will be hitting the show rooms very soon.

Some technical problems still have to be worked out and production costs must be brought down, but steady progress is being made. Before long, fuel cells will take their place as one of the top energy innovations of the new millennium, and Canadian industries are well placed to be part of this new technological advancement.

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(26) Mobil, *Ford and Mobil to Develop New Gasoline Reformer for Fuel Cell Vehicles*, News Release, 16 August 1999.

(27) General Motors, *GM and ExxonMobil Collaboration Develops Gasoline Processor for Fuel Cell Vehicles*, News Release, 10 August 2000.

(28) Natural Resources Canada, Press Release, *Backgrounder: Canadian Transportation Fuel Cell Alliance*, Ottawa, 11 June 2001.