Alberta Energy Research Institute
Institute for Fuel Cell Innovation

Feasibility Study of the Alberta Hydrogen and Fuel Cell Research and Business Development Cluster and Network of Excellence

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Portfire Associates
Marc Godin

Executive Summary

Energy Innovation Network for Hydrogen and Fuel Cells

While providing support for research and development projects, the primary focus of the Energy Innovation Network will be innovation and technology dissemination in the areas of hydrogen and fuel cells. It will need to build on the existing Alberta cluster and provide it with strategic direction, integration, and resources. It should be based on leading edge science, deep market knowledge, and outstanding business skills.

Rationale for Hydrogen Innovation in Alberta

- ✓ Cleaner energy products are a requirement for continued access to world markets and a stake in the perceived direction of the U.S. energy market.
- ✓ Should the delivered form of energy evolve from oil & gas to hydrogen or products with high hydrogen content, Alberta needs to ensure that it can produce and deliver the energy products demanded by North American markets by utilizing Alberta natural resources.
- ✓ Hydrogen is used in Alberta for treating and upgrading crude oil and crude bitumen from the oil sands. Hydrogen treatment removes sulfur and nitrogen contaminants and is a value added step in the production of higher-priced, cleaner, transportation fuels.
- ✓ The combination of increased demand for hydrogen and expected higher natural gas costs creates an opportunity for Alberta to invest in the development of technologies to produce hydrogen at a lower cost by utilizing low value hydrocarbon feedstocks, such as asphaltenes, coal, petroleum coke, and possibly abandoned oil wells.

Rationale for Fuel Cell Innovation in Alberta

- ✓ Worldwide technology development efforts in fuel cells will deliver devices that will offer compelling advantages as compared to other energy conversion devices, whether the fuel originated from a fossil, renewable, or nuclear source:
    - o The electrochemical process is inherently more efficient than combustion at converting chemical energy into electricity.

- Fuel cells are more scalable than combustion systems and can capture additional energy efficiencies through deployment in distributed generation approaches by avoiding losses in transmission and by utilizing fuel streams that are too small or too far for combustion systems.
- Fuel cells are quiet and will require less maintenance as compared to internal combustion engines and turbines, and are therefore more suitable for back-up and supplementary power applications in residential and isolated areas.
- The existing fuel cell cluster in Alberta is developing applications that will increase the useful energy extracted from Alberta natural resources, whether oil or coal, and that will create value-added products and manufacturing opportunities for Alberta.

Start-Up Business Plan

The existing Alberta hydrogen and fuel cell cluster is well developed and will be the foundation of the Energy Innovation Network. R&D groups are active at the University of Alberta, the University of Calgary and at the Alberta research Council, delivering new technologies and graduating highly qualified people. NAIT is establishing a training and demonstration centre. Companies such as Global Thermoelectric, Enbridge, Sustainable Energy Technologies, Westaim Ambeon and Energy Visions are developing products and markets. Power companies are participating in Clean Coal developments and may become important producers of hydrogen. Government agencies such as AERI, NRC, IRAP, NRCan, WEDC, and AIF have provided resources to high value projects.

The creation of the Energy Innovation Network for Hydrogen and Fuel Cells will be a major step forward but will require sustained efforts in the initial stage until momentum is achieved. During the start-up period, government agencies are expected to play a leading facilitating role. The following plan provides for the start-up of the Energy Innovation Network for Hydrogen and Fuel cells.

1. Start-Up Consortium

Government agencies agree to collaborate to provide support and resources to the start-up of the Energy Innovation Network for Hydrogen and Fuel Cells. This initiative is well aligned with the mandate of AERI, NRC, IFCI, NRCan, and WEDC.

2. Small Administrative Office

The Start-Up Consortium agrees to set-up a small office for the management and administration of Energy Innovation Network for Hydrogen and Fuel Cells. It is administered by a program officer assisted by support staff. The role of the office is to:

- ✓ Provide focus, integration and organization.
- ✓ Recruit contributing members
- ✓ Recruit members for the Advisory Committee
- ✓ Organize and manage networking and training activities
- ✓ Organize and manage innovation project activities

3. Executive Committee

The Executive Committee is responsible for the Energy Innovation Network for Hydrogen and Fuel Cells. It is composed of all contributing members, whether contributions are cash or in-kind. The role of the Executive Committee is to:

- ✓ Retain and supervise the program officer.
- ✓ Approve the legal framework for the Energy Innovation Network for Hydrogen and Fuel Cells and future amendments.
- ✓ Set membership fees.
- ✓ Approve membership applications
- ✓ Approve Advisory Committee membership.
- ✓ Approve the strategy, business plan and operating budget.

4. Advisory Committee

The role of the Advisory Committee is to provide strategic direction and integration. It ensures that the operations of the Energy Innovation Network for Hydrogen and Fuel Cells are based on leading edge science, deep market knowledge, and outstanding business skills.

The Advisory Committee is composed of representatives of the founding government agencies, of each contributing member, of providers of R&D, and of leading international experts.

5. Networking and Training Activities

The program officer and support staff propose, organize and implement networking and training activities such as:

- ✓ Networking opportunities for the broad fuel cell and hydrogen stakeholder group in Alberta.
- ✓ The organization of a Canadian fuel cell and hydrogen scientific symposium, associated with other scientific conferences.
- ✓ Cross-appointments for researchers between research and educational institutions such as IFCI, NINT, ICPET, NCUT, IMI, U of C, U of A, ARC and NAIT.
- ✓ Coordinate and exchange information regarding international conferences and technology watch activities.
- ✓ Sponsor Alberta and Canadian delegations to international events in hydrogen and fuel cells.

6. Innovation Project Activities

Based on the approved strategy, business plan and operating budget the program officer administer the project selection and implementation process:

- ✓ Solicit project proposals from R&D providers
- ✓ Managed the competition process
- ✓ Oversee disbursements within budget limits
- ✓ Identify opportunities for co-funding by other programs such as IRAP, NSERC, COURSE, SDTC, Environment Canada, NRCan, etc.
- ✓ Identify opportunities for collaboration on specific projects between academic institutions and IFCI as a non-academic partner. IFCI would provide in-kind contributions through the use of hydrogen safe laboratories and fuel cell test stations.
- ✓ Oversee the evaluation of performance reports and audits

✓ Report to the Executive and Advisory Committees.

Energy Innovation Network Strategy

The strategy for Alberta in the area of hydrogen and fuel cells should focus on the more efficient conversion of Alberta natural resources into cleaner forms of energy, such as hydrogen and electricity from fuel cells. Utilizing fossil fuels to produce hydrogen and to power fuel cells does not impede the development of an eventual hydrogen economy. On the contrary, cleaner fossil energy products have a positive environmental impact in the near term and they will facilitate the development of a hydrogen economy by establishing a hydrogen and fuel cell infrastructure that, in time, would be migrated from fossil energy to renewable energy sources. If zero emission renewable energy is the ultimate future destination, cleaner fossil energy products are certainly a valuable and achievable intermediate destination.

From an Alberta perspective, cleaner energy products are a requirement for maintaining access to the North American market that is mandating increasingly strict environmental regulations. Hydrogen and fuel cells are emerging technologies that offer considerable promise for cleaner fossil energy products and should therefore be a key platform in Alberta's energy technology strategy. Hydrogen is a clean energy carrier with benefits similar to those provided by electricity. Fuel cells are efficient and flexible energy conversion devices that are applicable to a wide range of applications. Both provide global and local environmental benefits because of higher levels of energy efficiency and because of the absence of the air pollutants produced by combustion. Higher energy efficiency mitigates the global problem posed by greenhouse gas emissions. The pollution free nature of hydrogen and fuel cells would dramatically improve air quality in densely populated areas and cities. In addition, certain fuel cell applications have value as backup power, battery replacement, and local power supply for use in remote locations, in portable devices and in distributed power generation system that would improve the reliability of the electrical grid.

Hydrogen

Two related environmental drivers support the push for the development of the hydrogen economy. The use of hydrogen as the fuel for vehicles would vastly improve air quality in densely populated cities. Secondly, hydrogen can be produced using renewable energy thereby eliminating the dependence on fossil fuel and the related greenhouse gas emissions.

Alberta, as an important energy producer, has a significant stake into the future direction of energy markets, particularly in the United States. In a simplistic way, should the delivered form of energy in the United States market evolve from oil & gas to hydrogen, Alberta needs to take adequate steps to ensure that it is able to produce and deliver hydrogen utilizing Alberta natural resources. In the near term, stricter environmental regulations in the United States will likely require more hydrogen for treating and upgrading an increased proportion of the oil and gas produced in Alberta. In the longer term however, the United States has put in place a substantial research and development program to move it toward the hydrogen economy. The U.S. Clean Coal program is driven by the additional consideration of energy security. The United States has very large coal reserves and the production of hydrogen and power from zero emission Clean Coal plants is, in part, aimed at reducing U.S. oil imports. The magnitude of the U.S. technology development programs for hydrogen is impressive. Alberta should take note that its major energy market is serious about developing hydrogen as a large scale energy carrier. Alberta's participation in research and business development of hydrogen and fuel cells is necessary to ensure that Alberta remains a premier energy provider.

Alberta is already a leading producer of hydrogen in Canada, and in the rest of the world. Hydrogen is produced in Alberta with on-purpose plants using steam methane reforming, and as a co-product of other chemical processes. Hydrogen is used in Alberta for treating and upgrading crude oil and crude bitumen from the oil sands. Hydrogen treatment removes sulfur and nitrogen contaminants from crude and is a value added step in the production of cleaner transportation fuels.

The cost of on-purpose hydrogen is greatly influenced by the cost of natural gas. In the future, anticipated increases in the price of natural gas are likely to overwhelm any efficiency improvements achieved through process R&D. Several refineries and chemical plants have offgas effluents that contain hydrogen mixed with other gases such as hydrogen sulfide, methane, and light hydrocarbons. These by-product streams are generally too small to justify the investment required for aggregation and production of chemical grade hydrogen. As a result, these streams are usually burned for fuel value, displacing an equivalent amount of purchased natural gas.

Hydrogen demand is likely to increase in the future, particularly in Alberta, because stricter regulations for clean gasoline will mean increases in the amount and intensity of hydrogen treatment of oil products. The cost of hydrogen is likely to increase as a result of the long term trend to higher natural gas prices. This combination of industry drivers creates an opportunity for Alberta to invest in the development of technologies to produce hydrogen at a lower cost by utilizing low value hydrocarbon feedstocks that are present in abundant quantities in the Province, such as asphaltenes, coal, petroleum coke, and possibly abandoned oil wells. The development of such technologies would give Alberta, a competitive cost advantage, as compared to the rest of North America in the area of hydrogen production and of hydrogen treatment of oil products.

Hydrogen supply to the United States is a long-term strategic issue for Alberta. It warrants further analysis and scoping of eventual scenarios for delivering hydrogen to the United States in collaboration with participants in the Alberta oil and gas, power and pipeline sectors.

Several companies in the Alberta Industrial Heartland produce hydrogen as a co-product. In particular, Alberta Envirofuel produces isooctane but also has a co-product stream of 100 kg/hour of 99% pure hydrogen. This stream presents a specific opportunity and could be used to supply a hydrogen re-fueling station for a demonstration of hydrogen vehicles in the Edmonton area.

Fuel Cells

Fuel cell devices offer compelling advantages as compared to other energy conversion devices, whether the fuel originated from a fossil, renewable or nuclear source. From an Alberta perspective, fuel cell technologies offer opportunities for economic and environmental benefits for energy generation using fossil fuels.

The development of fuel cells for stationary, automotive and portable electric power generation has been pursued globally with intensity for several years because of their anticipated benefits. From the point of view of Alberta's interests, the most relevant attributes of fuel cells are:

- ✓ Fuel cells pollute less than traditional power sources.
- ✓ Higher energy conversion efficiency as compared to combustion
- ✓ Fuel cell exhibit high electric generation efficiencies, ranging from 40% to up to 60% for pressurized systems.
- ✓ Potentially higher electrical efficiencies are possible with fuel cell/turbine hybrid configurations. Solid Oxide Fuel Cells (SOFC) can be designed for pressurized operation and coupled with gas and steam turbines. Electric generation efficiencies of 70% are targeted.
- ✓ The ability of high temperature fuel cells, such as SOFC to be used for applications involving the cogeneration of power and steam.
- ✓ High temperature fuel cells are also suitable combined power and heat applications.
- ✓ Modular nature and suitability for distributed power generation, resulting in additional energy efficiencies at the system (grid) level from the avoidance of transmission losses.
- ✓ Superior performance as compared to lithium ion batteries in portable applications.
- ✓ Opportunities to capture concentrated CO_2 for sequestration by using high temperature fuel cells, such as SOFC.

In a fuel cell system, energy and power are separate elements. The fuel cell stack provides power. The energy on the other hand is defined by the fuel. Fuel cells have a competitive advantage in the energy parameter because fuel cells can be refueled. Advantageous applications for fuel cell systems are those where the energy requirement is large and the power requirement is small.

This is true for portable applications. Applications for fuel cells in laptop computers and other electronic devices are expected to be first to market because the power requirement is relatively small and because fuel cells have a large competitive advantage over batteries in their ability to provide energy over an extended period of time. The development of micro fuel cells and of fuel cells for portable applications is emerging in Alberta.

Distributed generation is also an application where the energy requirement is large relative to the power requirement. Power generation for households and for small commercial users requires a relatively small power generator but needs to produce energy continuously. Fuel cells are therefore well suited to distributed power generation. The scalable nature of fuel cells provides them with the flexibility required for sizing systems to a wide variety of distributed power generation applications. The development of SOFC for distributed generation is at the demonstration and business development stage in Alberta.

Billions of dollars are being invested internationally on developing fuel cell systems for automotive applications. Fuel cells vehicles using on-board hydrogen are considered zero emission vehicles and would significantly reduce air pollution in cities. This benefit is an important justification for hydrogen fuel cell vehicles. Fuel cells also offer one of the only opportunities for the use of renewable energy in vehicles such as cars, buses and trucks. Alberta is unlikely to become a centre for the development of automotive fuel cells because of the absence of automotive and heavy manufacturing industries in Alberta. Vancouver is the location of Canada's recognized cluster for hydrogen fuel cell vehicles.

Development efforts by existing Alberta researchers and developers of fuel cells have focused on applications that use hydrocarbons, in addition to pure hydrogen. This situation arises from the presence of abundant hydrocarbon resources in Alberta. The most important effort is the development of SOFC for residential and small commercial applications by Global Thermoelectric with supporting R&D from the University of Calgary. There are also development projects on stationary fuel cells that can use hydrogen sulfide and on portable fuel cells using alcohols at the University of Alberta. Micro fuel cells and methanol fuel cells are in the early stage of development at the Alberta Research Council. Some of the drive behind alcohol fuel cells and micro fuel cells comes from interest in developing a value-added manufacturing industry in Alberta and from the possibility of using ethanol from agricultural sources.

With respect to markets, existing efforts in Alberta have mostly been directed at stationary applications, particularly for residential and small commercial applications. Electricity deregulation in Alberta has created a favorable business environment for the development of distributed generation. It is likely that when lower-cost fuel cells are commercially available, they will find a niche in Alberta's deregulated electricity sector. The Eastern blackout of August 14, 2003 caused an estimated $4 billion to $6 billion in losses in the United States and Canada. One outcome is that the value proposition for back-up power has increased significantly, particularly in the small commercial market.

In addition to the development of SOFC targeted at distributed generation in the residential and small commercial market, the opportunity exists in Alberta to adapt low-cost, mass produced, modular SOFC technology to industrial applications. Residential and small commercial fuel cells are designed to be fueled by natural gas and propane. Industrial applications involve the use of alternative fuels available from Alberta refineries, upgraders and chemical producers, such as off-gases that contain hydrogen, fuel gas mixtures, coal gas and syngas. Another alternative fuel is digester gas, which is generated by city landfills and agricultural operations. Alberta and other regions where the oil and chemical industries occupy a large place in the economy have an abundance of hydrogen present as a component in off-gas streams. These streams are currently used for fuel value and displace an equivalent amount of natural gas fuel. Fuel cells would allow the chemical energy present in these fuels to be converted into electrical power, thereby improving industrial efficiency and reducing greenhouse gas emission and air pollution. Combined power and heat, as well as cogeneration of power and steam could also be envisaged. Industrial plants that produce these co-product gas streams generally are also consumers of electricity, heat and steam. Electricity deregulation in Alberta would allow power to be sold into the grid where economically justified. The modular nature of fuel cells would allow systems to be scaled to the size of each fuel stream. The technology of choice is SOFC and the development of such fuel cells would build on the existing SOFC expertise in Alberta.

The benefits offered by fuel cell/gas turbine hybrids justify their inclusion in the Canadian Clean Power Coalition technology program. Fuel cell technologies would allow the replacement of the gas turbine by a fuel cell/gas turbine hybrid that would exhibit higher electrical efficiency and cause less air pollution than the gas turbine alone. Fuel cell/ gas turbine hybrids represent a superior power module option for gasification-based systems. The United States Department of Energy is funding a large-scale trial of a fuel cell that will be fueled by coal gas produced by an existing integrated gasification combined cycle (IGCC) coal gasifier at the Wabash River site in Indiana. Pressurized high temperature fuel cells also offer an opportunity for low cost CO_2 recovery and sequestration. A major trial is planned by Shell and Siemens in Norway.

At the R&D stage at the University of Alberta, fuel cells have been developed that can convert pure hydrogen sulfide into electrical energy, sulfur, and water. Sulfur is a frequent contaminant in the hydrocarbon natural resources present in Alberta. Current practice is two either convert hydrogen sulfide to sulfur using the Claus chemical process or to re-inject hydrogen sulfide into geological formations. In either case, the chemical energy contained in hydrogen is lost. Engineering and commercialization of this fuel cell technology would in effect transform a widespread pollutant into a natural resource for Alberta.

Another area where fuel cells are expected to play a prominent role is in portable devices like computer laptops, video cameras and cell phones. Laptop computers, camcorders and cell phones suffer performance restrictions because of the limited energy storage and short life of rechargeable batteries. Fuel cells permit the use of methanol or hydrogen which offer respectively 30 and 3 times the energy density of batteries. The opportunity for Direct Methanol Fuel Cells (DMFC) and micro fuel cells applications in Alberta does not appear as promising as distributed generation stationary power. While there is not a large presence of the electronic, telecommunication and computer industry in Alberta, the Province has diversified its economy and the geomatics and wireless industries are well positioned. Light manufacturing is advantaged in the Edmonton Calgary Corridor, as shown by a recent study by TD Bank. DMFC and micro fuel cell developments are presently at the emerging stage at the Alberta Research Council and may build on the low cost environment for manufacturing industries in Alberta.

Alberta Niches

- ✓ **Increased Hydrogen Production from Low Value Feedstocks:** Technologies should be developed to produce hydrogen from the vast quantities of low value fossil feedstocks that are present in Alberta. In particular, gasification of asphaltenes appears to be the most promising approach because liquid feedstocks require lower capital expenditures than solid feedstocks and because rejected asphaltenes are readily available from bitumen recovery operations. Hydrogen could also be produced by adapting in-situ combustion technology to abandoned oil wells. The University of Calgary has existing infrastructure and experience for this research.

- ✓ **SOFC for Distributed Generation in the Residential and Small Commercial Markets:** An industry should be promoted in Alberta for the development and commercialization of mass produced SOFC modules for combined heat and power distributed generation in the residential and small commercial markets. These modules will use natural gas or propane as fuels: Global Thermoelectric in Calgary and companies in the United States and Europe are developing manufacturing technology and products for this segment. Electricity deregulation in Alberta has permitted the development of the distributed generation industry in the Province. The natural gas and propane distribution infrastructures are well developed in Alberta. SOFC would provide higher energy conversion efficiency and less associated greenhouse gas emissions and air pollution than combustion in space heating furnaces or microturbines. In addition, fuel cells are expected to be low noise and low maintenance devices.
- ✓ **Fuel Cell/Gas Turbine Hybrids for Clean Coal:** The gasification of coal is a key platform technology for Alberta. The concept of using fuel cell/gas turbine hybrids rather than turbines for the conversion of coal gas into energy opens up new possibilities for the development of gasifiers. Development of fuel cell systems for coal gas should be made part of AERI's contribution the Canadian Clean Coal Coalition and possibly Clean Coal programs in the United States and Japan. Alberta should join forces with a development program that is already underway and seek to contribute to it new R&D projects executed in Alberta.
- ✓ **Fuel cell systems for alternative fuels available in Alberta:** Fuel cell systems should be developed for the utilization of alternative fuels such as "dirty" hydrogen, gas mixtures containing hydrogen, off-gas, syngas, fuel gas, digester gas and other opportunity fuels. This technology and market niche is an extension of the SOFC for distributed generation applied to the industrial market and takes advantage of opportunity fuels present in the Alberta energy and chemical industry, as well as landfill and agricultural gases.

- ✓ **Hydrogen sulfide fuel cells:** Based on basic technology developed at the University of Alberta, fuel cell systems should be optimized and engineered to use hydrogen sulfide gas. The presence of substantial amounts of hydrogen sulfide in Alberta gas wells and the continuous production of hydrogen sulfide by oil refineries and upgraders justify the further investigation and development of an emerging fuel cell technology to capture the chemical energy of hydrogen and convert it into electricity.
- ✓ **DMFC and Micro SOFC for Portable Power:** while at an early stage, these developments may hold the promise for the growth of value-added manufacturing in Alberta. The Alberta Research Council is focusing on applications such as DMFC forklift trucks and μSOFC.

Research and Market Development

Major research thrusts and market development areas that are well aligned with the Alberta strategy are:

- ✓ Integrated energy systems
- ✓ Enhanced science base for fuel cells
- ✓ Hydrogen storage in carbon nanotubes should be investigated in partnership with the National Institute for Nanotechnology
- ✓ Co-production of chemicals and electricity using fuel cells
- ✓ Direct oxidation of methane at the anode surface in SOFC
- ✓ Networking opportunities for fuel Cell applications and demonstrations in Alberta
- ✓ Networking opportunities for Canadian fuel cell researchers
- ✓ A study should be conducted for a hydrogen vehicle trial and associated hydrogen refueling station in the Alberta Industrial Heartland, north of Edmonton.
- ✓ A scoping study should be conducted of the economic and environmental merits of various methods for converting Alberta's vast hydrocarbon resources into hydrogen, in the event of an evolution to the widespread use of hydrogen in North America.

Framework for an Energy Innovation Network

The existing Alberta cluster for research and market development of hydrogen and fuel cell technologies appears to be developed enough to undertake the various projects contemplated under this strategy. R&D groups already exist and are fully functional at the University of Alberta, the University of Calgary and at the Alberta Research Council. What is required is program funding to increase the activity level inside the R&D cluster and to provide the integration framework required for the delivery of useful products and technologies that will cause the desired outcome.

A consortium based program to fund hydrogen and fuel cell R&D in Alberta would allow the implementation of several specific projects over a typical technology development and commercialization timeframe of about 10 years. The constancy of purpose and the reliability provided by a multiyear program will allow research organization to contemplate undertaking the full cycle of innovation from laboratory prototype to commercialization. It will give them the confidence to assemble the multi-disciplinary teams required to develop and successfully introduce useful products.

The Energy Innovation Network for Hydrogen and Fuel Cells should be managed by representatives of the funding organizations. Providers of R&D would compete with each others for funding by presenting project proposals. The proposals offering the greatest value to the Consortium and to Alberta would be approved for implementation in as stage gate manner.

Potential Members of the Energy Innovation Network – Hydrogen and Fuel Cells

AERI
NRC Institute for Fuel Cell Innovation
NRC IRAP
Sustainable Development Technology Canada
Western Economic Diversification Canada
Alberta Research Council
Fuel Cells Canada
Dynetek Industries
Global Thermoelectric
Siemens
NewERA
OPTI Canada
NOVA Chemicals
Shell Chemicals
Suncor
TransCanada
Methanex
Westaim Ambeon
ATCO Power
ENMAX
Alberta Research Council
University of Calgary
University of Alberta

Enbridge
EnCana
Nexen Inc.
Northern Alberta Institute of Technology
National Institute for Nanotechnology

Strategic Recommendations

1. Research projects on the production of hydrogen from low value feedstocks such as asphaltenes, coal and abandoned oil wells.
2. Research projects on the development of fuel cell systems that can utilize alternative fuels from Alberta refineries and petrochemical plants, including the co-production of chemicals and value-added products.
3. Support for the development of a strong distributed generation cluster in Alberta, based on SOFC.
4. Research projects on the development of fuel cell gas turbine hybrids that can utilize syngas from the gasification of coal.
5. Support at the strategic level for the Western Canada Fuel Cell Initiative and the NAIT research and demonstration facility.
6. Research projects in micro fuel cells and DMFC for value-added manufacturing applications in the portable market.
7. Support for networking opportunities for the broad fuel cell and hydrogen stakeholder group in Alberta to increase awareness and education and to increase the probability of identifying high-value innovation projects.
8. The organization of a Canadian fuel cell and hydrogen scientific symposium, associated with other industry conferences or with one of the annual meeting of the Chemical Institute of Canada.

Tactical Recommendations

9. A scoping study should be conducted of the economic and environmental merits of various methods for converting Alberta's vast hydrocarbon resources into hydrogen, and for distribution in the Fort McMurray to Red Deer corridor..
10. Research on hydrogen storage in carbon nanotubes should be investigated in partnership with the National Institute for Nanotechnology.

11. Research projects into the fundamental challenges associated with fuel cells, such as material science and electrocatalysts, particularly at the stack level for SOFC and μSOFC.

12. Fundamental research on direct oxidation of methane and other hydrocarbons at the anode surface, particularly for SOFC.

13. Fundamental and engineering studies on hydrogen sulfide fuel cells.

14. Demonstration trials of SOFC for distributed generation in the residential and small commercial market should receive support.

15. A hydrogen vehicle demonstration trial and associated hydrogen refueling station in the Alberta Industrial Heartland, north of Edmonton.

16. Demonstration of fuel cell systems for different fuels from Alberta refineries and petrochemical plants.

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1 Introduction

Energy production is a foundation of Alberta's economy. Alberta has the world's greatest repository of hydrocarbon resources. Bitumen and oil reserves contained in the oil sands are of a similar magnitude to the reserves of conventional oil in Saudi Arabia. Alberta is the leading Canadian producer of hydrogen, primarily produced from natural gas and used in oil refineries and bitumen upgraders. Coal-fired plants generate over 70% of Alberta's electricity. Clean Coal and bitumen gasification technology initiatives may add to Alberta's hydrogen production.

The Kyoto Protocol and the associated reduction in greenhouse gas emissions may place restrictions on the growth of the conventional energy industry in Alberta and the Province needs to transition from conventional to sustainable energy production. Investments in technology and capability will be required for the development of clean power, value-added products/processes, alternative energy, and to address environmental concerns.

Fuel cell research is active in Alberta with research groups at the University of Alberta, the University of Calgary and at the Alberta Research Council (ARC). The ARC is also involved in fuel cell business development with companies such as Energy Ventures. Alberta based industry leaders of hydrogen and fuel cell developments are Global Thermoelectric, and Dynetek.

A major component of the Strategic Business Plan of the Alberta Energy Research Institute (AERI) is Alternative Energy with a focus on hydrogen, fuel cells and bioenergy. Hydrogen (or hydrogen carrier fuels) is likely to be this century's fuel of choice. Alberta's participation in research and business development of hydrogen and fuel cells is necessary to ensure that Alberta remains a premier energy provider.

The Institute for Fuel Cell Innovation (IFCI) of the National Research Council (NRC) supports the innovation needs of Canadian fuel cell companies. At IFCI, a multidisciplinary team of over 60 researchers conducts research aimed at advancing fuel cell science and technology and facilitating the commercialization of fuel cells

This feasibility study is sponsored by AERI and IFCI. Its purpose is to review hydrogen and fuel cell technology, to investigate existing research and commercialization undertakings in Alberta, and identify needs and opportunities for Alberta.

2 Terms of Reference

The Alberta Energy Research Institute and the National Research Council Institute for Fuel Cell Innovation wish to actively encourage an Alberta hydrogen and fuel cell research and business development cluster and network of excellence. The purpose of this feasibility study is to define and understand who the key players are in the Alberta hydrogen and fuel cell cluster; their needs, their potential interest and their roles in a research, development and deployment network of excellence.

Specifically, the Terms of Reference for this feasibility study include:

- Understand who is doing what in hydrogen and fuel cell research worldwide and in Canada, particularly in the provinces around Alberta.
- Understand what they are not doing, or not doing in a world-class fashion. This will then indicate the opportunities and define some of the gaps.
- Prioritize those gaps in view of:
  - Alberta's needs and its long term direction, and
  - Potential partnerships among AERI, NRC, the Alberta Research Council, National Resources Canada, the University of Calgary, the University of Alberta and industry.
- Recommend the focus and the frame work of an Alberta hydrogen and fuel cell network of excellence in the context of the Western Canadian Fuel Cell Initiative.

The general intent of a Hydrogen and Fuel Cell Network would be to:

- Provide a focal point for hydrogen and fuel cell development activities and provide support to other related development activities within the province;
- Undertake selected research and development activities, including both pure and applied;
- Link to other research collaborations, including both within and outside Alberta;
- Provide relevant opportunities for training and training development; and
- Develop commercial spin-offs within Alberta for potentially marketable service and product opportunities.

3 Background

In order to set the stage for an analysis of the situation in Alberta, it is important to first examine the rationale for hydrogen and fuel cells. The views of environmental advocacy groups and policy actions of governments are briefly touched upon, as well as some of the major industry trends.

3.1 The Case for Hydrogen

Advocates for a greener earth promote a vision of sustainable development and of greater care of the environment. There are varying views regarding the required pace of change and specific components of the proposed agenda. One element of this vision is termed the hydrogen economy. Hydrogen would replace coal-burning power plants and associated emissions, and would end the need for gasoline and pollution-from automobiles. Two related environmental thrusts support the push for the development of the hydrogen economy. The use of hydrogen as the fuel for vehicles would vastly improve air quality in densely populated cities. Secondly, hydrogen can be produced using renewable energy thereby eliminating the dependence on fossil fuel and related greenhouse gas emissions.

The European Union plans to invest into research into renewable energy technologies, which they want to make the cornerstone of a hydrogen energy economy. Europe has committed to a benchmark of having 22 percent of its electricity, and 12 percent of its energy, come from renewable energy by 2010 [1]. Hydrogen, one of the most common elements on earth, can be derived from many sources. Today, it is commonly extracted from natural gas, or methane. For a truly pollution-free system, some environmentalists argue, the hydrogen must come from a source that does not pollute. Environmental groups say hydrogen is not an inherently clean technology and the hydrogen economy would only be as clean as the energy used to create hydrogen. A push to produce hydrogen from renewable energy technology such as wind, solar and geothermal power -and not fossil fuels or nuclear- is the answer. Following this line of thinking, Europe intends to place renewable energy sources at the heart of the hydrogen economy. The European Union understands that much of the hydrogen will have to be extracted from fossil fuels in the immediate future. Its long-term game plan is to rely increasingly on renewable sources of energy to extract hydrogen. During the transition period, coal, natural gas and other fossil fuels and possibly nuclear power will be needed to make hydrogen. However, in the longer term, renewable energy sources should become the most important source for the production of hydrogen.

The United States have resisted any such commitments. The U.S. hydrogen program is designed to eventually produce all hydrogen using emission-free technologies including almost half from renewable sources. President Bush has proposed a US$1.2 billion research program into hydrogen sources and half of this research money involves renewable energy [2]. The United States is also considering a US$3 billion research effort to push hydrogen fuel-cell development and the creation of a hydrogen fuel infrastructure [3]. The Energy Department has begun a $1 billion program to develop a new generation of coal-burning power plant that would make electricity and hydrogen, while capturing carbon dioxide and other pollutants [4]. The administration also supports a Senate proposal that calls for building a US$1.1 billion nuclear reactor that would produce hydrogen [5]. Hydrogen can be made from electricity generated by a coal-burning power plant or a nuclear reactor by using a process known as electrolysis where electricity splits water into hydrogen and oxygen. The hydrogen can then be stored and later used in a fuel cell where it reacts with oxygen to produce energy; water is the only by-product.

In early 2003, President Bush announced the FreedomCAR program, a US$ 1.2 billion program over five years for the development of a hydrogen fuel cell car. The program also includes: reducing vehicle weight, improving energy production and on-board storage, advancing the internal combustion engine, building electronic components, and developing robust hybrid electric drive trains.

Hydrogen can be burned in internal combustion engines and power plants to produce energy. Used in this way, hydrogen generates no carbon dioxide and significantly less air pollution than fossil fuels such as gasoline and coal. Some auto manufacturers such as BMW and Ford are developing hydrogen fueled internal combustion engines. This technology may be available sooner than fuel cell vehicles and may act as a catalyst to developing the required hydrogen infrastructure. In other words, the hydrogen internal combustion engine could be a bridge technology. The auto industry is also focusing on hybrid gasoline/electric vehicles. Hybrid vehicles are being introduced by Toyota, Honda, Ford, General Motors, and DaimlerChrysler. Hybrids are capable of significantly higher fuel efficiency than conventional vehicles and several carry ultra-low emission vehicle ratings (ULEV).

In Canada, the federal government will contribute $14 million to support hydrogen fuel research. One promising project uses hydrogen and oxygen in a fuel cell engine to power a fleet of cars. By early 2004, five standard Ford Focuses will be on Vancouver streets equipped with zero emission, fuel-cell engines designed and built by Vancouver's Ballard Power Systems [6].

3.2 The Case for Fuel Cells

Fuel cells use hydrogen and oxygen to produce power, with only water as a by-product. They pollute less than traditional power sources, producing little more than water as a by-product. Fuel cells vehicles using on-board hydrogen are considered zero emission vehicles. While hydrogen fuel cell vehicles do not emit pollutants, emissions may have been generated if the hydrogen was produced from fossil resources. Billions of dollars are being invested internationally on developing fuel cell systems for a wide range of power applications.

Based on an electrochemical process that was discovered over 150 years ago, fuel cells use an electrically conductive material to convert chemical energy from hydrogen and oxygen into electrical energy. Although similar to batteries in function, fuel cells have the advantage of continuous operation through refueling (like a traditional engine).

In the automobile industry, researchers expect that Proton Exchange Membrane fuel cells (PEMFC) will be twice as efficient as internal combustion engines and will cut carbon dioxide emissions in half. A number of automakers are now testing fuel cell vehicles. DaimlerChrysler is building 30 buses with fuel cell engines from Ballard Power Systems that will be deployed in European cities, such as Amsterdam, Barcelona, and London, where they will be driven for two years in normal traffic to see how they perform. General Motors, Ford, and Honda are also testing fuel cell prototypes. Mass production is expected in 2010-2015.

Fuel cells can be used anywhere that energy is required. The scalable nature of fuel cells permits their use as an option for distributed power generation. High temperature fuel cell technologies such as the Solid Oxide Fuel Cell (SOFC) and Molten

Carbonate Fuel Cell (MCFC) are favored for stationary power applications because of their ability to use hydrocarbon fuels internally in the fuel cell system and because high temperature exhaust gases can be employed to produce additional useful energy. A number of commercial fuel cell developers now working around the world. Companies such as UTC Fuel Cells, Siemens Westinghouse, Ballard Power Systems, Global Thermoelectric and others, are testing industrial and residential generators that not only produce electricity, but can also be used for water and space heating. The U.S. Department of Energy, the European Union and Japan are sponsoring research and demonstration trials for fuel cells up to the megawatt range to produce power from natural gas, coal gas and digester gas. The larger systems are hybrid systems using gas and turbines for targeted electrical efficiencies of 60% to 70% [7] . Stationary power applications are expected to see mass production in the 2009-2012 time frames.

Another area where fuel cells are expected to play a prominent role is in portable devices like computer laptops, video cameras and cell phones. Fuel cell technology was adapted to allow the use of methanol instead of hydrogen. Methanol is easier and safer than hydrogen in consumer applications. Direct Methanol Fuel Cells (DMFC) draw their power from methanol without the need for a reformer. Methanol has ten times the power of lithium batteries, and one cell could power a laptop computer for hours. The fuel cell would be fueled with methanol and draw oxygen from the air, emit water (probably collected in a bladder) and return to the atmosphere a small amount of carbon dioxide. To refuel the laptop, you would simply pop out the fuel cartridge and slip in a new one. MTI MicroFuel Cells has developed a prototype methanol mobile phone that will provide power for much longer periods than traditional cell phones when it is launched in 2004. Motorola, Toshiba, Casio, and Sanyo are developing miniature fuel cells for a variety of devices, including PDA, laptops, and cell phones. The U.S. Department of Transportation gave the industry a big boost last October when it announced that a fuel cell design by PolyFuel would be allowed on airplanes, a change from the airline industry's rigid no fuels policy in the passenger cabin of the airplane. Portable applications should be mass produced in 2005-2009.

The development of fuel cells for stationary, mobile and portable electric power generation has been pursued with intensity for several years and has benefited from government support because of the following attributes:

- Low environmental emissions, particularly NO_x and SO_x because combustion is not involved. However, if hydrogen is produced by reforming hydrocarbons, whether off-site, on-site or on-board, NO_x and other air pollutants are produced.
- Potential for high electric generation efficiencies, ranging from up to 40% for PEMFC to up to 60% for pressurized SOFC.
- The ability of high temperature fuel cells to match the requirements of many steam hosts for cogeneration applications.
- Potentially higher electrical efficiencies in fuel cell/turbine hybrid configurations. SOFC and MCFC can be designed for elevated pressure operation coupled with gas or steam turbines. The pressurized hot exhaust from the fuel cell is combusted in a gas turbine to generate additional electricity. The gas turbine may also be used to drive a steam turbine. Electric generation efficiencies of 60 to 70% have been projected. If the gas turbine is not fired with additional fuel, it produces no additional air emissions.
- Modular nature and suitability for distributed power generation.
- Superior performance as compared to lithium ion batteries in portable applications.

While this may sound great, all is not roses for the industry. Fuel cells are currently expensive to produce and the hydrogen they use is difficult to store and distribute. Yet, fuel cells today are much less expensive and more powerful than the prototypes used in the 1960s NASA space capsules. Many believe that mass-rollouts of the technology will occur in the next five to ten years in several areas, including automobiles, stationary power and mobile devices.

4 Overview of Worldwide Hydrogen and Fuel Cell Research and Business Development

In this section, the technology of hydrogen and fuels cells is described in some detail. While this is an emerging and rapidly evolving field, every effort has been made to present the best available and current information. Hydrogen technology is covered first, followed by a review of the major competing fuel cell technologies.

4.1 Hydrogen

Hydrogen Production

Reforming

Steam reforming of hydrocarbons such as methane (natural gas), methanol and gasoline are based on the same fundamental reaction with modified operating conditions depending on the hydrogen-to-carbon ratio of the feedstock. Reforming is an endothermic reaction conducted under high severity. Typical operating conditions are 30 atmospheres and temperatures exceeding 870°C [8, 9]. Conventional technology uses a fired heater filled with multiple tubes to ensure uniform heat transfer.

$$CH_4 + H_2O \rightarrow 3H_2 + CO$$

Typically the feedstock is pretreated to remove sulfur, a poison which deactivates nickel reforming catalysts. Guard beds, filled with zinc oxide or activated carbon, are used to pre-treat natural gas and hydrodesulfurization is used for liquid hydrocarbons. Commercially, the steam to carbon ratio is between 2 and 3. Higher stoichiometric amounts of steam promote higher conversion rates and minimize thermal cracking and coke formation.

Because of the high operating temperatures, a considerable amount of heat is available for recovery from both the reformer exit gas and from the furnace flue gas. A portion of this heat is used to preheat the feed to the reformer and to generate the steam for the reformer. Additional heat is available to produce steam for export or to preheat the combustion air.

Methane reforming produces a synthesis gas (syngas) with a 3:1 H_2/CO ratio. The H_2/CO ratio decreases to 2:1 for less hydrogen-rich feedstocks such as light naphtha. The addition of a CO shift reactor could further increase hydrogen yield from steam methane reforming according to the following equation:

$$CO + H_2O \rightarrow H_2 + CO_2$$

The shift conversion may be conducted in either one or two stages operating at three temperature levels. High temperature (350°C) shift utilizes an iron-based catalyst, whereas medium and low (205°C) temperature shifts use a copper-based catalyst.

The overall equation for steam reforming followed by shift conversion is therefore:

$$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$$

In other words, one mole (or one unit of volume) of methane (natural gas) will produce 4 moles of hydrogen. However, it is estimated that 30% more natural gas is required to convert it to hydrogen [10]. This 30% excess is required for combustion to provide the heat for the endothermic reaction. The net hydrogen yield from methane on a molar (and volume) basis is 3:1.

The heat of combustion of one mole of methane is 191 kcal/mole (900 BTU/ft^3). The heat of combustion of 3 moles of hydrogen is 231 kcal (837 BTU). In other words, steam reforming of methane results in hydrogen gas with approximately 93% of the heat of combustion of the input methane. This comparison, however, is in terms of combustion heat. Hydrogen is more valuable than methane in that a larger portion of its energy can be converted to electricity by fuel cells.

There are two options for purifying crude hydrogen. Most of the modern plants use multi-bed pressure swing adsorption (PSA) to remove water, methane, CO_2, N_2, and CO from the shift reactor to produce a high purity product (99.99%+). Alternatively, CO_2 could be removed by chemical absorption followed by methanation to convert residual CO_2 in the syngas.

Ford and Ballard have collaborated on a hydrogen-fueled internal combustion engine generator set, expected to be commercialized in 2003. The generator set is based on a Ford V10 engine and is rated at 91 kW when using hydrogen and 160 kW when using natural gas.

Gasification

Traditionally, gasification is used to produce syngas from residual oil and coal [11, 12]. More recently, it has been extended to process petroleum coke and asphaltenes. Other feedstocks include refinery wastes, biomass, and municipal solid waste. Although not as economical as steam methane reforming, there are a number of natural gas-based gasifiers.

In addition to the primary reaction shown by the following equation, a variety of secondary reactions such as hydrocracking, steam gasification, hydrocarbon reforming, and water-gas shift reactions also take place.

$$CaHb + a/2O_2 \rightarrow b/2H_2 + aCO$$

For liquid and solids gasification, the feedstocks react with oxygen or air under severe operating conditions (1,150°C to 1,425°C at 400 to 1,200 psig). In a hydrogen production plant, there is an air separation unit upstream of the gasifier. Using oxygen rather than air avoids downstream nitrogen removal steps.

In some designs, the gasifiers are injected with steam to moderate operating temperatures and to suppress carbon formation. The hot syngas could be cooled directly with a water quench at the bottom of the gasifier or indirectly in a waste heat exchanger (often referred to as a syngas cooler) or a combination of the two. Facilitating the CO shift reaction, a direct quench design maximizes hydrogen production. The acid gas (H_2S and CO_2) produced has to be removed from the hydrogen stream before it enters the purification unit.

When gasifying liquids, it is necessary to remove and recover soot (i.e., unconverted feed carbon), ash, and any metals (typically vanadium and nickel) that are present in the feed. The recovered soot can be recycled to the gasifier, although such recycling may be limited when the levels of ash and metals in the feed are high. Additional feed preparation and handling steps beyond the basic gasification process are needed for coal, petroleum coke, and other solids such as biomass.

Partial oxidation of fossil fuels in large gasifiers is another method of thermal hydrogen production [8]. It involves the reaction of a fuel with a limited supply of oxygen to produce a hydrogen mixture, which is then purified. Partial oxidation can be applied to a wide range of hydrocarbon feedstocks, including natural gas, heavy oils, solid biomass, and coal. Its primary by-product is carbon dioxide.

Electrolysis

Hydrogen can also be produced by using electricity in electrolyzers to extract hydrogen from water. Currently this method is not as efficient or cost effective as using fossil fuels in steam methane reforming and partial oxidation, but it would allow for more distributed hydrogen generation and open possibilities for using electricity made from renewable and nuclear resources. The primary by-products are oxygen from the electrolyzer and carbon dioxide from electricity generation [13] .

Electrolysis is decomposition of water into hydrogen and oxygen, as shown in the following equation [14]:

$$2H_2O + 4e^- => 2H_2 + O_2$$

Alkaline water electrolysis is the most common technology used in larger production capacity units. In an alkaline electrolyzer, the electrolyte is a concentrated solution of KOH in water, and charge transport is through the diffusion of OH^- ions from cathode to anode. Hydrogen is produced at the cathode with almost 100% purity at low pressures. Oxygen and water by-products have to be removed before dispensing.

Electrolysis is an energy intensive process. The power consumption at 100% efficiency is about 40 kWh/kg hydrogen; however, in practice it is closer to 50 kWh/kg. Since electrolysis units operate at relatively low pressures (10 atmospheres), higher compression is needed to distribute the hydrogen by pipelines or tube trailers compared to other hydrogen production technologies.

Production Costs

Hydrogen production costs vary according to the technology used, scale and the delivery and distribution method [15]. Table 1 provides a summary of estimated costs for the production of hydrogen. Lowest costs are obtained by steam methane reforming. Gasification costs vary depending on the feedstock used. Liquid feeds such as petroleum residues are less costly to gasify than solid feeds such as petroleum coke and coal. Biomass is more expensive because of its usually high moisture content. Electrolysis is the most expensive production method for hydrogen. Delivery and dispensing by liquid tanker is the less costly method, followed by gas tube trucks and pipelines.

Table 1 - Summary of Central Plant Based Hydrogen Costs (1,000 kg/d hydrogen)			
Delivery Pathway	**Liquid Tanker (US$/kg)**	**Gas Tube (US$/kg)**	**Pipeline (US$/kg)**
Natural Gas			
Production	2.21	1.30	1.00
Delivery	0.18	2.09	2.94
Dispensing	1.27	1.00	1.07
Total	3.66	4.39	5.00
Coal			
Production	3.06	2.09	1.62
Delivery	0.18	2.09	2.94
Dispensing	1.27	1.00	1.07
Total	4.51	5.18	5.62
Petroleum Coke			
Production			1.35
Delivery			2.94
Dispensing			1.07
Total			5.35
Residues			
Production			1.27
Delivery			2.94
Dispensing			1.07
Total			5.27
Biomass			
Production	3.53	2.69	2.29
Delivery	0.18	2.09	2.94
Dispensing	1.27	1.00	1.07
Total	4.98	5.77	6.29
Water			
Production	6.17	5.30	5.13
Delivery	0.18	2.09	2.94
Dispensing	1.27	1.00	1.07
Total	7.62	8.39	9.13
Source: National Renewable Energy Laboratory, 2002 [15]			

While most of the attention is focused on steam reforming of methane and electrolysis because they offer the best cost and efficiency, there are other methods that being developed. Table 2 provides a summary of commercial and alternate methods.

Table 2 - Comparison of Hydrogen Production Methods

Method	Maximum Process Temperature (°C)	Overall Efficiency (%)	Status
Sulfur-Iodine Thermo-chemical Cycle	850	45-49	Calculation
Calcium-Bromine Thermochemical Cycle	760	36-40	Pilot Plant
Copper-Chlorine Thermochemical Cycle	500	41	Bench
Electrolysis	90	20-30	Commercial
High-Temperature Electrolysis	800	40	Experimental
Steam Methane Reforming (SMR)	900	77	Commercial
SMR with CO_2 Sequestration	900	58	Calculation
Source: Argonne National Laboratory [16]			

Hydrogen Storage

Hydrogen can be stored as a gas or liquid or in a chemical compound. Currently available technologies permit the physical storage, transport, and delivery of gaseous or liquid hydrogen in tanks, trucks and pipeline systems. However, no current technology appears to satisfy all of the desired storage criteria sought by manufacturers and end users for the widespread use of hydrogen.

The storage of compressed hydrogen gas in tanks is the most mature technology. However, as shown on Table 3 the very low density of hydrogen translates to inefficient use of space aboard a vehicle which can however be mitigated with higher compression. Storage tanks are being developed with increased strength-to-weight ratio, reduced weight and volume, improved impact resistance, and improved safety. Compressed hydrogen storage is a mature technology, but improvements in cost, weight, and volume storage efficiency continue to be made. Current technology for stationary and on-board compressed hydrogen storage permits pressures from 3,000 psi (200 bar) to 12,500 psi (825 bar).

Table 3 - Density of Vehicle Fuel	
Fuel Type	**Density (kg/l)**
Compressed Hydrogen (400 atm; 6,000 psig)	0.016
Gasoline	0.80
Methanol	0.72
Source: National Renewable Energy Laboratory, 2002 [15]	

Liquid hydrogen takes up less storage volume than gas but requires expensive cryogenic containers. Furthermore, the liquefaction of hydrogen is an energy-intensive process and also results in large evaporative losses. About one-third of the energy content of the hydrogen is lost in the liquefaction process. Several automotive manufacturers are considering liquid hydrogen storage because of its good volumetric storage efficiency. However special handling requirements, long-term storage losses, and cryogenic liquefaction energy demands currently detract from commercial viability.

Hydrogen can be stored chemically at high densities as reversible metal hydrides or adsorbed on carbon structures. When the hydrogen is needed, it can be released from these materials by applying set temperature and pressure conditions. Metal hydrides offer the advantages of lower pressure storage, conformable shapes, and reasonable volumetric storage efficiency, but have weight penalties and thermal management issues. Adsorbing materials with high surface areas are emerging, but the design of practical systems awaits a better understanding of the fundamental adsorption/ desorption processes and development of high-volume manufacturing processes. The most promising carbon materials for hydrogen storage at this time appear to be carbon nanotubes but this technology is in the very early stage of development.

Chemical hydrides are emerging as another alternative. The chemical hydrides considered for storage applications are a class of compounds that can be stored in solution as an alkaline liquid. Their ability to release hydrogen is not a reversible process as it is the case for metal hydrides. Spent chemical hydride must be recycled and regenerated off-site. Although chemical hydrides present a potentially safer and more efficient option, several challenges remain be addressed, including cost, recycling, overall energy efficiency, and infrastructure.

Metal hydrides, nanostructures and chemical hydride systems are all at an early stage of development and much research remains to be done before reliable comparison of their efficiency and cost can be made to existing commercial approaches.

U.S Department of Energy Hydrogen Roadmap

Overview

The United States views hydrogen as a strategic energy carrier of the future and has proposed a roadmap for development and commercialization. Using hydrogen as a primary energy carrier could address three important energy policy concerns in the United States:

- Energy security
- Air pollution
- Greenhouse gas emissions.

In the United States, hydrogen offers the potential for an energy system that produces near-zero emissions and that could be based on abundant domestic natural resources such as coal, nuclear and renewable sources. Before hydrogen can achieve its promise, however, significant technical, economic, and institutional challenges must be overcome.

The National Hydrogen Energy Roadmap, released in 2002, outlines key issues and challenges in hydrogen energy development and suggests paths that government and industry can take to expand use of hydrogen-based energy. Hydrogen could affect every aspect of the U.S. energy system, from production through end-use. The individual segments of a hydrogen energy system are:

- Production

- Transportation
- Storage
- Conversion
- End-use applications.

Design and implementation of a hydrogen economy must address challenges in each of these segments as well as integration and systemic issues.

Production

The United States hydrogen industry currently produces nine million tons of hydrogen per year for use in chemicals production, petroleum refining, metals treating, and electrical applications. Steam methane reforming accounts for 95 percent of the hydrogen produced in the United States. Steam methane reforming is the most energy-efficient commercial technology currently available, and is most cost-effective when applied to large, constant loads.

Improvements to hydrogen production systems are required to lower costs, improve efficiency, and reduce the cost of carbon sequestration. Programs should focus on improving existing commercial processes such as steam methane reforming, gasification, and electrolysis for both central-plant and distributed hydrogen production. Novel production techniques such as biological methods and nuclear- or solar-powered thermo-chemical water-splitting should continue to receive attention.

Transportation

A distribution infrastructure will be needed to support the development of the hydrogen economy. A key element of government programs should be demonstration projects aimed at testing various hydrogen infrastructure components for both central and distributed systems in concert with end-use applications (e.g., fueling stations and power parks). Cost, safety, and reliability issues will influence the balance of central versus distributed production. R&D should be conducted into the development of better components, such as hydrogen sensors, pipeline materials, compressors, and high-pressure breakaway hoses.

Storage

Hydrogen storage is a key enabling technology and a critical gap. None of the current technologies satisfy all of the hydrogen storage attributes required by manufacturers and end users. Research and development is needed to lower costs, improve performance, and develop advanced materials. Improvements to existing commercial technologies, such as compressed hydrogen gas and liquid hydrogen, are required. R&D should continue into novel storage technologies such as lightweight metal hydrides and carbon nanotubes.

Conversion

Hydrogen may be converted into useful forms of electric and thermal energy using:

- Fuel cells
- Reciprocating engines
- Turbines
- Process heaters.

The U.S. Hydrogen Energy Roadmap calls for R&D to enhance manufacturing capabilities, to lower costs and to develop higher-efficiency fuel cells, reciprocating engines and turbines. Research is also required into advanced materials, electrochemistry, and fuel cell stack interfaces and to explore the fundamental properties of hydrogen combustion. Efforts should also include developing profitable business models for distributed power generation, optimizing fuel cell designs for mobile and stationary applications, and expanding tests of hydrogen-natural gas blending for combustion.

Applications

U.S. consumers demand safety, convenience, affordability, and environmental friendliness. Cost and performance issues must also be addressed in tandem with customer awareness and acceptance. Hydrogen systems need to reflect an understanding of consumer preferences.

Well-To-Wheels

As a result of the well-to-wheel study that General Motors (GM) conducted together with major energy companies, GM regards hydrogen as the fuel of the future to be used directly on-board the vehicle [17-20]. The hydrogen fuel cell vehicles offer the biggest potential in reducing greenhouse gas emissions as compared to conventional gasoline vehicles.

There are also indications that hydrogen internal combustion engines, as hybrids running on hydrogen, may be faster to market. Fuel cell cars will not be available commercially for 10 to 12 years, but hydrogen combustion engine-vehicles could be ready much sooner.

One of the critical key factors to the future commercial use of fuel cells is the supply of low-cost hydrogen. Hydrogen for stationary fuel cells can be generated on-site or supplied as a compressed gas via special pipelines from large central hydrogen production plants. For fuel cell vehicles, hydrogen can be generated and compressed at filling stations or delivered from large central plants to filling stations as liquid or compressed hydrogen. Hydrogen is then carried on-board in high pressure tanks. The development of on-board hydrogen production by reforming hydrocarbons presents major technical and cost challenges.

Iceland

By the year 2040 Iceland intends to become the world's first hydrogen economy free from fossil fuels. Hydrogen would be produced using renewable energy sources and used to run fuel cells. [21, 22, 23]

Currently, Iceland uses renewable energy to generate more than 70 percent of its power: 50% comes from geothermal and 20% from hydro resources. About 90 percent of Iceland's houses are heated by hot water from geothermal energy and a growing portion of the nation's electricity is produced using steam generated from geothermal resources.

The fact that just 17%of its geothermal and hydro energy resources have been harnessed has encouraged Iceland to go further and to become fully independent of fossil fuels. The plan is to use geothermal and hydro energy power to produce hydrogen and to convert the economy to hydrogen for transportation. This roadmap would result in between 90 and 95 percent of Iceland's total energy needs to be met using renewable sources.

Iceland is taking part in a European environmentally friendly power project, Ecological City Transport System (ECTOS), and aims to have three DaimlerChrysler hydrogen buses driving through the streets of Reykjavik. The cost of the project is covered 40% by the European Union. A plan to create a fishing fleet powered by hydrogen is a longer-term project.

While hydrogen production technology is available, Iceland is dependent upon the development of fuel cell technology and of technology for storage of hydrogen to realize this vision.

4.2 Fuel Cell Overview

Fuel cells are electrochemical devices that convert the chemical energy directly into electrical energy. Fuel cells generate electricity through an electrochemical process in which the energy stored in a fuel is converted directly into direct current (DC) electricity [24-29].

Operating Principle

All fuel cells have the same basic operating principle. An input fuel is catalytically reacted (electrons removed from fuel molecules) in the fuel cell to create an electric current. The basic physical structure or building block of a fuel cell consists of an electrolyte layer in contact with a porous anode and cathode on either side. The input fuel passes over the anode and oxygen (usually as air) passed over the cathode. Molecules are catalytically splits into ions and electrons. The electrons go through an external circuit to serve an electric load while the ions move through the electrolyte toward the oppositely charged electrode. At the electrode, ions combine to create by-products, primarily water and CO_2. Depending on the input fuel and electrolyte, different chemical reactions will occur.

There are six primary types of fuel cells which are based on the electrolyte or the fuel employed and a summary of their attributes is shown on Table 4:

- Alkaline Fuel Cell (AFC)
- Phosphoric Acid Fuel Cell (PAFC)
- Proton Exchange Membrane Fuel Cell (PEMFC)
- Direct Methanol Fuel Cell (DMFC)
- Molten Carbonate Fuel Cell (MCFC)
- Solid Oxide Fuel Cell (SOFC)

Table 4 - Fuel Cell Technologies [26, 29]						
	AFC	**PAFC**	**PEMFC**	**DMFC**	**MCFC**	**SOFC**
Electrolyte	Alkaline KOH solution	Phosphoric Acid	Polymer	Polymer	Molten Carbonate Salt	Ceramic
Operating Temperatures	120 °C to 250 °C	190°C to 210 °C	80°C	80°C	650°C	1000°C
Fuels	Pure hydrogen	H_2 Reformate	H_2 Reformate	Methanol	H_2/CO Reformate	H_2/CO Reformate
Reforming	Not applicable	External	External	Not applicable	External/Internal	External/Internal
Oxidant	O_2	O_2/Air	O_2/Air	O_2/Air	CO_2/O_2/Air	O_2/Air
Charge Carrier	H^+	H^+	H^+	H^+	$CO_3^{=}$	$O^{=}$
Electrical Efficiency	40-50%	40-50%	40-50%	45-55%	50-60%	45-55%
Time to Operation		2 to 4 hours	Seconds	> 10 hours	> 10 hours	> 10 hours
Power Density (watts/kg)	Similar to PEMFC	120-180	340-1500	25% to 33% of PEMFC	30-40	15-20

Fuel Cell Stack

As with batteries, individual fuel cells must be combined to produce appreciable voltage levels and so are joined by interconnects. All interconnects must be an electrical conductor and must be impermeable to gases. In the flat plate (planar) configuration used by most cell designs, interconnects become separator plates with two functions:

- To provide an electrical series connection between adjacent cells
- To provide a gas barrier that separates the fuel and oxidant of adjacent cells.

Other important parts of the cell stack are:

- The structure for distributing the reactant gases across the electrode surface and which serves as mechanical support
- The electrolyte reservoirs (in the case of liquid electrolyte cells to replenish electrolyte lost over life)
- Electrical current collectors that provide a path for the current between the electrodes and the separator of flat plate cells.

Systems must be built around the fuel cells to supply air and clean fuel, convert the power to a more usable form such as grid quality AC power, and remove the depleted reactants and heat that are produced by the reactions in the cells.

Tubular SOFC configuration is described later.

Fuel Cells Power Plants

Fuel cells power plants are typically comprised of four elements:

- Fuel processor
- Power section or fuel cell stack
- Power conditioner
- Balance of plant

Beginning with fuel processing, hydrogen is treated for potential impurities. Alternatively, a conventional fuel (natural gas, other gaseous hydrocarbons, naphtha, or coal gas) is cleaned, and then converted into a gas containing hydrogen. The hydrogen rich fuel is then fed into the power section to produce DC electricity and reusable heat. Air as the oxygen source is also provided. The power section includes a fuel cell stack which is a series of individual fuel cells interconnected to produce the desired quantity of electrical power. A varying number of cells or stacks can be matched to a particular power application. The output DC electricity is then converted to AC electricity in the power conditioning section where it also reduces voltage spikes and harmonic distortions. Power conditioning converts the electric power from DC into regulated DC or grid quality AC for consumer use. Balance of plant refers to the ancillary devices required for the continuous and reliable operation such as fans, pumps and control modules, as well as units required for start-up and shut-down.

Fuel utilization efficiencies at the anode appear to lie in the range of 70 to 85%. The unconverted fuel can be burned in an anode exhaust combustor to provide heat for fuel reforming in low temperature fuel cells. In hybrid SOFC/turbine configurations, the unconverted fuel can be burned in the gas turbine to generate additional electricity.

4.3 Fuel Cell Technologies

Alkaline Fuel Cell (AFC) [24-29]

The alkaline fuel cell was one of the first fuel cell systems to be developed in the early 1960s. The initial application was to provide on-board electric power for the Apollo space program. Desirable attributes of the AFC include its excellent performance on hydrogen and oxygen due to its active O_2 electrode kinetics and its flexibility to use a wide range of electrocatalysts.

The electrolyte in this fuel cell is concentrated (85 %) potassium hydroxide (KOH) for fuel cells operated at high temperature (about 250 °C), or less concentrated (35-50 %) KOH for lower temperature (<120 °C) operation. The electrolyte is retained in a matrix which is usually made with asbestos. A wide range of electrocatalysts can be used: nickel, silver, metal oxides, spinels, and noble metals such as platinum and palladium. Pure hydrogen must be used as the fuel supply. Non-reactive compounds may also be present in the fuel stream. Carbon monoxide (CO) is a poison, and carbon dioxide (CO_2) will react with the KOH. Even the small amount of CO_2 in air must be avoided with the alkaline cell.

It was recognized that pure hydrogen would be required as the fuel stream, because CO_2 in any reformed fuel reacts with the KOH electrolyte to form K_2CO_3, thus altering the electrolyte and reducing ionic mobility. Even the small amount of CO_2 in ambient air, would have to be scrubbed. The current view is that scrubbing of the small amount of CO_2 within the air, coupled with purification of the hydrogen, is not cost effective and that terrestrial application of the AFC could be limited to special applications, such as closed environments.

A recent development is the development of AFC with re-circulating electrolyte systems that can be replenished as needed. This approach could allow AFC to compete with other fuel cell technologies.

Phosphoric Acid Fuel Cell [24-29]

The Phosphoric Acid Fuel Cell (PAFC) is the most mature fuel cell technology in terms of system development and commercialization activities. It has been under development for more than 20 years and has received a total worldwide investment in the development and demonstration of the technology in excess of $750 million. The PAFC was selected for substantial development a number of years ago because of the belief that, among the low temperature fuel cells, it was the only technology which showed relative tolerance for reformed hydrocarbon fuels and thus could have widespread applicability in the near term. However, in recent years, research and development efforts have focused on PEMFC, MCFC and SOFC. There appears to be little research conducted on PAFC technology.

Electrochemistry

The electrochemical reactions occurring in a PAFC are:

- at the anode:

$$H_2 \rightarrow 2H^+ + 2e-$$

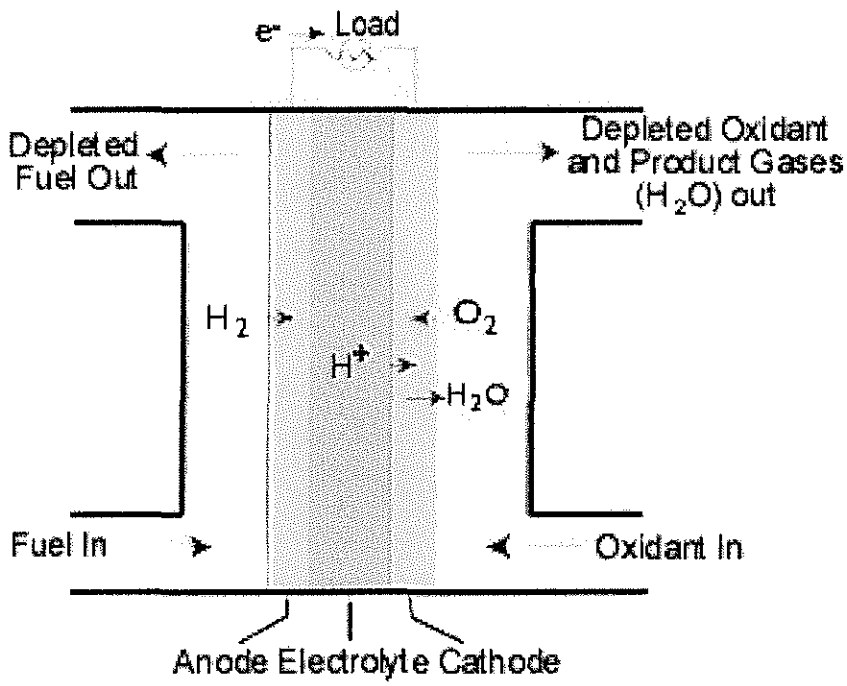
- at the cathode:

$$½\ O_2 + 2H^+ + 2e- \rightarrow H_2O$$

- with the overall cell reaction:

$$½\ O_2 + H_2 \rightarrow H_20$$

Figure 1 - Electrochemistry of the Phosphoric Acid Fuel Cell



Fuel

Phosphoric acid fuel cells operate on H_2. If a hydrocarbon such as natural gas is used as a fuel, reforming of the fuel into hydrogen is required. Reforming can be described by the following reactions:

- Steam methane reforming:

$$CH_4 + H_2O \rightarrow 3H_2 + CO$$

- and shift of the reformate

$$CO + H_2O \rightarrow H_2 + CO_2$$

Any sulfur compounds present in the fuel have to be removed prior to use in the cell (upstream of the reformer) to a concentration of less than 0.1 ppm. The fuel cell itself, however, can tolerate a maximum of 50 ppm of sulfur compounds. CO is a poison when present in a concentration greater than 0.5%.

Electrolyte

The electrolyte consists of concentrated phosphoric acid. A Teflon bonded silicon carbide matrix is used to retain the acid while both the electrodes are made from platinum or its alloys. The small pore structure of this matrix preferentially keeps the acid in place through capillary action. Some acid may be entrained in the fuel or oxidant streams and addition of acid may be required after many hours of operation.

At lower temperatures, phosphoric acid is a poor ionic conductor, and CO poisoning of the platinum electrocatalyst in the anode becomes severe. The relative stability of concentrated phosphoric acid is high compared to other common acids; consequently the PAFC is capable of operating at the high end of the acid temperature range (100 to 220 °C). In addition, the use of concentrated acid (100%) minimizes the water vapor pressure so water management in the cell is not difficult.

Temperatures of about 200 °C and acid concentrations of 100% H_3PO_4 are commonly used now while the operating pressure has exceeded 8 atm in an 11 MW electric utility demonstration plant.

Electrodes

The porous electrodes used in PAFC contain a mixture of the electrocatalyst supported on carbon black and a polymeric binder to bind the carbon black particles together forming an integral structure. A porous carbon paper substrate serves as a structural support for the electrocatalyst layer and as the current collector. The composite structure consisting of a carbon black/binder layer on carbon paper substrate forms a three phase interface, with the electrolyte on one side and the reactant gases on the other side of the carbon paper. Fuel and oxidant gases are supplied to the backs of the porous electrodes by parallel grooves formed into carbon or carbon-composite plates. These plates are electrically conductive and conduct electrons from an anode to the cathode of the adjacent cell. In most designs, the plates are bipolar in that they have grooves on both sides - one side supplies fuel to the anode of one cell, while the other side supplies air or oxygen to the cathode of the adjacent cell.

Stack Design

Several designs for the bipolar plate and stack components are being used. For example, in the multi-component bipolar plates, a thin impervious plate serves to separate the reactant gases in adjacent cells within the stack, and separate porous plates with ribbed channels direct the gas flow. The porous structure allows rapid gas permeability and also provides storage for additional acid to replace the acid lost by evaporation during the operating life of the cell.

Heat generated during cell operation is removed by either liquid or gas coolants which are routed through cooling channels in the cell stack. Complex manifolds and connections are required for liquid cooling but better heat transfer is achieved than with air cooling. Gas cooling on the other hand has simplicity, reliability, and relatively low cost.

Byproduct water is removed as steam on the cathode (air or oxygen) side of each cell by flowing excess oxidant past the backs of the electrodes. This water removal procedure requires that the system be operated at temperatures around 190°C. At lower temperatures, the product water will dissolve in the electrolyte and not be removed as steam. At approximately 210°C, the phosphoric acid begins to decompose.

Energy Efficiency

The conversion efficiency of fuel bound energy to electricity of a PAFC is typically 40 to 47%. The higher efficiency designs operate with pressurized reactants. The higher efficiency pressurized design requires more components and likely higher cost. PAFC power plants supply usable thermal energy. A portion of the thermal energy can be supplied at temperatures of about120 °C to about 150 °C. However, about half of the thermal energy is supplied at about 65 °C. The PAFC has a power density of 170 to 190 milliwatts/cm2 of active cell area

PAFC Research Project in Alberta

The Northern Alberta Institute of Technology (NAIT) in Edmonton is leading a $3.3-million public/private partnership to study the use of high-voltage fuel cell technologies. The partnership is composed of AERI, Western Economic Diversification Canada (WEDC), ATCO Gas and Climate Change Central. The research team will look for innovative ways to use fuel cell energy, including heating the school swimming pool and cooling academic buildings.

NAIT will install a 200-kilowatt PAFC which is Canada's first high voltage, fully operational fuel cell. In addition to electricity, the PAFC will produce useable heat energy in the form of hot water. The NAIT PAFC will produce 50% hot water and 50% warm water. The combined heat and power feature of the PAFC will result in 50% fewer greenhouse gas emissions and 99 per cent less pollutants.

Commercialization

In the 1994, H-Power (now Plug Power), Georgetown University, and the U.S. Department of Energy equipped a transit bus with a 50-kilowatt phosphoric acid fuel cell. In 1998, Georgetown, Nova BUS, and the U.S. Department of Transportation began tests on a bus powered by a 100-kilowatt phosphoric acid fuel cell supplied by International Fuel Cells, now UTC Fuel Cells. Buses and long-haul trucks are the most likely candidates for phosphoric acid fuel cells; the extended warm-up time required for the fuel cell to begin producing power limits their usefulness in personal automobiles.

The phosphoric acid fuel cell has demonstrated its use in a number of commercial buildings. Worldwide, there are over 40 MW of demonstrators in various phases of testing or under fabrication, mostly in the 50 to 200 kW capacity range.

The major industrial participant in the U.S. is UTC Fuel Cells. UTC Fuel Cells has been producing a commercial fuel cell power plant since 1991. UTC Fuel Cells' PC25 fuel cell power plant produces 200 kW of electricity and 900,000 BTUs of usable heat. The cost of the PC25 is reported to be US$ 4,000/kW uninstalled and US$ 5,500/kW installed. The PC25 is designed for 40,000 hours of operations, at which time it must be refurbished.

UTC Fuel Cells has delivered more than 250 PC25 systems and has installed units in 19 countries on five continents. Phosphoric acid fuel cells were installed at 30 U.S. Department of Defense (DOD) bases between 1994 and 1997 at a cost of US $ 37 million. DOD estimated that scheduled maintenance costs averages US$ 18,000 per unit per year, or US$ 90 per kW per year. Availability ranged between 59% and 86%. Other purchasers of the PC25 for back-up and uninterruptible power purposes include: First National Bank of Omaha, the United States Postal Service and Verizon.

In Japan the important developers are Fuji Electric Corporation, Toshiba Corporation, and Mitsubishi Electric Corporation. Fuji Electric has developed a 100 kW system and Mitsubishi Electric, a 200 kW unit. The European PAFC developed is Ansaldo in Italy.

Proton Exchange Membrane Fuel Cell [24-29]

The type of fuel cell known as the Polymer Electrolyte Membrane Fuel Cell (PEMFC) uses a proton conducting membrane as the electrolyte. The membrane is contained between two platinum impregnated porous electrodes. Within the cell, hydrogen at the anode provides protons and releases electrons which pass through the external circuit to reach the cathode. The protons solvate with water molecules and diffuse through the membrane to the cathode to react with oxygen while picking up electrons and forming water. The water does not dissolve in the electrolyte and is, instead, rejected from the back of the cathode into the oxidant gas stream. As the PEMFC operates at about 80°C, water is produced as liquid water and is carried out of the fuel cell by excess air flow.

Electrochemistry

The electrochemical reactions occurring in a PEMFC are:

- at the anode:

$$H_2 \rightarrow 2H^+ + 2e^-$$

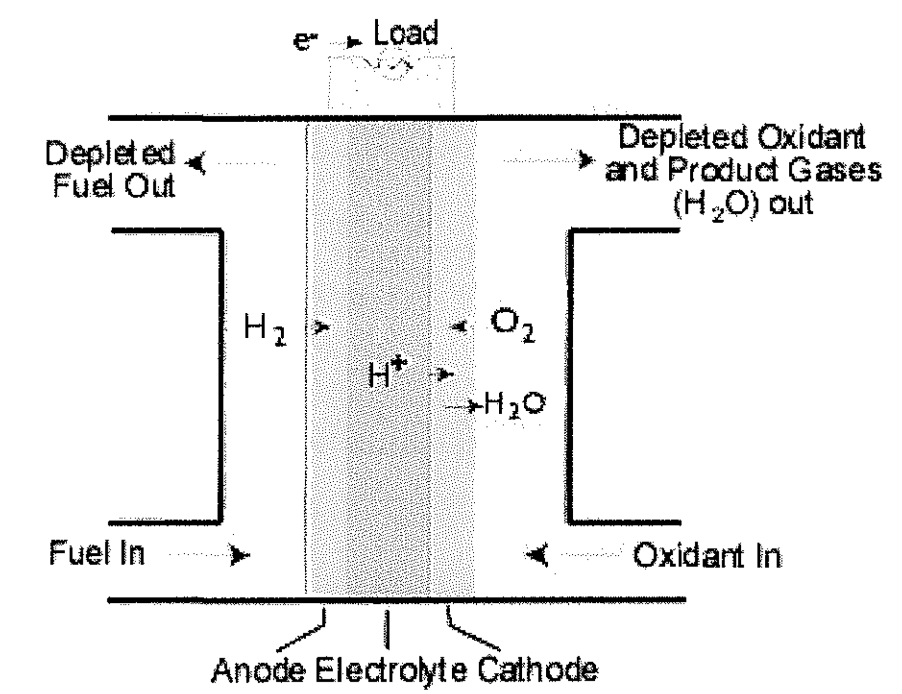
- at the cathode:

$$\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

- with the overall cell reaction:

$$\frac{1}{2} O_2 + H_2 \rightarrow H_2O$$

Figure 2 - Electrochemistry of the Proton Exchange Membrane Fuel Cell



Fuel

Hydrogen from the fuel gas stream is consumed at the anode, yielding electrons to the anode and producing hydrogen ions which enter the electrolyte. At the cathode, oxygen combines with electrons from the cathode and hydrogen ions from the electrolyte to produce water.

The fuel cell operates on hydrogen and only a few ppm of CO may be tolerated by the platinum catalyst at its operating temperature of about 80 °C.

In addition to pure hydrogen, the PEMFC can also operate on reformed hydrocarbon fuels. If a hydrocarbon fuel such as natural gas is used as a fuel, reforming of the fuel is required. Reforming is described by the reaction:

$$CH_4 + H_2O \rightarrow 3H_2 + CO \text{ (in the case of natural gas)}$$

followed by shifting of the reformate by the water gas shift reaction:

$$CO + H_2O \rightarrow H_2 + CO_2$$

Removal of the unconverted CO to ppm levels is required to generate fuel with the required purity. There is a limit on the CO concentration in the fuel gas to the fuel cell which is less than 10ppm. Traces of CO produced during the reforming process must be converted to CO_2 by a selective oxidation process before the fuel gas enters the fuel cell.

Any sulfur compounds present in a hydrocarbon fuel have to be removed prior to use in the reformer to a concentration of less than 0.1 ppm. Carbon dioxide is not a poison for the PEMFC and it can operate without removal or recirculation of the by-product CO_2.

The PEFC can operate on air. As is true with all fuel cells, performance is improved by pressurizing the air. In any application, there will be a trade-off between the energy and financial cost associated with compressing air to higher pressures and the improved performance. Pressures above 45 psig are not likely to be advantageous for most applications.

Electrolyte

The electrolyte in this fuel cell is an ion exchange membrane that is an excellent proton conductor. The membrane is an electronic insulator, but an excellent conductor of hydrogen ions. Suitable membranes include fluorinated sulfonic acid polymer, or other similar polymer. The materials used to date consist of a fluorocarbon polymer backbone, similar to Teflon, to which are attached sulfonic acid groups. The acid molecules are fixed to the polymer and cannot leach out, but the protons on these acid groups are free to migrate through the membrane. With the solid polymer electrolyte, electrolyte loss is not an issue with regard to stack life. The electrolyte membrane looks rather like a thick plastic sheet and can be handled easily and safely.

DuPont's poly-perfluorosulfonic acid Nafion membranes have been among the enablers to PEMFC developments. While Nafion membranes remain the standard for PEMFC, they are costly to produce by an extrusion process that yields thick membranes. R&D has been focused on producing thin membranes. A number of other organizations are offering alternative membranes. DuPont has developed a solution coating process for producing membranes less than 50 microns thick. Gore & Associates markets alternative membranes based on fluoropolymers. Hydration is still a critical factor with the Gore membranes.

The only liquid in this fuel cell is water; thus, corrosion problems are minimal. Water management in the membrane is critical for efficient performance. The fuel cell must operate under conditions where the byproduct water does not evaporate faster than it is produced because the membrane must remain hydrated. Because of the limitation on the operating temperature imposed by the polymer, usually less than 100 °C, and because of problems with water balance, a H_2-rich gas with minimal or no CO is typically used. Freezing of PEMFC can cause permanent damage

The ionic conductivity of the electrolyte increases with water content. It is necessary to maintain high enough water content in the electrolyte to avoid membrane dehydration and to maintain proper ion conductivity without flooding the electrodes. Thus, the balance between production of the water by hydrogen oxidation and its evaporation has to be controlled. Too little or too much water can cause the PEMFC to stop operating. Water management is a key design element of PEMFC.

Electrodes

The anode and cathode are prepared by applying a small amount of platinum black to one surface of a thin sheet of porous, graphitized paper which has previously been wet-proofed with Teflon. They are formed into flow field plates made of graphite in which channels have been formed. The ridges between the channels make electrical contact with the backs of the electrodes and conduct the current to the external circuit. The channels supply fuel to the anode and oxidant to the cathode. The back of the electrodes are coated with a hydrophobic compound such as Teflon in order to form a wet proof coating which provides a gas diffusion path to the catalyst layer.

The electrolyte is then sandwiched between the anode and cathode, and the three components are sealed together under heat and pressure to produce a single membrane/electrode assembly (MEA). This assembly, which is the heart of the fuel cell, is less than a millimeter thick.

The PEMFC uses platinum at both the anode and cathode. Higher catalyst loading than in the PAFC is required for both the anode and cathode. At the cell performance required, this represents a very significant cost penalty as compared with the PAFC.

The search for alternative catalysts for PEMFC electrodes continues. Bimetallic platinum catalysts, particularly using ruthenium as the secondary metal are being evaluated.

Energy Efficiency

PEMFC are capable of operation at pressures from 0.10 to 1.0 MPa and with suitable current collectors and supporting structure. The conversion efficiency of fuel energy to electricity of a PEMFC is 40 to 47%.

Advantages of PEMFC

Some of the advantages of the PEMFC result from the fact that PEMFC may be operated at high current densities. It offers an order of magnitude higher power density than any other fuel cell system, with the exception of the advanced aerospace AFC, which has comparable performance. Therefore, PEMFC can exhibit a compact and light weight design. Its low operating temperature provides instant start-up and requires no thermal shielding to protect personnel. The use of a solid polymer electrolyte eliminates the corrosion and safety concerns associated with liquid electrolyte fuel cells. There are no corrosive fluids that could cause a spillage hazard because the only liquid present in the cell is water. Thus, a PEMFC is well suited for use in vehicles. A disadvantage associated with this type of fuel cell, however, is that expensive noble metal catalysts are required as promoters for the electrochemical reaction.

The power density of PEMFC is roughly a factor of 10 greater than that observed for the other fuel cell systems. This represents a potential for a significant reduction in stack size and cost over that possible for other systems. At the fuel cell stack level, electrical efficiency is determined by the voltage at which the fuel cell is operated. Thus, a PAFC, a MCFC, or a PEMFC operating at 0.7 V/cell will be operating at the same stack efficiency. The higher power density of the PEMFC arises from the fact that, at a given stack efficiency (cell voltage), it will deliver more current and thus more power for a given size fuel cell. Alternatively, the PEMFC can provide the same power, at a given stack efficiency, from a smaller, less costly stack.

When hydrocarbon fuels are to be used or air is to be used as the oxidant, higher temperature fuel cells, such as the MCFC, the SOFC, and to some extent the PAFC, have an efficiency advantage over the PEMFC at the system level. The higher temperature waste heat of these systems can be used to drive air compressors, to assist in the reforming of hydrocarbon fuels, and, in the case of the MCFC and SOFC, to produce steam for thermal electric generation or other thermal load.

The PEMFC can be operated using either air or liquid cooling. For those applications requiring a compact power generator, liquid cooling will be the method of choice. This will also be the case if the excess heat is to be used for space or hot water heating in residential or utility cogeneration applications.

Because the PEMFC uses a solid electrolyte, a significant pressure differential can be maintained across the electrolyte. This allows the operation of the PEMFC with low pressure fuel and higher pressure air, if desired, to optimize performance.

Because the PEMFC operates at low temperatures and does not contain a liquid electrolyte, catalyst migration and recrystallization are not problems. Cell operating lifetimes in excess of 50,000 hours were demonstrated for the PEMFC during the NASA program.

The PEMFC typically operates at 70°C to 85°C. About 50% of maximum power is available immediately at room temperature. Full operating power is available within about 3 minutes under normal conditions. The low temperature of operation also reduces or eliminates the need for thermal insulation to protect personnel or other equipment.

The excess heat can be used for space heating or for residential hot water, but is not hot enough for generating steam for fuel reforming or for utility bottoming cycles.

Research and Development Targets

In general, the targets and issues addressed by organizations involved in the development of PEMFC are:

- Effective, low-cost electrode catalysts (e.g., reduced platinum loading, non-noble metals, etc.)
- Oxygen reduction catalysts with significantly lower overpotentials
- Methanol oxidation catalysts with lower overpotentials
- Increased catalyst tolerance to carbon monoxide
- Improved and lower cost membranes
- Higher temperature and less water-dependent membranes

- Improved and lower cost membrane electrode assemblies
- Low-cost, high-volume manufacturing processes for fuel cells, stacks and components
- Long-term reliability, durability, and performance stability
- Survivability and operability in a variety of environments
- Vehicle fuel cells with faster response times, higher power densities and lower capital costs

Key PEMFC Developers

Ballard Power Systems has been developing PEMFC for a range of vehicle, mobile and stationary applications and has developed a proprietary natural gas reforming technology for stationary products. Ballard is also developing electric drives for battery electric and hybrid vehicles, as well as complete power trains. Ballard is involved in a number of major alliances and appears to be working with almost every major automobile manufacturer for the supply of a fuel cell engine and is the exclusive supplier to DaimlerChrysler and Ford. Ballard has supplied the following:

- at least 11 50-75 kW fuel cell engines
- 11 fuel cell engines being demonstrated in the California Fuel Cell Partnership
- 30 205 kW engines to Mercedes-Benz for fuel cell buses to be demonstrated in 10 European cities
- Auxiliary Power Units (APU) have been demonstrated in a truck and in a passenger car.
- Eight 250 kW stationary power units including the fuel processing unit for field testing
- A 1.2 kW PEMFC for the stationary and portable market.

UTC Fuel Cells is a unit of United Technologies and was formerly known as International Fuel Cells. UTC Fuel Cells is the world's leading fuel cell supplier, having supplied more than 250 of its 200kW PAFC systems to customers worldwide and being the supplier of AFC to the U.S. space program. UTC Fuel Cells acquired PEMFC technology from General Electric and is now offering 150 kW PEMFC modules for stationary applications. The U.S. Electric Power Research Institute is proposing to demonstrate these new modules in 5 X 150 kW configurations at eight locations in a program to be sponsored by electric utilities. The expected installed cost of the system is reported to be US$ 2, 600/kW.

UTC Fuel Cells has a joint venture with Toshiba to combine each company's PEMFC research. UTC Fuel Cells also formed a joint venture with Shell Hydrogen called Hydrogen Source to develop and market fuel processors. In the residential market, UTC Fuel cells is developing 5 kW PEMFC systems in collaboration with Carrier (United Technologies' air conditioner unit), Toshiba and Buderus Heiztechnik (a European manufacturer of heating products). For the transportation market, UTC Fuel Cells is working with Nissan and Renault to develop vehicle PEMFC and fuel cell vehicle components. UTC Fuel Cells has also been working with Hyundai, BMW and bus makers Thor Industries and Irisbus.

General Motors has opted to design and build PEMFC largely on its own. GM and ExxonMobil are collaborating on the development of fuel processors. GM has also announced collaboration with ChevronTexaco to bring to market gasoline-fed fuel cell vehicles. GM is working with BP on fuel R&D. Also, GM has partnerships with General Hydrogen and Quantum Technologies regarding fuel storage and Suzuki Motors and Toyota.

Reports indicate that the GM PEMFC stack features a proprietary approach to water management. GM is also attempting to extend the reach of its 75 kW vehicle fuel cell into markets for stationary power.

Honda is also reported to have its own vehicle fuel cell program. **Siemens Westinghouse** is developing 30 t0 50 kW PEMFC modules for submarines of the German Navy. **Plug Power** is a developer of PEMFC for stationary applications up to 50 kW. **Nuvera Fuel Cells** is focused on the development of up to 5 kW PEMFC systems for stationary uses.

The industry also includes a number of organizations involved in research and component development, with the following being worth noting:

- **DuPont** is a leading producer of electrolyte membranes and bipolar plates. The Nafion membrane business is based in Wilmington, DE and the bipolar plate business is run from Kingston, ON.

- **Gore & Associates** has developed a novel membrane based on fluoropolymers and is a leading supplier of membrane electrode assemblies.
- **Celanese** has opened a pilot plant for producing its polybenzimidazole membrane electrode assemblies, which show promises for operations up to 200 °C.
- **NuVant Systems** is developing original technology from the Illinois Institute of Technology for proton conducting inorganic membranes able to perform in the 200 °C to 450 °C range. Higher temperatures would allow a significant reduction in platinum catalyst loading and make the electrodes resistant to carbon monoxide poisoning. In addition, higher temperatures may allow the internal reforming of methanol.
- **Johnson Matthey** is a leading developer and supplier of noble metal catalysts with expertise in fuel cell systems such as electrodes, reforming and gas clean-up.

Government involvement is very significant in the development of fuel cell systems both as a provider of funds and as a developer of technology. The United States stands out by the number of government laboratories that are active in the area:

- Argonne National Laboratory
- Lawrence Berkley Laboratory
- Lawrence Livermore National Laboratory
- Los Alamos National Laboratory
- Pacific Northwest National Laboratory
- U.S. Army Research Laboratory
- Electric Power Research Institute
- Gas Technology Institute

Stationary Power Demonstrations

Since 2001, PEMFC ranging in size from 1 to 20 kW are being demonstrated at U.S. military bases. Building applications are primarily residential facilities, but also include commercial and remote building applications. Highlights of the program are:

- Units to be installed at U.S. military facilities.

- Fuel cells will provide 1 year of fuel cell power with 90% unit availability.
- Fuel type: natural gas, propane, hydrogen, other
- Fuel options: fuel switching, no fuel switching, fuel blending
- Electrical interface: grid-connected, grid-independent, both (alternating)
- Thermal interface: cogeneration, no cogeneration
- Unit configurations: individual, multiple units

Table 5 - U.S. Department of Defense PEMFC Stationary Power Demonstration
(Demonstration period ended January 21, 2003)

Site Name	Building Application	Fuel Cell Mfg.	Input Fuel	Size (kW)	No. Units	Cogen. Y/N
Coast Guard Station New Orleans	Office Building	Plug Power	Natural Gas	5	1	Yes
Fort McPherson	Senior Officer's Residence	Plug Power	Natural Gas	5	1	Yes
Sierra Army Depot	Barracks	H-Power	Propane	4.5	1	Yes
Brooks AFB	Base Housing	Plug Power	Natural Gas	3	3	No
Ft. Bragg	Office Building	Plug Power	Natural Gas	5	1	No
Ft. Jackson	Officers' Quarters	Plug Power	Natural Gas	5	1	Yes
Barksdale AFB	Base Housing	Plug Power	Natural Gas	5	1	No
Patuxent River NAS	Office Building	H-Power	Propane	4.5	1	Yes

Patuxent River NAS	Base Housing	H-Power	Natural Gas	4.5	1	Yes
Geiger Field	Maintenance Facility	Avista Labs	Hydrogen	3	1	No
Watervliet Arsenal	Research Facility	Plug Power	Natural Gas	5 (2.5)	3	No
Watervliet Arsenal	Manufacturing Facility	Plug Power	Natural Gas	5 (2.5)	3	No
Watervliet Arsenal	Officers' Quarters	Plug Power	Natural Gas	5 (2.5)	4	No
Source: U.S. Department of Defense						

Ballard Generation Systems has produced a PEMFC stationary on-site plant. It has these characteristics:

- Power capacity:250 kW with natural gas fuel
- Electric efficiency: 40% LHV
- Thermal energy: 854,600 kJ/hour at 74 °C
- Plant dimensions: 2.4 m wide by 2.4 m high by 5.7 m long
- Plant weight: 12,100 kg

One plant demonstration, which began operation in August 1997, has been completed. The plant achieved an electric efficiency of 40%. Ballard is in the process of conducting additional field tests. Partners are GPU International (now First Energy), GEC Alsthom, and EBARA Corporation.

Direct Methanol Fuel Cell [24-30]

The direct methanol fuel cell (DMFC) also uses a proton exchange membrane and is sometimes classified as a PEMFC. While the PEMFC use hydrogen as fuel, the DMFC uses methanol. The DMFC is able to oxidize methanol directly without converting methanol into hydrogen in a prior step. Since methanol is oxidized directly within the DMFC, there is no need for a fuel processor and the overall system can be highly compact. In addition the energy density of methanol is far greater than that of hydrogen. These advantages have been the impetus for research and development into DMFC.

Electrochemistry

The electrochemical reactions occurring in a DMFC are:

- at the anode:

$$CH_3OH + H_2O \rightarrow 6H^+ + CO_2 + 6e-$$

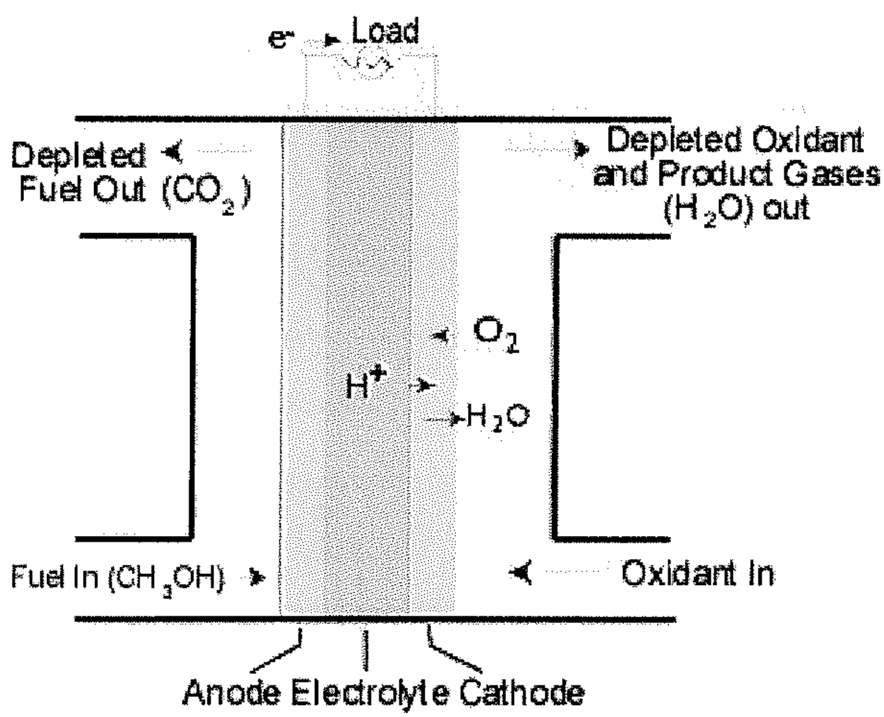
- at the cathode:

$$3/2\ O_2 + 6H+ + 6e- \rightarrow 3H_2O$$

- with the overall cell reaction:

$$CH_3OH + 3/2\ O_2 \rightarrow 2H_2O + CO_2$$

Figure 3 - Electrochemistry of the Direct Methanol Fuel Cell



The electrochemistry of methanol oxidation is more difficult than hydrogen oxidation. Methanol oxidation kinetics are slow. By contrast, the oxidation of hydrogen is very fast. Power densities reported for ambient temperature air-breathing DMFC are typically less than 10 mW/cm^2. Oxidation kinetics can be improved with high temperatures. The development of high temperature DMFC (200° C) has progressed. Researchers have reported power densities in the range of 200-250 mW/cm^2. However, stack development, particularly large stacks, is not as advanced as for hydrogen fuel cells.

Studies have shown that the rate of methanol oxidation increases with methanol concentration. However, high methanol concentrations lead to excessive methanol crossover. Given current membrane technology, an optimum has to be found between increasing oxidation kinetics and minimizing methanol crossover which reduces cathode activity.

Methanol oxidation also increases with temperature. Ambient temperature air-breathing operations, required for portable applications, lead to low power densities.

High temperature operations can result in power densities that are comparable to PEMFC.

DMFC can operate can operate either in the liquid or the vapor phase. Vapor phase systems benefit from faster mass transport and oxidation kinetics in part because of the higher temperatures involved. However they are faced with problems associated with thermal management and with separation of methanol from CO_2 at the anode. Liquid phase systems are favored because their design is simpler and because thermal management is easier. The anode effluent is a two phase system and requires a method to condensate or otherwise separate methanol vapors from CO_2 gas exhaust.

A major technical challenge for DMFC developers is called methanol crossover. Some methanol swells the electrolyte membrane and passes from the anode side to the cathode side. Presence of methanol in the cathode environment reduces performance and wastes fuel. Methanol crossover results in a depolarizing reaction on the cathode catalyst. It also leads to a reduction in fuel utilization. In addition, water management problems arise as a result of the presence of methanol in the cathode exhaust water.

The result of these shortcomings has been that the power density of DMFC amounts to one quarter to one third of the power density of PEMFC. The lower power densities must be overcome for DMFC to be contenders in vehicle applications and are a cost factor for mobile applications.

Electrolyte

DMFC can use conventional Nafion membranes. The concentration of methanol at the anode needs to be low in order to reduce the extent of methanol crossover with conventional electrolyte membranes. This results in a significantly reduced capacity of the system. In addition a control system for methanol concentration at the anode needs to be incorporated and the addition of this system presents design difficulties for meeting the volumetric requirements of micro fuel cells.

In general, increased methanol crossover is observed at higher temperature, thinner membranes, lower cathode side pressure and higher methanol feed concentrations. Highly concentrated methanol solutions need to be used to increase energy storage and power density to acceptable levels.

Reducing methanol crossover has been a major objective of membrane research and development. Alternative polymers have been proposed as electrolytes. Modified versions of Nafion membranes have been developed. For example, a membrane based on Nafion 117 has a modified barrier layer inside the membrane. This thin layer of polymer has a higher ratio of backbone carbon atoms to cation exchange groups and acts as a methanol exclusion membrane.

Another example of alternative membranes is acid doped polybenzimidazole. This membrane would also allow high temperature DMFC (200 °C). High temperature operations permit better anode kinetics and increase power density. However the ionic conductivity of conventional Nafion membranes falls considerably above 100° C. Therefore alternative membranes are required to fully realize the benefits of high temperature DMFC and to avoid the excessive methanol crossover associated with high temperatures.

Electrodes

Methanol can be directly oxidized at the anode, but this chemistry is more challenging that hydrogen oxidation. Higher loading of platinum catalysts are required to achieve reasonable power densities. There has been significant progress in the development of electrocatalysts for methanol oxidation. Platinum-ruthenium bimetallic catalysts are the most commonly used anode catalysts. There is also a growing interest in ternary and quaternary alloys containing platinum-ruthenium, together with osmium and iridium. These alloys are reported to provide enhanced methanol oxidation. The activity of ruthenium based alloys has been shown to depend on the proportion of ruthenium dioxide in the catalyst. Ruthenium dioxide is a good proton conductor and its presence can simplify anode catalyst architecture and increase activity.

Because of the acidic and high potential environment, the cathode catalyst of choice is platinum and its alloys. The presence of methanol in the cathode environment, as a result of methanol crossover, causes depolarization of the platinum catalyst and a loss of potential. Research into methanol resistant catalyst has focused on platinum alloys with cobalt, chromium and nickel. Other approaches have been the use of transition metal cluster catalysts (Ru-Se-Mo) and pyrolyzed transition metal macrocycles such as Fe and Co tetramethoxyphenyl porphyrins.

Fuel

Methanol instead of hydrogen is the fuel for DMFC. Methanol is a large volume petrochemicals produced on a worldwide basis. While the price of methanol will vary based on the petrochemical cycle, it is generally at a level similar to the price of gasoline. Methanol is produced from natural gas. The largest methanol producer in the world is Methanex. Low cost methanol production takes advantage of stranded natural gas reserves. These are natural gas reserves that exist far from populated areas and for which the construction of a pipeline would be prohibitive. Converting these natural gas reserves to methanol allows an energy product to be shipped by ocean tankers as liquid methanol.

Methanol is a liquid at ambient conditions. It can be handled as safely as gasoline and industrial solvents.

Methanol is considered to be a toxic chemical. Broad distribution of methanol may be faced with consumer opposition from some quarters.

Freezing temperatures also pose problems for methanol systems. Water, methanol and methanol solutions freeze at temperatures associated with winter conditions.

Commercialization

While work continues on transportation applications, portable and wireless applications are likely to be first-to-market. Laptop computers, camcorders and cell phones suffer performance restrictions because of the limited energy storage and life of rechargeable batteries. DMFC can offer longer operating times than rechargeable batteries because of the high energy content of methanol. In addition cartridge type refueling would provide for a convenient distribution system for methanol. These aspects of DMFC make them attractive for consumer applications and could allow DMFC to break into the growing rechargeable battery market. Worldwide sales for rechargeable batteries in 1999 were over U.S. $ 5 billion.

Realizing the potential for DMFC in portable applications will require solutions to technical challenges. Ambient temperature air-breathing DMFC have low power density which may limit their usefulness in some applications that require either a very compact design or high power densities. Methanol crossover problems need to be resolved in order to increase reliability and durability of these fuel cells. Water balance in micro fuel cells remains a challenge and convenient solution need to be found for water disposal.

Cellular telephones are a particularly challenging application because of their small size. While only one cubic centimeter of methanol would be required, the fuel cell area would need to be much larger because of the low power density of current DMFC at ambient temperature. In addition, the surface required for passive air intake would be large enough to present considerable design difficulties. However new concepts for micro fuel cells are being explored. An example being developed at Manhattan Scientifics is based on laterally interconnected micro fuel cells. This system has the advantage that it does not require by polar plates. It allows the production of high voltage - low current devices. New membranes are required to eliminate the methanol cross over problem.

Laptop computers and video cameras are relatively easier applications for micro fuel cells. However issues associated with water management and methanol emissions (at the anode with CO_2 gas and at the cathode with produced water) must still be resolved in economic, safe and user friendly manners. A promising application is chargers for rechargeable batteries for service in remote locations. Users of such devices would be forestry crews, search and rescue operations and the military.

Therefore, the market driver for portable applications is not environmental emissions but the needs of the users of portable and wireless electronic devices. DMFC are able to outperform lithium ion batteries by a factor of 3-4 and the value provided may justify the higher cost of fuel cells.

The benefit of DMFC for transportation application resides in the higher energy density of liquid methanol as compared to hydrogen. Methanol requires less volume than hydrogen to achieve equivalent storage and driving range. Therefore, vehicle design is easier and distribution infrastructure needs to be less extensive. In addition, methanol is a liquid at ambient conditions and can be transported, stored and distributed using methods similar to existing motor fuels.

Several challenges face the developers of DMFC for transportation applications. While methanol is easier to transport and distribute than hydrogen, and there is currently no extensive infrastructure for the transportation and distribution of methanol. Such infrastructure will need to be built. Methanol is considered to be highly toxic and will likely face consumer opposition in some quarters. While DMFC do not require a fuel converter to run on a liquid fuel, it is faces with cost issues arising from the need for specialized electrolyte membranes to deal with methanol cross-over and with high catalyst loadings because the oxidation kinetics of methanol are slower than for hydrogen. While the development of fuel cell vehicles based on methanol is possible, much research and development remains to be done.

Some niche markets may be more accessible for DMFC. Fuel cells in the range of 5 to 100 kW may be desirable for applications such as wheelchairs, forklift trucks, scooters and auxiliary power units. These applications are less challenging than either micro fuel cells or automotive applications. However, DMFC will face competition from PEMFC and SOFC in these applications.

Fuel cell companies involved in DMFC include: Ballard, DaimlerChrysler, Energy Visions, Giner Electrochemical Systems, and Polyfuel. In addition, some electronics manufacturers have undertaken their own DMFC program: Motorola, Toshiba, Matsushita (Panasonic), Manhattan Scientifics and others.

Molten Carbonate Fuel Cell [24-29, 31]

The Molten Carbonate Fuel Cell (MCFC) evolved from work in the 1960's aimed at producing a fuel cell which would operate directly on coal. While direct operation on coal seems less likely today, operation on coal-derived fuel gases or natural gas is viable.

SOFC and MCFC systems are widely known as "second generation" fuel cells. Both systems take advantage of higher operating temperatures to achieve significant cost reduction through improved fuel and thermal efficiencies. The efficiency gain realized by SOFC and MCFC technologies is significant, ranging from 45% to as much as 60% in single-cycle systems (where waste heat is not captured and used) as compared to 35% for conventional power plants and about 40% efficiency for "first generation" phosphoric acid fuel cells. Environmental performance is also enhanced, because higher efficiencies translate directly into lower CO_2 emissions per unit power produced. Finally, the higher operating temperatures also make SOFC and MCFC superior systems for combined cycle applications (use of steam exhaust for heating or incremental power production).

Electrochemistry

The electrochemical reactions occurring in the MCFC are:

- at the anode:

  $H_2 + CO3^{=} \rightarrow H_2O + CO_2 + 2e-$

- at the cathode:

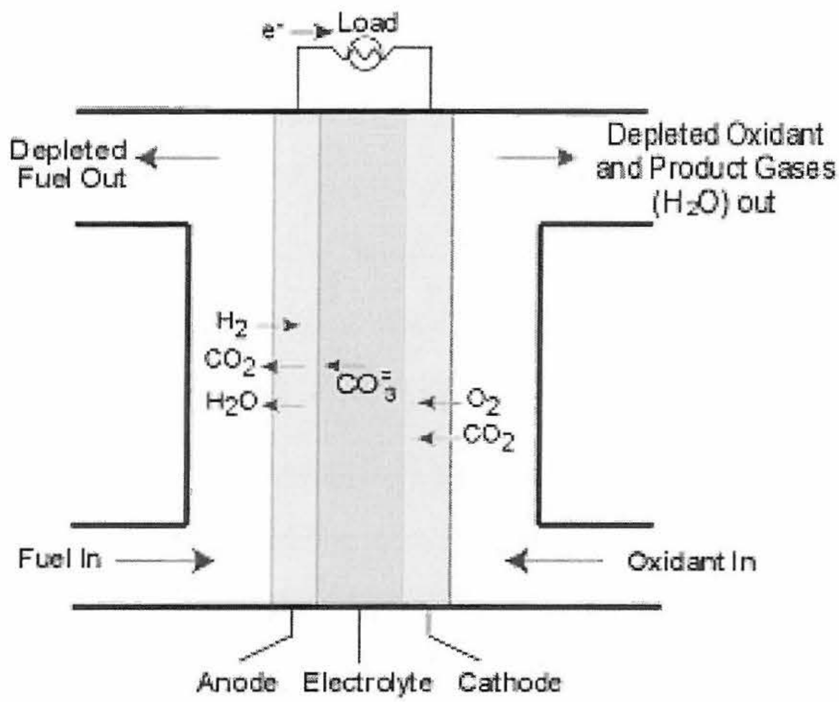
  $\frac{1}{2} O_2 + CO_2 + 2e- \rightarrow CO_3^{=}$

- with the overall cell reaction:

  $H_2 + \frac{1}{2} O_2 + CO_2 \text{ (cathode)} \rightarrow H_2O + CO_2 \text{ (anode)}$

The anode process involves a reaction between hydrogen and carbonate ions ($CO_3^{=}$) from the electrolyte which produces water and carbon dioxide (CO_2) while releasing electrons to the anode. The cathode process combines oxygen and CO_2 from the oxidant stream with electrons from the cathode to produce carbonate ions which enter the electrolyte. The need for CO_2 in the oxidant stream requires a system for collecting CO_2 from the anode exhaust and mixing it with the cathode feed stream.

Figure 4 - Electrochemistry of the Molten Carbonate Fuel Cell



The need for CO_2 in the oxidant stream requires that CO_2 from the spent anode gas be collected and mixed with the incoming air stream. Before this can be done, any residual hydrogen in the spent fuel stream must be burned. Additional equipment is required to either transfer the CO_2 from the anode exit gas to the cathode inlet gas or produce CO_2 by combustion of the anode exhaust gas and mixed with the cathode inlet gas. Future systems may incorporate membrane separators to remove the hydrogen for recirculation back to the fuel stream.

Electrolyte

The electrolyte typically consists of a combination of alkali (Na and K). The electrolyte is suspended in a porous, insulating and chemically inert ceramic matrix of $LiAlO_2$. The cell operates at temperature of 600 to 700 °C in order to keep the alkali carbonates in a highly conductive molten salt form. The electrolyte is potentially mobile and corrosive and therefore is controlled within the ceramic matrix. Carbonate ions provide ionic conduction. The cell performance is sensitive to operating temperature. A change in cell temperature from 650° C to 600° C results in a drop in cell voltage of almost 15%. The reduction in cell voltage is due to increased ionic and electrical resistance and a reduction in electrode kinetics.

The method for electrolyte management in order to establish a stable electrolyte/gas interface in the porous electrodes depends on a balance in capillary pressures to establish the electrolyte interfacial boundaries allowing the electrolyte matrix to remain completely filled with the molten carbonate, while the porous electrodes are partially filled, depending on their pore size distributions.

Electrodes

The high MCFC operating temperatures result in the fact that noble metal catalysts such as palladium or platinum are not required. The anode is a highly porous sintered nickel powder, alloyed with chromium to prevent agglomeration and creep at operating temperatures. The cathode is a porous nickel oxide material doped with lithium. Significant technology has been developed to provide electrode structures which position the electrolyte with respect to the electrodes and maintain that position while allowing for some electrolyte boil-off during operation. The electrolyte boil-off has an insignificant impact on cell stack life. A more significant factor of life expectancy has to do with corrosion of the cathode.

Fuel

The high operating temperature of the MCFC also offers the possibility that it could operate directly on gaseous hydrocarbon fuels such as natural gas. The natural gas can be reformed to produce hydrogen within the fuel cell itself. The high temperatures allow for direct, internal reforming of hydrocarbons.

A fuel such as natural gas is either reformed externally or within the cell in the presence of a suitable catalyst to form H_2 and CO by the reforming reaction:

$$CH_4 + H_2O \rightarrow 3H_2 + CO$$

CO can be oxidized at the anode. But generally it is not directly used by the electrochemical oxidation, because it is converted into additional H_2 by the faster water gas shift reaction:

$$CO + H_2O \rightarrow H_2 + CO_2$$

Any sulfur compounds present in the fuel have to be removed prior to use in the cell (upstream of the reformer) to a concentration of less than 0.1 ppm. The fuel cell itself, however, can tolerate a maximum of 0.5 ppm of sulfur compounds.

Energy Efficiency

Another advantage of the high operating temperature of the MCFC is that the overall thermal efficiency is high, with a potential of 50 to 60% conversion of the fuel (natural gas) to electricity without recovery and conversion of the exhaust heat. Also, the exhaust heat from the MCFC is at relatively high temperatures (650° C) and may be recovered for the generation of steam which further increases the efficiency. Efficiencies greater than 60% may potentially be achieved with the incorporation of a bottoming cycle. On the other hand, the higher operating temperature places severe demands on the corrosion stability and life of cell components.

As the operating temperature increases, the theoretical operating voltage for a fuel cell decreases and with it the maximum theoretical fuel efficiency. On the other hand, increasing the operating temperature increases the rate of the electrochemical reaction and thus the current which can be obtained at a given voltage. The net effect for the MCFC is that the real operating voltage is higher than the operating voltage for the phosphoric acid fuel cell at the same current density.

The higher operating voltage of the MCFC means that more power is available at higher fuel efficiency from a MCFC than from a PAFC of the same electrode area. As size and cost scale roughly with electrode area, the higher operating voltage of the MCFC presents it with a fundamental advantage of the PAFC. However, several other issues such as material of construction, balance of plant and manufacturing technology will affect the final cost of commercial systems and it is difficult to estimate the final outcome of the competition between alternative fuel cell technologies that are still in development.

Commercialization

Many of the disadvantages of the lower temperature can be alleviated with higher operating temperature fuel cells such as the MCFC. This temperature level results in several benefits: the cell can be made of commonly available sheet metals that can be stamped for less costly fabrication, the cell reactions occur with nickel catalysts rather than with expensive precious metal catalysts, reforming can take place within the cell provided a reforming catalyst is added, CO is a directly usable fuel, and the rejected heat is of sufficiently high temperature to drive a gas turbine and/or produce a high pressure steam for use in a steam turbine or for cogeneration. Another advantage of the MCFC is that it operates efficiently with CO_2-containing fuels such as bio-fuel and coal derived gases. This benefit is derived from the cathode performance enhancement resulting from CO_2 enrichment.

The MCFC has some disadvantages, however: the electrolyte is very corrosive and mobile, and a source of CO_2 is required at the cathode (usually recycled from anode exhaust) to form the carbonate ion. Sulfur tolerance is controlled by the reforming catalyst and is low, which is the same for the reforming catalyst in all cells. Operation requires use of stainless steel as the cell hardware material. The higher temperatures promote material problems, particularly mechanical stability that impacts life.

Two corporations were actively pursuing the commercialization of MCFC in the U. S.: Energy Research Corporation, and MC Power Corporation. In 1997, MC Power installed the world's first cogeneration molten carbonate fuel cell power plant, a 250-kilowatt unit, at the Miramar Naval Air Station in California. The company, however, ceased operations in the spring of 2000, transferring most of its fuel cell intellectual property to the Gas Technology Institute.

In 1993, Energy Research Corporation began testing a molten carbonate fuel cell stack that could extract hydrogen directly from natural gas inside the fuel cell, rather than relying on an external reformer. In 1996 the company installed a 2-megawatt pre-commercial test unit in Santa Clara, California that provided key data for design of commercial units. Energy Research Corporation changed its name to FuelCell Energy in 1999, the same year its first 250-kilowatt commercial-design Direct Fuel Cell power plant began operation. The 250 kW unit is used for 1.0 MW and 2.0 MW systems. The company claims to have 12 MW of orders worldwide including all three sizes. The cost for the current 250 kW unit is reported to be US$ 4,000/kW uninstalled and US$ 5,000/kW installed. Cost reductions of about 25% are projected with high-volume projections.

Products from FuelCell Energy are targeted at stationary and marine applications using such fuels as natural gas, digester gas and coal gas. Applications include: a brewery, a wastewater treatment plant, hotels, a coast guard base, a telecommunications center, an automobile factory, a college, a university and utility company sites.

In 2000, as part of the Vision21 program, the U.S. Department of Energy National Energy Technology Laboratory (NETL) awarded a US $40 million increase and three-year extension of an R&D agreement with FuelCell Energy. From 1994 to 2000 the agreement was worth approximately US $144 million including FuelCell Energy's cost share. NETL funding will allow the company to develop several classes of fuel cell power plants for delivery to commercial customers beginning in 2001. It also calls for a ramp up of the company's fuel cell manufacturing capability to 50 megawatts per year by early 2002. In particular, FuelCell Energy will be developing a hybrid pressurized MCFC and gas turbine system to increase overall electrical efficiencies. The 250 kW MCFC is expected to be coupled with 30 kW and 60 kW Capstone microturbines.

Beginning in 2000, FuelCell Energy signed agreements to build several molten carbonate fuel cell systems in the United States, Asia, and Japan. These include:

- Renton, Washington: a 1-megawatt power plant will be located at a wastewater treatment facility and fueled by wastewater digester gas.
- Japan: Marubeni Corporation has entered into a strategic alliance with FuelCell Energy with the expectation of ordering up to 45 megawatts of fuel cells between 2001 and 2003 for Japan and Asia.
- Los Angeles, California: the city's Department of Water and Power has ordered three 250-kilowatt plants.
- Cadiz, Ohio: Northwest Fuel Development will operate a 250-kilowatt fuel cell on coal-mine methane gas from the Harrison Mining Corporation and supply electricity back to the mining operation.
- Fort Story, Virginia: the U.S. Coast Guard Research and Development Center is testing a 3-kilowatt fuel cell power system using methanol for fuel at the Cape Henry Lighthouse.

- Tuscaloosa, Alabama: a 250-kilowatt fuel cell plant is helping to power a Mercedes-Benz production facility in a partnership with the Southern Company and Alabama Municipal Electric Authority.
- Bad Neustadt, Germany: in May 2001, a 250-kilowatt power plant began operating at the Rhon-Klinikum Hospital.
- University of Connecticut: a 250-kilowatt power plant will be delivered in 2002 under the purchase arrangement by the State of Connecticut as part of a Clean Energy Fund established in 1998.
- Europe: the MTU Friedrichshafen unit of DaimlerChrysler announced in September 2001 that it will install seven new 250-kilowatt Direct FuelCell power plants at an energy park, a ship building company, a telecommunications center, a tire manufacturing plant, a medical institute, and an industrial laundry.
- Bourne, Massachusetts: PPL Spectrum, Inc. will install a 250 kW power plant at the U.S. Coast Guard Cape Cod Air Station to provide electricity and heating to barracks, hangars, and administrative buildings.

FuelCell Energy has also signed an agreement with Caterpillar to distribute ultra-low emission fuel cell products for industrial and commercial use through selected Caterpillar dealers in the United States. Both companies will also pursue an alliance to jointly develop fuel cell systems, including highly efficient hybrid products integrating Caterpillar's turbine engine technology.

The U.S. Department of Energy (DOE) is funding the world's first fuel cell to be linked to a clean coal technology power plant. FuelCell Energy will install a two-megawatt fuel cell power plant at the Wabash River Energy coal gasification-combined cycle power plant in West Terre Haute, Ind. Most fuel cells entering commercial markets today are designed to use natural gas or methane gas produced from municipal waste treatment plants. The fuel cell planned for the Wabash River plant will be the largest ever to be fueled by gas made from coal. FuelCell Energy expects to be ready to ship the fuel cell in the second half of 2003. By the time it arrives at the site, the fuel cell will have been assembled and tested on natural gas. A one-year test program would begin soon after the fuel cell arrives and is connected to the coal gas system. The project cost will be US $32.3 million, half of which will be provided by U.S. DOE.

The 260-megawatt Wabash River plant has been operating since November 1995 and is currently one of only two commercial-scale coal gasification power plants running in the United States. Instead of burning coal like a conventional power plant, the Wabash River plant breaks coal apart into a gaseous mixture. More than 97 percent of the pollutant-forming sulfur impurities are cleaned from the gas before it is sent to a gas turbine to generate electric power. To boost power generating efficiencies, the turbine's hot exhaust is captured and used to make steam for a conventional steam turbine. With this type of gasification system, there are virtually no sulfur, nitrogen, or ash particle emissions.

The other U.S. MCFC developer is GenCell Corporation and they are focusing on small-scale fuel cells.

In Europe, leading developers are Brandstofel Nederland (BCN), Deutsche Aerospace AG, Ansaldo (Italy). The MOLCARE program, funded by Italy and Spain involves collaborative R&D to further develop the Ansaldo MCFC technology. MTU Friedrichshafen is operating a 250 kilowatt molten carbonate fuel cell system in Bielefeld, Germany. The power plant is located on the campus of the University of Bielefeld and provides electric power and by-product heat. The fuel cells were manufactured by FuelCell Energy but MTU developed a new power plant configuration for this unit termed a "Hot Module" that simplifies the balance of plant. The system began operation in November 1999 and logged over 4,200 hours by August, 2000. Electric efficiency is 45% (LHV).

In Japan Hitachi, Ishikawajima Harima Heavy Industries, and Mitsubishi Electric Corporation are developing MCFC technology. As part of the New Sunshine Program, 200 kW and 1.0 MW test facilities will be built by Hitachi and Mitsubishi. A pressurized 300 kW project is also underway.

Solid Oxide Fuel Cell [24-29, 32-38]

The Solid Oxide Fuel Cell (SOFC) uses a ceramic, solid-phase electrolyte which reduces corrosion considerations and eliminates the electrolyte management problems associated with the liquid electrolyte fuel cells. To achieve adequate ionic conductivity in such a ceramic, however, the system must operate at high temperatures, between 700° C and 1000° C.

SOFC differ in many respects from other fuel cell technologies. First, they are composed of all-solid-state materials. The anode, cathode and electrolyte are all made from ceramic substances. Second, because of the all-ceramic make-up, the cells can operate at temperatures as high as 1000° C which is significantly hotter than any other major category of fuel cell. This produces exhaust gases at temperatures ideal for cogeneration applications for use in combined-cycle electric power plants. Third, the cells can be configured either as rolled tubes or as flat plates and manufactured using many of the techniques now employed today by the electronics industry.

At high operating temperatures, oxygen ions are formed at the cathode. When a fuel gas containing hydrogen is passed over the anode, the oxygen ions migrate through the crystal lattice to oxidize the fuel. Electrons generated at the anode move out through an external circuit, creating electricity. Reforming natural gas or other hydrocarbon fuels to extract the necessary hydrogen can be accomplished within the fuel cell, eliminating the need for an external reformer.

The fuel-to-electricity efficiencies of SOFC are around 50 percent. If the hot exhaust of the cells is pressurized and used in a hybrid combination with gas turbines, the electrical generating efficiency is likely to approach 60%. In applications designed to capture and utilize the systems waste heat, overall fuel use efficiencies could top 80-85%.

Electrochemistry

The electrochemical reactions occurring within the cell are:

- at the anode:

  $½ O_2 + 2e- \rightarrow O^=$

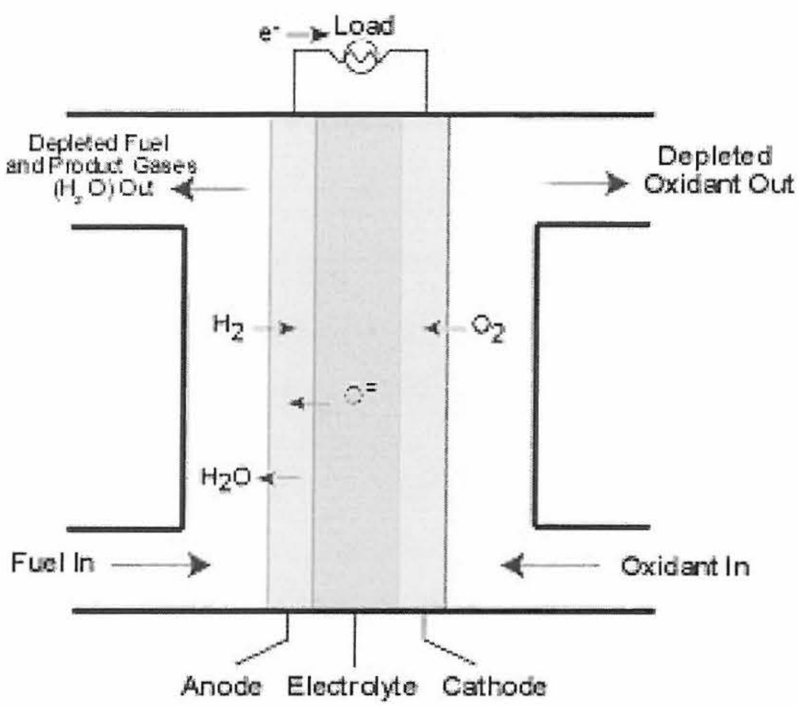
- at the cathode:

  $H_2 + O^= \rightarrow H_2O + 2e-$

- with the overall cell reaction:

  $½ O_2 + H_2 \rightarrow H_20$

Figure 5 - Electrochemistry of the Solid Oxide Fuel Cell



Fuel

The SOFC uses a solid, non-porous metal oxide (coated zirconium) electrolyte that contributes to the unit's expected high reliability and allows operating temperatures to reach as high as 1,000° C. These temperatures further enhance performance in combined-cycle systems and allow even greater flexibility in fuel choice.

As in the MCFC, the SOFC can use carbon monoxide (CO) as well as hydrogen as its direct fuel. The direct oxidation of carbon monoxide in fuel cells is well established but the gas shift reaction is thermodynamically favored.

Hydrocarbons such as CH4 can also be used as fuels in an SOFC. At the high temperatures within the cell, it is feasible for the steam reforming reaction to take place:

$$CH_4 + H_2O \rightarrow 3H_2 + CO$$ (in the case of natural gas)

as well as the water gas shift reaction:

$$CO + H_2O \rightarrow H_2 + CO_2$$

These reactions produce H_2 that is easily oxidized at the anode. SOFC can be designed for hydrocarbon fuel reforming to occur prior to the fuel cell stack or directly at the anode. The following problems prevent direct internal reforming at the anode:

- Carbon deposits on the anode surface results from methane and the presence of nickel catalyst.
- Reforming would proceed faster than electrochemical conversion at the anode. The endothermic reforming reaction would overpower the exothermic electrochemical conversion and cooling of the anode would result.
- It is difficult to maintain appropriate gas composition and temperatures across large fuel cell surfaces and stacks with simultaneous reactions occurring. The electrochemical reaction is governed in part by the electrical load placed on the fuel cell.

As a result, internal reforming, in the fuel cell system hot box, but separate from the anode compartment is preferred. Internal reforming is preferred to external reforming because it utilized the heat generated by the fuel cell stack and permits efficient thermal management.

The SOFC is also the most tolerant of any fuel cell type to sulfur. It can tolerate several orders of magnitude more sulfur than other fuel cells.

In operation, hydrogen or CO in the fuel stream reacts with oxide ions ($O^{=}$) from the electrolyte to produce water or CO_2 and to deposit electrons into the anode. The electrons pass outside the fuel cell, through the load, and back to the cathode where oxygen from air receives the electrons and is converted into oxide ions which are injected into the electrolyte.

The direct oxidation of CH_4 is the subject of investigations. Direct reforming at the SOFC anode is possible. Direct electrochemical oxidation of methane or other hydrocarbon occurs following the reactions:

- at the anode:

$$CH_4 + 4O^{=} \rightarrow 2H_2O + CO_2 + 8e^-$$

- at the cathode:

$$\frac{1}{2} O_2 + 2e^- \rightarrow O^{=}$$

As for the direct oxidation of methanol, the direct oxidation of hydrocarbons is a difficult reaction, demanding the transfer of several electrons. Nevertheless, basic R&D continues on the direct oxidation of hydrocarbons. Researchers at Northwestern University are investigating new types of ceramic-based anodes that can be used with hydrocarbons without coking. A team at the University of Pennsylvania reported direct electrocatalytic oxidation of toluene, n-decane and synthetic diesel using a copper-YSZ cermet instead of a Ni-YSZ cermet. Related work is being conducted at the Gas Technology Institute.

Electrolyte

Although a variety of oxide combinations have been used for solid oxide electrolytes, the most common to date has been a mixture of zirconium oxide and calcium oxide. Formed as a crystal lattice, the hard ceramic electrolyte is coated on both sides with specialized porous electrode materials. The preferred material, dense yttria-stabilized zirconia, is an excellent conductor of negatively charged oxygen (oxide) ions at high temperatures. The electrolyte consists of a solid, nonporous metal oxide, typically Y_2O_3 stabilized ZrO_2 with the anode made from $CoZrO_2$ or $NiZrO_2$ cermet, while the cathode is made from Sr doped $LaMnO_3$. The cell operates at 650 to 1000° C such that conduction by oxygen ions through the electrolyte is possible.

The use of a ceramic electrolyte has the advantage of being impervious to gas crossover from one electrode to the other. The absence of liquid also eliminates the problem of electrolyte movement or flooding in the electrodes.

Electrodes

The anode consists of metallic Ni and Y_2O_3-stabilized ZrO_2 skeleton, which serves to inhibit sintering of the metal particles and to provide a thermal expansion coefficient comparable to those of the other cell materials. The anode structure is fabricated with a porosity of 20 to 40% to facilitate mass transport of reactant and product gases. The Sr-doped lanthanum manganite ($La1\text{-}xSrxMnO_3$, x = 0.10-0.15) that is most commonly used for the cathode material is a p-type conductor. Similar to the anode, the cathode is a porous structure that must permit rapid mass transport of reactant and product gases.

Tubular and Planar Configurations

The SOFC is a solid state device and shares certain properties and fabrication techniques with semi-conductor devices. The SOFC with its solid state components may in principle be constructed in any configuration. Cells are being developed in several configurations such as:

- The tubular cell which is being commercialized by Siemens Westinghouse. This cell design constructs the fuel cell around a porous zirconia support tube through which air is supplied to the cathode which is deposited on the outside of the tube. A layer of electrolyte is then deposited on the outside of the cathode and finally a layer of anode is deposited over the electrolyte. A number of cells are connected together by high temperature semiconductor contacts.
- The planar or flat plate which has been adopted by many developers because of its potential for low-cost production methods. Current designs consist of the electrode, electrolyte, and interconnect material deposited in layers and sintered together to form a cell structure, the fabrication techniques differ, however, according to the type of cell configuration and developer.
- The monolithic design which is at a very early stage of development for fuel cell applications. A monolith is a ceramic block consisting of a large number of small straight and parallel channels. The monoliths are made by extrusion. A special mixture of clay, binders and additives is pushed through a sophisticated dye to create the monolith structure. The extruded material is dried, cut to the required length and fired at high temperatures. On the walls of the channels a catalytic active layer can be applied in which chemical reactions can take place. A well known application of monoliths is the three-way catalyst in automobiles. In this monolith reactor exhaust gas from automobile engines is cleaned. A monolith is mechanically strong so that it can survive the vibrations of a car in motion.

Tubular, planar and monolith designs offer different geometries that can be used by fuel cell developers to optimize mass transfer, electrical connections and balance plant configuration. In addition, these three design options imply different manufacturing methods each with different scale-up and cost profile.

The material selected for use in the SOFC are constrained by the chemical stability in oxidizing and/or reducing conditions, the conductivity and the thermo mechanical compatibility in high temperatures. Another restriction placed on the cell components is that they must be capable of withstanding thermal cycling.

The high operating temperature of the SOFC requires a significant start-up time. The cell performance is very sensitive to operating temperature. A 10% drop in temperature results in about a12% drop in cell performance due to the increase in internal resistance to the flow of oxygen ions. The high temperature also demands that the system include significant thermal shielding to protect personnel and to retain heat. While such requirements are acceptable in a utility application, they are not consistent with the demands of most transportation applications nor do they lend themselves to small, portable or transportable applications.

Temperature management is achieved through maintenance of proper volume of the air stream into the cell.

Advantages of SOFC

Advantages of the SOFC are that there is no liquid electrolyte with its associated corrosion and electrolyte management issues. With an operating temperature greater than 600 °C, internal reforming can be achieved. Overall thermal efficiencies are high; typically in the 45 to 50% range for conversion of the fuel (natural gas) bound energy to electricity on an LHV basis. Also, the exhaust heat from the SOFC is at very high temperatures (up to 1000° C) and may be used for cogeneration purposes which further increase the electrical efficiency. With hybrid cogeneration systems the conversion of the fuel bound energy to electricity may be as high as 70%. The high temperature is also conducive to fast reaction kinetics without requiring any noble metal catalysts, and producing high quality exhaust heat for cogeneration or for use in cogeneration. The high temperature of the SOFC, however, places stringent requirements on the materials of construction.

The advantages of SOFC can be summarized as follows:

- Ceramics can be cast into various shapes (tubular, planar or monolithic).

- The corrosion problems associated with liquid electrolyte fuel cells such as the MCFC, the PAFC and the AFC are avoided.
- Fuel flexibility
- Fast reaction kinetics without noble metal catalysts, reducing catalyst costs and eliminating carbon monoxide poisoning.
- High temperature, pressurized exhaust can be used in co-generation applications to increase overall electrical efficiency.

The disadvantages are:

- It is difficult to find suitable materials with matching thermal expansion coefficients which is essential to minimize thermal stress. Thermal cycling associated with shut-down and start-up may result in cracking and delamination.
- Sealing is difficult with planar SOFC.
- High temperatures place restriction on material selection and may result in difficult manufacturing processes.
- Start-up time is lengthy, up to 15 hours.

Since operability at lower temperatures would reduce material challenges, considerable R&D has been focused on SOFC that can be operated at 600° C to 800° C. Lower temperatures dictate a planar configuration to reduce electric resistance losses. However, effective sealing remains an issue with planar SOFC. A considerable amount of R&D has been expended on developing ceramic electrolytes that operate effectively at lower temperatures. One approach is to use cell with very thin electrolyte films, as thin as 10 microns. Thin films have low electric resistance losses and may permit lower operating temperatures.

Long tubular SOFC of the Siemens Westinghouse design have the disadvantage of high electrical impedance relative to planar SOFC. Planar designs have higher power densities. The key advantage of the tubular design is that it does not require any seals at the sides. Planar SOFC failures are reported to occur when glass seals crystallize under heat and crack. Glass also tends to react with electrode components at SOFC temperatures. The growing interest in compressive seal technology is at an early stage.

In the Siemens Westinghouse design, the tubular cathode is formed by extrusion. The electrolyte is added by electrochemical vapor deposition. The cathode is added by slurry deposition.

Planar SOFC are composed of trilayer flat plates, generally anode supported. However, the coefficient of expansion of the Ni-YSZ anode is greater than that of the YSZ electrolyte. This limits electrolyte thickness to less than 30 microns. Thin anode supported cells are preferred for lower temperature operations. Lower-cost stainless steel interconnects may be used in lower temperature designs. The use of thin ceramic films permits continuous manufacturing processes such as tape casting. The electrodes are applied by the slurry method, screen printing or plasma spraying. The "green" tape is then fired in an oven to produce the final ceramic structure.

Cost reduction opportunities largely hinge on the high-temperature fuel cell component. Moderation of operating temperature is required to reduce materials costs. Also beneficial would be more sulfur tolerance, and increased power density. Specific issues being addressed include:

- Increasing cathode reactivity
- Development of interconnects that work well at lower temperatures
- Development of thin electrolytes with better ionic conductivity at lower temperatures.

The U.S. Department of Energy has set its R&D programs to achieve a dramatic reduction in SOFC costs. It has formed the Solid State Energy Conversion Alliance (SECA) with a goal of producing a core solid-state fuel cell module that could be produced at a cost of no more than US$ 400 per kW. At this cost, fuel cells would compete with gas turbine and diesel generators and likely gain widespread market acceptance.

SECA is made up of several government agencies, fuel cell developers, universities and national laboratories. It is headed by the Energy Department's National Energy Technology Laboratory and its Pacific Northwest National Laboratory.

The key to the ambitious cost reductions will be the development of a compact, 5-kW module that can be mass-produced using many of the same manufacturing advances that have dramatically lowered costs in the electronics industry. The modularity of the system will permit the 5-kW unit to be clustered into a variety of custom-build stacks for a wide variety of applications – from small portable military power sources to multi-megawatt central generating stations.

The proposed solid state design will leverage numerous recent advances, such as the production of thin-film solid electrolyte materials and precise, automated manufacturing technologies developed largely in the semi-conductor industry. SECA's goal is to have this ultra-low cost fuel cell concept ready for commercial application by 2010.

SOFC Advantages vs. MCFC

The SOFC solves three important weaknesses of the MCFC:

- At operating temperature (~650° C) the MCFC electrolyte is liquid and tends to leak from the stack. It is very corrosive, so there is the combined challenge of topping up the electrolyte over time and minimizing the corrosion of the metallic stack components. The SOFC is an all solid state design with no corrosive liquids.
- There is a large volume expansion when the molten carbonate electrolyte is cooled below its melting point and solidifies. Just like water that freezes will crack its container, thermal cycling of a molten carbonate stack is very problematic with respect to maintaining the integrity of seals, contacts, etc. Thermal cycling and thermal stresses are issues with the SOFC, but to a lesser extent than with the MCFC because of the all solid state design of the SOFC.
- The MCFC power density is low, and the cells are quite large.

The solid state nature and higher power density of SOFC present distinct advantages over MCFC.

CO_2 Mitigation

Fuel cell systems based on hydrocarbons will exhibit lower CO_2 emissions than equivalent combustion systems because their hydrocarbon to electricity efficiency is higher. In addition, certain fuel cell systems offer advantages in CO_2 recovery because a CO_2 rich effluent is produced. In the MCFC and SOFC, CO_2 is produced in the anode compartment, with SOFC offering the best prospects. A demonstration of SOFC with CO_2 recovery is planned by Norske Shell and Siemens Westinghouse. Water can easily be separated from the anode effluent and the CO_2 can be compressed to the pressure required for sequestration. Compression requirements are less for pressurized SOFC hybrids. In combination with coal gasification, this approach could potentially provide the lowest cost route for CO_2 mitigation.

Energy Efficiency

Presently available, un-pressurized SOFC deliver fuel to electric efficiencies in the range of 45% (HHV). Argonne National Laboratories suggests that pressurized (3-4 atmospheres) systems could yield fuel efficiencies of 60% (HHV). Bottoming cycles, using the high temperature waste heat from the fuel cell, could add another few percent to the fuel efficiency of the SOFC system.

Major SOFC Developers

The **Siemens Westinghouse** 100 kW fuel cell stack contains 48 bundles of 24 cells each, for a total of 1,152 cells. Fuel conversion by the fuel cell is about 85%. The balance of the fuel is combusted to assist with thermal management. The 100 kW system has an AC electrical efficiency of 46% (LHV).

Siemens Westinghouse intends its commercial units to run unattended. In 2000, a prototype Siemens Westinghouse 100-kilowatt solid oxide fuel cell at a power station in Westervoort, the Netherlands, exceeded 16,600 hours in total operating time, becoming the longest running fuel cell in the world. When the planned test program concluded, Siemens Westinghouse moved the fuel cell to the Fuel Cell Pavilion at the Meteorit Park site in Essen, Germany, where it was restarted continues to operate.

A 25-kilowatt Siemens Westinghouse field test system in California at the National Fuel Cell Research Center at the University of California, Irvine has operated for more than 9,000 hours on a variety of fuels, including natural gas, diesel and jet fuel. The system was restarted in August 2000 after being idle for two years. It started up with no difficulty and continues to operate. An earlier Siemens Westinghouse test unit in the 25 kW range operated for more than 13,000 hours, with a non-stop run of over 6500 hours. This system was sponsored by Tokyo Gas and Osaka Gas of Japan.

The high-temperature operation of a solid oxide fuel cell and its capability to operate at elevated pressures makes it an attractive candidate for linking with a gas turbine in a hybrid configuration. The hot, high pressure exhaust of the fuel cell can be used to spin a gas turbine, generating a second source of electricity.

The world's first solid oxide fuel cell/gas turbine hybrid system is at Southern California Edison for operation at the National Fuel Cell Research Center in Irvine, California. The hybrid system includes a pressurized solid oxide fuel cell module integrated with a microturbine/generator supplied by Ingersoll-Rand Energy Systems (formerly Northern Research and Engineering Corp.). The system has a total output of 220 kW, with 200 kW from the fuel cell and 20 from the microturbine generator. The fuel cell is pressurized to 3-4 atmospheres. The gas turbine is unfired. The microturbine is being driven by the hot pressurized exhaust produced by the fuel cells, which accounts for its high efficiency. In the California unit, the two technologies combine to produce approximately 190 kilowatts of electricity. The combination is pushing power efficiencies. The unit has operated for over 10,000 hours on a variety of fuels, including natural gas, diesel and jet fuel. Early test data show electrical efficiencies of approximately 53%, for operation on natural gas. Improvements in the technology could ultimately raise efficiencies to 60% for smaller systems and 70% or higher for larger 20 MW systems. Its emissions of nitrogen oxide, which can contribute to urban smog, are nearly 50 times less than today's average natural gas turbine.

Siemens is projecting a mature cost of US$ 1,500/kW for a 250 kW hybrid plant based on manufacturing output of 100 MW per year.

At the conclusion of the joint development program with the Energy Department, Siemens Westinghouse contemplates two major product lines with a series of product offerings in each:

- 250-kilowatt and 1-megawatt cogeneration systems, operating at atmospheric pressure with electrical efficiencies of 47-50% and overall system energy efficiency of more than 80%, assuming steam/hot water or other cogeneration. The first prototype project of the new Siemens Westinghouse CHP250 cogeneration system will be with Kinectrics (Ontario Power Generation). The second CHP250 prototype will be delivered to BP for operation at their gas-to-liquids plant in Nikiski, Alaska, in 2003. A 250 kW SOFC system will be also fabricated for Shell in Norway to demonstrate the principle of CO_2 capture from power plants. By keeping the fuel and air streams separate, the CO_2 generated can be captured, and the SOFC power system will essentially have clean water as its only effluent.

- Fuel cell/gas turbine hybrid systems, sized at 300 kilowatts and 1 megawatt, operating at elevated pressures of 3-4 atmospheres, with electrical efficiencies of 58-70%, and overall system energy efficiency of around 80% if hot water is also produced. 300 kW SOFC/gas turbine hybrid systems are in development for RWE in Germany and for Edison Spa in Italy.

In 2001, Siemens Westinghouse announced that it would site its commercial SOFC manufacturing facility in the Pittsburgh area. Siemens Westinghouse selected a 22-acre site for its 430,000-square-foot facility about four miles from its R&D facility near Churchill, Pennsylvania. Siemens Westinghouse has approximately 160 people devoted exclusively to its fuel cell program.

Rolls-Royce SOFC design is a combination of both planar and tubular geometries. Modules containing up to 60 flat tubes have been fabricated. The European Union is supporting a 20 kW stack test program. Partners include: RISO National Laboratory (Denmark), Gaz de France, Advanced Ceramics and Imperial College.

Acumentrics claims to have a unique small tubular SOFC design with fast start-up time and with the ability to reform natural gas internally at the anode. Electric efficiency is reported to be 45% to 50%. Prototypes have been delivered to partners such as ChevronTexaco, General Dynamics, NiSource, Northeast Utilities and Sumitomo.

ZTEK is the original planar SOFC developer. It has built a 25 kW system under the sponsorship of the Tennessee Valley Authority. The stack operates at 1,000° C and uses natural gas. About 60% of the natural gas is reformed by a proprietary reformer and the balance in the stack. ZTEK is also designing a SOFC gas turbine hybrid with a capacity of 200 kW.

GE Hybrid Power Generation Systems has developed a manufacturing process for thin SOFC by tape calendering. The objective is to obtain high power densities at operating temperature of about 800 °C. GE is projecting costs under US$ 400/kW for the mature system. GE is working on both civilian and military applications. The latter involve the use of diesel logistic fuels. GE is also working on SOFC gas turbine hybrids.

Global Thermoelectric acquired an anode supported planar SOFC technology from Forschungszentrum, one of Germany's largest technical institutes. Global has used its manufacturing pilot plant to achieve cost reductions, higher yields and larger are cells. The manufacturing technology utilizes high-volume tape casting, screen printing, and tunnel kiln units. The SOFC technology operates between 600° C and 750° C and includes a high temperature heat exchanger and pre-reformer module. Global is focusing on the 2 kW residential market and 10 kW remote location applications. Global has partnered with Enbridge, Citizen Gas, the Bonneville Power Administration, Montana-Dakota Utilities, Suburban Propane and Superior Propane. Delphi Automotive Systems is using Global stacks to develop automotive auxiliary power units (APU).

McDermott and its subsidiary **SOFCo** are developing low-cost SOFC stacks in collaboration with Advanced Refractory Technologies. In partnership with Cummins Power Generation, McDermott is developing a 10 kW automotive APU. This effort is supported by the U.S. Department of Energy.

NexTech Materials is developing low-cost fabrication methods for anode supported planar SOFC. The U.S. Department of Energy and the State of Ohio are supporting NexTech's R&D efforts.

Other U.S. early stage planar SOFC developers are **Versa Power Systems**, **Ceramic Fuel Cells** and **Technology Management Inc**.

In Europe, **Rolls-Royce** and **Sulzer-Hexis** are allocating significant resources to developing small scale SOFC systems with major support from the European Union. In Japan, **Fuji Electric**, **Mitsubishi Electric**, **Chubu Power**, **Murata Manufacturing**, **Osaka Gas**, **Tokyo Gas** and **Tonen** are conducting SOFC development programs supported by the government's New Sunshine Program.

In Canada, **Kinectrics** (Ontario Power Generation), in cooperation with the Government of Canada and a number of other partners, will build and operate a solid oxide fuel cell combined heat and power plant. The new system is the first prototype project of the new Siemens Westinghouse CHP250 cogeneration system and is expected to have an electrical efficiency of about 50 percent and an overall fuel conversion efficiency of up to 85 percent with heat recovery. The system eliminates energy lost through power transmission and distribution because it can be located where the energy is needed and has a high-temperature output. The $18-million project is also being funded by the U.S. Department of Energy and Siemens Westinghouse. The Government of Canada is investing more than $2 million to help develop and build this prototype. Of these funds, $1.1 million will come from the Technology Early Action Measures (TEAM) component of the Government of Canada's Climate Change Action Fund (CCAF), and $373,000 from Natural Resources Canada.

Fuel Processing Systems

Fuel Processing Systems (FPS) refer to small scale hydrogen production systems. Generally, FPS are based on reforming fossil fuels, but some systems based on the electrolysis of water are being developed. Three categories of FPS are being pursued:

- On-site hydrogen production for fuel cell vehicle refueling stations
- On-board FPS for fuel cell vehicles
- Very small scale FPS for stationary residential and small commercial applications

FPS based on reforming approaches may use steam methane reforming, partial oxidation or autothermal reforming. Small systems will produce hydrogen with the low carbon monoxide content required by PEMFC, but hydrogen concentration is generally 40 to 50% because of dilution by nitrogen. Larger units may include a pressure swing adsorption (PSA) unit to obtain 99.9+ hydrogen purity. Companies such as QuestAir are developing small scale PSA units for use with small scale FPS. For example, Hydrogen Source offers FPS modules in the following sizes: 5 kW, 50 kW, 150 kW and 200 kW. They are based on partial oxidation of hydrocarbons to CO as opposed to complete oxidation the CO_2, except the 200 kW module which is based on steam methane reforming.

Numerous process engineering and industrial companies have FPS available or under development, including: ChevronTexaco, Air Products, Haldor Topsoe, Linde, Praxair, Howe-Baker, Petrofac, Technip, HyRadix (UOP and Sud Chemie JV) and Hydrogen Source (Shell and UTC Fuel Cells JV). In addition, some fuel cell developers own proprietary FPS technology that they integrate into their systems. Ballard has its own

FPS integrated into its prototype 250 kW stationary PEMFC. ZTEK, a SOCF developer will supply a FPS to the California Fuel Cell Partnership demonstration for on-site reforming at a filling station. Other companies with FPS products include H2Gen Innovations (backed by Air Products and Chrysalix), McDermott Technologies and Johnson Matthey.

Developers of small-scale electrolysis systems include Stuart Energy and Teledyne. Proton Energy Systems is developing an electrolysis system with internal solid-state electrochemical compression to reduce mechanical compression requirements.

Hybrid Fuel Cell Power Systems

The heart of hybrid power systems is the high-temperature fuel cell such as commercially ready solid oxide fuel cells and molten carbonate fuel cells. The high thermal output of SOFC and MCFC make possible the hybrid cycle, where the combined performance potential of the power components far surpasses that of individual components alone. Co-production of electricity and hydrogen also are achievable. Hybrids have the potential for fuel-to-electricity efficiencies of 75% or more, far exceeding that of other known high-performance natural gas-based power systems.

Over the past years, capital costs have been reduced for SOFC and MCFC systems putting them on a track to potentially bring capital costs down to US $1,500 to $2,000/kW at high production rates. Performance enhancements supporting capital and operating cost reduction include:

- Increased fuel-to-electricity efficiency
- More tolerance of fuels used
- Operating temperatures sufficient for supporting fuel reforming
- High-value process heat sufficient for leveraging thermal efficiency in combined heat and power and combined cycle applications.

A number of hybrid cycles offering synergistic operation are possible. These include:

- Hybrid combinations of fuel cell/turbine
- Fuel cell/fuel cell
- Fuel cell/reciprocating engine
- Fuel cells with other heat engines.

The focus of present efforts is in developing the fuel cell/turbine hybrid because the technology database and components are the most mature.

The U.S. Department of Energy has initiated R&D and demonstration programs that are focused on bringing SOFC costs down to US$400/kW, a cost that would enable fuel cells to find applications in a large variety of power markets. This effort is being undertaken by the NETL Fuel Cell Program is Solid State Energy Conversion Alliance (SECA). SECA leverages previous work on the SOFC with the objective of developing a next-generation, mass produced, 5 kW SOFC module that can be combined like batteries to meet a broad range of applications. This mass customization approach resolves the dilemma of initial costs being high, because limited markets do not warrant mass production. Increasing power density and reducing material and fabrication costs of the SOFC are key technical developments requisite to meeting cost

In the near to mid-term, fuels used with the hybrids will be natural gas and transportation fuels, and sizes will be up to several megawatts, which are capable of supporting distributed generation applications. In the longer term, the hybrids will be linked to gasification technologies capable of converting coal, biomass, and solid waste feedstocks to clean synthesis gas. These gasification linked hybrids will support central power applications.

The fuel cell/turbine (FC/T) hybrid, which currently is receiving the greatest attention, combines a high-temperature fuel cell and a gas turbine in one of two basic operating modes: direct or indirect. In the direct mode the fuel cell serves as the combustor for the gas turbine. The residual fuel in the already high-temperature fuel cell exhaust mixes with the residual oxygen in an exothermic oxidation reaction to further raise the temperature to a temperature below the thermal NOx formation temperature. Both the fuel cell and the gas turbine generate electricity, and the gas turbine provides some balance-of-plant functions for the fuel cell, such as supplying air under pressure and preheating the fuel and air in a heat exchanger called a recuperator. In the indirect mode, the recuperator (in this case a high-temperature heat exchanger) transfers the fuel cell exhaust energy to the compressed air supply, which in turn drives the turbine, and the expanded air is supplied to the fuel cell. The indirect mode uncouples the turbine compressor pressure and fuel cell operating pressure, which increases flexibility in turbine selection. Development projects are being pursued for both direct and indirect approaches and time will tell if one approach is found superior to the other.

FC/T hybrids represent a superior power module option for gasification-based systems. Gasification extends the range of fuels that can be used by the hybrid, converting solid fuels, such as coal, and wastes to a syngas which is compatible with high-temperature fuel cells. These gasification systems can be configured with either direct or indirect FC/T hybrid technology. By performing the reforming function, the gasifier enables the fuel cell portion of the hybrid to operate at the highest possible efficiency.

Another concept of particular interest is a fuel cell/fuel cell (FC/FC) hybrid. The FC/FC hybrid appears to perform well in both power generation and hydrogen co-production modes. The FC/FC concept leverages the internal reforming ability of the SOFC and relatively low stack costs of the low-temperature PEMFC. PEMFC stack costs are reaching commercially viable levels through extensive development for transportation applications. But PEMFC systems suffer from availability of a cheap supply of hydrogen. In the FC/FC hybrid, the SOFC becomes the hydrogen source for the PEMFC while also producing electricity. The SOFC exports reformed natural gas (carbon monoxide and hydrogen). This reformate gas stream is H_2 enriched by adding steam, which shifts the CO and H_2 to CO_2, H_2, and H_2O. Because the PEMFC is intolerant of CO, either a selective oxidation step is used to convert the CO to CO_2 or a gas separation device is used to provide pure H_2 to the PEMFC. The gas separation approach affords the option to produce pure H_2 for other uses, such as a transportation fuel, in times of low electricity demand. And, the separation membrane produces a concentrated CO_2 stream, making it directly available for recycle or sequestration. The FC/FC concept is at an early stage of development and can be applied in many different configurations. Design flexibility comes from the fact that the sizing of the fuel processor associated with the SOFC is de-coupled from the requirements of the SOFC. The fuel processor can be sized to supply the SOFC, a PEMFC and a hydrogen storage facility. This flexibility offers many design options that remain to be explored by fuel cell developers.

While hybrids will find initial application in the distributed generation market, they must ultimately be integrated into coal-based, 100+ megawatt central power generation systems to fully realize their efficiency and environmental performance potential. Coal-, residual oil -, and petroleum coke-based integrated gasification combined-cycle (IGCC) technology is beginning to penetrate the base load power generation market, with efficiencies of 40% and capital costs of US$1,200 to 1,300/kW.

Research and Development Issues for Hybrid Systems

Transient states such as the sudden loss of load present a problem to fuel cell/turbine hybrids. Upon loss of electrical load, the fuel cell almost instantaneously stops the hydrogen reaction because the electrons are not available to support chemical conversion. The fuel shut-off control is slower than the cessation of hydrogen conversion. This time lag can result in an important fuel buildup that is a problem because it can lead to combustion. Solutions to the load loss issue will require some combination of rapid blow-off valves in the turbine compressor circuit, fuel diversion for controlled catalytic oxidation, and bottled nitrogen for fuel dilution.

Load following or the ability of the system to respond to load changes, introduces control issues as well. Short-term load excursions of 10 to 15% are readily handled by the fuel cell. Longer-term load excursions are handled by fuel control to the fuel cell. The difficult control issues occur in turndown conditions and during major download adjustments. Fuel cell efficiency increases significantly as load drops significantly. Therefore, turndown requires not only fuel control but either reduced air flow or air inlet temperature, or both. Another control factor is introduced in direct-fired hybrid cycles, where the fuel cell is pressurized directly by the compressor. Pressure impacts fuel cell performance and needs to be controlled to avoid pressure surges.

Sensors and controls must be designed and developed to measure and act upon key parameters, such as gas composition, temperatures, pressures, and fuel and air flows throughout the system. Conditions placed on many of the sensors and controls are harsh and demand rapid response and tight control.

The direct current output of the fuel cell and alternating current of the turbine must be integrated and conditioned to meet the power quality specifications of the application.

The potential range of applications includes conditions where the loads are highly variable and the system may be started up and shut down repeatedly over a short period of time. These transient conditions impose a significant burden on the power conditioning and control system that must deliver the power needed while protecting the integrity of the system. All components need to be better, faster, cheaper, and tolerant of the high-temperature environment.

Internal reforming is essential to system efficiency. Internal reforming is also an integral part of thermal management in the fuel cell because it serves to control the heat produced in the electrochemical reactions. Development of efficient high-temperature heat exchangers takes on increased importance.

Computer simulations need to be developed to accelerate investigation and resolution of compatibility, operation and control, and thermal management issues. These simulations also document technical understanding and advances, and serve as a foundation for future research.

4.4 Markets

Transportation

Over the last two decades, there has been a strong push to develop fuel cells for use in vehicles. A major impetus is the need for clean, efficient cars, trucks, and buses in order to improve air quality in densely populated areas and to reduce greenhouse gas emissions. Fuel cell vehicles are being developed to operate on conventional fuels (gasoline, diesel), as well as renewable and alternative fuels (hydrogen, methanol, ethanol, natural gas, and other hydrocarbons). With hydrogen as the on-board fuel, such vehicles would be zero emission vehicles. With on-board fuels other than hydrogen, the fuel cell systems would use an appropriate fuel processor to convert the fuel to hydrogen, yielding vehicle power trains with very low acid gas emissions and high efficiencies. These developments are being sponsored by various governments in North America, Europe, and Japan, as well as by major automobile manufacturers worldwide. Several fuel cell-powered cars, vans, and buses operating on hydrogen and methanol have been demonstrated.

In 1994 and 1995, H-Power (now Plug Power) led a team that built three PAFC/battery hybrid transit buses. These buses used a 50 kW fuel cell and a 100 kW nickel cadmium battery. Subsequently, major activities in transportation fuel cell development have focused on the PEMFC. In 1993, Ballard Power Systems demonstrated a light-duty transit bus with a 120 kW fuel cell system, followed by a 200 kW, heavy-duty transit bus in 1995. These buses use no batteries for propulsion. They operate on compressed hydrogen as the on-board fuel. In 1997, Ballard provided 205 kW PEMFC units for a small fleet of hydrogen-fueled, full-size transit buses for demonstrations in Chicago and Vancouver. Working in collaboration with Ballard, DaimlerChrysler built a series of PEMFC-powered vehicles, ranging from passenger cars to buses. The first such vehicles were hydrogen-fueled. A methanol fueled PEMFC car was unveiled by DaimlerChrysler in 1997.

A hydrogen-fueled (metal hydride for hydrogen storage), fuel cell/battery hybrid passenger car was built by Toyota in 1996, followed in 1997 by a methanol-fueled car built on the same platform. Other major automobile manufacturers, including General Motors, Volkswagen, Volvo, Honda, Nissan, Toyota, and Ford, are also building prototype PEMFC vehicles operating on hydrogen, methanol, or gasoline. UTC Fuel Cells and Plug Power and Ballard Power Systems are involved in separate programs to build 50 to 100 kW fuel cell systems for vehicles. Other fuel cell manufacturers are involved in similar vehicle programs. Some are developing fuel cell-powered utility vehicles, golf carts, fork lift trucks, etc.

In addition to automotive propulsion the use of fuel cells as auxiliary power units (APU) for vehicles has received considerable attention. APU applications may be an attractive market because it offers a true mass-market opportunity that does not require the challenging performance and low cost required for propulsion systems for vehicles. Auxiliary power units are devices that can provide all or part of the non-propulsion power for vehicles. Such units are already in widespread use in a range of vehicle types and for a variety of applications, in which they provide a number of potential benefits. Fuel cell APUs will likely have to operate on gasoline, and for trucks preferably on diesel fuel, in order to match the infrastructure available, and preferably to be able to share on-board storage tanks with the main engine. The small amount of fuel involved in fueling APUs would likely not justify the establishment of a specialized infrastructure (e.g. a hydrogen infrastructure) for APUs alone. Similarly, fuel cell APUs should be water self-sufficient, as the need to carry water for the APU would be a major inconvenience to the operator, and would require additional space and associated equipment.

The main difference in SOFC stack cost structure as compared to PEMFC cost relates to the simpler system configuration of the SOFC-based system. To provide some perspective on the viability of SOFC in APU applications from a cost perspective, NETL sponsored an estimate of the cost structure of small-scale (5 kW), simple cycle SOFC anode-supported system, operated on gasoline. The estimated manufacturing cost for such systems could well be close to that estimated for comparable PEMFC systems, while providing somewhat higher system efficiency.

Stationary Power

One of the characteristics of fuel cells is that their efficiency is nearly unaffected by size. Small, relatively high efficient power plants can be developed, thus avoiding the high investment cost associated with large plants. As a result, initial stationary plant development has been focused on several hundred kW to low MW capacity plants. Smaller plants (several hundred kW to 1 to 2 MW) can be sited at the user's facility and are suited for combined heat and power operation, that is, the plants produce electricity and thermal energy. Larger plants (1 to 10 MW) are likely to be used for distributed generation. The plants are fueled primarily with natural gas. Once these plants are commercialized and price improvements materialize, fuel cells will be considered for large base-load plants because of their high efficiency.

The base-load plants could be fueled by natural gas or coal. The fuel product from a coal gasifier, once cleaned, is compatible for use with fuel cells. Systems integration studies show that high temperature fuel cells closely match coal gasifier operation [35].

Operation of complete, self-contained, stationary plants has been demonstrated using PEMFC, AFC, PAFC, MCFC, tubular SOFC, and planar SOFC technologies. A case in point is the 200 kW PAFC on-site plant, the PC-25, that is the first to enter the commercial market. The plant was developed by UTC Fuel Cells. The Toshiba Corporation of Japan and Ansaldo SpA of Italy are partners with UTC. The on-site plant is proving to be an economic and beneficial addition to the operating systems of commercial buildings and industrial facilities because it is superior to conventional technologies in reliability, efficiency, environmental impact, and ease of siting. Because the PC-25 is the first available commercial unit, it serves as a model for fuel cell application. Because of its attributes, the PC-25 could be installed in various applications, such as hospitals, hotels, large office buildings, manufacturing sites, wastewater treatment plants, and institutions, to meet the following requirements:

- Continuous power – backup
- Uninterrupted power supply
- Combined heat and power generation

An eventual market for fuel cells is for large (100 to 300 MW), base-loaded, stationary plants operating on coal or natural gas. Another related opportunity would be to re-power older, existing plants. High-temperature fuel cells (MCFC and SOFC) coupled with coal gasifiers have the best attributes to compete for the large, base load market. The rejected heat from the fuel cell system can be used to produce steam for the existing plant's turbines. Studies showing the potential of high-temperature fuel cells for plants of this size have been performed. These plants are expected to attain from 50 to 60% efficiency.

Coal gasifiers produce a fuel gas product requiring cleaning to the stringent requirements of the fuel cells' electrochemical environment, a costly process. The trend of environmental regulations has also been towards more stringent cleanup. If this trend continues, coal-fired technologies will be subject to increased cleanup costs that may worsen process economics. This will improve the competitive position of plants based on the fuel cell approach. Fuel cell systems will emit less than target emissions limits. U.S. developers have begun investigating the viability of coal gas fuel to MCFC and SOFC A FuelCell Energy 20 kW MCFC stack was tested for a total of 4,000 hours on coal gas as well as pipeline gas. The test included syngas from a slip stream of a Destec entrained gasifier. The fuel processing system incorporated cold gas cleanup for bulk removal of H_2S and other contaminants, allowing the 21 kW MCFC stack to demonstrate that the FuelCell Energy technology can operate on either natural gas or coal gas.

The fuel cell HotModule from MTU CFC Solutions (Germany) is a highly integrated MCFC system for decentralized stationary power & heat cogeneration or "tri-generation" of power, heat, and cold. It produces the "consumable" energy forms using decentralized available fuels like natural gas, biogas etc. Utilizing gases from thermal gasifiers is a big target with the consequence of opening the possibility to use waste material as a sustainable energy source. MTU will start manufacturing of the HotModule in 2005.

Nuvera Fuel Cells is developing a stationary power product called Forza to exploit the emerging hydrogen infrastructure. Forza is a megawatt-scale PEMFC system that will run off the by-product hydrogen generated by industrial electrolyzers at chlor-alkali plants during the production of chlorine and caustic soda. Forza is expected to offer plant managers a 15-20% savings on their electricity bills.

Baxi Group, Europe's third biggest manufacturer of boilers, estimates that combined heat and power products to be a future market. Therefore, Baxi's strategy is to develop with SenerTec combined heat and power products from 1.5 kW to 12 kW and to develop future markets with European Fuel Cell. The vision is that in 10 years home will have a 1.5kW fuel cell based home energy center to produce power and heat. To meet the requirements of comfort for room heating and hot water a condensing boiler would be integrated in the home energy center.

Major R&D objectives associated with small scale combined heat and power fuel cell products are:

- Increased lifetime
- Meeting cost targets.

Distributed generation is small, modular power systems that are sited at or near their point of use. The typical system is less than 30 MW, used for generation or storage, and extremely clean. Examples of technologies used in distributed generation include proven gas turbines and reciprocating engines, biomass-based generators, concentrating solar power and photovoltaic systems, fuel cells, wind turbines, micro-turbines, and flywheel storage devices.

The market for distributed generation is aimed at customers dependent on reliable energy, such as hospitals, manufacturing plants, grocery stores, restaurants, and banking facilities. There is currently over 15 GW of distributed power generation operating in the U.S. Over the next decade, the domestic market for distributed generation, in terms of installed capacity to meet the demand, is estimated to be 5-6 GW per year. The projected global market capacity increases are estimated to be 20 GW per year. Several factors have played a role in the rise in demand for distributed generation. Utility restructuring is one of the factors. Energy suppliers must now take on the financial risk of capacity additions. This leads to less capital intensive projects and shorter construction periods. Also, energy suppliers are increasing capacity factors on existing plants rather than installing new capacity, which places pressure on reserve margins. This increases the possibility of forced outages, thereby increasing the concern for reliable service.

There is also a demand for capacity additions that offer high efficiency and use of renewable resources as the pressure for enhanced environmental performance increases.

There are many applications for distributed generation systems. They include:

- Peak shaving - Power costs fluctuate hour by hour depending upon demand and generation therefore customers would select to use distributed generation during relatively high-cost on peak
- Combined heat and power –The thermal energy created while converting fuel to electricity would be utilized for heat in addition to electricity in remote areas and electricity and heat for sites that have a 24 hour thermal/electric demand.
- Grid support – Strategic placement of distributed generation can provide system benefits and preclude the need for expensive upgrades and provide electricity in regions where small increments of new base load capacity is needed.
- Standby power – Power during system outages is provided by a distributed generation system until service can be restored. This is used for customers that require reliable back-up power for health or safety reasons, companies with voltage sensitive equipment, or where outage
- Remote/Stand alone – The user is isolated from the grid either by choice or circumstance. The purpose is for remote applications and mobile units to supply electricity where needed.

Distributed generation systems have small footprints, are modular and mobile making them very flexible in use. The systems provide benefits at the customer level, the supplier level as well as the national level. Benefits to the customer include high power quality, improved reliability, and flexibility to react to electricity price spikes. Supplier benefits include avoiding investments in transmission and distribution (T&D) capacity upgrades by locating power where it is most needed and opening new markets in remote areas. At the national level, the market for distributed generation establishes a new industry, boosting the economy. The improved efficiencies also reduce greenhouse gas emissions.

However, there are also a number of barriers and obstacles to overcome before distributed generation can become a mainstream service. These barriers include technical, economic, institutional and regulatory issues. Many of the proposed technologies have not yet entered the market and will need to meet performance and pricing targets before entry. Questions have also risen on requirements for connection to the grid. Lack of standardized procedures creates delays and discourages customer-owned projects. Siting, permitting and environmental regulations can also delay and increase the costs of distributed generation projects.

- IdaTech LLC (formerly Northwest Power Systems), of Bend, Oregon, an Idacorp subsidiary, delivered the first of 110 planned fuel cell systems to the Bonneville Power Administration (BPA), Portland, Oregon in June 2000. The BPA program is part of a fuel cell test and development phase intended to commercialize fuel cell systems for home and small commercial.
- Avista Labs, an affiliate of Avista Corp., of Spokane, Washington, received a US patent in March 2000 that covers 162 claims for its modular, cartridge-based PEMFC. The fuel cell cartridges can be removed and replaced while the power system continues to operate. Additional elements of the patented system include proprietary designs that simplify the humidifying and cooling systems, resulting in lower manufacturing costs and higher efficiency. Currently, Avista has over 30 fuel cells installed around the U.S.
- Bewag AG's Treptow heating plant, located in Berlin, Germany received a 250 kW PEM fuel cell unit in April 2000 from Ballard Generation Systems.

- Plug Power, Inc, of Latham, NY manufactured six alpha fuel cells to be field tested as part of the Clean Energy Initiative, the Long Island Power Authority (LIPA), Uniondale, NY. Hofstra University was the site of the first tests, which began in February 2000. By the 60-day mark, the fuel cells had generated approximately 1900 kWh and operated in parallel with LIPA's T&D system.
- Energy USA, a subsidiary of NiSource Inc, of Merrillville, Ind formed a joint venture with the Gas Technology Institute called Mosaic Energy LLC. They designed fuel cells for the core of the home's energy-generating system to be used in a Chesterton, Indiana housing development. Space heating and other household needs will be provided by the byproduct heat production.
- UTC Fuel Cells has the most commercially advanced fuel cell for electricity generation, the PC25, a 200-kW phosphoric acid fuel cell (PAFC). UTC has over 200 fuel cells delivered around the world.
- Siemens Westinghouse, of Pittsburgh, PA has manufactured the largest tubular solid oxide fuel cell system. The Dutch/Danish consortium EDB/Elsam operates the system, which supplies 110 kW of electricity to the grid and 64 kW to the city of Westervoort, Netherlands district heating system. The efficiency is about 46% with exhaust gas values for NOx, SOx, CO and VHC under 1 ppm each. Commercial units ranging in size from 250 to 1000 kW are expected in 2004. Siemens Westinghouse installed a 250 kW unit at the National Fuel Cell Center.

Portable Market

PEMFC and DMFC are being developed for electronic devices such as laptops, video cameras, cell phones, etc. PEMFC are preferred for applications with high power needs while DMFC are favored when operation time is more important than high power densities [42].

The important competitive advantage of fuel cells for portable application is their capability for energy storage. Batteries have an energy density of 0.13 kWh/l. By comparison, methanol contains 4.2 kWh/l and hydrogen compressed at 300 bar, 0.4

kWh/l. [24]. Fuel cells allow the use of methanol or hydrogen which offer respectively 30 and 3 times the energy density of batteries. Methanol fuel cell systems have ten times the power of lithium batteries, and one cell could power a laptop computer for hours.

In consumer applications, methanol is easier to handle and safer than hydrogen. Cartridge type refueling would provide for a convenient distribution system for methanol. The DMFC obtains power from methanol without the need for a reformer. The system is fueled by methanol from a cartridge and oxygen from the air. It emits water, likely collected in a bladder and returns to the atmosphere a small amount of carbon dioxide.

MTI MicroFuel Cells has developed a prototype methanol mobile phone that will provide power for much longer periods than traditional cell phones when it is launched in 2004. Motorola, Toshiba, Casio, and Sanyo are developing miniature fuel cells for a variety of devices, including PDA, laptops, and cell phones. The U.S. Department of Transportation gave the industry a big boost in October 2002 when it announced that a fuel cell design by PolyFuel would be allowed on airplanes, which is a change from the airline industry's rigid policy banning fuels in the passenger cabin of an airplane. Portable applications should be mass produced in 2005-2009.

These aspects of DMFC make them attractive for consumer applications and could allow DMFC to break into the growing rechargeable battery market. However, achieving the potential for DMFC in portable applications will require solutions to technical challenges. Ambient temperature air-breathing DMFC have low power density which limits their usefulness in applications that require either a very compact design, such as cell phones or high power densities, such as power tools. Methanol crossover problems need to be resolved in order to increase reliability and durability. Water balance in micro fuel cells remains a challenge and convenient solutions need to be found for water disposal.

DMFC appear to be the technology of choice for portable applications because of the ability to start quickly and because methanol is a safer and easier fuel to handle at the consumer level. Laptop computers and video cameras are the relatively easier applications for micro fuel cells. Small transportation applications such as forklift trucks and wheel chairs are also being developed. A promising application is chargers for rechargeable batteries for service in remote locations. Users of such devices would be forestry crews, search and rescue operations and the military.

Military Applications

Utility applications at the U.S. Department of Defense (DOD) are power plants that serve the load of particular sites and they range in size from a few megawatts for distributed power generation to 100+ MW. There is significant potential for improving the security of electrical power used by the DOD by using onsite power generation. The increased concern of environmental issues has made producing clean power desirable and mandatory. In addition, because most central heat plants on U.S. military installations are nearing the end of their useful life, there are opportunities to replace outdated existing equipment with modern technologies.

The military also finds certain characteristics of fuel cell power plants desirable for field duty. Foremost, a fuel cell unit is quiet and, therefore, can be close to the front line. It has a low heat trace, and can be scaled to various sizes, from a few kW backpacks to larger mobile power plant. The main drawback for the military is that the existing military infrastructure is limited to logistic fuels. Logistic fuels (defined as easily transportable and stored, and compatible with military uses) are difficult to convert to hydrogen for fuel cell use. The burden of changing the fuel infrastructure to accommodate lighter fuels, normally used in fuel cells, is far greater than the benefits fuel cells offer the military. The Advanced Research Projects Agency of DOD funded several projects to investigate adapting logistics fuels to fuel cell use. Demonstration projects have shown that fuel cell units can be operated with military logistic fuels.

One effort, being run in collaboration with the Army Research Office, has demonstrated a prototype fuel cell designed to replace in many applications a popular military standard battery. The target application is the Army's BA-5590 primary (i.e., use-once-and-dispose) lithium battery. The Army purchases approximately 350,000 of these batteries every year at a cost of approximately $100 per battery, including almost $30 per battery for disposal. Fuel cells, on the other hand, are not thrown away after each use but can be reused hundreds of times. Mission weight savings of factors of 10 or more are projected. The prototype fuel cell, which has the same size and delivers the same power as a battery, has been tested in all orientations and under simulated adverse weather conditions, and was enthusiastically received by Army senior management.

Other fuel cell opportunities arise from U.S. Army plans to reduce battlefield fuel consumption 75% by the year 2020. This will make supplying combat units easier, while also making it easier to protect supply lines. One example of military-sponsored research is the all-electric tank with an electromagnetic rail gun. The gun would use a powerful magnetic field to propel a small armor-piercing projectile to hypersonic speeds. Such a vehicle would be fast, quiet, and capable of firing flurries of rounds at multiple targets. In the future, the Army must also reduce vehicle exhaust emissions during peacetime. The Army owns a large number of vehicles equipped with non-emission controlled diesel engines, and will still own a significant number of these engines in 2020.

The Navy is studying the concept of all electric ships. These new ships will not have a central engine room and long drive shafts. The ships will depend on redundancy of generator capacity for combat survival, rather than protection of a centralized engine room.

Fuel cells can serve as a generator, battery charger, battery replacements and heat supply. They can adapt to most environments, even locations in Arctic and Antarctic regions.

Demonstration Programs

California Fuel Cell Partnership

The California Fuel Cell Partnership benefits from substantial support from automakers, fuel cell developers, and the oil industry. The program seeks to demonstrate fuel cell vehicles by operating and testing passenger cars and buses. It also includes demonstration of alternative fuel infrastructure for methanol and hydrogen.

Clean Urban Transport for Europe (CUTE)

This demonstration program is sponsored by the European Union and will involve 30 DaimlerChrysler hydrogen fuel cell buses operating in ten European cities between 2001 and 2006. Also included are the design, construction and operation of the necessary hydrogen infrastructure for production and refueling. About 30 industrial companies are participating.

FUERO – Cluster Land Transport by Fuel Cell Vehicles

FUERO is a cluster of nine research projects for the development of fuel cell components and systems. The purpose is to speed-up the introduction of fuel cell vehicles by coordinating research efforts. Eight automakers are participating: Renault, Citroen, Peugeot, Volkswagen, Fiat, Opel, BMW and DaimlerChrysler. Technology objectives are:

- High-temperature PEMFC
- Improved DMFC
- Evaluation of ammonia for fuel cells
- Reforming of gasoline to hydrogen with CO2 clean-up
- Low-temperature methanol reforming
- Production of ethanol from biomass, on-board ethanol reforming and direct ethanol fuel cells.

Hydrogen and Fuel Cell Demonstration Project (Japan)

The Japan Electric Vehicle Association and the Engineering Advancement Association are involved in an extensive demonstration program with support from the Ministry of Economy, Trade and Industry (METI). The program includes road testing of fuel cell vehicles and six associated hydrogen filling stations. Companies participating in the program are: Honda, Nissan, Toyota, DaimlerChrysler, GM, Cosmo Oil, Nippon Oil, Tokyo Gas, Nippon Sanso, Air Liquide, Iwatani, Showa Shell Sekiyu, Nippon Steel and Japan Air Gases. There is also a stationary fuel cell component to this program.

5 Assessment of Hydrogen and Fuel Cell Research and Business Development in Alberta and Western Canada

5.1 Hydrogen and Fuel Cells in Alberta

Advanced Measurements (Calgary, AB)

Advanced Measurements manufactures customized test and specializes in fuel cell testing. The test system measures fuel-cell characteristics such as voltage, current, humidity, temperature and gas flows into a fuel cell. The system also controls all aspects of the test environment. Fuel cell test systems are designed to be flexible and to allow fuel cell developers to reduce their development cycle and shorten time to market.

Advanced Measurement believes that fuel cell R&D should be targeted at achieving cost reductions and performance improvements. They collaborate on projects with the University of Calgary and with the Institute for Fuel Cell Innovation.

Alberta Ingenuity Fund

Alberta Ingenuity is the trade name of the Alberta Heritage Foundation for Science and Engineering Research. The fund was established by the Government of Alberta in 2000, with an endowment of $500 million. Interest from the endowment is used to support a balanced, long-term program of science and engineering research based in Alberta. The mandate of the fund is to nurture the discovery of new knowledge and encourage applications that benefit Albertans. It provides support for world-class research that will advance science and engineering.

Albert Ingenuity views climate change as an issue of relevance to Alberta. In 2002, the funded sponsored a conference on climate change. Scientist and experts explored the scientific basis for concern about climate change and examined ways to address the situation. Hydrogen and fuel cell technology areas have the potential to make a significant contribution to reducing the impact of human activities on climate change.

Hydrogen and fuel cell research is emerging in Alberta according to Albert Ingenuity. Research groups are active at the University of Alberta in the Faculty of Engineering and at the University of Calgary in the Faculty of Science. The industrial sector in Alberta includes companies such as Global Thermoelectric and Dynetek.

Hydrogen and fuel cell technologies have the potential to address key needs of the energy sector in Alberta. It is not clear to Alberta ingenuity what should be the Alberta niches in the area of hydrogen and fuel cell. Alberta is not yet a research leader in this area.

A potential focus area appears to be solid oxide fuel cells (SOFC). Alberta Ingenuity has encouraged Alberta research groups to build up their reputation and to demonstrate collaboration with other research groups worldwide. Options include attracting to Alberta researchers with a global reputation in the area of hydrogen and fuel cells. To be successful in obtaining AIF funding, emerging research groups in Alberta need to show awareness and collaboration with other groups internationally.

SOFC would probably be a good niche for Alberta, particularly when using hydrocarbon fuels. In the area of hydrogen, there are clear links between hydrogen research and the Alberta energy sector. Hydrogen is used for upgrading bitumen into synthetic crude oil. Increased R&D into production of hydrogen from non conventional sources such as bitumen would be a good fit with the Alberta situation. However Albert Ingenuity believes that this must be done with a focus on building up the international reputation of Alberta research group and increasing collaboration with other centers of expertise worldwide.

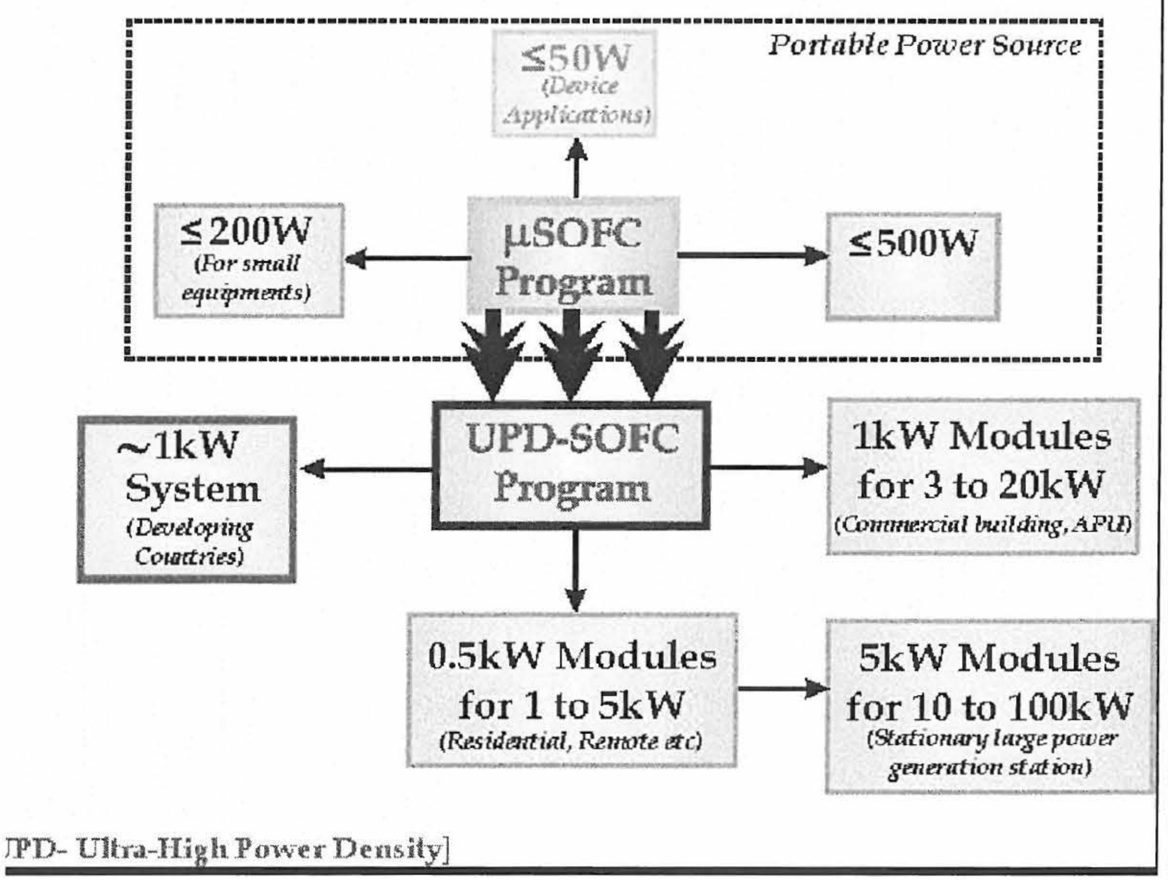
Alberta Research Council (Calgary and Edmonton, AB)

The Alberta Research Council (ARC) is developing a High Surface Area Micro Solid Oxide Tubular Fuel Cell (μSOFC). The key goal of ARC's Solid Oxide Fuel Cell (SOFC) program is to develop high volumetric powder density and quick start-up/cool-down capability fuel cell. The core technology is based on small diameter (micrometer to mm diameter size) tubular design fuel cells. This approach increases the volumetric power density by increasing the surface area of the electrolyte. This design also provides the capability of quick heat-up and cool-down by increasing thermal shock resistance of the fuel cell.

One of the key expertise's necessary to manufacturing SOFC stack is ceramic and ARC has one of the world recognized ceramic group. Building on its expertise in ceramics engineering, ARC has produced very fine ceramic tubes using a proprietary electrophoretic deposition process. Electrophoresis is the motion of charged particles in a suspension under the influence of an electric field. Deposition is the coagulation of particles to a dense mass. Electrophoretic deposition permits the fabrication of small structures with multiple thin ceramic layers. Applied to SOFC, this process allows the production of membrane electrode assemblies with a thin electrolyte layer, as low as less than10 microns. The key technology is the manufacturing of such tubes with very thin layers without pinholes. The process has been applied to micro-filtration applications and it offers substantial opportunities for fuel cells.

ARC's base SOFC technology is easily adoptable for portable applications (Watt-power range) to large hybrid system (MW-power range). Fuel cells for small portable applications are called micro-SOFC (μSOFC) and large ones (>kW) are called Ultra-High Power Density Stack (UPD) by ARC. ARC's development strategy for its core SOFC technology is described on Figure 6.

Figure 6 - SOFC Development at ARC



Source: Alberta Research Council

For portable application, this technology is called μSOFC. For stationary application μSOFC is deployed in power modules from 1 kW to, eventually, the MW range. Bundles of μSOFC units form ultra-high density tubular SOFC (UHD-SOFC) modules that can be stacked to meet the needs of the application. UHD-SOFC has a number of advantages over conventional SOFC:

- ✓ small foot print
- ✓ high thermal shock resistance
- ✓ fast start-up
- ✓ potential cost savings in manufacturing.

Research and development in μSOFC is a necessary step to UPD-SOFC. In order to reach the kW and MW range, ARC needs to develop 10 W and 100 W modules that can be fabricated economically. ARC's long term objective is to develop UPD-SOFC in the kW and MW ranges.

ARC is focused on developing a cost effective manufacturing process for SOFC. This involves the development, the design and the manufacturing process for small diameter tubular SOFC. Technology has been developed for single cell fabrication, current collection, stack design and other components. The ARC research team employs a multi disciplinary modeling and simulation procedure to design virtual prototype schemes in order to speed-up development time. The aspects that have been explored include the following:

- o Physical models for electrode potential loss and current collector design by equivalent circuit
- o Fluid dynamic models considering that consider gas delivery flow design
- o Thermal management models considering heat balance on both single cell and stack
- o Solid structure model considering the reliability of the ceramic material in the elevated temperature environment
- o Thermodynamic model considering both the fuel cell reaction and its influence on both single cell and stack design

Modeling allows evaluating the system effects that geometry, temperature and the parameters of each individual component have on each other. Computer modeling assists the development of physical prototypes that, in turn, are used to validate the computer model.

The operating temperature of ARC's μSOFC/UHPDS is 800 °C or below. Individual tubular cells exhibit high thermal shock resistance because the layers are very thin. The high temperature nature of the mSOFC creates challenges for the development of portable fuel cell applications. Another challenge is the assembly of the considerable amount of individual cells that are required to fabricate stacks in the kW range.

ARC is allocating the following resources to SOFC Program development:

- Lab space - about 300 square meters
- Researchers - 5 professionals, 1.5 techs, 1 summer student
- 8 patent applications, one on base technology allowed
- Publications – in general ARC does not favor publishing its results, but they have about 6 conference symposium papers concerning fuel cells.

ARC's electrophoretic deposition based Hollow Ceramic Membrane technology can be extended into the membrane reactor area such as portable compact devices able to reform and separate hydrogen in same reactor, ceramic mixed conductor based syngas reactors, and high temperature fuel reformers and processors that convert hydrocarbons to hydrogen for use in fuel cells.

SOFC Researchers at ARC:

- Partho Sarkar, Group Leader, Alternate Energy Program, Advanced Materials
- Hongsang Rho, Advanced Materials
- Gary Kovacik, Sensor Engineering
- Luis Yamarte, Advanced Materials
- Rong Zheng, Advanced Materials
- Chris Astle, Carbon and Energy Management
- Allan Chamber, Carbon and Energy Management

Dynetek Industries (Calgary AB)

Dynetek Industries designs, produces and markets light and advanced fuel storage and refueling systems for compressed hydrogen, zero emission fuel cell vehicles and for compressed natural gas, low emission vehicles. Dynetek has established strategic relationships with major manufacturers around the globe. Dynetek has extensive knowledge in composite cylinder and systems design. Dynetek also serves the industrial gas and energy sectors in the bulk transport and storage of compressed gases.

Dynetek has provided safe and certified hydrogen storage for automotive, transit buses and stationary storage applications. The available pressures range from 3,000 psi (200 bar) to 5,000 psi (350 bar). Dynetek has also recently developed a 12,500 psi (825 bar) cylinder for stationary storage that is designed to be used with a 10,000 psi (700 bar) on-board automotive system.

The DyneCell composite cylinder is built from a seamless thin wall of aluminum with a carbon fiber overwrap. The technology permits light weight high pressure containers for compressed gases such as hydrogen and natural gas. The overwrap is corrosion resistant and non permeable. It is designed for harsh automotive environments and achieves two to four fold weight reduction over conventional designs.

Energy Visions Inc. (Calgary, AB)

EVI was formed to develop proprietary innovative technologies for use in the manufacturing of the portable power systems such as batteries and fuel cells. The initial step was the acquisition of two rechargeable battery systems and the licensing of a third battery technology. In 2003, EVI acquired a company that indirectly owns a manufacturing facility in Amherst, Nova Scotia with the capability of making more than 100,000,000 batteries annually. The plant currently manufactures rechargeable alkaline manganese-zinc batteries. EVI's proprietary nickel zinc batteries can be manufactured on the existing equipment after some modifications.

EVI has expertise and proprietary technology in the areas of Direct Methanol Fuel Cells (DMFC) and believes its future will be as a worldwide leader in the fuel cell industry. EVI is a portable power technology integrator, currently developing hybrid DMFC/battery portable applications. EVI conducts research, development and commercialization of technologies both with its in-house expertise and through technical and commercial alliances with international organizations. Laboratories are located on the campus of the National Research Council of Canada in Ottawa and at the Alberta Research Council in Calgary.

EVI has a strong IP position in flowing electrolyte DMFC technology. The development program is past proof of concept and into the development of engineering prototypes. Recently, improvements have been made in electrode structure, catalysts and cell design leading to increased power densities. The company has been able to double single cell electrolyte chamber performance over previous designs while simultaneously achieving a simpler, more compact, lower cost design. These achievements move EVI's DMFC substantially closer to commercialization.

Target markets include small vehicles such as fork lift trucks and other transportable applications. EVI's designs could include combining DMFC with nickel-zinc rechargeable batteries creating a hybrid fuel cell/battery power source technology. The fuel cell provides a long-lasting source of base power while the rechargeable battery is used for peak power. EVI could the only company developing both rechargeable batteries and fuel cells. Methanol is likely to become the fuel of choice for fuel cells because of the difficulties associated with hydrogen transportation and storage.

Global Thermoelectric (Calgary, AB)

Global Thermoelectric is a leading developer of natural gas and propane compatible solid oxide fuel cell (SOFC) technology for residential and light commercial applications and is also the world's largest manufacturer and distributor of thermoelectric stationary power generators for use in remote locations. Global's core competency is the development of SOFC membrane and stack technology. The company is currently prototyping systems for residential and remote applications [39].

Global's intellectual patent portfolio includes the filing of 77 U.S. and international patent applications (36 cell, 26 stack and 15 system) describing 27 distinct inventions. Fuel cell research, engineering and product development costs are about $ 18 million per year. There are about 140 employees directly involved in fuel cell development.

Global is collaborating on research projects with the University of Calgary and has provided a letter of support for the Western Canada Fuel Cell Initiative. The strengthening of a SOFC R&D and commercialization cluster in Alberta would be beneficial. However, because Global is reluctant to share IP, joint product development is difficult to implement with any outside institution such as universities and government laboratories. Publicly funded research is best deployed on solving fundamental issues in areas of industrial importance. For Global, this would mean that fundamental R&D on SOFC by universities, ARC and NRC would be beneficial.

Global has begun testing RP2 system prototypes in its facility in conjunction with Enbridge. The RP2 incorporates a number of improvements including a modular approach to component design and layout, and enhanced serviceability particularly around the fuel cell stacks. Recent testing of four new 20-cell stacks in an RP2 natural gas system yielded peak power output of 3.1 kW and demonstrated a 43% improvement in stack power density (power output measured as a function of surface area). Current development programs are focused on improving performance attributes such as durability and cost. Prototypes are produced and tested. Failure analysis is used to learn and develop improved prototypes. The manufacturing pilot plant is used to develop manufacturing low-cost production methods.

In order to conserve cash, Global is not undertaking a large-scale prototype program until technology advancements are made in terms of performance, reliability and cost reductions commensurate with those required for a commercial product. Global is anticipating a product launch of its initial commercial applications in the second half of 2005. Global's next generation natural gas fuel cell prototype, named Aurora should start prototype trials in 2003. The Aurora embodies improvements in performance, cost reduction and provides a stable and flexible platform, permitting 2 kW to 5 kW systems.

Over the last year, Global has developed partnerships with distribution partners including Citizens Gas, Suburban Propane, Superior Propane, Bonneville Power Authority, and Montana-Dakota Utilities. Partners will form the basis for the SOFC system co-development, demonstration, and commercialization activities to be jointly funded.

Recent Developments

In April 2003, Quantum Fuel Systems Technologies Worldwide proposed a stock swap offer to take control of Global Thermoelectric. Quantum, an Irvine, Calif.-based supplier of components and fuel systems to General Motors and other automakers, intended to merge head office functions while leaving research and product development in Calgary.

Enbridge, a product development and distribution partner of Global had opposed the offer from Quantum on the basis it jeopardized its $25-million investment in Global. However, Enbridge reached an agreement with Quantum and Global.

In August 2003, the board of Global Thermoelectric said it accepted a rival takeover offer from FuelCell Energy and terminated the bid from Quantum. FuelCell Energy is a leading U.S. developer of MCFC and is involved a major U.S. DOE project for coal gasification and using the coal gas as feedstock for a MCFC. FuelCell Energy is described in the MCFC section of this report.

FuelCell Energy and Global Thermoelectric are both developing high-temperature fuel cells and face many of the same challenges developing their power units. They complement one another in that regard. They also offer complementary products and the merger could be a good strategic fit. The proposed merger will allow Global SOFC products to compete in the Solid-State Energy Conversion Project (SECA), a $139-million US, 10-year initiative partly funded by the U.S. Department of Energy. FuelCell Energy intends to complete Global's SOFC development and to continue the relationship with Enbridge, possibly as a distributor because FuelCell Energy does not have any strategic alliances in Canada.

Northern Alberta Institute of Technology

The Northern Alberta Institute of Technology (NAIT) in Edmonton is one of Canada's largest institutes of technology. It has approximately 17,000 full-time and apprenticeship students, and about 42,500 continuing education registrations. About 2,400 people work at NAIT's four campuses. NAIT confers certificates, diplomas, and applied degrees. The Institute offers over 190 programs including 32 apprenticeship offerings. Over 1,200 continuing education courses are also available.

NAIT is heading a recently announced $3.3-million public/private partnership to study the use of high-voltage fuel cell technologies. The partnership is composed of AERI, Western Economic Diversification Canada (WEDC), ATCO Gas and Climate Change Central.

NAIT will install a 200-kilowatt PAFC from UTC Fuel Cells. This fuel cell installation will be Canada's first high voltage, fully operational fuel cell. In addition to electricity, the PAFC will produce useable heat energy in the form of hot water. The NAIT PAFC will produce 50% hot water and 50% warm water. The combined heat and power feature of the PAFC will result in 50% fewer greenhouse gas emissions and 99 per cent less pollutants.

NAIT's applied research project team will investigate ways to use the clean energy produced by the 200 kW phosphoric acid fuel cell, such as heating the swimming pool in winter and cooling buildings in summer. The team will also collaborate with other western Canadian research institutions to continue work on improving environmentally friendly fuel cell technologies through research partnerships.

The project team will also look for innovative uses for fuel cells and focus on public awareness and education about the benefits of fuel cell technology from a consumer's point of view. An interactive interpretive centre-incorporating the 200kW fuel-cell will open at NAIT in early 2004 making information about the technology more accessible to the public and explaining the environmental benefits of fuel cells.

The project will also place NAIT's Power Engineering program at the forefront of international fuel-cell education, creating a growing trained workforce capable of applying the emerging technology worldwide. NAIT technology graduates will be able to enter the workforce with a working knowledge of fuel cell technology. Alberta will be well positioned to commercially adopt the new technology and provide a well-trained workforce for the global fuel cell market.

This project is the first of a number of projects in the fuel-cell area. The second project is the installation of a 5 kW SOFC in the Power Engineering Laboratory. A potential third project would be the installation of a PEMFC in the same Laboratory. The purpose is to expose students to the leading fuel-cell technologies in order to give them a broad background and for understanding of the strengths and weaknesses of each technology.

NAIT also plans to experiment with different fuels for the SOFC.

Demonstration projects such as the fuel-cell project at NAIT are an excellent vehicle for the promotion of energy efficient technologies such as hydrogen and fuel-cells. Another example for a demonstration project would be the installation of a fuel-cell at community centers in Alberta. It would allow the community center to stand on its own in the event of a power blackout. The community center would become a shelter and emergency center available to the community. This would particularly be valuable if a blackout were to occur in very cold weather.

Snow Leopard (Calgary, AB)

In 2002, Snow Leopard had signed a Letter of Intent with the U.S. company Eltron Research for the acquisition of world-wide licensing rights catalytic membrane reactor and hydrogen sulphide solid oxide fuel cell (SOFC) technology. The purpose was to demonstrate and commercialize a fuel cell system utilizing hydrogen sulfide. In May 2003, Snow Leopard announced that efforts to reach a definitive agreement with Eltron Research, with respect to licensing hydrogen sulfide fuel cell technology developed by Eltron, had been terminated. Snow Leopard has been unable to meet the financial terms of the Letter of Intent.

At this time, no source of funding has been identified to sustain operations beyond June 30, 2003. To conserve its financial resources, the company has given notice to all staff that their services will no longer be required effective June 19, 2003.

Sustainable Energy Technologies (Calgary, AB)

Sustainable Energy develops products that enable a renewable energy resource to become an integral part of the electrical power system. The company has developed electrical device technology that converts the raw electricity from renewable energy devices into usable electricity for specific applications. In particular, the company has inverter technology to convert direct current (DC) into alternating current (AC).

A key product is an inverter that converts DC electricity from a solar array or a fuel cell to grid-quality AC power. This inverter technology is highly efficient and allows maximum capture and transfer of renewable energy production to electric distributed generation. This technology will also enable the economic integration of renewable energy with remote diesel power generation.

Renewable energy inverters convert the DC output of a renewable energy resource such as a photovoltaic module or a fuel cell into an acceptable ac power source for and/or utility. Sustainable Energy's Pulsed Step Inverter is intended to be a production volume, commercial product that interfaces residential and small c scale DC distributed resources to the grid. As an interface, the inverter must accommodate the different characteristics of the electrical circuits on both sides.

When supplying power to the grid, the inverter must behave as a variable DC source supplying a high quality AC current onto the grid. When back feed is required for the startup of a fuel cell system, the inverter should maintain a stable DC, drawing a high quality current waveform from the grid. In order to achieve high production, the same inverter hardware must be able to be configured to meet the requirements of different applications and distributed resources such as photovoltaic cells, fuel cells and small wind turbines, as well as storage technologies such as batteries and flywheels. All of these resources have characteristics that must be accommodated by the grid interactive inverter in delivering energy efficiently to the grid.

Sustainable Energy has also developed a wind turbine technology that will enables integration of wind energy where it is most needed yet most difficult to access. The vertical axis wind turbine is specifically designed for the integration of wind power with remote diesel power generation.

Sustainable Energy's 250 kW vertical axis wind turbine, captures wind energy and converts it into electricity. It is a uniquely Canadian solution to reducing the consumption of diesel fuel for power generation in remote markets, such as on small islands, in circumpolar regions and in developing countries. Sustainable Energy expects that its wind turbine technology will fill a gap in the diesel/wind market and will aid the industry in overcoming the barriers normally associated with integrating wind energy with remote diesel power generation.

University of Alberta (Edmonton, AB)

Alternative fuel cells are being developed at the University of Alberta based on resources derived from the Alberta land base. Fuel cell feeds that are abundant in Alberta include hydrogen sulfide (H_2S), hydrocarbons, and syngas produced from coal, petroleum coke and biomass. These fuel cell systems are at different stage of development at the University in partnerships with industry and government agencies.

Hydrogen Sulfide Fuel Cells

Fuel cells for the conversion of H_2S developed at the University of Alberta generate power and produce only elemental sulfur and steam as material products, with no harmful emissions. Researchers at the University of Alberta have developed anode catalysts that are not poisoned by sulfur, hydrocarbons or oxides of carbon.

Alberta extracts and produces a large quantity of H_2S from sour natural gas and as a by-product of the producing, refining and manufacturing sectors. H_2S is a major pollutant that must be removed from all fuel streams without being vented. At present, it is largely converted to elemental sulfur using the Claus process or capture techniques. The chemical energy in H_2S is mostly lost rather than converted to high-grade energy. Natural gas wells having 70-94% H_2S are rarely producing wells. They are typically shut in. Shell, in particular, has an interest in the development of sour natural gas wells. An economical on-site process for removal of H_2S, without affecting the hydrocarbons, is required to open these and other wells. Fuel cells developed at the University of Alberta can convert H_2S to sulfur efficiently. Performance of the fuel cells is unaffected by the presence of CO_2 or hydrocarbons, except for dilution effects. They have also shown that hydrocarbons in the feed are unaffected during operation under mild conditions. The University of Alberta H_2S fuel cell systems have the following attributes:

- convert H_2S efficiently
- produce elemental sulfur and steam
- power densities over 200 mW/cm^2
- no noxious emissions or greenhouse gases
- unaffected by hydrocarbons in the feed during low temperature operation
- not poisoned by CO_2 in the feed
- do not convert hydrocarbons in the feed, and so allow clean-up of sour streams
- not poisoned by components of natural gas and sour effluent streams

Fuel Cells for Syngas

An alternative approach to the combustion of heavy hydrocarbons, including coal and high-sulfur cokes, is to convert them to syngas (CO and H_2) which contains impurities such as HCN, NH_3, mercaptans and H_2S. The syngas can then be used to generate electricity in a power plant. To improve efficiency, the gas mixture can be used to generate power in fuel cells. Conventional fuel cells require that the concentration of sulfur and other impurities in the feed be less than 1 ppm. Cleaning "dirty" syngas to this low level may not be cost effective. There is therefore an economic incentive to develop fuel cells that can operate with a dirty syngas and coal gas.

Fuel cell systems developed at the University of Alberta could be adapted for conversion of dirty syngas derived from coal and coke, without the need for expensive removal of impurities such as H_2S, HCN, NH_3 and mercaptans. Further research is required to demonstrate the performance of these fuel cells with all the components present in dirty syngas.

Co-Production of Power and Chemicals

Fuel cells are also being developed at the University of Alberta for the co-production of power and chemicals. Conversion of hydrocarbons to value-added products such as from ethane to ethylene and from propane to propylene often uses processes that either vent energy as heat or are not highly selective, and these processes cause release of environmentally deleterious effluents. Separation processes are expensive and they generate polluting emissions including greenhouse gases. Fuel cells can be adapted into new processes for selective production of value-added products, with recovery of high-grade energy without releasing pollutants.

Hydrocarbon feedstocks are converted to value-added products in fuel cells with higher selectivity than thermal processes Fuel cell processes generate less waste and lower emissions. Alkanes are converted selectively to the corresponding alkenes, such as ethane to ethylene and propane to propylene. Researchers at the University of Alberta have successfully demonstrated conversion of propane to propylene with high selectivity, and have generated over 100 mW/cm^2. They have also shown that power can be generated by dehydrogenation of butane. Further research is required to develop these systems.

Existing processes for production of propylene oxide each have drawbacks and are costly to perform. The chlorohydrin or styrene monomer routes are capital intensive. The recently announced hydrogen peroxide technology (BASF, Dow) has lower capital costs but uses expensive hydrogen peroxide. The University of Alberta is proposing a

SOFC fuel cell system with a designed anode catalyst systems based on experience in catalytic oxygenation of propylene to propylene oxide. Feasibility studies will be conducted at the University of Alberta into the manufacture of propylene oxide from propylene.

Fuel Cell Program

The fuel cell program at the University of Alberta is targeted at the more efficient, more selective and more environmentally friendly utilization of Alberta's natural resources. New fuel cell materials are being developed, including electrode catalysts and electrolytes, to address needs for alternative fuel cells. Seven patent applications have been filed in North America and internationally to protect the processes, fuel cell design, and new catalysts for activating the fuels. The research results were the object of 20 papers. One process was developed further in pilot studies by a Calgary company and their US partner. Other processes are being developed at the laboratory scale in collaboration with Alberta and international partners.

Researchers at the University of Alberta have also started preliminary development of a new formulation for an electrolyte that may have utility in a conventional methanol fuel cell. Further work is required, especially long term testing to confirm that there is no cross over of methanol to the cathode compartment.

The University of Calgary and the Alberta Research Council are also developing fuel cell research programs based on different combinations of talents, opportunities and systems. There is a strong potential for cross-fertilization of ideas and synergies between these three institutions based on the excellent relationships among the research teams.

Research to date has been conducted using simple laboratory cells and instrumentation. Current space allocated to fuel cell research is:

- current laboratories - 320 sq meters
- current office - 115 sq meters (not including faculty offices)
- additional laboratories (2005) - 180 sq meters
- by end of calendar 2005 the University of Alberta could have nearly 700 sq meters committed to non-hydrogen fuel cell research.

Research personnel currently stand as follows:

- Faculty members - 10

- Graduate students - 22
- Post doctoral fellows / researchers - 9
- Undergraduates - 7
- Technicians - 2

There are no facilities available at The University of Alberta for parallel testing of multiple cells to obtain engineering data for design and modeling of pilot industrial units. In addition, resources are required for detailed studies of pertinent materials, surfaces and interfaces. The University does not have capacity for automated testing of systems for prolonged periods (several weeks to months on line) with full monitoring of operating parameters and performance. The following new resources are needed for pursuing the proposed program:

- Separate advanced fuel cell testing stations for the fuel cell research using different fuels: H_2S, ethane, and light hydrocarbons.
- Recruitment of additional research staff and graduate students.
- Full capability to prepare designed nano-scale materials in a highly controlled manner.
- Strong analytical capability to determine the chemical and physical structures of materials.
- The ability to examine interfaces and surfaces in detail. The structures of materials have importance for mass transfer of feeds and products. Consequently, the internal structures of materials must be fully characterized as well as suitably designed.

University of Alberta Researchers

Steve Bergens	Chemistry (Methanol and ethanol based fuel cells)
Mike Brett	Electrical and Computer Engineering
Karl Chuang	Chemical and Materials Engineering (Alternative fuel cells)
Tom Etsell	Chemical and Materials Engineering.
Murray Gray	Conversion of Hydrocarbon to Hydrogen
Bob Hayes	Chemical and Materials Engineering
Biao Huang	Fuel Cell research
Doug Ivy	Fuel Cell research

Jingli Luo	Chemical and Materials Engineering (Alternative fuel cells)
Scott Meadows	Chemical and Materials Engineering (Modeling of fuel cells)
K Nandakumar	Chemical and Materials Engineering
Alan Nelson	Chemical and Materials Engineering.

University of Calgary (Calgary, AB)

Hydrogen and fuel cell research is conducted at the University of Calgary by 11 researchers and 37 students and technicians from the Departments of Chemistry, Chemical and Petroleum Engineering, and Mechanical and Manufacturing Engineering. The following researchers are involved in fuel cell and hydrogen research:

- **R. Paul, V. Birss (Chemistry):** leading a research group of 3 research associates, 10 graduate students and 5 undergraduate students. This research group has authored about 15 publications, and filed one patent last year. The focus of the work is both SOFC and DMFC, as well as on understanding ion transport through fuel cell separators for PEMFC and DMFC. The research group has discovered new catalysts and new methods of making nanoparticulate materials for both anodes and cathodes for both SOFC and DMFC that result in much better performance and significantly lower cost (patent filed). They have also developed methods which can reverse poisoning of SOFC anodes by sulfur, during cell operation, in collaboration with NRC and Global Thermoelectric.
- **J. Hill, R. Kydd (Chemical and Petroleum Engineering; Chemistry):** heading a research group composed of one post doctoral fellow, 4 students and one technician. This group is active in both DMFC and SOFC and has authored many conference presentations and papers.
- **G. Shimizu and G. Liu (Chemistry):** making novel higher temperature proton conducting separators and novel catalyst structures for DMFC.
- **D. Xue (Mechanical and Manufacturing Engineering):** working on fuel cell systems modeling and associated publications
- **T. Khan**: working on interconnects for SOFC.
- **T. Ziegler (Chemistry)**: leading a group of about 15 people and working on fundamentals of interactions of fuels on catalyst surfaces. This is world

class fundamental work that is very relevant to fuel cells that is published in journals other than fuel cell journals.

- **David Cramb (Chemistry):** working on membranes.
- **Bill Shaw (Mechanical and Manufacturing Engineering):** working on hydrogen embrittlement and combinations of metals and ceramics.

In addition, the Department of Chemical and Petroleum Engineering has plans to revive a past Chair in Hydrogen Research. The Department has world class small and large scale equipment to conduct the high temperature and high pressure laboratory work required for research into production of hydrogen using low value feedstocks such as asphaltenes, petroleum coke and coal. In addition, **G. Moore** is working in the area of in-situ combustion and programs could be extended to maximize in-situ production of hydrogen from pressure depleted or otherwise non-functioning reservoirs.

At the University of Calgary fuel cell efforts are focused on overcoming fuel cell degradation and on increasing power output for electricity generation. The emphasis at the University is somewhat more on the science than on engineering. University of Calgary researchers collaborate with industrial partners such as Ballard and Global Thermoelectric, with the University performing scientific research and associated companied performing related engineering work. Companies involved in fuel cell development are realizing that fundamental research is needed to solve the remaining problems of cost, longevity, and performance. The breakthroughs needed by the industry will come from fundamental discoveries in the area of material sciences, including nano-structures materials. Most of the fuel cell work at the University of Calgary is on SOFC which could be considered the Alberta niche. However, work is also conducted on direct alcohol fuel cells and on understanding fundamental issues that have broad implications for any type of fuel cell. Pure hydrogen is not an area of focus. However impure or "dirty" hydrogen is a key research objective, as well as the utilization of reformate, syngas and coal gas.

Researchers at the University of Calgary were instrumental in the development of the Western Canada Fuel Cell Initiative (WCFCI), a valuable mechanism for coordinating infrastructure and information sharing between research projects at universities in Western Canada. One outcome of the WCFCI has been a joint application for a $ 5 million grant from the Canada Foundation for Innovation that would support strengthening fuel cell laboratory infrastructure at the University of Calgary and at the University of Alberta. Should the grant application be successful, universities in Western Canada will benefit from world class laboratories for fuel cell research. The next funding need will be for research programs aligned with WCFCI objectives and to pay students and support staff.

The University of Calgary is actively establishing the National Institute for Sustainable Energy, Environment and Economy (NISEEE) – a major multidisciplinary, multi-partner, multi-sectorial initiative. This undertaking is aimed at establishing a hub of activities on the international scene that will attract high-caliber talent to the University. It is anticipated that NISEEE will provide technology innovations for industry, policy solutions for government, and economic and risk management answers for the public. It will create opportunities for intellectual property and commercialization and will build a cluster of companies around the Energy, Environment and Economy theme. NISEE will conduct research into three core domains:

- Bio-energy and biomass
- Alternative energy, including fuel cells and hydrogen
- Climate change policy and energy systems.

The WCFCI could become a building block for the alternative energy component of NISEEE.

Westaim Ambeon (Fort Saskatchewan, AB)

Westaim Ambeon is a leader in composite material technologies for advanced power generation and electronic applications. A new catalyst materials group within the division is aiming to apply its capabilities in composite materials to assist the fuel cell industry in achieving the required material breakthroughs for components such as fuel reformers, membrane electrode assemblies and SOFC anodes.

Western Canada Fuel Cell Initiative

Universities in Western Canada have come together to form the Western Canada Fuel Cell Initiative (WCFCI). This Initiative has been a valuable mechanism for coordinating infrastructure and information sharing between research projects at the various Universities. The WCFCI reflects a consensus perspective on the science and engineering research in fuel cells in western Canada. The following institutions are represented:

- University of Manitoba
- University of Saskatchewan
- University of Alberta
- University of Calgary
- Alberta Research Council
- Northern Alberta Institute of Technology
- Alberta Energy Research Institute.

The WCFCI recognizes the importance of exploring possible relationships with federal programs including the NRC Institute for Fuel Cell Innovation in Vancouver, the NRCan laboratories around Devon and the NRC Institute for Chemical Process and Environmental Technology (ICPET) in Ottawa.

The scope of the WCFCI includes the science and engineering research domains required to develop operating fuel cell systems, as follows:

- Fuel Studies:
  - Hydrogen
  - Biogas/Syngas/Carbon
  - Hydrogen Sulfide
  - Methanol/Ethanol
- Electrocatalyst Studies:
  - Nanoscience, Thin Film and Synchrotron Observation Techniques
  - Solid Oxide Systems
  - Degradation and Poisoning
- Fuel Cell Modeling Studies
  - Molecular Modeling
  - Micro-Modeling
  - Macro-Modeling
- Integrated Energy System Studies
  - Design, Manufacturing and Optimization

    - Life Cycle Studies
    - Integrated Systems
- Membranes, Corrosion and Characterization Studies
    - Membranes
    - Corrosion
    - Characterization

While the list of identified research domains is broad, the WCFCI aligns research projects according to two major research thrusts:

1. **Integrated energy systems:** The WCFCI focuses on the applications of fuel cells for power generation. The clear bold objective identified is to develop an integrated energy system where alternative fuels such as coal, coke and biomass could be used as the primary energy source for fuel cell systems that would provide electric power. Such a target matches stated needs for Alberta, Saskatchewan and Manitoba and is closely aligned with the Alberta Energy Research Institute strategy. Such an objective builds strongly on the existing competencies at the University of Calgary, the University of Alberta, the University of Saskatchewan and the University of Manitoba. It could also involve key competencies within the Alberta Research Council, the Saskatchewan Research Council and Manitoba Hydro. Links to community colleges with the three provinces, such as the Northern Alberta Institute of Technology, the Southern Alberta Institute of Technology and the Red River College (Manitoba), would allow the key technical training requirements to be focused on real system requirements rather than more general hypothetical possibilities. A core aspect of the research program for the objective would involve the preparation of the fuel systems. A number of options exist, ranging from the traditional water gas shift process, the partial oxidation of coal and biogas gasification to the more exotic but efficient processes such as supercritical oxidation or partial oxidation. These processes would be studied as options for transformation of the primary energy source. It is recognized that this objective will require the involvement of a broad interdisciplinary effort,

including management and economics expertise, and will need to be coupled to interests expressed by both the utilities sector and the fuel cell manufacturing industry. Such an objective would also provide a strong basis for international collaboration, in particular with the United States Clean Coal program. Also, many developing nations are in need of power systems based upon biomass that utilize their agricultural and forest wastes.

2. **Enhanced science base for fuel cells**: The development of a much stronger scientific base than currently exists is required to meet bold objectives and to fully exploit the potential for fuel cells, including their relationship to the hydrogen economy. This enhanced science base for fuel cells would involve work on nano-structured electrodes and membranes, work on developing materials with more robust potential for dealing with degradation phenomena caused by corrosion and impurities, and would bring together modeling expertise at the molecular, micro-, and macro-levels dealing with a spectrum of fuel systems from hydrogen, methanol/ethanol right through to the syngas and biogas aspects that are part of the objective. Specifically, it will be important to include studies on ethanol systems in general to recognize the value of ethanol production from agricultural product streams.

Longer term, the WCFCI could be a building block for the fuel cell component of the proposed National Institute for Sustainable Energy, Environment and Economy (NISEEE) which would be a Centre of Excellence located at the University of Calgary.

Western Economic Diversification Canada

Western Economic Diversification Canada (WEDC) is a department of the Government of Canada. Its purpose is to stimulate the development and diversification of Western Canada's economy and to advance the interests of the West in national economic policy.

WEDC is supporting programs and activities that advance innovation, encourage entrepreneurship and build sustainable communities. WEDC promotes the commercialization of technology; leverages new funding; brings together companies and other partners to work jointly on projects; and supports the development of clusters in key sectors of the Western economy.

The innovation group at Western Economic Diversification Canada has identified 10 priority areas. Fuel cells are a priority area as well as greenhouse gases. The Vancouver office of WEDC is the lead office regarding fuel cells. WEDC is also heavily involved with Fuel Cells Canada (FCC) and recently WEDC extended additional funding to FCC. WEDC has also helped funding for one of the hydrogen safe laboratory at the Institute for Fuel Cell Innovation in Vancouver. In Manitoba, WEDC has supported a fuel-cell project involving buses powered by fuel cell engines.

In Alberta, WEDC is a partner AERI in the project to install a fully operational fuel-cell at the Northern Alberta Institute of technology (NAIT). WEDC has also funded strategy development at the University of Calgary for the Western Canada Fuel-Cell Initiative. WEDC has provided financial support for fuel-cell conferences in Alberta held in 2003 at the University of Calgary and in 2001 at the University of Alberta.

WEDC is considering participating in a potential project for a hydrogen fueling station in the Alberta Industrial Heartland with AERI. Hydrogen and fuel cells are a priority area for WEDC and projects proposed by AERI are technically strong and well justified. WEDC has worked well with AERI in the past and looks forward to continuing this fruitful relationship in the future.

5.2 Power Utilities

ATCO Gas

ATCO Gas is part of the ATCO Group of companies and is based in Alberta. The ATCO Group is one of Canada's largest corporations with a worldwide network of companies employing more than 6,000 persons engaged in utilities, power generation, logistics and energy services, and technologies and industrials.

ATCO Gas is a leader in delivering natural gas to consumers. Its core business is investing in infrastructure to deliver energy to Albertans.

ATCO Gas will invest $1.2 million to develop new research focused on determining viable commercial applications for power generated by fuel cells. Along with AERI, WEDC and NAIT, ATCO Gas is part of the consortium that is installing

Canada's first high voltage, fully operational fuel cell. A 200 kW phosphoric acid fuel (PAFC) cell and a smaller, 5kW solid oxide fuel cell (SOFC) will be installed at the Northern Alberta Institute of Technology (NAIT). Total project costs are estimated at $3.25 million.

ATCO Gas is participating in this venture to research breakthrough ways to generate clean energy and to develop innovative applications to use the electricity and heat. ATCO Gas expects that this applied research will return environmentally positive dividends because fuel cells generate 50 per cent fewer greenhouse gas emissions and 99 per cent less pollutants than conventional alternatives.

ENMAX

ENMAX Corporation is an energy distribution, supply and service company. It is wholly owned by the City of Calgary. ENMAX operates and competes in the Alberta deregulated electricity industry.

Distributed generation is a threat as well as an opportunity for electric utilities like ENMAX. The deregulation of the Alberta electricity industry has opened up the door for distributed generation and ENMAX is actively involved with this opportunity. ENMAX is active in developing the distributed generation industry in Alberta and is a founding member of NewERA, the industry association for the emerging industry. In Alberta, interconnect guidelines are available or in the final stages of approval, and this allows distributed generation to be safely connected to the grid. ENMAX has a major presence in wind energy generation in Alberta.

Residential fuel cells applications are being developed by Global and Enbridge. While residential fuel cells would reduce the amount of electricity that a residence would purchase from ENMAX, it could offer opportunities for new business models such as leasing and servicing of residential fuel cells. ENMAX is also interested in SOFC auxiliary power units (APU) for its fleet of trucks. An APU would reduce greenhouse gas emissions and air pollution from service trucks because the engine is kept running to power service equipment.

ENMAX is more active with microturbines than with fuel cells because fuel cells are still in development. Microturbines are available and ENMAX has conducted trials of a 60 kW Capstone microturbine for applications such as using landfill gas. Combined heat and power distributed generation units are sized according to the required heat load. Sites such as swimming pools, small hotels, greenhouses and northern locations should be first to market. In general, it appears that the microturbine industry has rushed its product to market and some reliability issues remain to be solved. This is particularly important point regarding residential combined heat and power fuel cells because failure in winter months would result in major inconveniences.

Stationary fuel cell development should be seen in the context of the distributed generation industry, along with other sources such as wind and microturbines.

Epcor Utilities

EPCOR was incorporated in 1995 and established as management holding company for companies formerly known as Edmonton Power, Aqualta, and Eltec. Epcor was the first strategic linking of power and water utilities in Canada. The City of Edmonton is the sole shareholder. Epcor has 3,500 employees.

Epcor does not expect the hydrogen economy to occur in the near term. It is a long term proposition. The first jurisdiction in the world that is likely to have a hydrogen economy is Iceland, and Iceland's target is 2040. In addition, the implementation of the hydrogen economy will require the installation of an expensive infrastructure.

Epcor does not consider hydrogen as an energy source, but as an energy carrier. The sources of energy remain coal, oil and alternative energy such as wind power and hydroelectricity. Epcor produces electricity from coal. Significant R&D is required for hydrogen transportation and storage in areas such as compression, liquefaction, metal hydrides, and chemical hydrides. However, AERI should carefully consider the uncertainties and the costs associated with the hydrogen economy before funding R&D in this area. Waiting for more information to develop would be a good approach according to Epcor.

Fuel cells would be useful from an environmental point of view if running on hydrogen. However, information reviewed by Epcor indicates that fuel cells are not necessarily more efficient than current IGCC technology when running on hydrocarbon fuels. Currently, fuel cells are expensive for electricity generation. For Epcor to have an interest in fuel cells, they would need to make commercial sense. Applications where fuel cell may have commercial value are remote locations and some stationary power applications. However, Epcor believes that it is still too early to determine the potential benefit of fuel cells.

NewERA

NewERA is an industry-led association of organizations dedicated to fostering the development of the micro-power distributed generation cluster in Alberta and Canada. NewERA stands for New Energy Resources Alliance. NewERA is working to promote the growth of a micro-power and distributed generation industry cluster. NewERA is accelerating a paradigm shift from centralized, unidirectional distribution to decentralized or distributed multidirectional distribution

NewERA is an industry-led alliance that can offer support to fuel cell technologies as part of a strongly linked, dynamic and prosperous national cluster located in Alberta and Canada. The cluster will provide the nation with a significant amount of affordable, reliable and clean energy. The cluster will have large and growing sales of innovative products and services including fuel cell technologies. The energy industry is ready for distributed generation. Credible forecasts illustrate that there is scope for continued fuel cell development in Alberta and throughout Canada. AERI and NewERA have many synergies – research and development in stationary power fuel cells with cogeneration capabilities is one example.

The current membership of NewERA is as follows:

- Alberta Research Council (founding sponsor)
- Climate Change Central (founding sponsor)
- ENMAX (founding sponsor)
- GE Services
- GeomatIKa Information Systems
- Green Energy Technologies
- Innovative Power Solutions
- JMK Consulting
- Macleod Institute
- Mariah Energy
- Pyecombe Consulting Services
- Southern Alberta Institute of Technology

- Snow Leopard Resources

TransAlta

TransAlta is Canada's largest non-regulated power generation and wholesale marketing company. TransAlta operates central power plants that are coal-fired, gas-fired, and based on hydro and renewable generation resources in Canada, the U.S., Mexico and Australia.

TransAlta is part of the Canadian Clean Power Coalition. Clean Coal technology involves gasification of coal into syngas which is a mixture of hydrogen and carbon monoxide. Therefore, it is possible that TransAlta may become a hydrogen producer at some time in the future. Currently TransAlta's hydrogen related activities are with the Canadian Clean Power Coalition.

TransAlta has an active alternative energy program. Wind energy is the preferred alternative followed by geothermal energy. TransAlta is not active in fuel cells at the moment because fuel cell technology is at an early stage.

5.3 Oil and Gas Industry

Alberta Industrial Heartland and Strathcona County

The Alberta Industrial Heartland promotes development in the regions surrounding northeast Edmonton, while balancing the needs of industry and the environment. The Alberta Industrial Heartland is composed of the counties of Lamont, Strathcona and Sturgeon, the City of Fort Saskatchewan and the City of Fort Saskatchewan.

This regional industrial association is an agreement to work co-operatively on the industrial development of the region. The Alberta Industrial Heartland covers more than 200 square kilometers and includes several modern world-scale facilities constructed by major industrial leaders such as Agrium, Albchem, Amoco, Chevron, CXY Chemicals, Degrussa-Huls, Dow Chemical, Oxy Vinyls, Nova, Praxair, Shell Chemical, Sherritt International and Westaim. These industries represent investments of over $11-billion. The area is known for some well-developed transportation and pipeline systems. The 22 major industrial companies in the area employ more than 4,000 people.

The Alberta Industrial Heartland believes that there is significant worldwide interest in the hydrogen economy. Trials of fuel cell vehicles are being conducted in Europe and the United States with government support. In Canada, a similar trial was announced for Vancouver.

Fuel cells are also being used for portable applications.

In Texas, Dow and General Motors plan to use fuel cells to produce electricity from off-gases containing hydrogen. Dow expects that up to 35 megawatts of electricity could eventually be produced using about 500 GM fuel cells. Jim Wright has spoken to Dow in Alberta and they intend to apply in Alberta the learnings from the Texas project. The Alberta Industrial Heartland association is interested in encouraging the use of hydrogen produced by companies in the region.

Several companies in the industrial heartland produce hydrogen as a co-product. Alberta Envirofuel produces isooctane but also has a co-product stream of 100 kg/hour of 99% pure hydrogen. This stream could be used to supply a hydrogen refueling station for a demonstration of fuel cell vehicles in Edmonton.

For other companies in the region, co-produced hydrogen is usually contained in a gas stream along with other chemical components. These co-product streams are usually used as fuel. The reasons why this hydrogen is not purified and gathered for its chemical value are:

- ✓ The co-product nature of the production implies a lack of reliability as to availability and quality. Users of hydrogen that need a reliable source such as Shell have built their own hydrogen plant using natural gas to ensure security of supply.
- ✓ The infrastructure required to purify and store hydrogen is expensive. A salt cavern would have to be built to store hydrogen. Pipelines would have to be constructed to distribute hydrogen.

Other applications for hydrogen and fuel cell technology in Alberta include hydrogen sulfide and syngas. New technology is being developed to convert hydrogen sulfide into electricity. With the large amount of hydrogen sulfide available in Alberta, this technology may have promising the economic benefits. Syngas can be produced by gasifying coal or petroleum residues. If syngas can be converted to electricity using fuel cells this would open new economic possibilities in Alberta

Automotive applications for fuel cells are not likely to find a competitive advantage in Alberta because of the absence of an automotive industry here. However, the Alberta Industrial Heartland believes that one should not discount fuel cell applications for the electronic and wireless industries in Alberta. The Province is a low cost jurisdiction for manufacturing industries and Edmonton and Calgary have diversified their industrial base in recent years. Therefore economic and technology opportunities based on manufacturing and advanced materials should be a focus for the future economic development of Alberta.

The Alberta Industrial Heartland thinks that a demonstration program for hydrogen vehicles would be a good idea in the region. A source of high purity hydrogen is available from Alberta Envirofuel. Cars or intercity buses fueled by hydrogen could be demonstrated here

The Alberta Industrial Heartland believes that government support for the development of new technology is important. Government acts as a catalyst for new opportunities. It is important that development programs be generally accessible without onerous paperwork. A program supporting the exploitation of hydrogen sources available in the industrial heartland would be a benefit

Enbridge

In Canada and the U.S., Enbridge operates the world's longest crude oil and liquids pipeline system. These pipeline systems have operated for over 50 years and now comprise approximately 15 000 kilometers of pipeline, delivering more than 2 million barrels per day of crude oil and liquids. As a distributor of energy, Enbridge owns and operates Canada's largest natural gas distribution company, Enbridge Gas Distribution, which provides gas to industrial, commercial and residential customers in Ontario, Quebec and New York State. Enbridge distributes gas to more than 1.6 million customers and is developing a gas distribution network in New Brunswick. The company employs more than 4,000 people, primarily in Canada, the U.S. and South America.

In July 2000, Enbridge and Global Thermoelectric established a strategic alliance to develop and distribute natural-gas-fueled fuel cell products suitable for the supply of electric power and heating to individual residential homes. Enbridge invested $25 million in Global preferred shares to fund further technology, design and product development work required to reach a commercial launch of the residential units. Enbridge will have exclusive distribution rights for the resulting products for all of Canada.

The purpose of the strategic alliance is to us to accelerate the commercialization of SOFC distributed power systems, especially in the residential market. The strategic alliance with Global also presents Enbridge with opportunities for growth in sales, installation and servicing revenue from exclusive distribution rights throughout Canada. The potential in Ontario alone is significant because of Enbridge's 1.5 million customers. From Enbridge's perspective, the additional gas required to supply residential fuel cells will most directly benefit its gas distribution businesses in Ontario, Quebec and New Brunswick, and affiliates in Quebec and Alberta, through increased efficiency from higher volume.

EnCana

EnCana is the largest Canadian oil and gas company. EnCana is not involved in oil upgrading. It is mostly an exploration and production company. It does have some midstream assets, but no refineries or upgraders.

EnCana considered the applicability of fuel cells to energy production but determined that the technology was not mature enough. Co-generation turbine technologies are more mature and feasible, and EnCana has program in this area. EnCana does not see hydrogen in its immediate future. The company typically focuses on technologies that are further developed. EnCana's view on hydrogen and fuel cells is that these technologies are still in the R&D stage and therefore it is too early for EnCana to participate. Technologies of interest to EnCana are those that could be used in its operations in the near future. EnCana sees the hydrogen economy has been too far in the future.

The company has approved $10 million for environmental projects. Fuel cells could be candidates for such projects, if they could be used in company operations in the near term. EnCana is part of PTAC and invests in R&D at the demonstration and commercialization phase. Technology needs to be beyond the laboratory and bench phases for EnCana to be interested in participating. EnCana is collaborating with Azure Technologies regarding the development of hybrid vehicles for specific applications.

However, EnCana would not support with its funds the development of a hydrogen fuel cell vehicle, because such project is not related to the company's business. However, fuel cell products that could be useful in remote drilling locations or in gas treatment plants would be considered.

Technology to utilize pure hydrogen sulfide in fuel cells could be of interest to EnCana. The University of Alberta is developing such technology. EnCana operates several large scale gas treatment plants. If fuel cells could be developed that could utilize acid gases and EnCana might be interested in participating in a pilot project at the feasibility testing and commercialization phase.

Nexen Inc.

Nexen is an independent global energy and chemicals. The company was originally known as Canadian Occidental Petroleum, Ltd. Nexen operates in the deep-water Gulf of Mexico, the Athabasca oil sands of Alberta, in Yemen and West Africa, through full-cycle oil and gas exploration and development. Nexen Chemicals is involved in manufacturing and marketing of sodium chlorate and chlor-alkali products (chlorine, caustic soda and muriatic acid) for industrial bleaching chemical applications.

Nexen does not have R&D projects concerning fuel cells or hydrogen but is interested in fuel cells in the long term for applications such as generating power from flare gas. In this application, fuel cells would have to compete with microturbines. It is likely that SOFC would offer better overall performance than PEMFC. Global and Ballard have done work in this area with mixed results.

The conversion of hydrogen sulfide using fuel cells is not likely to be a good market because, in Alberta, all the required Claus plants have already been built.

Regarding hydrogen, it is likely that fuel cells will use direct methanol or direct methane as the fuel because the storage of hydrogen is neither safe nor easy. On-board reforming is unwieldy for cars.

In Alberta, fuel cell fit in AERI's alternative energy strategy and should be part of the portfolio along with wind energy, microturbines and IGCC cogeneration.

NOVA Chemicals

NOVA Chemicals Corporation is a focused commodity chemical company, producing olefin petrochemicals, polyolefin resins and styrenic products at 18 locations in the United States, Canada, France, the Netherlands, and the United Kingdom.

NOVA Chemicals is at an early stage of fuel cell research in collaboration with the University of Alberta and the Alberta Energy Research Institute. One area of interest is the co-production of power and chemicals using fuel cells.

NOVA Chemicals is a major producer of hydrogen in Alberta. Hydrogen is a co-product of the production of ethylene by the steam cracking of ethane. Some of the hydrogen produced at NOVA Chemicals' Joffre site is purified using a pressure swing adsorption (PSA) unit and shipped by pipeline to neighbor Agrium. The balance of produced hydrogen is used as fuel, displacing natural gas purchases. It is not economic to ship hydrogen from Joffre to Edmonton or Fort McMurray for oil refining applications.

NOVA Chemicals would have an interest in fuel cell systems that could use hydrogen co-produced with ethylene production. The hydrogen stream is not pure and fuel cells designed to utilize this quality of hydrogen would be beneficial.

The Alberta fuel cell strategy should be based on improving the exploitation of Alberta natural resources. The development of fuel cells that can accept contaminated hydrogen, syngas or even hydrogen sulfide is a worthwhile target.

Shell Chemicals

Shell is working with fuel cell researchers in three areas:

- Shell Hydrogen is pursuing the supply of hydrogen to the emerging fuel cell and alternative energy industry for power and transportation applications. Shell Hydrogen is working with companies like Ballard and Chrysalix.
- Shell is exploring the potential of fuel cells to be used in converting hydrogen sulfide to power and elemental sulfur. In this application, fuel cell would have to compete with the mature Claus technology.
- Shell is also interested in applications of fuel cells to co—produce power and chemicals.

The current priorities for fuel cell research are to reduce costs and improve performance. More R&D is required into the fundamentals of fuel cell to enable the development of more efficient devices and systems. The direct use of hydrocarbons by fuel cells is also an attractive research area.

There are considerable R&D efforts in the United States into conventional fuel cells. Alberta is unlikely to be able to match the scale of U.S. program. However, niche areas such as novel fuels and co-production of chemicals are receiving less attention and may be an opportunity to develop expertise in Alberta.

In particular, Shell is interested in building on the existing work at the University of Alberta concerning the conversion of hydrogen sulfide with fuel cells. Shell has the strength to form industry teams for such project because of its size and because it is a potential buyer of fuel cells for energy related applications.

Suncor

Suncor has no activities in the area of fuel cells and hydrogen. The alternative energy program at Suncor is focused on wind energy. Suncor recently announced that it is planning to build a 30 MW wind energy project in Southern Alberta. The selection of wind energy is based on the fact that the technology is available commercially and that the energy comes from a renewable resource.

There might be some niche opportunities for fuel cells in Alberta, but they would need to compete with high performing microturbines and co-generation turbine technology. Alberta should not replicate projects that are being implemented in other jurisdiction, but should study them and learn from them.

The production of hydrogen from low value hydrocarbons is an area that Alberta should investigate and that could add value existing natural resources.

Syncrude

Syncrude Canada is the world's largest producer of crude oil from oil sands and the largest single source producer in Canada. Syncrude currently supplies 13 percent of Canada's petroleum requirements. Syncrude operates a large oil sand mine, a utilities plant, a bitumen extraction plant and an upgrading facility that processes bitumen and produces value-added light, sweet crude oil for domestic consumption and export.

Syncrude does not currently conduct research and development in the areas of hydrogen and fuel cells. Hydrogen is not currently on the technology development radar screen at Syncrude. Hydrogen can be produced by reforming natural gas in a manner that is technically and commercially acceptable.

Eventually, natural gas reserves in Alberta will be depleted. New production techniques for hydrogen will then be needed. Syncrude has studied the gasification of petroleum coke and of heavy bitumen that could result in the production of hydrogen. However they have found that this technology is very expensive. However this is not an immediate need and it will take at least ten years before the subject of alternative methods for hydrogen production becomes a priority at Syncrude.

TransCanada

TransCanada operates a network of about 38,000 kilometers of pipeline that transports most of Western Canada's natural gas production to markets in Canada and the United States. TransCanada also own, control or are constructing power plants that produce more than 4,500 megawatts of power.

TransCanada pipeline is not a fuel-cell company and is not involved in the development of fuel cells. TransCanada is a pipeline company concerned with the transmission of natural gas from Western Canada to Eastern Canada and the United States. Is also a power company that operates cogeneration power plants in Canada that are fueled with natural gas. TransCanada is always looking for opportunities to reduce greenhouse gas emissions. In this respect the company would be interested in fuel cells for remote areas in order to reduce environmental emissions and increase efficiency.

However, TransCanada is not interested in participating in the research and development of fuel cells. However it could be interested in the operation of commercial fuel-cell systems or in the demonstration of emerging fuel-cell systems that would be of value to TransCanada, particularly in remote operations. One specific application would cathodic protection of natural gas pipelines. The units involved would be small and less than 5 kW.

5.4 Hydrogen and Fuel Cells in British Columbia and Canada

Angstrom Power

Angstrom Power is a technology company that is developing technology for micro structured fuel cells. It is applying micro fabrication techniques using novel architecture and fabrication techniques. Applications include battery replacement and portable power.

Micro fuel cells use the same chemistry as other fuel cells. However the challenge lies in the architecture and fabrication technology for very small systems. In addition, testing and evaluation systems for micro fuel cells are different than those for larger fuel cells. Angstrom is familiar with the micro fabrication expertise at the University of Alberta and could do more work using the capabilities of the Nanotechnology Institute that is being established in Edmonton.

Alberta is seen as a source of low cost hydrogen for the hydrogen economy and for automotive fuel cell applications.

Portable fuel cell application that could be applied in Alberta includes fuel cells for small utility trucks and fuel cells for radios used in remote locations. In addition, a local hydrogen refueling station could be built using hydrogen available from the oil industry.

A key research need is metrology. There is a need for regional expertise in high resolution imagery for use in material characterization of porous media. Access to equipment is available at ICPET in Ottawa. However Ottawa is very far from Vancouver and the availability of similar equipment and expertise in Western Canada would be extremely useful. While equipment may be available in Western Canada, organizations which such equipment do not have the expertise required for characterizing fuel cell materials. In addition trust and a commitment to absolute confidentiality are paramount.

There is a need for an information clearinghouse on fuel cells. It is difficult for a small company to know who has what expertise and what equipment. The availability of such information would facilitate partnerships and joint developments.

Angstrom believes that increased funding to universities with matching funds from industry is required to enable the level of research effort that is required. Industry based consortiums are useful and can be seen as the validation of the need for research. However obtaining matching funds is always a problem.

Ballard Power Systems

Ballard Power Systems was founded in 1979 and is a leading company in developing, manufacturing and marketing zero-emission proton exchange membrane (PEMFC) fuel cells. Ballard is commercializing fuel cell engines for transportation applications and fuel cell systems for portable and stationary products. Ballard's proprietary technology is enabling automobile, bus, electrical equipment, portable power and stationary product manufacturers to develop environmentally clean products. Ballard is partnering with world-leading companies, including DaimlerChrysler, Ford, EBARA, ALSTOM and First Energy, to commercialize Ballard fuel cells. They have supplied fuel cells to Honda, Nissan, Volkswagen, Yamaha, Cinergy and Coleman Powermate, among others.

Ballard has approximately 1,300 employees as of December, 2002.

Ballard's research and development headquarters is located in Burnaby, BC. This facility is used for fuel cell and fuel cell systems development, assembly and testing, and for heavy-duty fuel cell engine activities. Ballard's initial 10,200 square meter fuel cell manufacturing facility, Plant 1, is located adjacent to Ballard's research and development facility in Burnaby. Ballard's facility in Nabern, Germany, near Stuttgart is used for fuel cell engine and fuel processing development, assembly and testing, and for PEM fuel cell module development. Ballard has additional manufacturing facilities in Lowell, Massachusetts, and Dearborn, Michigan.

Ballard's lines of products build upon its proprietary fuel cell technology and include:

- The Nexa power module, the PEMFC fuel cell module designed for integration into a wide variety of stationary and portable power generation applications.
- 250-kW stationary fuel cell power generator and one-kW co-generation fuel cell power generator designed specifically for the Japanese residential market.
- XCELLSIS fuel cell engines used in sedans, jeeps, and buses.

- AVCARB carbon fabrics and milled fibers for use in applications in the aerospace, automotive, electrical, and sports equipment industries.

Ballard develops and markets its products through strategic alliances with leading companies worldwide. The first of these alliances created a jointly owned venture known as XCELLSIS Fuel Cell Engines Inc. among Ballard, DaimlerChrysler and Ford. In 2001, Ballard acquired the interests of DaimlerChrysler and Ford in XCELLSIS and the interests of EBARA in Ballard Generation Systems. Ballard supplies fuel cells to Nissan, Honda, Volkswagen and General Motors.

In 2002, Ballard's management announced intentions to tighten its focus on its business plan and to significantly decrease cash consumption. Ballard suspended the development of its 10kW and 60kW stationary generators, two products not expected to have a near-term impact on revenues. In addition, Ballard is looking to sell or license its fuel-processing-technology operations, in part, because fuel-cell users appear to be focusing on pure hydrogen as the best energy source for the cells.

BC Hydro

BC Hydro's primary business activities are the generation and distribution of electricity. BC Hydro serves more than 1.6 million customers in British Columbia and has constructed an integrated hydroelectric system of close to 11,500 megawatts of generating capacity – over 87% of which is hydroelectric. BC Hydro operates 32 hydroelectric facilities, 2 gas-fired thermal power plants and 2 combustion turbine stations. Electricity is delivered through an interconnected system of over 72,000 kilometers of publicly owned transmission and distribution lines. Through its wholly owned power marketing subsidiary, Powerex, BC Hydro is extensively involved in energy trade outside the province.

Cellex Power

Cellex Power is a developer of a fuel cell based power products. Cellex is a technology integrator and an application developer. It is focused on developing products for powered industrial vehicles such as lift trucks for use in distribution centers. Other interests are scooters, mining vehicles and military applications. Cellex believes that these smaller markets may develop more quickly than cars and mainstream automotive applications. In these markets fuel cells compete with batteries.

Cellex believes that the cost of fuel cell needs to be reduced for fuel cells to find widespread applications. In addition the durability or life expectancy of fuel cells needs to be increased. Fuel cells need to work well over many years of service life.

According to Cellex, hydrogen is an important area for the fuel cell industry. The availability of low cost hydrogen is a key to the development of the fuel cell industry. The production of hydrogen can be done using known processes such as reforming and electrolysis. Hydrogen storage is a key issue. The density of storage and the safety of stored hydrogen need to be improved.

Methanol is an excellent fuel. It can be used directly in a fuel cell or can be reformed onboard. However for methanol to be used as a fuel, the direct methanol fuel cell will need to become more reliable and cost effective.

A critical need seen by Cellex is to develop improved methods for the storage of hydrogen. Compressed hydrogen can be stored into high pressure vessels such as those developed by Dynetek. Other approaches involved the use of metal hydride. It would be useful if NRC and Alberta could collaborate to develop improved methods for the storage of hydrogen.

Chrysalix Energy

Chrysalix Energy is an investment company in early stage new fuel cell and hydrogen economy companies. Investment targets are typically companies that have promising innovative proprietary technologies which can be effectively combined with capital and strategic partnerships to grow into significant successful businesses. Chrysalix seeks early stage companies and opportunities which are strategically positioned to capitalize on the future growth phases of the fuel cell and hydrogen economy industry.

Fuel Cells Canada

Fuel Cells Canada a non-profit organization and the national industry association for the hydrogen and fuel cell industry. Its mandate is to promote the Canadian fuel cell industry in the global market; and encourage a national strategic approach to fuel cell industry development. It is involved in facilitating demonstration projects that allow fuel cell companies to test and perfect their pre-commercial fuel cell technologies.

Fuel Cell Canada believes that Canada has a unique opportunity to build on the presence of world-leading fuel cell technology developers. Through early adoption of fuel cell technology, Canada could retain and grow the fuel cell knowledge base, set new standards for the developing industry, lead in the supply of components, sub-systems, and services and attract complementary technology and capital and expertise that result in the development of new industrial clusters.

Fuel Cell Canada contributes to the development of the hydrogen economy. Improved technology must be developed in order to provide abundant low cost hydrogen. A distribution infrastructure for hydrogen must be developed. Sources of hydrocarbons and hydrogen are not generally found near cities and issues related to transportation of hydrogen must be investigated.

Alberta is a region that is rich with hydrocarbon natural resources. Hydrocarbons can be used to produce hydrogen for the hydrogen economy. This is an important and key contribution that Alberta can make. Development in Alberta should therefore be focused on hydrogen. The oil and gas industry in Alberta should be engaged in research to convert hydrocarbons into hydrogen more effectively and at a lower cost. Transportation issues such as hydrogen embrittlement of pipelines also need to be researched. Reforming technology is used in the oil and gas sector can be applied to reforming hydrocarbons into high purity hydrogen for fuel cell applications.

Alberta should focus on hydrogen research rather than on fuel cell research. Reforming technology for converting hydrocarbons to hydrogen is required. Improved methods for purifying hydrogen are also needed. Improve methods for transporting hydrogen either by pipeline or compressed tanks are also required. Issues related to hydrogen purity and fuel cells must be explored.

General Hydrogen

General Hydrogen sees the convergence of hydrogen and electricity as the dominant modes of energy service delivery of the future. General Hydrogen calls this process: Hydricity.

General Hydrogen develops and installs hydrogen-based energy delivery systems. For the industrial market, the company is developing end-to-end systems to replace forklift batteries with fuel cell. The product is called Hydricity Packs and achieves significant increases in forklift productivity. With Hydricity Packs, forklifts will run up to three times longer than batteries — up to 24 hours of continuous use—and refuel completely in less than a minute with General Hydrogen's simple, semi-automated fuel storage and dispensing systems. This eliminates battery changing completely, saving operator time on every shift and eliminating bulky battery changing and charging facilities. Hydricity Packs swap directly for lead-acid batteries, so forklifts don't need modification. And Hydricity Refueling Systems occupy little or no floor space, so distribution centers can be easily changed over to hydrogen systems.

With this same technology, General Hydrogen also provides distributed generation solutions for back-up power and UPS, scalable to demand.

Greenlight Power Technologies

Greenlight Power is a manufacturer of test stations for fuel cell stacks, components, fuel reformers, electrolyzers and fuel cell systems. The research activities of Greenlight are focused on onboard diagnostic equipment for fuel cell applications. Greenlight provides testing equipment for several fuel cell technologies such as PEMFC, SOFC, MCFC and DMFC. Markets served are automotive, stationary and micro fuel cells.

Greenlight is actively involved in the development of the hydrogen and fuel cell industry. They are working on the joint development of core technology with NRC in Vancouver. New products are under all going testing at the pre-commercial level. Greenlight is also involved in demonstration of fuel cell vehicles where some of their products are being used.

Greenlight views the opportunity for Alberta as the production of hydrogen for fuel cell applications. Alberta is a region that has significant amount of hydrocarbons that could be converted into hydrogen.

According to Greenlight, more research is needed to understand the failure modes of fuel cell. Uncovering how fuel cells fail will enable the development of sensors that can optimize fuel cell operations and avoid their premature failure. The development of improved equipment, sensors and diagnostic tools for fuel cells is an area of high importance.

Heliocentris

Heliocentris Energy Systems provides fuel cell and hydrogen technology systems for education, outreach and demonstration. Heliocentris products include fuel cell systems, promotional items, lesson books, CD-ROMs, videos and posters and cover the range from low-cost demonstrations to fully functional stack systems.

Heliocentris is a partner of the Institute for Fuel Cell Innovation.

Methanex

Methanex is the global leader for production and distribution of methanol. Methanex has production facilities in North America, New Zealand and Chile. In addition to these manufacturing facilities, Methanex has marketing offices in the United States, Chile, New Zealand, Belgium, the United Kingdom and Korea. The extensive global marketing and distribution system of Methanex makes them the largest supplier of methanol to each of the major international markets. In 2002, Methanex sales accounted for approximately 24% of the total world market for methanol.

According to Methanex, the fuel cell industry is developing rapidly. The cost of fuel cells has come down significantly in the last fifteen years. In addition to automotive applications, new applications are being developed for fuel cells such as forklift trucks, wheel chairs, laptop computer and cell phones.

In Methanex' view, hydrogen is a very difficult to transport, store and distribute. The delivered price of hydrogen can be as much as $4.00 per kilogram. Hydrogen is produced by reforming natural gas. However, only fifteen percent of developed areas are covered by natural gas distribution. In addition, natural gas prices are increasing sharply. Methanol, on the other hand, is a better energy carrier than hydrogen for fuel cells. Methanol can be distributed in it in a safe convenient and low cost manner anywhere in the world. Methanex produces methanol from low costs stranded natural gas reserves.

Methanex is partnering with certain fuel cell developers for certain markets. Announcements have not been made yet. But products of interests to Methanex are fuel cells for forklift trucks and micro fuel cells for laptop computers.

In Methanex' experience, fuel cell developers and researchers in Alberta are not integrated with the global network. Alberta does not market its technology development efforts and its resources. Awareness is low about fuel cell developments in Alberta.

Methanex estimates that Proton exchange membrane fuel cells (PEMFC) are facing challenges. Durability is a major issue particularly beyond 2,000 hours of operating time. It is expected that a new generation of PEMFC will need to be developed to meet performance requirements. The direct methanol fuel cell (DMFC) on the other hand can reach 5,000 hours of operating time without problems. With new membranes, the DMFC could reach high power densities. Costs targets of $1,000 to $2,000 per kilowatt are within reach. A number of companies are developing direct methanol fuel cells in the smaller power categories. Applications include forklift trucks, scooters and wheelchairs. Automotive applications are at least fifteen years away. The solid oxide fuel cell (SOFC) has been plagued by constant delays. It is a good technology but it is not yet ready.

Methanex may be interested in supporting research and development in the area of direct methanol fuel cells. DMFC have momentum at the present time particularly for smaller fuel cells. Methanex may be interested in demonstration projects and early commercialization efforts. There is not a lack of potential partners for Methanex.

NRC Institute for Fuel Cell Innovation

The Institute for Fuel Cell Innovation is located in Vancouver and is part of the National Research Council. It is a research laboratory and innovation center focused on hydrogen and fuel cells. Its mission is to develop core competencies relevant to the long term strategic technology needs of Canada with particular emphasis on engagement of stakeholders and cluster development.

The Institute for Fuel Cell Innovation has a national mandate in the area of hydrogen and fuel cells. It coordinates the activities of several NRC laboratories across Canada on the subject of hydrogen and fuel cells. It conducts collaborative research with companies primarily in the Vancouver area. The vision of the Institute for Fuel Cell Innovation has two areas of focus. A high priority is to support the BC fuel cell cluster. The Institute also provides leadership across Canada for the NRC fuel cell program. The institute is the only NRC Institute that is focused on fuel cell technology. It is a good catalyst to bring together partners in order to build provincial clusters across Canada for development of the hydrogen and fuel cell industry.

IFCI's strategy is to:

- ✓ Concentrate on technologies where Canada has a competitive edge or can develop one, such as PEMFC and SOFC
- ✓ Engage and retain excellent personnel to build core competencies
- ✓ Balance mass market, next generation fuel cell R&D with niche market fuel cell testing and evaluation services
- ✓ Support product field trials and fueling infrastructure demonstrations
- ✓ Strengthen and expand cluster stakeholder relationships
- ✓ Lever IFCI's resources through R&D collaboration and consortia; regionally, nationally and internationally

The IFCI has applied expertise in PEMFC, SOFC, systems integration, testing and evaluation, modeling, micro-technology and sensing, prototyping, integration and evaluation. The IFCI has 9 hydrogen-ready laboratories, onsite gases, a hydrogen-ready environmental chamber controlled for temperature, altitude and humidity, and facilities for testing, evaluation, and demonstration. R&D is conducted on short-term projects that speed commercialization. Long-term studies are carried in areas with breakthrough potential. Testing and evaluation is performed to support of both long and short-term research. In 2002, R&D revenues were $300,000, and there were 8 co-locator companies and one spin-off company. Targets for 2006 are R&D revenues of $2,050,000, 20 co-locator companies and 3 spin-off companies.

Like the Alberta Research Council, NRC occupies the space between university research and corporate research. NRC works together with universities for idea generation and fundamental research. NRC is hiring researchers with joint appointments with SFU and UBC.A similar approaches could be undertaken with the University of Calgary and the University of Alberta. NRC also works with industry for application development and industry growth. NRC is setting up the Institute for Fuel Cell Innovation in Vancouver to accelerate the commercialization of fuel cell technology in Canada. The institute has been very active with Ballard in Vancouver but is also involved in other areas of fuel cell development. The institute coordinates all NRC fuel cell activities. For example ICPET has a $1 million program to develop electrode materials and alternate interconnect materials.

The IFCI views Alberta and British Columbia as two energy rich provinces. They should join forces to also become the alternative energy engine of Canada. The Institute for Fuel Cell Innovation could play a facilitating role to overcome some of the rivalry that exists between the University of Alberta and the University of Calgary. The Institute could be a partner and a conduit for collaboration in Alberta. The IFCI believes that organizations developing hydrogen and fuel cell technology should join forces and work together. Partnerships between industry university and government laboratories are excellent conduits for collaboration and NRC is well placed to play a facilitating role.

Abundant natural resources in Alberta could lead to the production of excess hydrogen that could be exported to fuel cell applications in other jurisdictions. Alberta should become a source for abundant and low cost hydrogen for the hydrogen economy because of the presence of vast hydrocarbon resources. Fuel cell increase energy efficiency and provide a cleaner energy source. Other areas of interest include coal gasification and fuel cell systems that utilize hydrocarbons.

The IFCI believes that Alberta should focus on hydrogen research. New reforming technology for converting hydrocarbons to hydrogen is required. Improved methods for purifying hydrogen are also needed. Improve methods for transporting hydrogen either by pipeline or compressed tanks are also required. Issues related to hydrogen purity and fuel cells must be explored. The use of nuclear energy to produce hydrogen is also a topic of interest

The Alberta fuel cell niche should be energy sector SOFC. An emerging cluster already exists in this area in Alberta. NRC has expertise in micro fuel cell technology and could provide assistance and partnership to micro fuel cell programs at the Alberta Research Council. The IFCI could work in partnership with the Alberta Research Council in providing a conduit for research to move from university laboratories to industry.

Reducing the cost of fuel cells is a critical issue. IFCI believes that fuel cells are within contact of the cost target. Mass production of fuel cells is required to reach cost targets and to lower the cost per unit. About 50 percent of the cost comes from the fuel cell stack while the balance is contributed by the other components. An approach to reduce cost is to reduce the total number of supporting components.

The micro fuel program at IFCI is based on PEMFC and will likely use methanol as the fuel. The emphasis is on long term research. Micro fuel cells are used for portable devices such as cell phones and laptop computers. The developers of micro fuel cells fall in one of three categories:

- ✓ But pure technology development companies such as an MGI. and Manhattan
- ✓ Battery companies
- ✓ Large electronic companies such as Motorola and Toshiba.

Other applications for micro fuel cells include battery chargers for utilization away from the electrical grid. Fuel cell battery chargers may be of value for search and rescue operations, forestry companies and oil and gas exploration activities.

Micro fuel cell technology is an area that is developing rapidly. R&D is needed for improved catalyst with a better dispersion and new materials. Fabrication and mass production technologies need to be developed in order to reduce the cost per kilowatt of fuel cells. New geometries for membrane electrode assemblies are being developed to facilitate sealing and assembly.

The Institute for Fuel Cell Innovation will collaborate with Alberta in the strategy that is chosen by Alberta. IFCI recognizes is that SOFC research and business development is already active in Alberta. Should the Alberta emerging cluster continue to grow the Institute will support that growth.

Palcan

Palcan is a technology company that is developing technology and applications for proton exchange membrane fuel cells (PEMFC). The flagship product of Palcan is a scooter powered by a fuel cell. Asia, particularly China and Taiwan, would be large markets for scooters powered by fuel cells. Palcan has development joint venture in Asia.

Palcan's view is that transportation and automotive applications for fuel cells are likely to use hydrogen as the fuel. A hydrogen fueling infrastructure is needed. Transportation applications of fuel cells will require a distribution network for high purity hydrogen.

An important issue for Palcan is the certification and standardization of fuel cell systems. Hydrogen storage is a key issue. Palcan is part of an ISO committee for metal hydrides portable canisters for storing hydrogen. Re-usable canisters are the storage solution that fit best with Palcan's fuel cell scooters. Exchangeable canisters based on metal hydrides offer a low pressure and safe solution for transportation of hydrogen. It is important to develop a certification and standardization procedure and too fast track approvals. Transport Canada and NRCan are working on the issue.

At the moment, Alberta would be a region that is too cold for demonstrating fuel cell vehicles. Proton exchange membrane fuel cells freeze and are damaged by freezing temperatures.

Palcan would like to see more research on metal hydride storage solutions for hydrogen. In particular, methods need to be developed on how to fill a metal hydride canister with hydrogen. Another issue is how out to get the metal alloy into the canister while maximizing the surface area. High purity hydrogen is required for fuel cells. A better understanding of contaminants and purification technology is required. In addition there is a need to understand the effects of air quality on fuel cells. According to Palcan, contaminants presents in the air such as fluorocarbons and phenols have an affect on the long term life of fuel cells. New storage solutions for hydrogen should be explored such as the use of carbon nanotubes and polymer encapsulated rare earth alloys.

With respect to fuel cell devices, Palcan sees the need for new alternative materials. There is also a need for better performing conductive materials.

The recently announced trial of six fuel cell cars in Vancouver puts Canada into the forefront. The hydrogen refueling station will be an important development. A beta test site for refueling scooters powered by fuel cells would also be a valuable demonstration according to Palcan.

Palcan believes that collaborative R&D is an effective approach. It allows small companies to benefit from research while spreading the cost over several organizations. However the intellectual property aspects must be properly addressed. University research is also valuable on fundamental science issues.

QuestAir Technologies

QuestAir develops and markets systems for hydrogen purification intended for stationary PEMFC and hydrogen fuelling of mobile PEMFC. Recent advances in pressure swing adsorption (PSA) technology developed by QuestAir allow for a significant reduction in both the size and cost of PSA systems. QuestAir has recently launched the QuestAir H-3200 hydrogen purification product for use in stationary PEM fuel cell systems, and distributed hydrogen fuelling stations. Fuel cell-quality hydrogen can be separated from all types of reformers and a variety of off-gas streams. QuestAir's patented rotary value technology allows for the smallest sized, most compact, and mechanically simple PSA systems available.

University of British Columbia

Membrane Reactor Technology is a technology development company in Vancouver. It is built around a patented fluidized bed membrane reactor for producing hydrogen from hydrocarbons such as natural gas. The technology was developed at UBC.

Research into hydrogen production is a key for the hydrogen economy. Of particular importance is the production of high purity hydrogen. MRT has developed a novel reforming reactor. They have done laboratory work with natural gas and converted it to hydrogen. They want to work with other hydrocarbon fuels such as propane, LPG and diesel. MRT is also active in the area of gasification.

MRT is working with Westaim in Alberta for the development of catalysts. The membrane reactor uses a palladium alloy a catalyst on a thin porous membrane. One part of the reactor is used for reforming while and other part is used for shift conversion.

John Grace of UBC and MRT has worked with Syncrude in the past. He has also been funded by Suncor.

Hydrogenics Corporation (Mississauga, ON)

Hydrogenics Corporation is a designer and developer of commercial PEMFC fuel cell systems for transportation, stationary and portable power applications. The company is a leader in fuel cell balance-of-plant and operating system technology and is applying this extensive knowledge and expertise to the development and manufacture of fuel cell power modules and fully integrated power generators.

Hydrogenics is a member of the General Motors' Alliance of fuel cell commercialization companies. Hydrogenics' fuel cell advanced testing systems (FCATS) products have been instrumental to GM's advanced fuel cell development. Hydrogenics continues to optimize fully integrated fuel cell systems around GM's stack.

Hydrogenics had 160 employees as of December, 2001. The Company's headquarters are located in Mississauga, ON. They also have Asia-Pacific operations in Tokyo, Japan, a facility in upstate New York, and European operations in Germany.

For the portable market, Hydrogenics has introduced the HyPORT series of portable generators, which are fully automatic. These generators are capable of operating within 0 to 40° C and are currently configured to offer 1 to 5kW of power. The HyPORT Power Generator is a portable fuel cell power generator and integrated hydrogen generation system, with a power configuration of 100W to 1kW. The generator has an advanced composite fuel cell stack and a high energy density chemical hydride hydrogen subsystem that eliminates the need for a hydrogen storage vessel. The product is particularly suited for battery recharging.

In addition, Hydrogenics has the HyPORT E auxiliary power unit, which was developed under contract by the U.S. Army for deployment and testing on army vehicle platforms. The APU is comprised of individual modules for the fuel cell system, electrolyzer and hydrogen storage. The PEM electrolyzer module will recharge the hydrogen supply while the vehicle engine is operating. This will supply the hydrogen storage subsystem with sufficient fuel to operate the fuel cell auxiliary power system for up to five hours with a load of 3kW average, and peak demand of 5kW.

In January, 2003, Hydrogenics announced that it had acquired Greenlight Power Technologies Inc. (Burnaby, BC).

Siemens

[Interview to be conducted in July]

Siemens is a global technology company operating in the following markets:

- Information and Communications
- Automation and Control

- Power
- Transportation
- Medical
- Lighting

Siemens Westinghouse, the power generation division, had net sales of 8,563 million Euro in 2002. Major products are gas turbines and electrical generators. The fuel cell group is located in Pittsburgh PA.

The Siemens Westinghouse solid oxide fuel cell is made up of an electrolyte and two electrode layers in a tubular design. This design eliminates the need for seals required by other types of fuel cells, such as planar SOFC. It also allows for thermal expansion. In a tubular SOFC design, air flows through the interior of the cell, and fuel flows on the outside of the cell. At elevated temperatures, the oxygen in the air ionizes and the resulting ions flow through the electrolyte and combine with the fuel on the cell's exterior. Electricity is generated by the reaction.

Siemens Westinghouse has the largest number of SOFC prototypes and demonstrations and is the world leader for SOFC. This is due largely to the unique tubular cell, and the simple design of the stack. The stack is cooled using process air, and during normal operation uses no external water. It also has integrated thermally and hydraulically within its structure a natural gas reformer that produces the hydrogen and carbon monoxide utilized by the cell. Also, except during start up, no external heat source is needed.

Siemens takes advantage of the fact that SOFC can also utilize carbon monoxide as well as hydrogen. This makes them more fuel flexible and also generally more efficient with available fuels, such as natural gas or propane. Hydrogen and CO can be produced from natural gas and other fuels by steam reforming, for example. Fuel cells like SOFC that can reform natural gas internally have significant advantages in efficiency and simplicity when using natural gas because they do not need an external reformer.

The benefits of the Siemens Westinghouse SOFC are presented as follows:

- Process air cooled stack, water independent
- Can operate at elevated pressures, especially for hybrid cycles
- Integrated in-stack natural gas reformer

- Elegantly simple power generation cycle
- High system reliability via simplicity
- Solid state cells (no liquid electrolyte that can migrate)
- No corrosion
- Tubular cell with closed end (no high integrity seals needed)
- Thermal cycle toughness (> 100 thermal cycles between ambient and 1000 °C)
- Stack lifetime potential: 5-10 years expected for early production systems
- Operating time demonstrated > 69,000 hours (~8 years)
- Voltage stability: Degradation < 0.1% per 1000 hours after 36,000+ hours
- Combined heat and power generation
- Combined cycle SOFC and gas turbine (exhaust gas at >800 °C)
- Cost competitive in high volume manufacture

During SOFC development, it was discovered that pressurizing a solid oxide fuel cell increases its voltage and thus improves electrical efficiency. By pressurizing a SOFC module and combining it with a gas turbine, electrical efficiency increases dramatically. This is the principle behind the pressurized SOFC/gas turbine hybrid system (SOFC/GT). In this highly integrated system, air is pressurized by the turbine's compressor and heated in a recuperator before entering the fuel cell module. The resulting exhaust is a hot pressurized gas flow that drives the turbine generator. The advantage of this combined - or hybrid - cycle is that both the fuel cell module and the gas turbine generator produce electrical power using the same fuel and airflow. The expected system configurations are:

- 46-50% electrical efficiency at 1 atmosphere pressure for SOFC combined heat and power systems (250 kW to 1 MW)
- 57-60% electrical efficiency at 3 atmospheres pressure for SOFC/GT hybrid systems (300 kW to 1 MW)
- 60-70% electrical efficiency at 7 atmosphere pressure for SOFC/GT hybrid systems (2 MW to ~20 MW)

Siemens Westinghouse leads the way in the development hybrid systems incorporating a SOFC and a gas turbine and is the only company to have developed such a system. In 2000, a 220 kW SOFC/GT hybrid system was delivered to Southern California Edison.

Siemens Westinghouse systems in demonstration trials:

- 100 kW SOFC combined heat and power, Essen, Germany: A 100 kW SOFC cogeneration system first operated in the Netherlands. The system has a peak power of about140 kW, typically feeding 109 kW into the local grid and 64 kW of hot water into the local district heating system. It is operating at an electrical efficiency of 46%. It is the first demonstration of the commercial prototype 150-cm cells in a full scale SOFC module and has shown no performance degradation.
- 220 kW SOFC/Gas Turbine Hybrid System at National Fuel Cell Research Center, Irvine CA: The world's first SOFC/gas turbine hybrid system was delivered to Southern California Edison for operation at the University of California, Irvine's National Fuel Cell Research Center. The hybrid system includes a pressurized SOFC module integrated with a microturbine/generator supplied by Ingersoll-Rand Energy Systems. The system has a total output of 220 kW, with 200 kW from the SOFC and 20 from the microturbine generator. This system is the first-ever demonstration of the SOFC/gas turbine hybrid concept. This proof of concept demonstration is expected to demonstrate an electrical efficiency of about 55%. The system is being tested at the NFCRC to determine its operating characteristics and operating parameters. Eventually, such SOFC/GT hybrids should be capable of electrical efficiencies of 60-70%.
- 25 kW SOFC System at National Fuel Cell Research Center, Irvine CA: A 25 kW field test system in California at the NFCRC at the University of California, Irvine has operated on a variety of fuels, including natural gas, diesel and jet fuel. The system was re-started in August 2000 after being idle for two years. It started up with no difficulty and continues to operate well, demonstrating the excellent shelf life of tubular SOFC systems. An earlier Siemens Westinghouse test unit in the 25 kW range operated for

more than 13,000 hours, with a non-stop run of over 6500 hours. This system was sponsored by Tokyo Gas and Osaka Gas of Japan.

Siemens Westinghouse is planning two major product lines with a series of product offerings in each line. The first product will be a 250 kW combined heat power system operating at atmospheric pressure with electrical efficiency of 47-50% and overall system energy efficiency of more than 80%, assuming steam/hot water or other utilization for high quality heat.

This will be followed by a pressurized SOFC/gas turbine hybrid system of approximately 0.5MW, operating at elevated pressures of 3-4 atmospheres, with electrical efficiencies of 58-70%, and overall system energy efficiency of about 80% if hot water is also produced. After initial production, larger systems are expected as well. Also, a system capable of separating CO2 from the exhaust is planned as an eventual product or option to other products.

The performance of these prototype demonstrations, together with market and cost information, will contribute to the decision to take commercial orders and build a factory for large scale production, with commercial deliveries expected two years later.

6 Hydrogen Focus Areas and Gaps for Alberta

Previous sections of this report have first reviewed background information about global drivers for hydrogen and fuel-cells. This was followed by a technical overview of the current situation for leading hydrogen and fuel-cell technologies on a worldwide basis. Finally, the focused was placed on Alberta with an in-depth review and summary of interviews with Alberta organizations involved in the hydrogen and fuel cells sector, the electrical power industry and the oil and gas industry.

The report now turns its attention to analyzing the accumulated information from an Alberta perspective. The purpose is to identify focus areas and gaps, with a view to propose niches for the industry and for Alberta organizations.

6.1 Hydrogen Production

Alberta is already a leading producer of hydrogen in Canada, and in the rest of the world. Hydrogen is produced in Alberta in on-purpose plants using steam methane reforming and as a co-product of other chemical processes. As reported by producers and consumers of hydrogen in Alberta, hydrogen production technology does not appear to be a gap because efficient and commercial technology exists. The cost of on-purpose hydrogen is greatly influenced by the cost of natural gas. In the future, anticipated increases in the price of natural gas are likely to overwhelm any efficiency improvements achieved through process R&D.

Alberta companies view hydrogen as an energy carrier, as opposed to a source of energy. Molecular hydrogen is not present in nature. Energy from either fossil resources or renewable sources must be used to produce molecular hydrogen from compounds containing hydrogen, such as water and hydrocarbons. Companies engaged in the power and energy sector in Alberta consider oil, gas and coal as their primary sources of energy. Renewable energy sources are also being exploited, particularly wind and hydro. Companies distribute this energy as electricity, and as value-added oil and gas products. Should a market emerge for hydrogen, Alberta companies would consider distributing the energy they produce as hydrogen. However, the vast majority of companies interviewed see this potential opportunity has a long term prospect.

Energy Market Trends in the United States

Population and economic growth are the main drivers for growth in global energy demand. There is a consensus among most energy forecasters that world demand for energy is expected to continue to grow through the year 2020. In a recent review of the world energy situation, OPEC forecasts that global energy demand is most likely to grow by 2% per year between 2002 and 2020 with 95% of the additional demand met mainly by fossil fuels [40]. OPEC estimates that by the year 2020, fossil fuels will represent 91% of the world's energy demand, or 2% higher than in the year 2000. Oil will continue to be a dominant energy source.

Alberta, as an important energy producer, has a significant stake into the future direction of energy markets, particularly in the United States. In a simplistic way, should the delivered form of energy in the United States market evolve from oil and gas to hydrogen, Alberta needs to take adequate steps to ensure that it is able to produce and deliver hydrogen utilizing Alberta natural resources. In the short term, energy markets in the United States will likely follow the global pattern referred to above. The United States will certainly continue to use energy products from Alberta in the form of oil and gas. Stricter environmental regulations in the United States will likely require more upgrading of oil and gas products in Alberta. For the longer term however, the United States has put in place a substantial research and development program to move it toward the hydrogen economy.

The United States is slated to begin a transition to cleaner gasoline in 2004. The average sulfur content in today's gasoline is about 270 parts per million. The new rules mandate a cut of the average sulfur content in gasoline to 120 parts per million in 2004, with a final goal of just 30 parts per million by 2006. The new rules also mandate a 97 percent reduction in the sulfur content of most diesel fuels used in buses and trucks. By mid 2006, the maximum allowable sulfur content of diesel will drop to 15 parts per million, down from 500 parts per million today.

U.S. refiners must spend over $10 billions to comply with the strict Federal low sulfur standards for gasoline and diesel. The process to remove sulfur from oil and gasoline is called hydrodesulfurization. Hydrogen is added to the oil and/or to the transportation fuel in order to react with the sulfur contained in hydrocarbon molecules.

Sulfur reacts with hydrogen to form hydrogen sulfide gas. Refiners then isolate and recover the sulfur from hydrogen sulfide gas. Elemental sulfur can be sold to fertilizer companies.

Market effects of the switch to cleaner transportation fuels are expected to be as follows:

- ✓ A few small refineries that will not be able to pay for expensive upgrades will have to shut down.
- ✓ Gasoline imports, which have been growing in recent years, are expected to shrink. Foreign refiners will no longer be able to sell in the United States gasoline with high sulfur content.
- ✓ Removing sulfur from gasoline will cause gasoline production to be reduced by about one percent.
- ✓ Approximately $10 billion is expected to be spent on new hydrogen treating units to remove sulfur at refineries. Additional hydrogen production plants will be built to supply these hydrotreaters.

The likely impact on Alberta of U.S. cleaner gasoline and diesel regulations will be that hydrogen treating of oil would increase in Alberta. Hydrotreating is the key technology to remove sulfur and nitrogen contaminants from oil products. It is expected that hydrogen production and consumption in Alberta will increase in the decade to come.

In the long-term, the United States is committed to cleaner energy technologies. How clean energy technology is deployed in the United States is therefore a potential threat to Alberta energy exports. For example, one of the drivers behind the substantial U.S. Clean Coal program is energy security. The United States has very large coal reserves and the production of hydrogen and power from zero emission Clean Coal plants is, in part, aimed at reducing U.S. oil imports.

The impetus for a cleaner environment also features prominently in U.S. energy policy. Two related environmental pillars support the push for the development of the hydrogen economy in the United States. The use of hydrogen as the fuel for vehicles would vastly improve air quality in densely populated cities. Secondly, hydrogen could be produced using zero emission Clean Coal technology thereby eliminating the dependence on oil and related greenhouse gas emissions. The U.S. hydrogen program is designed to eventually produce all hydrogen using emission-free technologies including almost half from renewable sources. President Bush has proposed a US$1.2 billion research program into hydrogen sources. The United States is also considering a US$3 billion research effort to push hydrogen fuel-cell development and the creation of a hydrogen fuel infrastructure. The administration also supports a Senate proposal that calls for building a US$1.1 billion nuclear reactor that would produce hydrogen. The Energy Department has begun a $1 billion program to develop a new generation of coal-burning power plant that would make electricity and hydrogen, while capturing carbon dioxide and other pollutants. In early 2003, President Bush announced the FreedomCAR program a US$ 1.2 billion over five years for the development of a hydrogen fuel cell car. The program also includes: reducing vehicle weight, improving energy production and on-board storage, advancing the internal combustion engine, building electronic components, and developing robust hybrid electric drive trains. The magnitude of the US technology development programs for hydrogen is impressive. Alberta should take note that its major energy market is serious about developing hydrogen as a large scale energy carrier.

Hydrogen production in Alberta

There is significant production and consumption of hydrogen in Alberta. At least two short haul hydrogen pipelines are in service:

- ✓ Between the ethylene plant of NOVA Chemicals and the nitrogen fertilizer plant of Agrium in the Red Deer region,
- ✓ Between the ethylene plant of Dow and Shell's upgrader north of Edmonton.

Several refineries and chemical plants have offgas effluents that contain hydrogen mixed with other gases such as hydrogen sulfide, methane, and light hydrocarbons. These by-product streams are generally too small to justify the investment required to produce chemical grade hydrogen. As a result these streams are usually burned for fuel value, displacing an equivalent amount of purchased natural gas. Large consumers of hydrogen such as the oil upgraders in the Alberta Industrial Heartland and in Fort McMurray have generally chosen to build their own hydrogen plant rather than to separate, to transport and to aggregate available hydrogen from the many offgas streams. In addition to the cost issues mentioned above, a major reason for building rather than buying hydrogen is security of supply. Across-the-fence by-product hydrogen effluents are more vulnerable to interruptions than on-site, on-purpose production.

Therefore, the reasons for not extracting available hydrogen do not relate to the absence of efficient technology. They arise from costs and from business needs. Similar economic realities are experienced in other industrial regions. It is instructive that on the U.S. Gulf Coast, Dow Chemical, a major producer of hydrogen as a co-product has chosen to pilot General Motors fuel cells to capture hydrogen's chemical energy. It is possible that it might be more economic to convert hydrogen contained in off-gases to electricity locally by using fuel cells rather than building an infrastructure to separate, aggregate, transport and distribute pure hydrogen. The chemical value and the associated environmental benefits of hydrogen are therefore captured where the hydrogen is generated, rather than in the engine of a fuel cell vehicle. As similar approach using fuel cells could be chosen for Alberta, particularly in the Alberta Industrial Heartland, to extract full value from the hydrogen contained in byproduct gas streams. Hydrogen separation using membrane technology is starting to be used in Alberta. For example, Syncrude is reported to be installing a hydrogen separator to recover hydrogen for use in oil upgrading. This approach, while acceptable to avoid wasting co-produced hydrogen, does not provide a solution to the needs of a future hydrogen economy. Nor does it provide an alternative to maintain Alberta's energy exports to the United States in the event of an evolution there to the hydrogen economy.

Hydrogen is produced in Alberta, by steam reforming of methane. This is a mature and commercial technology that appears to meet the needs of the oil industry in the Province. This production method utilizes natural gas as its feedstock. The cost of hydrogen produced in this matter is therefore significantly influenced by the cost of natural gas. Anticipated increases in the price of natural gas over the long-term imply associated increases in the cost of hydrogen in a manner that is likely to overwhelm any efficiency improvement that could be achieved through process innovation. To achieve cost reductions in the production of hydrogen, one needs to consider technologies for the production of hydrogen from low value feedstocks such as coal, petroleum coke, asphaltenes and possibly abandoned oil wells. R&D into the adaptation of gasification technologies to feedstocks available in Alberta would be an advantageous route to lowering hydrogen costs.

Hydrogen demand is likely to increase in the future, particularly in Alberta, because stricter regulations for clean gasoline will mean increases in the amount and intensity of hydrogen treatment of oil products. The cost of hydrogen is likely to increase as a result of the long term trend to higher natural gas prices. This combination of industry drivers creates an opportunity for Alberta to invest in the development of technologies to produce hydrogen at a lower cost by utilizing low value hydrocarbon feedstocks that are present in abundant quantities in the Province. The development of such technologies would give Alberta, a competitive cost advantage, as compared to the rest of North America in the area of hydrogen production and of hydrogen treating of oil products.

Currently, Alberta exports significant quantities of crude oil and crude bitumen to the United States. Refineries in the United States treat such crude energy products with hydrogen, in order to produce high quality transportation fuels. Refineries in both Alberta in the United States currently produce hydrogen from natural gas. If the refining industry in Alberta develops technology for the low-cost production of hydrogen by utilizing low value hydrocarbons, Alberta refineries would enjoy a cost advantage as compared to the United States. It would not be easy for U.S. refiners to replicate this cost advantage because it would be based on the presence in Alberta of abundant quantities of low value hydrocarbons. The benefit for Alberta, would be a larger amount of value added processing occurring in the Province and greater exports of value added (hydrogen treated) synthetic crude oil and transportation fuels.

It is therefore important for Alberta to watch closely, even to collaborate, with the United States on the development of hydrogen, Clean Coal and related technology programs. With respect to hydrogen research in particular, the area that should be of intense interest to Alberta is **production of hydrogen from low value hydrocarbons such as asphaltenes, petroleum coke, coal, and, possibly, abandoned oil wells.**

Supply of hydrogen and hydrogen related products to the United States

Hydrogen, like electricity, is a high quality energy carrier, which can be used with very high efficiency and zero or near zero emissions at the point of use. Electricity is a household and industrial energy carrier that is emissions and pollutant free at the point of use thereby reducing local air pollution, particularly in densely populated areas. Hydrogen offers similar benefits for transportation applications. Automobiles and trucks fueled by hydrogen would significantly reduce air pollution in cities. This benefit is an important driver for hydrogen as an energy carrier.

As described earlier in the report, the use of hydrogen for transportation, heating and power generation has been demonstrated, and it could replace fossil fuels in all their present uses in the long-term. For this to happen, however, the technical, economic and infrastructure challenges posed by the large scale introduction of a new energy carrier will need to be addressed. Commercial technologies exist for the production, storage, transportation and distribution of hydrogen. The building of a potential hydrogen infrastructure is the challenge that governments are starting to address, particularly with R&D programs and with demonstrations trials of hydrogen storage and re-fueling stations.

In a future North American hydrogen economy, hydrocarbons and coal from Alberta would need to be converted to hydrogen for use in fuel cell vehicles and other applications. The vast fossil resources of Alberta could be utilized as the energy source to produce the hydrogen energy carrier for a future hydrogen economy. In this future scenario however, Alberta natural resources would compete in North America with renewable energy sources and with the nuclear industry.

Hydrogen supply to the United States is a long-term strategic issue for Alberta. It warrants further **analysis and scoping of eventual scenarios for delivering hydrogen to the United States** in collaboration with participants in the Alberta oil and gas, power and pipeline sectors.

Conceptually, there are three potential high level approaches:

- ✓ Produce hydrogen in Alberta, aggregate it and ship it by pipeline to the U.S., should the United States build a hydrogen pipeline infrastructure.
- ✓ Produce natural gas and ship natural gas to the United States using the existing

pipeline infrastructure. Natural gas is converted to hydrogen at on-site reforming, storage and refueling centers in the United States. This approach is being proposed by oil and gas companies such as ChevronTexaco and would involve the development of economic small-scale reforming technology.

- ✓ Produce electricity in Alberta using zero/low emission technologies such as Clean Coal and export electricity to the United States. In the U.S., electricity is used to produce pure hydrogen by electrolysis at refueling stations. This approach is compatible with technology developed by Stuart Energy in partnership with Shell Hydrogen.

In the medium term however, oil and fossil transportation fuels will remains the dominant transportation fuels, as indicated above by the OPEC study. Nevertheless, the world will continue to move to even cleaner fossil energy products. The hydrogen content of transportation fuels can be seen as the measure of environmental friendliness, with pure hydrogen as the ultimate energy carrier. By adding hydrogen to its oil products, Alberta would increase the value of these products. Hydrogen addition can be viewed as a value adding activity, and as an environmental mitigation action. Hydrogen produced in Alberta need not to be exported as pure hydrogen to have a beneficial environmental impact. It can be exported as contained hydrogen in energy products, such as high quality synthetic crude oil and transportation fuels.

In the medium term also, North America is likely facing a tight supply/demand situation for natural gas. Long term forecasts are for sustained increases in the price of natural gas because of increasing demand and because of expected decline in production from low cost production regions such as Alberta. It is anticipated that the price of natural gas will continue to increase until it is high enough to justify the development of high cost supply from LNG terminals, from the Mackenzie Valley and from Alaska. The above discussion on the production of hydrogen from abundant low value hydrocarbons in Alberta can also lead to a solution to the anticipated tight supply/demand situation for natural gas. The first step in the conversion of hydrocarbons into hydrogen is the production of syngas, which is a mixture of hydrogen and carbon monoxide. If hydrogen is desired, the carbon monoxide in syngas is further reacted with water and converted into additional hydrogen via the water-gas shift reaction. However, syngas itself is a fuel gas that can be used as a natural gas substitute. It is not likely that syngas could be produced in Alberta and shipped via pipeline to the United States because of logistical issues. On the other hand, production of hydrogen in Alberta from low value hydrocarbons could be designed to co-produce syngas as well as hydrogen. Syngas could be used locally in Alberta by the energy industry for the production of steam used in bitumen recovery and for other industrial uses in Fort McMurray and in the Alberta Industrial Heartland. Syngas from low value hydrocarbons may become a low cost natural gas substitute for the Alberta energy industry and may free up additional volumes of natural gas for export to the United States.

Hydrogen from Renewable Energy

Renewable energy resources are those that are renewed in a relatively short time frame by the energy received from the sun. Solar, wind and hydro are the usual forms of renewable energy. However, fossil energy resources such as oil, gas and coal are very important Alberta assets. While it will take a long period of time to deplete Alberta's fossil resources, they will eventually be depleted. Production of conventional crude oil has already peaked in Alberta. Natural gas production from conventional wells is also expected to peak in the near future. Therefore, it is important to also develop Alberta's renewable energy resources.

The European Union plans to invest into research into renewable energy technologies, which they want to make the cornerstone of a hydrogen energy economy. For a truly pollution-free system, some environmentalists argue, the hydrogen must come from a source that does not pollute. Environmental groups say hydrogen is not an inherently clean technology and the hydrogen economy would only be as clean as the energy used to create hydrogen. A push to produce hydrogen from renewable energy technology such as wind, solar and hydro -and not fossil fuels - is the answer according to this line of thinking. Europe intends to place renewable energy sources at the heart of the hydrogen economy.

At first glance, hydrogen and fuel cells do not appear to be directly related to renewable energy production. Fuel cells consume hydrogen molecules which can be produced from either fossil or renewable sources.

Renewable energy sources such as wind and hydro are already harnessed today for stationary power generation at the commercial scale. Turbines powered by the wind or by the movement of water produce electricity at central plants and at distributed generation sites. Hydrogen and fuel cell technologies do not appear to offer possibilities to further enable or to enhance the efficiency of current methods for extracting energy from renewable sources at stationary power generation plants.

On the other hand, hydrogen and fuel cell technologies are a strategic enabler for the use of renewable energy in vehicles. Renewable energy sources produce heat and electricity. Electricity can be used to power vehicles. For example, Calgary's Light Rail Transit is powered with electricity generated by wind turbines in the Pincher Creek area. In this case, green electricity is provided to the transit vehicles by wires. However, wire technology is not suitable for vehicles such as cars, buses and trucks. Attempts to commercialize electric vehicles have been hampered by the technical limitations of battery technology.

Hydrogen and fuel cells offer two opportunities for the use of renewable energy in vehicles such as cars, buses and trucks. Both involve firstly the production of electricity from a renewable source such as wind or hydro. This electricity is then used to produce hydrogen by electrolysis of water. This green hydrogen, from a renewable energy production path, may be used to power vehicles:

- ✓ By combustion in a hydrogen internal combustion engine
- ✓ By conversion in a fuel cell.

Both opportunities are being explored and may see commercial implementation. Hydrogen fueled internal combustion engines, while less energy efficient than fuel cells, may come to market sooner because of their similarity to existing internal combustion engines. Some consider hydrogen internal combustion engines to be a bridge technology to fuel cell vehicles.

Therefore, one element of the strategic importance of hydrogen and fuel cells is that they promise to allow vehicles such as cars, buses and trucks to be powered by renewable energy.

Hydrogen from Nuclear Energy

Over 30 years ago nuclear energy represented the promise of abundant low cost electricity. Since that period, well known nuclear accidents have caused the construction of new nuclear reactors to all but com to a halt. However, nuclear energy remains the only proven and economic large scale source of electricity from non fossil resources.

Electricity from nuclear reactors can also be used directly to power stand-alone hydrogen production facilities, without generating carbon dioxide emissions. The electrolytic production of hydrogen is one viable way to produce a hydrogen energy carrier that could displace today's fossil-based transportation fuels.

Using hydrogen as fuel for transportation would help to reduce greenhouse gas emissions and air pollutants that cause smog. Atomic Energy of Canada estimates that building CANDU reactors at the rate of one reactor per year between 2005 and 2025 would supply enough emission-free electricity to produce hydrogen for 13 million hydrogen-powered vehicles by 2025. This creates the opportunity to avoid 120 million metric tonnes of carbon dioxide emissions per year.

This report does not intend to discuss the merits of nuclear energy. However, nuclear reactors have been suggested for Alberta in order to produce the energy and the hydrogen required for the exploitation of the oil sands.

Current technology for the recovery and upgrading of oil sands makes extensive use of natural gas. Steam is produced by burning natural gas for use in Steam Assisted Gravity Drainage (SAGD) operations for the in-situ recovery of bitumen from oil sands deposits. Nuclear reactors produce electricity by first producing steam from the heat of the nuclear reaction. Nuclear reactors have been proposed for Alberta as very good steam generators that could save billions of cubic feet of natural gas. However, the problem associated with this approach is the difficulty, if not the impossibility, to ship steam over the long distances involved in Northern Alberta oil sands operations.

Upgrading bitumen to synthetic crude oil requires hydrogen to eliminate sulfur and nitrogen contaminants. Nuclear reactors have been proposed for Alberta to generate electricity that could be used for producing hydrogen from water by electrolysis. The nuclear industry remains a contender for large scale production of electricity. Recently, the United States administration approved funds for research and development into enhanced nuclear reactors, including U. S. $1.1 billion for in the construction of a nuclear reactor to produce hydrogen. Alberta however is endowed with vast natural resources that could be utilized to produce hydrogen. The presence of abundant low cost hydrocarbons such as asphaltenes, petroleum coke and coal in combination with the appropriate technology could give Alberta a competitive advantage in the production of hydrogen. Therefore, it makes sense for Alberta to focus its research and development into gasification and hydrocarbon reforming technologies rather than into the development of advanced nuclear technologies.

In the context of the oil sands, asphaltenes gasification can be economically implemented at the scale of an individual oil sands recovery operation. In other words, a nuclear reactor must be built as large centralized power generation facilities while asphaltenes gasification plants can be built in a distributed manner at the level of individual operations. Because of the large central plant design, electricity is the only form of energy that nuclear reactors can distribute over the area that they would serve. Local asphaltenes gasification facilities on the other hand can produce and supply all of electricity, steam and hydrogen to an oil sands recovery and upgrading facility. The first such asphaltenes gasification facility is slated for implementation by OPTI Canada and Nexen at the Meadow Lake oil sands project in Northern Alberta.

6.2 Hydrogen Storage and Distribution

Technology Development

Hydrogen can be stored as a gas or as a liquid or in a chemical compound. Current commercial technologies permit the storage, transport, and delivery of compressed gaseous or liquid hydrogen in tanks, trucks and pipeline systems. At least two short haul hydrogen pipelines are in service are in service in Alberta.

However, current technologies do not appear to satisfy all of the desired storage criteria sought by manufacturers and end users for the widespread use of hydrogen.

Technology options for hydrogen storage and distribution include:

- ✓ Compressed or liquefied hydrogen for portable and automotive applications

- ✓ Metal hydrides with pressure a small fraction of that for compressed hydrogen. Metal hydrides are often the targeted option for small scale hydrogen storage because of their safety aspect.
- ✓ Chemicals hydrides have a high percentage of hydrogen by weight but are irreversible.
- ✓ Carbon based hydrogen storage such as storage of hydrogen on carbon nanotubes: this new technology is the subject of much attention in the last few years but only time will tell the real potential of this technology.

The storage of compressed hydrogen gas in tanks is a mature technology. Improvements in cost, weight, and volume storage efficiency continue to be made. Dynetek in Calgary supplies cylinders for stationary and on-board compressed hydrogen storage with pressures that range from 3,000 psi (200 bar) to 12,500 psi (825 bar). Dynetek has also participated in a number of demonstration trials for hydrogen storage and distribution at re-fueling stations for fuel cell vehicles. However, the very low density of hydrogen translates to inefficient use of space aboard a vehicle. Even at the high compression currently achieved by world leader such as Dynetek, the density of hydrogen is still about five times less than that of gasoline. The density of gasoline is 0.8 g/cm^3 while the density of compressed hydrogen (6,000 psi or 400 bar) is only 0.016 g/cm^3 [15]. Because the energy content of hydrogen is also lower than hydrocarbon fuels, hydrogen compares even less favorably in term of energy available per unit of mass or volume. The energy content of diesel and gasoline are 8.3 kWh/l and 7.0 kWh/l respectively. Hydrogen compressed at 300 bar has an energy content of 0.4 kWh/l, or about 17 times less than gasoline. By comparison, methanol contains 4.2 kWh/l and batteries 0.13 kWh/l [24].

Liquid hydrogen takes up less storage volume than compressed gas but requires expensive cryogenic containers. Furthermore, the liquefaction of hydrogen is energy-intensive and there are significant evaporative losses. About one-third of the energy content of the hydrogen is lost in the liquefaction process. Special handling requirements, long-term storage losses, and cryogenic liquefaction energy demands currently detract from commercial viability.

Hydrogen can be stored chemically at high densities as reversible metal hydrides and can be reversibly adsorbed on carbon structures. These emerging systems offer the advantages of lower pressures, conformable shapes, and reasonable volumetric storage efficiency, but they present weight penalties and thermal management issues. These technologies are at an early stage of development. The most promising carbon materials for hydrogen storage at this time appear to be carbon nanotubes.

Research into metal and chemical hydrides does not appear to be an active area in Alberta. However, there is interest in the fuel cell research community for working with the National Institute for Nanotechnology that is being established at the University of Alberta. **Hydrogen storage in carbon nanotubes would be a key potential area for research in Alberta, along with nanostructured materials for membrane electrode assemblies**.

Irreversible chemical hydrides are emerging as another alternative. The chemical hydrides considered for storage applications are a class of hydrogen containing compounds that can be stored in solution as an alkaline liquid. Although chemical hydrides present a potentially safer and more efficient option, several challenges remain be addressed, including cost, recycling, overall energy efficiency, and infrastructure.

Therefore, hydrogen storage and distribution remains a key enabling technology and a critical gap. None of the current technologies satisfy all of the hydrogen storage attributes sought by the industry. Conventional technologies such as compression and liquefaction are relatively expensive and mature. It is reasonable to expect that further research will yield incremental improvements but no breakthroughs. The opportunity for step change improvements in cost, portability and safety appears to lie in novel approaches such as metal hydrides, chemical hydrides and adsorption onto nanostructures. Research and development is needed to lower costs, improve performance, and develop advanced materials. R&D should continue into novel storage technologies such as lightweight metal hydrides and carbon nanotubes. Metal hydrides, nanostructures and chemical hydride systems are all at an early stage of development and much research remains to be done before reliable comparison of their efficiency and cost can be made to existing commercial approaches.

Technology Demonstration

Several companies in the Alberta Industrial Heartland produce hydrogen as a co-product. Table 6 provides a list of co-produced hydrogen opportunities. In particular, Alberta Envirofuel produces isooctane but also has a co-product stream of 100 kg/hour of 99% pure hydrogen. This stream presents a specific opportunity and could be used to supply **a hydrogen re-fueling station for a demonstration of hydrogen vehicles in the Edmonton area**. There currently no hydrogen and fuel cell infrastructure projects in Alberta and this opportunity could be used to fill a critical gap.

In Vancouver, one promising project is a hydrogen re-fueling station to demonstrate advanced technologies for hydrogen storage and distribution. Part of this project is the associated fleet of five standard Ford Focuses equipped with zero emission, fuel-cell engines designed and built by Vancouver's Ballard Power Systems.

Hydrogen infrastructure projects are part of the mandate of the Canadian Transportation Fuel Cell Alliance (CTFCA), which is a new initiative that was launched in 2001 [43]. Natural Resources Canada (NRCan) is the lead Federal government department. CTFCA has a budget of $23 million over five years. It is focused on developing a fueling infrastructure for fuel cell vehicles. The aim of the CTFCA is showcasing fueling and fuel cells technologies and integrating key related activities. Fueling demonstrations are the major program element, accounting for 70% of the budget. CTFCA could be a partner in an Alberta demonstration of a hydrogen re-fueling station using technology from Calgary-based Dynetek.

Table 6 - Sources of Hydrogen in Strathcona County

Alberta Envirofuels

Volume: 3 metric tonnes /hour (11,000 cu. ft. =1 metric ton)
Purity: 78%
Impurities: 1% nitrogen
0.1% CO
traces CO2
19% methane
0.3% ethane
traces ethylene
0.4% C3s
1.4%
Pressure: 4 bars, or about 58 lbs. (perhaps a bit higher)
Current use: fuel
Other: this stream is available after conversion of Alberta Envirofuels to produce isooctane. The hydrogen needs purification for uses incompatible with the impurities. Use of this source requires natural gas replacement as fuel.

Alberta Envirofuels

Volume: 100 kilograms / hour
Purity: 99.9% (psa quality)
Impurities: n/a
Pressure: n/a
Current use: n/a
Other: can be available for research or other purposes

Praxair

Volume: 24 metric tonnes / day (~281,000 sm3 / day)
Purity: 99.9% (nominal, minimum by volume)
Impurities: ppm levels of methane, nitrogen, carbon dioxide, and minor O2 compounds.
Pressure: 800 lbs. / sq. inch.
Current use:
Other: H2 originates from Celanese methanol production in Edmonton. It is cleaned at Celanese and goes by 8" pipeline to Praxair in Ft. Saskatchewan. From there it goes to Dow and Shell as a process component. The pipeline has a capacity of 80 million cu. ft. of H2 / Day but is currently operating at 66% of capacity. Celanese could supply 75 metric tonnes per day but there is insufficient market and the clean-up plant would require expansion over a six month period to meet the capacity demand. Currently, excess H2 from Celanese is used as fuel. As a single source, any user would be subject to supply disruptions whenever Celanese had a plant shut-down. There is the possibility tube trailers of hydrogen could be brought in from Joffre depending on the volumes required.

Nexen Chemicals Bruderheim Sodium Chlorate Facility Volume: 8,500 Kg is vented per day when plant is running at full load (does not H2 consumed as fuel in company). Purity: 99.9% Impurities: approximately 0.2 ppm Cl2 v/v approximately 100 ppm CO2 v/v saturated with water vapor Pressure: approximately 25 Kpag at 20 deg.C. Current use: excess H2 is vented to atmosphere as indicated above. Other: n/a
Albchem Volume: 4,000 Nm3 / hour of H2 Purity: 91% H2 in molecular weight Impurities: nitrogen, oxygen, water, and traces of chlorine Pressure: n/a Current use: vented to atmosphere and burned as fuel Other:
Source: Strathcona County, 2003

7 Fuel Cells Gap Analysis and Focus Areas for Alberta

7.1 Advantages of Fuel Cells

Fuel cell devices offer compelling advantages as compared to other energy generation devices, whether the fuel originated from a fossil, renewable or nuclear source. Of particular interest for Alberta, fuel cell technologies offer opportunities for economic and environmental benefits for energy generation using fossil fuels.

The development of fuel cells for stationary, mobile and portable electric power generation has been pursued globally for several years because of their anticipated benefits. From an Alberta perspective, the most relevant attributes of fuel cells are:

- ✓ Fuel cells pollute less than traditional power sources, producing little more than water as a by-product. Environmental emissions are very low, particularly NO_x and SO_x because combustion is not involved.
- ✓ Higher conversion efficiency as compared to combustion
- ✓ Fuel cell exhibit high electric generation efficiencies, ranging from up to 40% for PEMFC to up to 60% for pressurized SOFC.
- ✓ Potentially higher electrical efficiencies in fuel cell/turbine hybrid configurations. SOFC and MCFC can be designed for elevated pressure operation coupled with gas and steam turbines. The pressurized hot exhaust from the fuel cell drives a gas turbine to generate additional electricity. The gas turbine exhaust may also be used in turn to generate steam to drive a steam turbine. Electric generation efficiencies of 70% have been projected. If the gas turbine is not fired with additional fuel, it produces no additional air emissions.
- ✓ The ability of high temperature fuel cells to match the requirements of many steam hosts for applications involving the cogeneration of power and steam.
- ✓ Fuel cells are also suitable for many, if not all, combined power and heat applications.
- ✓ Modular nature and suitability for distributed power generation, resulting in additional energy efficiencies at the system (grid) level from the avoidance of transmission losses.

- ✓ Superior performance as compared to lithium ion batteries in portable applications.
- ✓ Less greenhouse gas emissions resulting from improved energy efficiency
- ✓ Opportunities to capture concentrated CO2 for sequestration by using high temperature fuel cells.

7.2 Fuel Cell Application Segments in Alberta

In a fuel cell system, energy and power are separate elements. The fuel cell stack provides power and depends on the cell active area, the number of cells, and operating conditions. The energy on the other hand is defined by the fuel. Compared to batteries, fuel cells have a competitive advantage in the energy parameter because fuel cells can be refueled [42]. Advantageous applications for fuel cell systems are those where the energy requirements are large. Given the current state of technology development, the power element of fuel cells is relatively expensive. At this point in time therefore, applications that would offer competitive advantages for fuel cell systems are those where the energy requirements are large and the power requirement is small.

This is true for portable applications. Applications for fuel cells in laptop computers and other electronic devices are expected to be first to market because the power requirement is relatively small and because fuel cells have a large competitive advantage over batteries in their ability to provide energy over an extended period of time. The development of micro fuel cells and of fuel cells for portable applications is emerging in Alberta.

Distributed generation is also an application where the energy requirement is large relative to the power requirement. Power generation for households and for small commercial users would require a relatively small power generator but would need to produce energy continuously. Fuel cells are therefore well suited to distributed power generation. The scalable nature of fuel cells provides them with the flexibility required for sizing systems to a wide variety of distributed power generation applications. The development of SOFC for distributed generation is at the demonstration and business development stage in Alberta.

Billions of dollars are being invested internationally on developing fuel cell systems for automotive applications. Fuel cells vehicles using on-board hydrogen are considered zero emission vehicles and would significantly reduce air pollution in cities. This benefit is an important driver for hydrogen fuel cell vehicles. Fuel cells also offer an opportunity for the use of renewable energy in vehicles such as cars, buses and trucks. Fuel cells can use "green" hydrogen made from a renewable energy production path. Alberta is unlikely to become a centre for the development of automotive fuel cells because of the absence of automotive and heavy manufacturing industries in Alberta. The PEMFC appears to be the platform of choice for vehicle applications because of its ability to start quickly and to deliver high power densities. Vancouver is the location of Canada's recognized cluster for hydrogen fuel cell vehicles based on PEMFC technology.

Development efforts by existing Alberta researchers and developers of fuel cells have focused on applications in the portable and distributed generation segments that use hydrocarbons and hydrogen sulfide, in addition to pure hydrogen. This situation arises from the presence of abundant hydrocarbon resources in Alberta. The most important effort is the development of SOFC for residential and small commercial applications by Global Thermoelectric with some supporting R&D at the University of Calgary. There are also development projects on stationary fuel cells that can use hydrogen sulfide and on portable fuel cells using alcohol at the University of Alberta. Micro fuel cells and DMFC are in the early stage of development at the Alberta Research Council. Some of the drive behind alcohol fuel cells and micro fuel cells comes from interest in developing value-added manufacturing industries and from the possibility of producing ethanol from agricultural sources.

With respect to markets, existing efforts have mostly been directed at stationary applications, particularly for residential and small commercial applications. Electricity deregulation in Alberta has created a favorable business environment for the development of distributed generation. Small distributed generation systems are already being installed in Alberta based on photovoltaic arrays and microturbines for combined heat and power generation. Larger scale cogeneration power plants have been built recently in the province fueled by natural gas and using combined cycle gas and steam turbines. It is likely that when lower-cost fuel cells are commercially available, they will find a niche in Alberta's deregulated electricity sector.

In the following pages, opportunities for Alberta in the distributed generation and the portable segments will be discussed. In addition, the potential implications of fuel cell technology for Alberta's Clean Coal program will be reviewed.

7.3 Distributed Generation

Distributed Generation Market

In recent years, Alberta has progressively deregulated its electrical industry. This has led to a significant expansion of distributed generation in Alberta, particularly for wind energy. A deregulated industry and a developing consumer market for premium green electricity have been favorable to the development of wind power in Alberta. Small-scale distributed generation systems using micro turbines are being piloted in the Province. For example, Enmax is trialing a Capstone microturbine using digester gas from one of Calgary landfill facilities. Mariah Energy is developing a business with microturbines for combined heat and power applications. Targeted segments are facilities with swimming pools and with laundry facilities. This type of facilities offer important base load heat demand that would consume on a continuous basis the heat produced by the distributed generation system .Organizations in the emerging distributed generation cluster have formed an industry association called NewEra. The purpose of NewEra is to promote the benefits of distributed generation and to work toward an increasing number of demonstration trials. These favorable conditions in Alberta would also be beneficial to the development of a fuel cell industry for distributed stationary power generation.

Distributed generation systems provide benefits at the customer level, the supplier level as well as the Alberta level:

- ✓ They have small footprints, are modular and possibly mobile making them very flexible in use.
- ✓ Benefits to the customer include high power quality, improved reliability, and flexibility to react to electricity price spikes. Distributed generators can be designed to operate properly when islanded, giving local distribution systems and customers the ability to ride out major or widespread outages.
- ✓ Supplier benefits include avoiding investments in transmission and

distribution (grid) capacity upgrades by locating power where it is most needed and opening new markets in remote areas.

- ✓ Distributed generation enhances the stability of the regional grid and can help reduce the reliability and capacity problems to which an aging or overstressed grid is liable. In general, given reasonably reliable units, a large number of small units will have greater collective reliability than a small number of large units, thus favoring distributed resources. Multiple small units are far less likely to fail simultaneously than a single large unit. The consequences of failure are far smaller for a small than for a large unit. Distributed resources tend to avoid the high voltages and currents and the complex delivery systems that are conducive to grid failures. Appropriately designed distributed inverters can actively cancel or mitigate transient events in real time at or near the customer level, improving grid stability.
- ✓ At the Alberta level, the improved efficiencies reduce greenhouse gas emissions.
- ✓ The market for distributed generation may establish a new industry, boosting the Alberta economy.

There are different types of applications for distributed generation systems:

- ✓ Combined heat and power applications
- ✓ Distributed and cogeneration power plants

Combined Heat and Power Applications

In combined heat and power applications, electricity and heat are co-produced and both are utilized beneficially by the application. Heat is used typically for space heating and hot water. Combine heat and power distributed generation applications are attractive from the point of view of total energy efficiency. However, their use is limited by the fact that applications with a large and stable heat demand are difficult to find. For most applications heat demand is very small during summer months. In warm and moderate climate regions, space heating is not required in the summer. There would be at year round need for space heating in arctic regions. Therefore the overall efficiency benefit of combine heat and power applications are not realized when they heat generated by the system is not utilized. The situation is worse in cases where the heat generated by the system creates an additional load for air-conditioning systems.

Generally, combined heat and power systems are sized to meet base load heat demand in order to maximize total energy efficiency and economic benefits. Examples of applications that exhibit a large reliable heat load are swimming pools and small hotels with laundry facilities. Therefore, combined heat and power systems tend to be relatively small ranging from 1 kW to about 10 kW. Their market is limited by the fact that applications requiring a large heat base load demand are difficult to find. In Europe, MTU CFC Solutions (Germany) is developing the fuel cell HotModule from is a highly integrated MCFC system for decentralized stationary power, heat and cold cogeneration or "tri-generation". This unit would be capable of generating electricity, heating and cooling as required. This system is still in the development phase. In Alberta, Global Thermoelectric is developing small-scale SOFC systems that can be used for residential and small commercial combined heat and power applications.

Small size distributed generation is aimed at customers dependent on reliable energy, such as hospitals, manufacturing plants, grocery stores, restaurants, banks and many other facilities. There is currently over 15 GW of distributed power generation operating in the U.S. Over the next decade, the market for distributed generation is estimated to expand 5-6 GW per year. Projected global market capacity increases are estimated to be 20 GW per year.

Small size distributed generation systems are targeted at the residential and small commercial markets. Fuel cell systems are designed for use of natural gas and propane which are readily available in Alberta and most regions. The justification for installing small size distributed generation systems are:

- ✓ Combined heat and power -The thermal energy created while converting fuel to electricity is utilized for heat. Electricity and heat are generated for sites that have a 24 hour thermal/electric demand.
- ✓ Standby power - Power during system outages is provided by a distributed generation system until service can be restored. This is used for customers that require reliable back-up power for health or safety/security reasons.
- ✓ Remote/Stand alone - The purpose is for remote applications and mobile

units to supply electricity where needed.

- ✓ Peak shaving - Power costs fluctuate hour by hour depending upon demand and generation therefore customers would select to use distributed generation during relatively high-cost on peak

The big blackout of August 14, 2003 caused an estimated $4 billion to $6 billion in losses in the United States and Canada. The blackout has firmed up the perception, if not the reality, that the electrical grid is antiquated and not as reliable as it should be. This perception should be expected to last for many years because there are no "quick fixes" to the problems experienced by the grid. One outcome is that the value proposition of standby power has increased significantly. In the days following the blackout, Home Depot and Lowe's, the United States' largest home improvement chains, both did big business in generators. While a lot of the attention was focused on the residential market, the value proposition in the small commercial market became very compelling. In New York City alone, the city's 22,000 eateries lost between $75 million to $100 million in wasted food and lost business as a direct result of the blackout, as calculated by the New York State Restaurant Association. Reliable, quiet, 1 to 10 kW fuel cells connected to the natural gas distribution network or to propane tanks are likely to be a valuable insurance policy for small and medium sized businesses.

Distributed and Cogeneration Power Plants

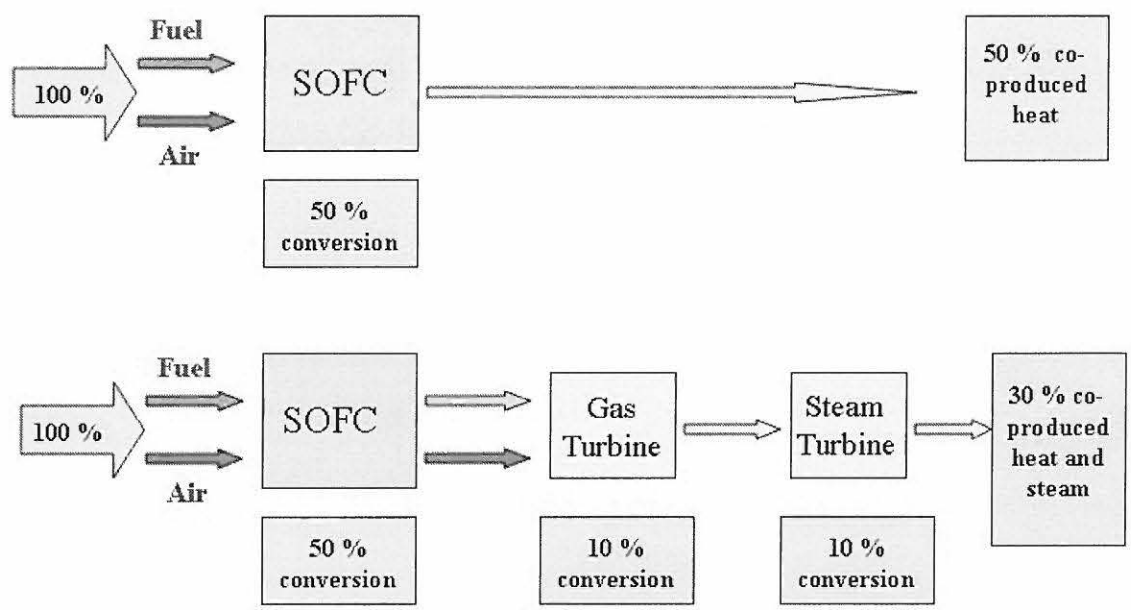
Advanced gas turbine systems and the wide availability of natural gas as a cleaner fuel than other fossil fuels has led in recent years to the construction in North America of a large number of clean and efficient distributed power plants with capacities from 20 MW to higher than 200 MW. Current technology uses advanced gas turbines to produce electricity by combusting a fuel gas. A recuperator transfers heat from the hot exhaust gas to the incoming fuel gas in order to maximize efficiency. These systems generally utilize natural gas.

Gas turbine technology has progressed to combined cycle systems where a gas turbine is combined with a steam turbine. The hot gases exiting the gas turbine are utilized to produce high-quality steam that is used by the steam turbine to produce additional electricity.

Cogeneration systems are typically systems that are designed for the combined production of electricity and steam. The hot exhaust from the gas turbine is used to produce high quality steam that is used to drive a steam turbine for generation of additional electricity. Steam exiting the steam turbine is then used for local industrial applications. Cogeneration plants are generally sited inside industrial complexes that have significant demand for both electricity and steam. The ability of these plants to co-generate valuable heat or steam depends on the availability of on-site demand for large amounts of heat or steam because heat and steam cannot be transported over distances of any magnitude. Generally, cogeneration plants are sized to fit local demand for heat and steam.

Fuel cell/gas turbine hybrids are being developed in the United States and Japan as high electrical efficiency distributed generation devices. First a pressurized high temperature fuel cell converts fuel gas containing hydrogen into electricity. The pressurized high temperature exhaust of the fuel cell is fed to a gas turbine. High pressure and temperature creates work in the turbine that is used for generating additional electricity. It is also possible to combust in the turbine any un-reacted fuel. The system can also be designed to allow a feed stream of additional fuel gas to the turbine to increase the amount of electricity generated in this manner. As with current cogeneration technology, it is also possible to add a steam turbine for the generation of additional electricity and for steam production. . The gases exiting the gas turbine are at a high enough temperature to transform water into steam. The produced steam is at a temperature and pressure sufficient to drive a steam turbine which provides a third additional source of electricity generation from the system. Such systems are called "Triple Cycle" and are illustrated on Figure 7.

Figure 7 - Energy Conversion of Triple Cycle Systems



Hybrids fuel cell/gas turbine systems, including triple cycle systems, can be fueled with hydrogen. However the vast majority of development targets natural gas as the fuel. Hybrid systems must use a high temperature fuel cell to produce the high quality heat required by the gas turbine. High temperature fuel cells are able to reform natural gas into hydrogen internally. Fuel cell gas turbine hybrids therefore are being developed as an alternative to combined cycle turbine generation systems. As with combustion based combined cycle systems, fuel cell hybrid systems can be used in situations where combined power and steam are utilized and, in these applications, can lead to very high overall energy efficiency.

Hybrid approaches involving high temperature fuel cells and gas turbines offer greater electrical efficiencies than either gas turbines or fuel cells alone. High temperature fuel cells are required to produce the high quality heat that can be utilized by the gas turbine. The heart of hybrid power systems is the high-temperature fuel cell such as the SOFC and MCFC. The high thermal output of the SOFC and MCFC make possible the hybrid cycle, where the combined performance of the power components far surpasses that of individual components alone. The fuel cells must also operate at under pressurized conditions. A high temperature atmospheric fuel cell has an efficiency of approximately 50% while pressurized fuel cell systems coupled to a gas turbine can increase electrical efficiency to 70% as shown on Figure 5. The hybrid approach permits an increase in the electrical efficiency of the device at the expense of the heat energy output. Because the cost per kW of the turbine element of the hybrid system will be less than that of the fuel cell element, the overall capital cost per kW of the hybrid will be less than a fuel cell system alone.

Pressurized high temperature fuel cells offer an option for low cost CO_2 recovery and disposal. CO_2 is available at a high partial pressure in the anode exhaust of pressurized SOFC and MCFC. Recognizing the value of this approach, Shell and Siemens are conducting a trial in Norway with SOFC technology.

The US Department of Energy, as well as major companies in Japan, has recognized the superior potential of fuel cell and gas turbine hybrid approaches for the production of electricity in a distributed generation environment and have dedicated substantial budgets to the development and commercialization of this technology.

The US Department of Energy is sponsoring the development of 1 to 2 megawatt hybrid fuel cell and gas turbine systems with an expected electrical efficiency of about 70%. The objective is to achieve higher levels of electrical efficiency than existing gas turbines cogeneration systems. Development is occurring in the U.S. and in Japan and is focused on natural gas as the fuel.

Hybrid fuel cell and gas turbine systems are being developed into systems offering higher electrical efficiency and less air pollution than the equivalent turbine based system, be it simple cycle, combined cycle or cogeneration.

SOFC for Distributed Generation in Alberta

In Alberta, the market of choice for fuel cells is stationary power generation. Automotive fuel cells applications for are unlikely to take roots in the Province because of the absence of an auto industry. Portable applications are emerging and could grow on the foundation of growth in value added manufacturing. However, energy production is a pillar of Alberta's economy. Hydrogen production and stationary fuel cells can play a synergistic role with the energy industry in the Province.

Fuel cells offer higher electrical efficiency than combustion based systems. In order to compare fuel cells with other available systems for distributed generation, an evaluation of system efficiency is necessary. Combustion systems such as the internal combustion engine can convert chemical energy into mechanical energy, which is then is transformed into electrical energy by means of a rotating generator. The combustion of a hydrocarbon is accompanied by a rise in temperature because the combustion reactions are exothermic. The reaction products are usually gasses. The heat increase causes and expansion of the formed gasses which in turn produces mechanical work by causing pistons in the internal combustion engine to move. The maximum efficiency of this system is given by the Carnot efficiency equation. In general, the efficiency of combustion systems does not exceed 50% for the most efficient heat engines such as steam turbines and is often lower for internal combustion engines.

For a fuel cell, the efficiency can be calculated from the Gibbs free energy and the enthalpy change of the electrochemical reaction. For fuel cell systems using hydrogen, the theoretical electric output is equal to the Gibbs free energy change of the reaction:

$$4H_2+2O_2 => 4H_2O$$

The Gibbs free energy change depends on temperature. The higher the temperature, the lower the free energy change. For a fuel cell operating at 825° C (in the SOFC range), the free energy change is 179 kcal and the reaction heat is 237.6 kcal. The theoretical efficiency can thus be taken as 179/237.6 = 75.3%.

In practice, the efficiency of fuel cell systems is reduced by losses due to electrode overpotential and by the electrolyte resistance of the cell. Cells of different designs and using different components will exhibit varying efficiencies. In addition, there is the possibility of parallel electrochemical reactions which can lead to a lower current yield than theoretically possible. For example, the formation of formaldehyde or formic acid during the oxidation of methanol reduces the number of exchanged electrons from six to two or four. In some systems, there is also the possibility of heterogeneously catalyzed chemical reactions taking place at the electrode surfaces. Published electric efficiencies for fuel cell systems range from 40% to as high as 60% for highly efficient pressurized SOFC systems.

Fuel cells are therefore energy conversion devices that are more energy efficient than alternative technologies, including gas turbines.

It is important to maximize the electric efficiency of fuel cell devices for use in stationary power generation in Alberta and to increase the ratio of electrical energy to heat energy produced. Fuel cell technologies offering the highest electrical efficiency would be preferred.

High temperature fuel cells, such as MCFC and SOFC tend to exhibit higher electrical efficiency than their lower temperature counterparts. The high temperatures increase the oxygen reduction kinetics dramatically. The production of high temperature heat permits hybrid systems that include a gas turbine to generate additional electricity. The turbine is able to convert high temperature heat into electricity thereby shifting the ratio of energy produced from heat to electricity. The hybrid systems that are being developed are capable of electricity efficiencies up to 70%. Electrical efficiency is a key selection parameter for stationary power applications.

High temperature fuel cell technologies such as the SOFC and MCFC are also favored for stationary power applications because of their ability to use hydrocarbon fuels internally in the fuel cell system. Fuel cells operating on natural gas or propane for small commercial distributed generation could be widely installed in Alberta in the next few years when commercial systems are available because of the broad distribution of these fuels in the Province.

Custom engineered systems such as oil upgraders achieve cost reductions through economies of scale and require large plants to be built in order to meet economic requirements. Fuel cell achieve low-cost through mass production of small modular units. Millions of modular fuel cell units could be mass produced at low individual cost. The required number of modular fuel cell units is then arranged in an array sized to the requirement of each individual project. The design flexibility inherent to modular fuel cell units permits the exploitation of localized fuel sources such asphaltenes rejected at the mine site, petroleum coke stock piles and agricultural wastes.

As compared with MCFC, the SOFC offers greater opportunities for cost reduction through mass production. The solid state nature of planar SOFC allows the use of mass production methods used in the electronics industry. The advantages of SOFC can be summarized as follows:

- ✓ Ceramics can be cast into various shapes (tubular, planar or monolithic).
- ✓ The corrosion problems associated with liquid electrolyte fuel cells such as the MCFC, the PAFC and the AFC are avoided.
- ✓ Fuel flexibility
- ✓ Fast reaction kinetics without noble metal catalysts, reducing catalyst costs and eliminating carbon monoxide poisoning.
- ✓ High temperature, pressurized exhaust can be used in co-generation applications to increase overall electrical efficiency.

The remaining technology development challenges are:

- ✓ Finding suitable materials with matching thermal expansion coefficients in order to minimize thermal stress. Thermal cycling associated with shut-down and start-up may result in cracking and delamination.
- ✓ Sealing is difficult with planar SOFC.
- ✓ High temperatures place restriction on material selection and result in challenges for the development of a low cost manufacturing process.
- ✓ Start-up time is lengthy, up to 15 hours.

The U.S. Department of Energy has initiated R&D and demonstration programs that are focused on bringing SOFC costs down to US$400/kW, a cost that would enable fuel cells to find applications in a large variety of power markets. The modular design would allow the possibility of building arrays of low-cost SOFC modules into larger scale power plants. The key to the ambitious cost reduction program will be the development of a compact, 5-kW module that can be mass-produced using many of the same manufacturing advances that have dramatically lowered costs in the electronics industry. The modularity of the system will permit the 5-kW unit to be clustered into a variety of custom-build arrays for a wide variety of applications - from small portable military power sources to multi-megawatt central generating stations. The proposed solid state design will leverage numerous recent advances, such as the production of thin-film solid electrolyte materials and precise, automated manufacturing technologies developed largely in the semi-conductor industry. The goal of this program is to have ultra-low cost fuel cell concepts ready for commercial application by 2010.

High temperature fuel cells, combined with a gas turbine and deployed in a distributed generation manner offer the highest energy efficiency and the greatest opportunity for mitigation of greenhouse gas emissions. Mass produced, modular SOFC units offer the best current opportunity to achieve the cost reductions needed for the broad commercial roll-out of fuel cells in residential, commercial and industrial applications. Alberta, with its deregulated electricity sector, its growing distributed generation industry and its widespread distribution networks for natural gas and propane is an excellent market for the development of residential and small commercial SOFC systems.

Environmental Benefits of Fuel Cells and Distributed Generation

All things being equal, distributed generation permits a higher overall efficiency than centralized generation, because distributed generation avoids transmission and distribution losses, which are generally estimated to be about 10%. A recent analysis of power generation options was completed by Kinectrics in Ontario. A summary of the conclusions is provided in Table 7. Pressurized SOFC, combined with a gas turbine provides the highest electrical efficiency at 70%. A combined heat and power SOFC results in the highest overall energy efficiency at 85%, but the presence of an adequate base load heat demand is necessary.

The energy efficiency of fuel cells is higher than turbine and microturbines. Theoretically, the electrochemical reaction of a fuel cell is thermodynamically more efficient than the Carnot cycle. In addition, fuel cells convert chemical energy directly into electrical energy while combustion converts chemical energy first into mechanical energy and then into electrical energy. However, advanced gas turbine systems offer higher electrical efficiency than simple fuel cell systems. To achieve high levels of electrical efficiency, fuel cell systems need to be combined with gas turbine in order to converts the high quality heat into additional electricity through the gas turbine. The higher efficiency of fuel cells implies greater environmental benefits. .

Table 7 - Energy Efficiency and CO2 Emissions for Distributed Generation and Central Plant

	Central Plant			Distributed Generation					
				Gas Turbines			Fuel Cells		
	Coal	Natural Gas with Combustion Turbine	Oil	Simple Cycle	Advanced Recuperated Turbine	Combined Heat and Power Plant	Atmospheric	Pressurized Fuel Cell Combined with Gas Turbine	SOFC Combined Heat and Power Plant
Fuel	Coal	Natural Gas	Oil	Natural Gas			Natural Gas		
Efficiency	35%	40%	37%	30%	40%	69%	50%	70%	85%
Transmission and Distribution Losses	10%	10%	10%	None	None	None	None	None	None
CO_2 Emissions (Gg/yr)	935	555	725	665	500	290	400	305	235
CO_2 Emissions Reduction vs. Central Coal Plant	-	40%	22%	29%	47%	69%	57%	67%	75%
Source: Kinectrics, 2002 [41]									

As shown on Table 7, fuel cells will result in less greenhouse gas emissions than the comparable combustion based system. Fuel cells also offer the additional environmental benefits of zero emissions of pollutants such as NO_x, SO_x and particulates

Industry Presence in Alberta

Global Thermoelectric of Calgary is developing 1 to 5 kW SOFC systems that can operate on natural gas and propane. Residential applications are being piloted in conjunction with Enbridge. Global's current RP2 system incorporates a modular approach to component design and layout, providing enhanced serviceability particularly around the fuel cell stack. Current development programs are focused on improving performance attributes such as durability and cost. Global's manufacturing pilot plant is used to develop low-cost production methods.

Global is anticipating a product launch of its initial commercial applications in the second half of 2005. Global's next generation natural gas fuel cell prototype, named Aurora should start prototype trials in 2003. The Aurora embodies improvements in performance, cost reduction and provides a stable and flexible platform, permitting 2 kW to 5 kW systems.

Global is collaborating on research projects with the University of Calgary and is supportive of the Western Canada Fuel Cell Initiative. Collaborative projects strengthen the SOFC R&D and commercialization cluster in Alberta.

In addition to Enbridge, Global has developed partnerships with other distribution partners in the United States and Canada such as Superior Propane, Citizens Gas, Suburban Propane, Bonneville Power Authority, and Montana-Dakota Utilities.

In August 2003, the board of Global Thermoelectric said it accepted a takeover offer from FuelCell Energy, a leading U.S. developer of MCFC that is involved a major U.S. Department of Energy project for coal gasification and using coal gas as feedstock for a MCFC. FuelCell Energy is described in the MCFC section of this report. FuelCell Energy intends to complete Global's SOFC development and to continue the relationship with Enbridge, possibly as a distributor because FuelCell Energy does not have any strategic alliances in Canada.

The proposed merger will allow Global SOFC products to participate in the Solid-State Energy Conversion Project (SECA), a US$139-million, 10-year initiative partly funded by the U.S. Department of Energy. FuelCell Energy and Global Thermoelectric are both developing high-temperature fuel cells and face many of the same challenges developing their power units. They complement one another in that regard. They also offer complementary products and the merger could be a good strategic fit.

7.4 SOFC for Alternative Fuels

In addition to the development of SOFC using natural gas and propane targeted at distributed generation in the residential and small commercial market, the opportunity exists to adapt low-cost, mass produced, modular SOFC technology to industrial applications involving the use of alternative fuels such as hydrogen containing off-gases, fuel gas mixtures coal gas, syngas, and digester gas, which is generated by city landfills and agricultural operations.

Alberta and other regions where the oil and chemical industries occupy a large place in the economy have an abundance of hydrogen present as a component in off-gas streams. These streams are currently used for fuel value and displace an equivalent amount of natural gas fuel. A list of hydrogen containing gas streams available in the Alberta Industrial Heartland is shown on Table 6.

Off-gases containing hydrogen mixed with other gases are opportunity fuels that are too small to justify the investment required for their exploitation by conventional means. The varying composition of these co-product gas streams and their distribution over a wide geographical area argues against the aggregation of the streams into central processing plants. Therefore, they are burned for fuel value. Fuel cells would allow the chemical energy present in these fuels to be converted into electrical power, thereby improving industrial efficiency and reducing greenhouse gas emission and air pollution. Combined power and heat, as well as cogeneration of power and steam could also be envisaged. Industrial plants that produce these co-product gas streams generally are also consumers of electricity, heat and steam Electricity deregulation in Alberta would allow power to be sold into the grid where economically justified. The modular nature of fuel cells would allow systems to be scaled to the size of each fuel stream. The technology of choice is SOFC and the development of such fuel cells would build on the existing SOFC expertise in Alberta.

Therefore fuel cells offer the opportunity to convert a co-product stream into useful forms of energy in a way that would exhibit very high overall energy efficiency because of the opportunity for combined utilization of power and heat or power and steam and because of the avoidance of the energy costs associated with the movement of hydrogen and electricity to and from a central processing plant.

7.5 Fuel Cells and Clean Coal

The Alberta Energy Research Institute (AERI) is already part of the Canadian Clean Power Coalition (CCPC) for the development of technologies for the production of electricity from coal with benign environmental impact. AERI is contributing $550,000 over three years for the first phase of the CCPC's planned development and construction of Canada's first "Clean Coal" power plant. The total cost for this phase is $5 million and is funded by a government/industry partnership. The first phase involves a feasibility study that includes detailed research and engineering studies leading to technology selection in 2004. The first complete Clean Coal demonstration plant is expected to be in operation in Canada in 2007.

The future power plants envisaged by this program would be large scale centralized power plants for converting coal into electricity with minimal or zero air emissions. The ability of these plants to co-generate heat or steam would be limited to the availability of on-site demand for large amounts of heat or steam. Heat and steam cannot be transported over distances of any magnitude. In effect, this technology development effort would result in the next generation of coal based electrical power plants.

Current Clean Coal technology development programs are based on Integrated Gasification Combined Cycle technology (IGCC). Advanced technology is used for gasifying coal into syngas and in turn converting the syngas into electricity in a gas turbine with the possible addition of a steam turbine to achieve higher levels of electrical efficiency. Coal is pulverized and fed to a gasifier. The gasification unit transforms coal into syngas which is a mixture of CO and hydrogen. Under conditions of high pressure and high-temperature and in the presence of a suitable catalyst, coal undergoes partial oxidation to CO which is further processed into hydrogen via the water gas shift reaction.

The gasification of coal into syngas is followed by the combustion of syngas in an advanced and energy efficient gas turbine system to generate electricity.

Fuel cell technologies would allow the replacement of the gas turbine by a fuel cell/gas turbine hybrid that would exhibit higher electrical efficiency and less air pollution than the gas turbine alone. Fuel cell/ gas turbine hybrids represent a superior power module option for gasification-based systems.

R&D projects in the United States and in Japan are targeted at utilizing coal gas as the fuel. The gas turbine elements of Clean Coal technology is replaced with a fuel cell/gas turbine hybrid. The objective is to produce a higher level of electrical efficiency and to avoid the air pollution associated with combustion reactions in a fired gas turbine. The United States Department of Energy is funding a large-scale trial of a MCFC that will be fueled by the coal gas produced by an existing coal gasifier at the Wabash River site in Indiana. This 260-megawatt power facility is the largest plant of its type to operate in a fully commercial setting. It uses Integrated Gasification Combined Cycle (IGCC) to generate electricity. Rather than burning coal directly, the plant first converts the coal into a combustible syngas. Then the syngas is burn in a high-efficiency gas turbine. The fuel cell planned for the Wabash River plant will be a two-megawatt MCFC from FuelCell Energy and will be the largest to be fueled by syngas made from coal.

Pressurized high temperature fuel cells offer an option for low cost CO_2 recovery and disposal. In combustion systems, a large amount of air is required and CO_2 produced is diluted by the presence of nitrogen and excess air. In the SOFC, CO_2 is produced in the anode compartment. With a pressurized system, CO_2 is available at a high partial pressure in the anode exhaust. When using coal derived syngas (hydrogen and CO) as the fuel in the SOFC, both the hydrogen and the CO react directly in the anode compartment with pure oxygen transported through the electrolyte and form CO_2 and water. Cooling and condensation remove water and a pressurized and concentrated CO_2 stream is immediately available for sequestration. The CO_2 can be further compressed to the pressure required for sequestration. Compression requirements are less for pressurized SOFC hybrids.

A demonstration of SOFC with CO_2 recovery is planned by Norske Shell and Siemens Westinghouse in Norway. In combination with coal gasification, this approach could potentially provide the lowest cost route for CO_2 mitigation.

Coal, asphaltenes, residual oil, and petroleum coke-based Integrated Gasification Combined-Cycle (IGCC) technology is beginning to penetrate the base load power generation market. While hybrids will find initial application in the distributed generation market, they must ultimately be integrated into coal-based, 100+ megawatt central power generation systems to fully realize their efficiency and environmental performance potential. In the longer term, the hybrids will be linked to gasification technologies capable of converting coal, biomass, and solid waste feedstocks to clean synthesis gas. These gasification linked hybrids will support central power applications.

The benefits offered by fuel cell/gas turbine hybrids justify their inclusion in the Canadian Clean Power Coalition technology program.

7.6 Hydrogen Sulfide Fuel Cells

Sulfur is a frequent contaminant in the hydrocarbon natural resources present in Alberta. Natural gas is often contaminated with varying amounts of hydrogen sulfide gas. Oil and bitumen contain chemically bound sulfur that is removed by upgraders and refineries as hydrogen sulfide gas. Current practice is two either convert hydrogen sulfide to sulfur using the Claus chemical process or to re-inject hydrogen sulfide into geological formations. In either case, the chemical energy contained in hydrogen is lost. At the R&D stage at the University of Alberta, fuel cells have been developed that can convert pure hydrogen sulfide into electrical energy, water and sulfur. Engineering and commercialization of this fuel cell technology would in effect transform a widespread pollutant into a natural resource for Alberta.

There are aspects of the technology that need to be explored further. At first brush, it appears that the market in Alberta for hydrogen sulfide fuel cells would be limited because all of the Claus plants have been built and because the Western Canadian Sedimentary Basin is maturing. However, electrocatalysts that convert H_2S into power should be viewed as a technology platform that could be deployed in different ways:

- ✓ Claus units simply remove sulfur from effluents and do not create value from the chemical energy of H_2S. As a result, sour gas wells with high H_2S content are shut-in. A H_2S fuel cell may be the tool required to exploit these wells.

- ✓ SOFC and PEMFC do not tolerate H_2S very well. It is possible that H_2S fuel cells could be used to remove H_2S from hydrocarbon streams ahead of the fuel processor in SOFC and PEMFC systems, or that the H_2S electrocatalyst could be incorporated into the anode structure of other fuel cell technologies.

7.7 DMFC and Micro SOFC for Portable Applications

Another area where fuel cells are expected to play a prominent role is in portable devices like computer laptops, video cameras and cell phones. Laptop computers, camcorders and cell phones suffer performance restrictions because of the limited energy storage and life of rechargeable batteries. Fuel cells can offer longer operating times than rechargeable batteries because energy supply is independent of power generation. In other words, fuel cells can be re-fueled.

The important competitive advantage of fuel cells for portable application is their capability for extended energy storage. Batteries have an energy density of 0.13 kWh/l. By comparison, methanol contains 4.2 kWh/l and hydrogen compressed at 300 bar, 0.4 kWh/l. [24]. Fuel cells permit the use of methanol or hydrogen which offer respectively 30 and 3 times the energy density of batteries. Methanol fuel cell systems have ten times the power of lithium batteries, and one cell could power a laptop computer for hours.

Fuel cell technology was adapted to allow the use of methanol in addition to hydrogen. In consumer applications, methanol is easier to handle and safer than hydrogen. Cartridge type refueling would provide for a convenient distribution system for methanol. Direct Methanol Fuel Cells (DMFC) draw their power from methanol without the need for a reformer. The system draws in methanol from a cartridge and oxygen from the air. It emits water, likely collected in a bladder and returns to the atmosphere a small amount of carbon dioxide.

These aspects of DMFC make them attractive for consumer applications and could allow DMFC to break into the growing rechargeable battery market. However, achieving the potential for DMFC in portable applications will require solutions to technical challenges. Ambient temperature air-breathing DMFC have low power density which limits their usefulness in applications that require either a very compact design, such as cell phones or high power densities, such as power tools. Methanol crossover problems need to be resolved in order to increase reliability and durability. Water balance in micro fuel cells remains a challenge and convenient solutions need to be found for water disposal.

The opportunity for DMFC applications in Alberta does not appear as promising as distributed generation stationary power. Methanol production has been decreasing in Alberta. Methanex has closed part of its production capacity in Medicine Hat. The reason is the relatively high cost of natural gas in North America and Alberta. Methanex is able to produce methanol from low cost stranded natural gas reserves in regions that are far from populated areas and for which pipeline construction is prohibitive. Methanex produces methanol in Chile and New Zealand. Therefore, DMFC for stationary generation of electric power to not appear to be a good fit with the situation in Alberta because the Province does not have a cost advantage for the production of methanol.

DMFC for portable applications are not directly related to the availability of low cost methanol. Direct methanol micro fuel cells are battery replacement applications in electronic devices. While there is not a large presence of the electronic, telecommunication and computer industry in Alberta, the Province has diversified its economy and the wireless industry is well positioned in Calgary. Light manufacturing is advantaged in the Edmonton Calgary Corridor. Several studies continue to indicate the fact that Alberta is a competitive jurisdiction for manufacturing industries. Indeed industrial diversification and value-added manufacturing have been growing in the province in several sectors, including geomatics and wireless networks.

For example, the recent study of the Calgary-Edmonton Corridor by TD Bank indicates that the Corridor is the only Canadian urban centre to amass a U.S.-level of wealth while preserving a Canadian-style quality of life. At nearly US$40,000, GDP per capita in the region is about 10 per cent above the average of U.S. metropolitan areas, and a respectable 40% above its Canadian colleagues. The Corridor has one of the strongest growths in both real GDP and population increases in North America over the last decade.

Alberta has for years consistently presented a number of advantages for business, manufacturing and entrepreneurship:

- ✓ The lowest overall taxes in Canada
- ✓ No provincial sales tax (the only province in Canada without one)
- ✓ No general capital or payroll taxes prevalent in other provinces and US states
- ✓ A highly entrepreneurial and competitive business community
- ✓ A government committed to less regulation to enhance business competitiveness
- ✓ A fiscally responsible government that has eliminated its net debt
- ✓ A highly skilled, educated, and motivated workforce that is the most productive in Canada
- ✓ A strong science and technology culture
- ✓ World-class infrastructure to support business, including transportation, telecommunications, and utilities, as well as excellent hospitals, schools, and post-secondary institutions.

The outcome has been a rapidly growing manufacturing base in Alberta. Between 1992 and 2002, manufacturing industry shipments increased 117 per cent to $41.0 billion.

In the last few years, Alberta's electronics industry has become one of the fastest growing and largest sectors in the province's economy. Over the past 10 years industry revenues have increased from $800 million to $5.5 billion. In the same time period, the number of electronic companies operating in Alberta has grown from 100 to about 250. The sector now employs close to 10,000 highly educated and qualified people. Electronics manufacturing activity accounts for over five per cent of Alberta's economy, with real output expected to increase by two to three per cent in the near future.

Almost 80 per cent of Alberta homes and businesses are connected to computer networks and the Internet. Fiber optic cable constitutes a significant proportion of land line networks in the Province. Alberta has the highest proportion of households in Canada making regular use of the Internet (45 per cent). It also has the highest rate of households with computers (63 per cent), telephones (99 per cent) and cellular phones (51 per cent).

DMFC appear to be the technology of choice for portable applications because of the ability to start quickly and because methanol is a safer and easier fuel to handle at the consumer level. DMFC and micro fuel cell developments are presently at the emerging stage at the Alberta Research Council. Emerging technology development efforts are also occurring in Vancouver. Laptop computers and video cameras are the relatively easier applications for micro fuel cells. Small transportation applications such as forklift trucks and wheel chairs are also being developed. A promising application is chargers for rechargeable batteries for service in remote locations. Users of such devices would be forestry crews, search and rescue operations and the military.

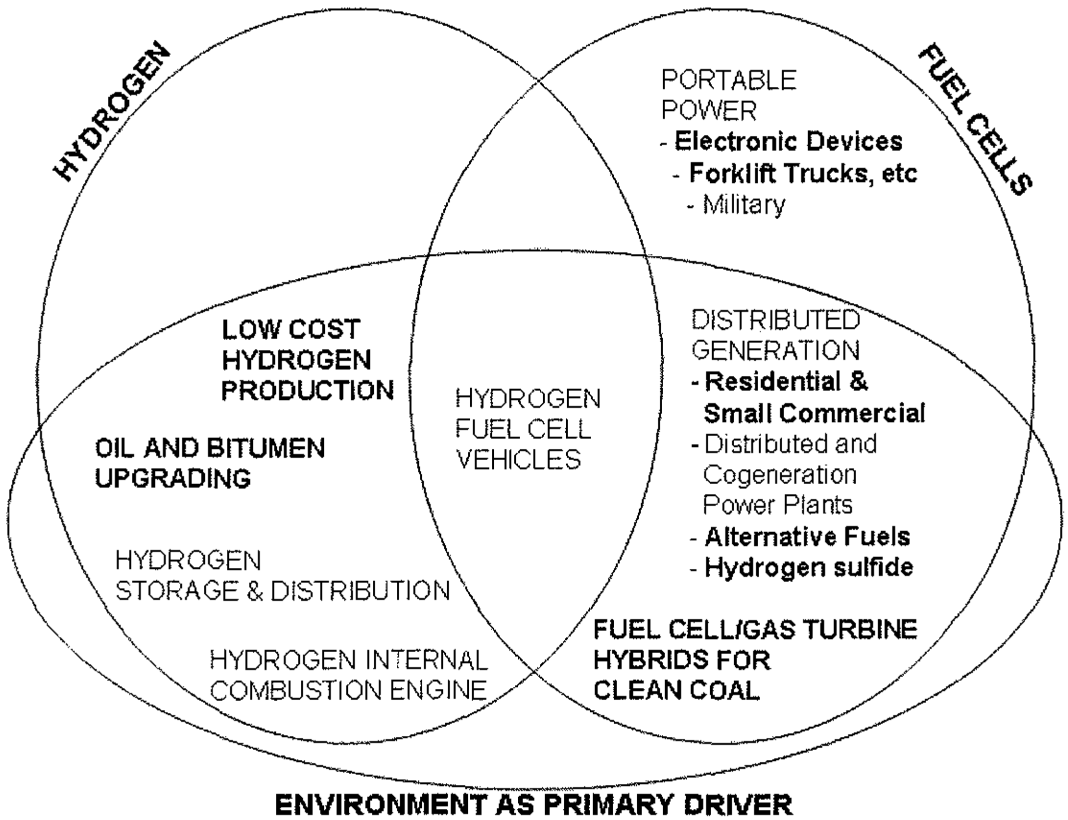
DMFC technology for portable applications may build on the low cost environment for manufacturing industries in Alberta but it is difficult to predict how the future of these developments will evolve.

8 Alberta Niches in the Hydrogen and Fuel Cell Technologies

The recommended niches for Alberta in the area of hydrogen and fuel cells are shown on Figure 8. They are based of the competitive advantages currently existing in the Province. They are primarily supported by the dominant presence of the energy industry in Alberta. The following market and technology niches are recommended:

- ✓ Increased hydrogen production from low value feedstocks
- ✓ SOFC for distributed generation in the residential and small commercial markets
- ✓ Fuel cell/gas turbine hybrids for Clean Coal
- ✓ Fuel cell systems for alternative fuels available in Alberta
- ✓ Hydrogen sulfide fuel cells
- ✓ DMFC and micro-SOFC for portable power

Figure 8 – Hydrogen and Fuel Cell Market Segments
(Alberta market segments shown in bold)



8.1 Increased Hydrogen Production from Low Value Feedstocks

Technologies should be developed to produce hydrogen from the vast quantities of low value fossil feedstocks that are present in Alberta. In particular, gasification of asphaltenes appear to be the most promising approach because liquid feedstocks require lower capital expenditures than solid feedstocks and because rejected asphaltenes are readily available from bitumen recovery operations. Hydrogen could also be produced by adapting in-situ combustion technology to abandoned oil wells.

Value:

- ✓ Hydrogen is a strategic technology for environmentally friendly vehicles.
- ✓ Hydrogen addition is the dominant technology for producing cleaner oil energy products from crude oil and bitumen.

Rationale for Alberta:

- ✓ The United States is Alberta's largest export market for energy products. The U.S. is implementing cleaner gasoline and diesel regulations that will require additional hydrogen treatment of Alberta oil products.
- ✓ The U.S. is implementing a strategy to use hydrogen as a primary energy carrier in order to reduce air pollution from motor vehicles, to curb greenhouse gas emissions and to increase energy supply security.
- ✓ Alberta is a leading jurisdiction for hydrogen production and utilization. Alberta refineries and upgraders manufacture hydrogen for addition to bitumen and heavy oil for the production of synthetic crude oil. Alberta currently exports hydrogen as contained hydrogen in synthetic crude oil.
- ✓ Increasing the hydrogen content of Alberta oil products improves their performance with respect to environmental requirements. Oil products with improved environmental performance are expected to be in increased demand in the future.
- ✓ Alberta has the opportunity to develop a North American competitive cost advantage with respect to the production of hydrogen. U.S. refineries may produce hydrogen and upgrade Alberta bitumen in the U.S. However, the current preferred route for hydrogen production is steam reforming of

methane. The relatively high prices forecasted for natural gas for the coming decade will increase the cost of producing hydrogen from natural gas. Alberta's potential future advantage lies in the presence of vast amounts of currently low value feedstocks in the vicinity of the refineries and upgraders in the Alberta Industrial Heartland and in Fort McMurray. Low value feedstocks such as asphaltenes rejected during the upgrading process can be gasified into hydrogen. OPTI Canada and Nexen are planning to build an asphaltenes gasifier integrated with the bitumen upgrading process. The presence of low value feedstocks near Alberta upgraders offers the opportunity to increase hydrogen production from low cost non-conventional feedstocks, and to increase the hydrogen content of Alberta oil exports.

- ✓ Production of hydrogen from low value hydrocarbons could be designed to co-produce syngas as well as hydrogen. Syngas could be used locally in Alberta by industrial users in Fort McMurray and in the Alberta Industrial Heartland. Syngas from low value hydrocarbons may become a low cost natural gas substitute for the Alberta energy industry and may free up additional volumes of natural gas for export to the United States.

Actions:

- ✓ Support research and development projects for the production of hydrogen by gasification of low value feedstock such as asphaltenes.
- ✓ Support research and development projects for the production of hydrogen by in-situ gasification of abandoned oil wells.
- ✓ Support research and development projects for improved and novel catalysts for hydrogen addition to bitumen and heavy oil.

8.2 SOFC for Distributed Generation in the Residential and Small Commercial Markets

An industry should be promoted in Alberta for the development and commercialization of mass produced SOFC modules for combined heat and power distributed generation in the residential and small commercial markets. These modules will use natural gas or propane as fuels: Global Thermoelectric in Calgary and companies in the United States and Europe are developing manufacturing technology and products for this segment. Electricity deregulation in Alberta has permitted the development of the distributed generation industry in the Province. The natural gas and propane distribution infrastructures are well developed in Alberta. SOFC would provide higher energy conversion efficiency and less associated greenhouse gas emissions and air pollution than combustion in space heating furnaces or microturbines. In addition, fuel cells are expected to be low noise and low maintenance devices. Demonstration programs sponsored by government would assist with early market development.

The principal market segment of this niche is SOFC systems for small-scale combined heat and power generation. These systems are designed for residential and small commercial application. They are in the one to 10 kW capacity range. They are designed to use readily available fuels such as natural gas and propane. Global Thermoelectric in Calgary is developing such a system in partnership with Enbridge, Superior Propane, and several other U. S. based distribution partners.

Value:

- ✓ Fuel cells offer the potential for higher energy conversion efficiency and lower environmental emissions than combustion-based technologies such as microturbines.
- ✓ Combined power and heat generation permit very high overall energy efficiency.
- ✓ Distributed generation provides additional energy efficiency at the system level by avoiding transmission losses.

Rationale for Alberta:

- ✓ Presence in Alberta of companies that are developing SOFC for distributed generation, such as Global Thermoelectric and their suppliers and partners

- ✓ Presence in Alberta research and development groups with expertise in SOFC such as the Alberta Research Council, the University of Alberta and the University of Calgary
- ✓ Deregulation of the Alberta electricity industry
- ✓ Presence in Alberta of NewERA, the industry association for distributed power generation
- ✓ Opportunity for a "new to the world" industry niche, combining new fuel cell technology with innovative business models and marketing approaches.

Action:

- ✓ Support relevant research and development projects of the WCFCI
- ✓ Support efforts to develop the distributed energy generation industry in Alberta
- ✓ Develop programs to support early adopters of SOFC for distributed power generation
- ✓ Support programs to demonstrate and prove relevant technologies and market applications. An example would be SOFC in community centers for combined heat and power and back-up power in the event of community emergencies.

8.3 Fuel Cell/Gas Turbine Hybrids for Clean Coal

The gasification of coal is a key platform technology. The concept of using fuel cell gas turbine hybrids rather than turbines for the conversion of coal gas into energy opens up new possibilities for the development of gasifiers.

Development of fuel cell systems for coal gas should be made part of AERI's contribution the Canadian Clean Coal Coalition and possibly Clean Coal programs in the United States and Japan. Alberta should join forces with a development program that is already underway and seek to contribute to it new R&D projects executed in Alberta. For example, researchers in Alberta, with AERI support could develop new catalysts for low BTU syngas that would be a useful contribution to the Canadian, U.S. or Japanese program.

Value:

- ✓ Integrated Gasification Combined Cycle (IGCC) is recognized as a promising technology to exploit coal while minimizing emissions.
- ✓ Hybrid approaches involving high temperature fuel cells (MCFC and SOFC) with gas and steam turbines (FC/GT) offer opportunities for additional improvements in electrical efficiency as compared to IGCC
- ✓ Hybrid FC/GT approaches offer opportunities for the recovery and sequestration of concentrated CO2 streams.

Rationale for Alberta:

- ✓ Coal is a substantial natural resource in Alberta.
- ✓ Technology that would allow the exploitation of coal in an environmentally friendly manner is of strategic value to Alberta.

Actions:

- ✓ Seek opportunities for partnership with technology world leaders in hybrid FC/GT, such as participants in U.S. Department of Energy programs and in Japan.
- ✓ Support research and development projects for the utilization of coal gas in high temperature fuel cells.

8.4 Fuel cell systems for alternative fuels available in Alberta

Fuel cell systems should be developed for the utilization of alternative fuels such as "dirty" hydrogen, gas mixtures containing hydrogen, off-gas, syngas, fuel gas, digester gas and other opportunity fuels. This technology and market niche is an extension of the SOFC for distributed generation applied to the industrial market and taking advantage of opportunity fuels present in the Alberta energy and chemical industry, as well as landfill and agricultural gases.

Value:

- ✓ Fuel cell systems that can utilize "dirty" hydrogen and hydrogen diluted with other chemicals would provide the opportunity to increase the overall energy efficiency of industry.
- ✓ Greenhouse gas emission reduction and lower air pollution as a result of using electrochemical conversion instead of combustion

Rationale for Alberta

- ✓ There exist in Alberta a substantial number of co-product gas streams that contain hydrogen with varying levels of purity. Off-gases containing hydrogen mixed with other gases are opportunity fuels that are too small to justify the investment required for their exploitation by conventional means. Therefore, they are burned for fuel value.
- ✓ Fuel cells would allow the chemical energy present in these fuels to be converted into electrical power, thereby improving industrial efficiency and reducing greenhouse gas emission and air pollution.
- ✓ Electricity deregulation in Alberta would allow power to be sold into the grid where economically justified. The modular nature of fuel cells would allow systems to be scaled to the size of each fuel stream in a distributed generation manner.
- ✓ The technology of choice is SOFC and the development of such fuel cells would build on the existing SOFC expertise in Alberta.

Actions:

- ✓ Support research and development projects for the utilization of alternative fuels in SOFC, building on technology developed for natural gas and propane.

8.5 Hydrogen sulfide fuel cells:

Based on basic technology developed in Alberta, fuel cell systems should be optimized and engineered to used hydrogen sulfide gas.

Value

- ✓ Extraction of the chemical energy of hydrogen sulfide for useful purposes
- ✓ No greenhouse gas emissions

Rationale for Alberta

- ✓ The presence of substantial amounts of hydrogen sulfide in Alberta gas wells and the continuous production of hydrogen sulfide by oil refineries and upgraders justify the further investigation and development of an emerging fuel cell technology to capture the chemical energy of hydrogen and convert it into electricity.
- ✓ While the deployment of fuel cell to replace existing and functioning Claus units would not represent a large opportunity, electrocatalysts that convert H_2S into power should be viewed as a technology platform that could be deployed in other ways:
- ✓ Claus units simply remove sulfur from effluents and do not create value from the chemical energy of H_2S. As a result, very sour gas wells are shut-in. A H_2S fuel cell may be the tool to exploit these wells.
- ✓ SOFC and PEMFC do not tolerate H_2S very well. It is possible that H_2S fuel cells could be used to remove H_2S from hydrocarbon streams ahead of the fuel processor in SOFC and PEMFC systems, or that the H_2S electrocatalyst could be incorporated into the anode structure of other fuel cell technologies.

Actions:

- ✓ Support research and development for the optimization and engineering of fuels that use hydrogen sulfide.

8.6 DMFC and Micro SOFC for Portable Power

DMFC: while at an early stage, these developments may hold the promise for the growth of value-added manufacturing in Alberta. The Alberta Research Council is focusing on applications such as forklift trucks with its partner EVI.

Micro SOFC: The μSOFC technology being investigated by ARC is in the early stage of development. It appears to hold significant promises for developing efficient, low-cost SOFC systems. Fuel cell research is a long-term endeavour and may require significant investment. If portable applications of μSOFC can be commercialized first, it may help to build a cluster in Alberta and create a bridge to applications involving Alberta natural resources. The μSOFC technology may also hold the potential for SOFC in distributed generation applications that would need considerably less space to operate. In addition, the electrophoretic deposition technology could be extended into separation membranes and catalytic surfaces.

Value:

- ✓ Significant competitive advantage over rechargeable batteries because of the large energy capacity of fuel cells.
- ✓ Many electronic devices and portable equipment are limited by the short life of batteries

Rationale for Alberta:

- ✓ Opportunity to build on recent growth of the manufacturing and electronics industries in Alberta.
- ✓ The Edmonton-Calgary Corridor is one of the fastest growing industrial clusters in North America.

Actions:

- ✓ Support research and development in portable fuel cell applications.

9 Research and Market Development

9.1 Research and Development

The Western Canada Fuel Cell Initiative has identified two major research thrusts that are well aligned with the business development opportunities open to Alberta:

- ✓ **Integrated energy systems:** The WCFCI focuses on the applications of fuel cells for power generation using alternative fuels such as asphaltenes, coal, coke and biomass. This objective builds strongly on the existing competencies at the University of Calgary, the University of Alberta, the University of Saskatchewan and the University of Manitoba. It also involves key competencies within the Alberta Research Council, the Saskatchewan Research Council and Manitoba Hydro.
- ✓ **Enhanced science base for fuel cells:** The development of a much stronger scientific base than currently exists is required to fully exploit the potential for fuel cells, including their relationship to the hydrogen economy. This enhanced science base for fuel cells would involve work on nano-structured electrodes and membranes, work on developing materials with more robust potential for dealing with degradation phenomena caused by corrosion and impurities, and would bring together modeling expertise at the molecular, micro-, and macro- levels dealing with a spectrum of fuel systems from hydrogen, methanol/ethanol right through to the syngas and biogas aspects that are part of the objective.

Other research areas relevant to the Alberta situation are:

- ✓ **Hydrogen storage in carbon nanotubes** should be investigated in partnership with the National Institute for Nanotechnology
- ✓ **Co-production of chemicals** and electricity using fuel cells
- ✓ **Direct oxidation of methane** at the anode surface in SOFC.

One role for government is to remove part of the risk associated with long-term R&D. Government support for the WCFCI would be instrumental to the implementation of research projects aimed at reducing the cost of fuel cells and at improving their performance.

9.2 Networking Opportunities for Fuel Cell Applications and Demonstrations in Alberta

The potential stakeholder community that would be interested in fuel cells is potentially large in Alberta, particularly for distributed generation. Potential stakeholders include organizations already active in fuel cells such as universities, government institutes and laboratories, fuel cell developers and component suppliers. However, fuel cells could appeal to a much broader stakeholder group that could include power companies, oil and gas companies, chemical and petrochemical producers, town and cities, forestry facilities and Northern and remote locations.

It would be fruitful to create networking opportunities for this broad stakeholder group for awareness and education purposes. Increased communications would also allow high-value demonstration projects to be identified by bringing interested parties together.

9.3 Networking Opportunities for Canadian Fuel Cell Researchers

Canada is one the recognized leaders in fuel cell research and commercialization, along with the United States, Germany and Japan. The Western Canada Fuel Cell Initiative appears to be a very useful vehicle to increase communication and collaboration between researchers. The continuation and possible extension of this initiative to other provinces would be useful. However this raises the issue of permanent administrative support and funding.

In addition, the organization of a Canadian fuel cell and hydrogen scientific symposium associated with other industry conferences or with one of the annual meeting of the Chemical Institute of Canada would also provide rich opportunities for exchange of ideas, improved communication and enhanced collaboration.

9.4 Market Development

Hydrogen Re-Fueling Station in the Alberta Industrial Heartland

The opportunity exists for a hydrogen vehicle trial and associated hydrogen refueling station in the Alberta Industrial Heartland, north of Edmonton. In particular, Alberta Envirofuel has a co-product stream of 100 kg/hour of 99% pure hydrogen. This stream presents a specific opportunity and could be used to supply a hydrogen re-fueling station for a demonstration of hydrogen vehicles in the Edmonton area. There currently no hydrogen and fuel cell infrastructure projects in Alberta and this opportunity could be used to fill a critical gap. The Canadian Transportation Fuel Cell Alliance (CTFCA) could be a partner in an Alberta demonstration of a hydrogen re-fueling station using technology from Calgary-based Dynetek.

Scoping Study for Delivering Hydrogen to the United States

A scoping study should be conducted of the economic and environmental merits of various methods for converting Alberta's vast hydrocarbon resources into hydrogen, in the event of an evolution to the widespread use of hydrogen in North America. Hydrogen supply to the United States is a long-term strategic issue for Alberta. It warrants further analysis of eventual scenarios for delivering hydrogen to the United States such as:

- ✓ Produce hydrogen in Alberta, aggregate it and ship it by pipeline to the U.S., should the United States build a hydrogen pipeline infrastructure.
- ✓ Produce natural gas and ship natural gas to the United States using the existing pipeline infrastructure. Natural gas is converted to hydrogen at on-site reforming, storage and refueling centers in the United States.
- ✓ Produce electricity in Alberta using zero/low emission technologies such as Clean Coal and export electricity to the United States. In the U.S., electricity is used to produce pure hydrogen by electrolysis at refueling stations.

10 Recommendations

10.1 Energy Innovation Network - Hydrogen & Fuel Cells

While providing support for research and development projects, the primary focus of the Energy Innovation Network will be innovation and technology dissemination in the areas of hydrogen and fuel cells. It will need to build on the existing Alberta cluster and provide it with strategic direction, integration, and resources. It should be based on leading edge science, deep market knowledge, and outstanding business skills.

Rationale for Hydrogen Innovation in Alberta

- ✓ Cleaner energy products are a requirement for continued access to world markets and a stake in the perceived direction of the U.S. energy market.
- ✓ Should the delivered form of energy evolve from oil & gas to hydrogen or products with high hydrogen content, Alberta needs to ensure that it can produce and deliver the energy products demanded by North American markets by utilizing Alberta natural resources.
- ✓ Hydrogen is used in Alberta for treating and upgrading crude oil and crude bitumen from the oil sands. Hydrogen treatment removes sulfur and nitrogen contaminants and is a value added step in the production of higher-priced, cleaner, transportation fuels.
- ✓ The combination of increased demand for hydrogen and expected higher natural gas costs creates an opportunity for Alberta to invest in the development of technologies to produce hydrogen at a lower cost by utilizing low value hydrocarbon feedstocks, such as asphaltenes, coal, petroleum coke, and possibly abandoned oil wells.

Rationale for Fuel Cell Innovation in Alberta

- ✓ Worldwide technology development efforts in fuel cells will deliver devices that will offer compelling advantages as compared to other energy conversion devices, whether the fuel originated from a fossil, renewable, or nuclear source:
    - o The electrochemical process is inherently more efficient than combustion at converting chemical energy into electricity.

- Fuel cells are more scalable than combustion systems and can capture additional energy efficiencies through deployment in distributed generation approaches by avoiding losses in transmission and by utilizing fuel streams that are too small or too far for combustion systems.
- Fuel cells are quiet and will require less maintenance as compared to internal combustion engines and turbines, and are therefore more suitable for back-up and supplementary power applications in residential and isolated areas.
- The existing fuel cell cluster in Alberta is developing applications that will increase the useful energy extracted from Alberta natural resources, whether oil or coal, and that will create value-added products and manufacturing opportunities for Alberta.

Start-Up Business Plan

The existing Alberta hydrogen and fuel cell cluster is well developed and will be the foundation of the Energy Innovation Network. R&D groups are active at the University of Alberta, the University of Calgary and at the Alberta research Council, delivering new technologies and graduating highly qualified people. NAIT is establishing a training and demonstration centre. Companies such as Global Thermoelectric, Enbridge, Sustainable Energy Technologies, Westaim Ambeon and Energy Visions are developing products and markets. Power companies are participating in Clean Coal developments and may become important producers of hydrogen. Government agencies such as AERI, NRC, IRAP, NRCan, WEDC, and AIF have provided resources to high value projects.

The creation of the Energy Innovation Network for Hydrogen and Fuel Cells will be a major step forward but will require sustained efforts in the initial stage until momentum is achieved. During the start-up period, government agencies are expected to play a leading facilitating role. The following plan provides for the start-up of the Energy Innovation Network for Hydrogen and Fuel cells.

1. Creation of Start-Up Consortium

Government agencies agree to collaborate to provide support and resources to the start-up of the Energy Innovation Network for Hydrogen and Fuel Cells. This initiative is well aligned with the mandate of AERI, NRC, IFCI, NRCan, and WEDC.

Resources can be cash and in-kind. In-kind contributions are for the provision of personnel and office space. Cash contributions are used to pay expenses.

2. Small Administrative Office

The Start-Up Consortium agrees to set-up a small office for the management and administration of Energy Innovation Network for Hydrogen and Fuel Cells. It is administered by a program officer assisted by support staff. The individual is likely to be a member of AERI, NRC, NRCan or WEDC located in Alberta. In the initial stages, this is likely to be a part-time assignment.

The role of the office is to:

- ✓ Provide focus, integration and organization.
- ✓ Recruit contributing members such as Enbridge, Global Thermoelectric, Energy Visions, Sustainable Energy Technologies, Westaim Ambeon, TransCanada, TransAlta, Epcor, Suncor, Shell, EnCana, PetroCanada, Imperial, Nexen, Syncrude, etc.
- ✓ Recruit members for the Advisory Committee
- ✓ Organize and manage networking and training activities
- ✓ Organize and manage innovation project activities

3. Executive Committee

The Executive Committee is responsible for the Energy Innovation Network for Hydrogen and Fuel Cells. It is composed of all contributing members, whether contributions are cash or in-kind. The role of the Executive Committee is to:

- ✓ Retain and supervise the program officer.
- ✓ Approve the legal framework for the Energy Innovation Network for Hydrogen and Fuel Cells and future amendments.
- ✓ Set membership fees.
- ✓ Approve membership applications

- ✓ Approve Advisory Committee membership.
- ✓ Approve the strategy, business plan and operating budget.

4. Advisory Committee

The program officer forms the Advisory Committee to provide guidance to the Energy Innovation Network for Hydrogen and Fuel Cells. The role of the Advisory Committee is to provide strategic direction and integration. It ensures that the operations of the Energy Innovation Network for Hydrogen and Fuel Cells are based on leading edge science, deep market knowledge, and outstanding business skills.

The Advisory Committee is composed of representatives of the founding government agencies, of each contributing member, of providers of R&D, and of leading international experts.

5. Networking and Training Activities

The program officer and support staff propose, organize and implement networking and training activities such as:

- ✓ Networking opportunities for the broad fuel cell and hydrogen stakeholder group in Alberta.
- ✓ The organization of a Canadian fuel cell and hydrogen scientific symposium, associated with other scientific conferences.
- ✓ Cross-appointments for researchers between research and educational institutions such as IFCI, NINT, ICPET, NCUT, IMI, U of C, U of A, ARC and NAIT. This would provide easier access to laboratory facilities for researchers and increase multi-disciplinary collaboration between institutions.
- ✓ Coordinate and exchange information regarding international conferences and technology watch activities.
- ✓ Sponsor Alberta and Canadian delegations to international events in hydrogen and fuel cells.

6. Innovation Project Activities

Achieving a significant and valuable portfolio of innovation projects is one of the core objectives of the Energy Innovation Network for Hydrogen and Fuel Cells. This element will require the prior set-up of the Executive Committee and of the associated funding. Based on the approved strategy, business plan and operating budget the program officer administer the project selection and implementation process:

- ✓ Solicit project proposals from R&D providers
- ✓ Managed the competition process
- ✓ Oversee disbursements within budget limits
- ✓ Identify opportunities for co-funding by other programs such as IRAP, NSERC, COURSE, SDTC, Environment Canada, NRCan, etc.
- ✓ Identify opportunities for collaboration on specific projects between academic institutions and IFCI as a non-academic partner. IFCI would provide in-kind contributions through the use of hydrogen safe laboratories and fuel cell test stations.
- ✓ Oversee the evaluation of performance reports and audits
- ✓ Report to the Executive and Advisory Committees.

Strategy

Hydrogen is a clean energy carrier that offers benefits similar to electricity in that it causes no local air pollution. It is also a strategic enabler for renewable energy sources to be made available to vehicles such as cars, busses and trucks. For these reasons, hydrogen is the object of considerable research and development worldwide, particularly in the United States, Europe and Japan.

Fuel cells are inherently more efficient than the equivalent combustion system such as the internal combustion engine and gas turbines. In addition, fuel cells emit significantly less greenhouse gas and air pollutants than combustion systems. As compared to turbines, and particularly micro turbines, fuel cells offer the benefit of having virtually no moving parts and the associated expectation of higher reliability. Fuel cells are flexible and scale to the desired capacity by adding together the required number of fuel cell units. While turbine systems achieve economies of scale through the design of large central facilities, fuel cells are expected to achieve cost reduction through the mass production of standardized fuel cell units.

The strategy for Alberta in the area of hydrogen and fuel cells should focus on the more efficient conversion of Alberta natural resources into cleaner forms of energy.

Alberta natural resources such as gas, oil and coal are of fossil origin and are non-renewable. From an environmental perspective, renewable resources such as hydro and wind would be preferred. However, in the near and medium-term, fossil energy will be required to supply anticipated demands. The contribution to a better environment that can be made by producers of fossil energy is to produce cleaner fossil energy more efficiently. From the perspective of environmental policy, cleaner fossil energy products are an unavoidable bridge technology to a future where renewable energy could dominate. Utilizing fossil fuels to produce hydrogen and to power fuel cells does not impede in the development of an eventual hydrogen economy. On the contrary, cleaner fossil energy products have a positive environmental impact in the near term and they are likely to facilitate the development of a hydrogen economy by establishing a hydrogen and fuel cell infrastructure that, in time, could be migrated from fossil energy to renewable energy sources. If zero a mission renewable energy is the ultimate destination, cleaner fossil energy products certainly are a valuable practically achievable intermediate destination.

From an Alberta perspective, cleaner fossil energy products are a requirement to maintain access to a North American market that mandates increasingly strict environmental regulations. Hydrogen and fuel cells are emerging technologies that offer considerable promise for cleaner fossil energy products and should therefore be a key platform in Alberta's energy technology strategy. Hydrogen is a clean energy carrier with benefits similar to those provided by electricity. Fuel cells are efficient and flexible energy conversion devices that are applicable to a wide range of applications. Both provide global and local environmental benefits because of higher levels of energy efficiency and because of the absence of the air pollutants produced by combustion. Higher energy efficiency mitigates the global problem posed by greenhouse gas emissions. The pollution free nature of hydrogen and fuel cells would dramatically improve air quality in densely populated areas and cities. In addition, certain fuel cell applications have value as backup power, battery replacement, and power supply in remote locations and for portable devices.

Hydrogen and fuel cell technologies are at the development stage at this point in time. They are the object of significant amounts of R&D worldwide, particularly in the

United States, Europe and Japan. A large number of significant demonstration projects are happening in the United States, in Europe, in Japan and in Canada. Governments worldwide provide a significant portion of the funding required in partnership with commercial organizations. Mass commercialization of the smaller size fuel-cell systems for portable applications and for distributed stationary power generation is expected within the next five years.

From a prospective of greater utilization of Alberta and natural resources, the benefits of fuel cells are:

- ✓ higher electrical efficiency than the equivalent internal combustion system or gas turbine system
- ✓ lower levels of greenhouse gas emissions as a result of higher energy efficiency
- ✓ none of the air pollution associated with combustion based systems
- ✓ can be fueled by widely available hydrocarbons such as natural gas and propane
- ✓ can be adapted to utilize alternative fuels such as coal gas, dirty hydrogen, digester gas and opportunity fuels
- ✓ applicability to distribution generation systems, thereby avoiding transmission and distribution losses
- ✓ applicability to combined heat and power applications for high overall energy efficiency
- ✓ applicability to cogeneration systems [power and steam] for high overall energy efficiency
- ✓ applicability to combined cycle [gas turbine and steam turbine] systems, or so-called triple cycle systems
- ✓ can be adapted to utilize hydrogen sulfide as the fuel, transforming a common pollutant into a valued resource
- ✓ have virtually no moving parts and promise higher reliability than turbine systems

Alberta Niches

- ✓ **Increased hydrogen production from low value feedstocks:** Hydrogen is a strategic technology for environmentally friendly vehicles because it is used to power fuel cell vehicles but also because hydrogen addition is the dominant technology for producing cleaner oil energy products from crude oil and bitumen. In particular for Alberta, asphaltenes which are currently a co-product waste from the recovery of oil sands bitumen should be a primary feedstock for the production of hydrogen. The U.S., Alberta's largest export market for energy products, is implementing cleaner gasoline and diesel regulations that will require additional hydrogen treatment of Alberta oil products. The U.S. is also implementing a strategy to use hydrogen as a primary energy carrier in order to reduce air pollution from motor vehicles. Increasing the hydrogen content of Alberta oil products improves their performance with respect to environmental requirements. Alberta has the opportunity to develop a North American competitive cost advantage with respect to the production of hydrogen. The relatively high prices forecasted for natural gas for the coming decade will increase the cost of producing hydrogen from natural gas. Alberta's potential future advantage lies in the presence of vast amounts of currently low value feedstocks in the vicinity of the refineries and upgraders in the Alberta Industrial Heartland and in Fort McMurray. The presence of low value feedstocks near Alberta upgraders offers the opportunity to increase hydrogen production from low cost non-conventional feedstocks, and to increase the hydrogen content of Alberta oil exports.

✓ **SOFC for distributed generation in the residential and small commercial markets:** SOFC is recognized as the most promising fuel cell technology for distributed stationary power generation. The high temperature characteristic of SOFC enables fuels such as natural gas, propane, coal gas and opportunity fuels to be reformed internally in the SOFC system. The high-quality heat produced by SOFC can be used to produce additional electricity with an associated gas turbine or can be used to produce steam for cogeneration applications. Planar SOFC offers the best prospects for the development of low-cost manufacturing technology than MCFC, the competing high temperature fuel cell technology, because planar SOFC can utilize manufacturing methods that are similar to those used to mass-produce electronic components. Widely available natural gas and propane fuels can be converted to electricity at the point of consumption. The primary benefit is capturing overall very high energy efficiency from combined heat and power applications. Additional benefits are backup power and security of supply.

- ✓ **Fuel cell/gas turbine hybrids for Clean Coal:** the Alberta Energy Research Institute is already part of the Canadian Clean power Coalition for the development of technologies for the production of electricity from coal with benign environmental impact. The production facilities envisaged by this program are large scale centralized power plants for converting coal into electricity with minimal or zero air emissions. The current technology development programs are based on advanced technology for gasifying coal into syngas and in turn converting the syngas into electricity in a gas turbine with the possible addition of a steam turbine to achieve higher levels of electrical efficiency. Fuel cell technologies would allow the replacement of the gas turbine by fuel cell/gas turbine hybrids that would exhibit higher electrical efficiency and less air pollution than the gas turbine alone. The benefits offered by fuel cells justify their inclusion in the Canadian Clean Power Coalition technology program.
- ✓ **Fuel cell systems for alternative fuels available in Alberta:** Alberta and other regions where the oil and chemical industries occupy a large place in the economy have an abundance of hydrogen present as a component in co-product gas streams. These streams are generally used for fuel value and displace an equivalent amount of natural gas. Fuel cells would allow capturing the chemical value of the hydrogen contained in the streams. The varying composition of these core product gas streams and their distribution over a wide geographical area argues against the aggregation of the streams into a central processing plant. Fuel cells able to convert the chemical energy of hydrogen in to electricity could be sized to each particular stream and

located where the stream is produced. The industrial plants that produce these co-product gas streams generally are also consumers of electricity, heat and steam. Therefore fuel cells offer the opportunity to convert a co-product stream into useful forms of energy. They would exhibit very high overall energy efficiency because of the opportunity for combined utilization of power, heat and steam and because of the avoidance of the energy costs of transporting hydrogen and electricity to and from a central processing plant.

- ✓ **Hydrogen sulfide fuel cells:** sulfur is a frequent contaminant in the hydrocarbon natural resources present in Alberta. Natural gas is often contaminated with varying amounts of hydrogen sulfide gas. Oil in bitumen contained chemically bound sulfur that is removed by upgraders and refineries as hydrogen sulfide gas. Current practice is two either convert hydrogen sulfide to sulfur using the Claus chemical process or to re-inject hydrogen sulfide into geological formations. In either case, the chemical energy contained in hydrogen is lost. At the R&D stage in Alberta, fuel cells have been developed that can convert pure hydrogen sulfide into electrical energy, water and sulfur. Engineering and commercialization of this fuel cell technology would in effect transform a widespread pollutant into a natural resource for Alberta.
- ✓ **DMFC and micro-SOFC for portable application:** These technologies are at an early stage of developments but they may hold the promise for the growth of value-added manufacturing in Alberta. The Alberta Research Council is focusing on applications such as forklift trucks with its partner EVI. The μSOFC technology being investigated by ARC appears to hold significant promises for developing efficient, low-cost SOFC systems. In addition, the electrophoretic deposition technology could be extended into separation membranes and catalytic surfaces.

Consortium Framework

In a consortium, government and industry join forces in a program that allows each party to achieve of their own goals. Governments benefit from a vehicle to facilitate the achievement of desired policy outcomes. Industry seeks to gain access to business opportunities.

Companies tend to favor doing R&D without the presence of their direct competitors in order to gain competitive advantage. This is particularly true for technology development close to the core of the company's business. When they can afford it, companies generally prefer to conduct proprietary research. For example, EnCana has chosen to withdraw from the AERI /ARC core industry (AACI) research consortium for oil sands recovery in order to fund its own proprietary research. However, even large companies who can afford to conduct their own research may still be interested in consortium research:

- ✓ In non core areas
- ✓ In high-risk areas such as long-term and fundamental research
- ✓ In partnership with companies that are not there direct competitors, such as suppliers, customers and complimenters
- ✓ For demonstration trials for the purpose of developing markets for the industry.

Potential Members of the Energy Innovation Network – Hydrogen and Fuel Cells

- ✓ AERI
- ✓ NRC Institute for Fuel Cell Innovation
- ✓ NRC IRAP
- ✓ Sustainable Development Technology Canada
- ✓ Western Economic Diversification Canada
- ✓ Alberta Research Council (Calgary and Edmonton, AB)
- ✓ Fuel Cells Canada
- ✓ Dynetek Industries (Calgary AB)
- ✓ Global Thermoelectric (Calgary, AB)
- ✓ Siemens
- ✓ NewERA
- ✓ Enbridge
- ✓ EnCana

- ✓ Nexen Inc.
- ✓ OPTI Canada
- ✓ NOVA Chemicals
- ✓ Shell Chemicals
- ✓ Suncor
- ✓ TransCanada
- ✓ Methanex
- ✓ Westaim Ambeon
- ✓ ATCO Power
- ✓ ENMAX
- ✓ Alberta Research Council
- ✓ University of Calgary
- ✓ University of Alberta
- ✓ Northern Alberta Institute of Technology
- ✓ National Institute for Nanotechnology

Implementation

The existing Alberta cluster for research and development into hydrogen and fuel cell technologies appears to be developed enough to undertake the various projects contemplated under this strategy. R&D groups already exist and are fully functional at the University of Alberta, the University of Calgary and at the Alberta research Council. What is required is program funding to increase the activity level inside the R&D cluster and to provide the integration framework required for the delivery of products and technologies that will cause the desired outcome.

A consortium based program to fund hydrogen and fuel cell R&D in Alberta would allow the implementation of several specific projects over a typical technology development and commercialization timeframe of about 10 years. The constancy of purpose and the reliability provided by a multiyear program will allow research organization to contemplate undertaking the full cycle of innovation from laboratory prototype to commercialization. It will give them the confidence to assemble the multi-disciplinary teams required to develop and successfully introduce useful products. The program should allow projects to evolve through the various stages of development:

- ✓ Basic R&D
- ✓ Proof of concept
- ✓ Prototypes
- ✓ User trials
- ✓ Market studies
- ✓ Demonstration pilots
- ✓ Commercial introduction.

The Consortium should be managed by representatives of the funding organizations. Providers of R&D would compete with each others for funding by presenting project proposals. The proposals offering the greatest value to the Consortium and to Alberta would be approved for implementation in as stage gated manner. The value of proposals should be measured along the following attributes:

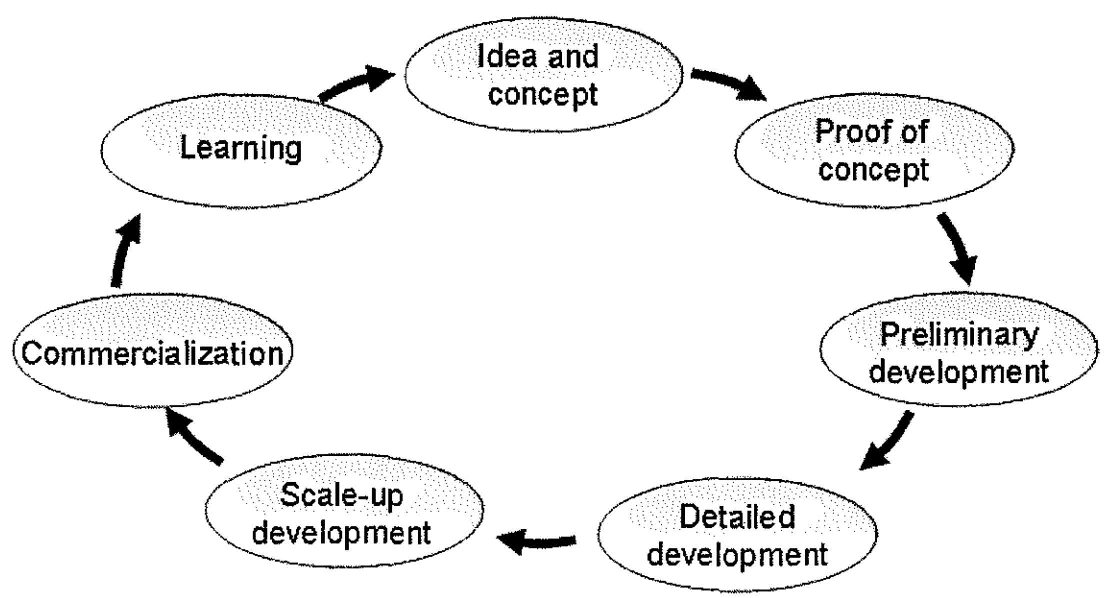
- ✓ Opportunity for increased efficiency in the utilization of Alberta and natural resources
- ✓ The degree of innovation associated with the project
- ✓ The opportunity to create a niche and a new industry in Alberta
- ✓ The opportunity to develop highly qualified people in Alberta
- ✓ The opportunity to develop or strengthen an Alberta center of excellence
- ✓ The opportunity to strengthen links and relationships with centers of excellence worldwide
- ✓ A realistic path to commercial implementation
- ✓ The inclusion of multi-disciplinary skills required for success
- ✓ Partnerships with commercial organization for implementation and distribution

One characteristic of fuel cell R&D is that the required infrastructure does not require very large equipment and substantial capital expenditures as is the case for oil recovery and upgrading research. One fuel cell or a small fuel cell stack fits into a laboratory fume hood. As a result, single researchers and small teams can fruitfully conduct research. However, the development and production of a commercial device requires the integration of multiple disciplines such as chemistry, chemical engineering, mechanical engineering and electrical engineering. A key challenge is to integrate the various skills required into a coherent multidisciplinary team. Cost reduction through mass production technology is often cited as a necessary path to follow for fuel cells to become widely available. This implies R&D in manufacturing processes and substantial investments into manufacturing pilot plants by commercial organizations.

The typical phases of a stage gate process are shown on Figure 9:

- ✓ **Phase 1:** Idea and concept generation
- ✓ **Phase 2:** Proof of concept: preliminary engineering and cost-benefit analysis
- ✓ **Phase 3:** Preliminary developments and laboratory trials
- ✓ **Phase 4:** Detailed development including complete basic engineering at the system- level including support modules.
- ✓ **Phase 5:** Scale-up including manufacturing pilots plant, market trials and demonstration trials
- ✓ **Phase 6:** Commercialization
- ✓ **Phase 7:** Audit, feedback and lessons learned

Figure 9 – Stage Gate Process



In the early phase of a project costs are lower but also probability of success is also low. Relatively speaking, proof of concept is not expensive. However significant uncertainties remain as to the eventual success of the project. Towards the end of the project, the opposite is true. Costs are relatively higher, but so is probability of success. The consortium program for hydrogen and fuel cell technologies should fund several early-stage projects with the expectation of selecting only a few of the best projects for funding all the way through completion.

10.2 Specific Program Recommendations

Strategic Recommendations

1. Research projects on the production of hydrogen from low value feedstocks such as asphaltenes, coal and abandoned oil wells.
2. Research projects on the development of fuel cell systems that can utilize alternative fuels from Alberta refineries and petrochemical plants, including the co-production of chemicals and value-added products.
3. Support for the development of a strong distributed generation cluster in Alberta, based on SOFC.
4. Research projects on the development of fuel cell gas turbine hybrids that can utilize syngas from the gasification of coal.
5. Support at the strategic level for the Western Canada Fuel Cell Initiative and the NAIT research and demonstration facility.
6. Research projects in micro fuel cells and DMFC for value-added manufacturing applications in the portable market.
7. Support for networking opportunities for the broad fuel cell and hydrogen stakeholder group in Alberta to increase awareness and education and to increase the probability of identifying high-value innovation projects.
8. The organization of a Canadian fuel cell and hydrogen scientific symposium, associated with other industry conferences or with one of the annual meeting of the Chemical Institute of Canada.

Tactical Recommendations

9. A scoping study should be conducted of the economic and environmental merits of various methods for converting Alberta's vast hydrocarbon resources into hydrogen, and for distribution in the Fort McMurray to Red Deer corridor..
10. Research on hydrogen storage in carbon nanotubes should be investigated in partnership with the National Institute for Nanotechnology.
11. Research projects into the fundamental challenges associated with fuel cells, such as material science and electrocatalysts, particularly at the stack level for SOFC and μSOFC.
12. Fundamental research on direct oxidation of methane and other hydrocarbons at the anode surface, particularly for SOFC.
13. Fundamental and engineering studies on hydrogen sulfide fuel cells.
14. Demonstration trials of SOFC for distributed generation in the residential and small commercial market should receive support.
15. A hydrogen vehicle demonstration trial and associated hydrogen refueling station in the Alberta Industrial Heartland, north of Edmonton.
16. Demonstration of fuel cell systems for different fuels from Alberta refineries and petrochemical plants.

11 Conclusion

Hydrogen is a clean energy carrier that can be produced using renewable or fossil energy resources. Its use as the fuel for vehicles would vastly improve air quality in densely populated cities. Fuel cells are efficient and flexible energy conversion devices that are applicable to a wide range of applications.

Alberta, as an important energy producer, has a significant stake into the future direction of energy markets, particularly in the United States. In a simplistic way, should the delivered form of energy in the United States market evolve to hydrogen, Alberta needs to take adequate steps to ensure that it is able to produce and deliver hydrogen utilizing Alberta natural resources. Cleaner fossil energy products are a requirement to maintain market access in a North American market that mandates increasingly strict environmental regulations. Hydrogen and fuel cells are emerging technologies that offer considerable promise for cleaner fossil energy products and should therefore be a key platform in Alberta's energy technology strategy.

Alberta is already a leading producer of hydrogen in Canada, and in the rest of the world. Hydrogen is produced in Alberta using on-purpose plants based on steam methane reforming, and as a co-product of other chemical processes. The cost of on-purpose hydrogen is greatly influenced by the cost of natural gas. In the future, anticipated increases in the price of natural gas are likely to overwhelm any efficiency improvements achieved through process R&D.

Hydrogen demand is likely to increase in the future, particularly in Alberta, because stricter regulations for clean gasoline will mean increases in the amount and intensity of hydrogen treatment of oil products. The cost of hydrogen is likely to increase as a result of the long term trend to higher natural gas prices. This confluence of industry trends creates the opportunity for Alberta to invest in the development of technologies to produce hydrogen at a lower cost by utilizing low value hydrocarbon feedstocks that are abundant in the Province such as asphaltenes, coal, petroleum coke, and possibly abandoned oil wells. The development of such technologies would give Alberta, a competitive cost advantage, as compared to the rest of North America in the area of hydrogen production and of hydrogen treating of oil products.

The development of fuel cells for stationary, mobile and portable electric power generation has been pursued globally for several years with intensity because of their anticipated benefits. From an Alberta perspective, fuel cell technologies offer opportunities for economic and environmental benefits for energy generation using fossil fuels.

Fuel cells are well suited to distributed power generation. The scalable nature of fuel cells provides them with the flexibility required for sizing systems to a wide variety of distributed power generation applications. The development of SOFC for distributed generation is at the demonstration and business development stage in Alberta. The development of micro fuel cells and of fuel cells for portable applications is emerging in Alberta. However, Alberta is unlikely to become a centre for the development of automotive fuel cells because of the absence of automotive and heavy manufacturing industries in Alberta. Vancouver is the location of Canada's recognized cluster for hydrogen fuel cell vehicles.

The hydrogen and fuel cell niches where Alberta would enjoy competitive advantage are:

- ✓ Increased Hydrogen Production from Low Value Feedstocks
- ✓ SOFC for Distributed Generation in the Residential and Small Commercial Markets
- ✓ Fuel Cell Gas Turbine Hybrids for Clean Coal
- ✓ Fuel cell systems for alternative fuels available in Alberta
- ✓ Hydrogen sulfide fuel cells
- ✓ DMFC and Micro SOFC for Portable Power

The existing Alberta cluster for research and market development of hydrogen and fuel cell technologies appears to be developed enough to undertake the various projects contemplated under the strategy proposed in this report. R&D groups already exist and are fully functional at the University of Alberta, the University of Calgary and at the Alberta research Council. Program funding is required to increase the activity level inside the R&D cluster and to provide the integration framework required for the delivery of products and technologies that will cause the desired outcome.

A consortium based program to fund hydrogen and fuel cell R&D in Alberta would allow the implementation of several specific projects over a typical technology development and commercialization timeframe of about 10 years. The constancy of purpose and the reliability provided by a multiyear program will allow research organizations to contemplate undertaking the full cycle of innovation from laboratory prototype to commercialization. It will give them the confidence to assemble the multi-disciplinary teams required to develop and successfully introduce useful products.

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Appendix 1: Detailed Interview Reports

Advanced Measurements
Interview Report

Organization: Advanced Measurements
Calgary, AB

Date: June 4, 2003

Representative: Len Johnson
President

Description:

Advanced Measurements manufactures customized test and specializes in fuel cell testing. The test system measures fuel-cell characteristics such as voltage, current, humidity, temperature and gas flows into a fuel cell. The system also controls all aspects of the test environment. Fuel cell test systems are designed to be flexible and to allow fuel cell developers to reduce their development cycle and shorten time to market.

Research and Development Needs for Hydrogen and Fuel Cells

Advanced Measurement believes that fuel cell R&D should be targeted at achieving cost reductions and performance improvements. They collaborate on projects with the University of Calgary and with the Institute for Fuel Cell Innovation.

Marc Godin

Alberta Energy Research Institute
Interview Report

Organization: Alberta Energy Research Institute
Calgary, AB

Date: June 2, 2003

Representative: Catherine Laureshen
Research Manager
COURSE Program

Description:

The Alberta Energy Research Institute (AERI) advises the Minister of Innovation and Science and the Alberta government on energy research policy. It provides strategic direction to position Alberta for the future in energy development. It also supports applied research that will lead to technology implementation that will contribute to the future sustainability of Alberta's energy industry. AERI promotes energy research, technology evaluation and technology transfer in areas including oil and gas, heavy oil and oil sands, coal, electricity, renewable and alternative energy. AERI promotes consortium approaches and builds networks of industry players, federal and provincial governments, research providers and universities.

Opportunities for Alberta in Hydrogen and Fuel Cells

Global Thermoelectric is developing technology based on solid oxide fuel cells (SOFC). The next step for Global will be to do demonstration projects. Enbridge is partnering with Global for the residential market.

Both the University of Calgary and University of Alberta are active in fuel cell research. The COURSE program has provided funding for fuel cell research projects in Alberta.

Research and Development Needs for Hydrogen and Fuel Cells

Government funding for technology research needs to move from project funding to program funding. This will insure greater reliability and efficiency for university researchers. In the area of fuel cells particularly, research is a multi-disciplinary effort. It involves chemistry and engineering, including electrical, chemical and manufacturing engineering. Catalysts and material issues need to be investigated. Multi-disciplinary projects tend to be larger and longer in scope.

Marc Godin

Alberta Environment
Interview Report

Organization: Alberta Environment
Edmonton, AB

Date: June 2, 2003

Representative: Shannon Flint

Description:

Alberta Environment is considering potential offsets in the area of greenhouse gas emissions. Specifically at to moment, the Genesee coal power plant with TransAlta may be the subject of greenhouse gas emission offsets. However, a more generalized program is being studied. The program may allow for power generation using fuel cells to create offsets in greenhouse gas emissions. An Alberta system for emissions trading is also being considered.

Distributed power generation is proceeding in Alberta under deregulation. Interconnection guidelines are in place.

Net metering would allow small producers, including residential producers, to sell the power they generate into the grid at the same price they are buying power from the grid. The issue of net metering is being studied currently. Climate Change Central is leading in the study with input from environmental and energy industry groups. In addition to economic and policy issues there are some technical issues to be resolved. For example, electrical meters are generally calibrated in one direction only. While they can work forward and backward, they are generally calibrated and certified in only one direction. A recent project in Manitoba indicated that it was possible to calibrate these meters in both directions period

Marc Godin

Alberta Industrial Heartland
Interview Report

Organization: Alberta Industrial Heartland
Strathcona County

Date: June 26, 2003

Representatives: Larry Wall
Executive Director
Alberta Industrial Heartland

Jim Wright
Strathcona County

Description:

Alberta's Industrial Heartland promotes development in the regions surrounding northeast Edmonton, while balancing the needs of industry and the environment. The Alberta Industrial Heartland is composed of the counties of Lamont, Strathcona and Sturgeon, the City of Fort Saskatchewan and the City of Fort Saskatchewan.

This Regional Industrial Association in an agreement to work co-operatively on the industrial development of the region. The Alberta's Industrial Heartland covers more than 200 square kilometers and includes several modern world-scale facilities constructed by major industrial leaders such as Agrium, Albchem, Amoco, Chevron, CXY Chemicals, Degrussa-Huls, Dow Chemical, Oxy Vinyls, Nova, Praxair, Shell Chemical, Sherritt International and Westaim. These industries represent an $11-billion investment, with another $3 billion proposed before 2002.The area is known for some of the best developed transportation and pipeline systems on the continent. The 22 major industrial companies in the area employ more than 4,000 people.

Alberta's Industrial Heartland is managed by an inter-municipal committee of mayors, reeves and chief administrative officers from the primary members.

Views on the Hydrogen and Fuel Cell Sector:

But there is significant worldwide interest in the hydrogen economy. Trials of fuel cell vehicles are being conducted in Europe and the United States with government support. In Canada, a similar trial was announced for Vancouver.

Fuel cells are also being used for portable applications.

In Texas, Dow and General Motors plan to use fuel cells to produce electricity from off-gases containing hydrogen. Dow expects that up to 35 megawatts of electricity could eventually be produced using about 500 GM fuel cells. Jim Wright has spoken to Dow in Alberta and they intend to apply in Alberta the learnings from the pilot project in Texas. The Alberta Industrial Heartland association is interested in encouraging the use of hydrogen produced by companies in the region.

Opportunities for Alberta in Hydrogen and Fuel Cells:

Several companies in the industrial heartland produce hydrogen as a coal product. Alberta Envirofuels produces isooctane but also has a co-product stream of 100 kg/hour of 99% pure hydrogen. This stream could be used to supply a hydrogen refueling station for a demonstration of fuel cell vehicles in Edmonton.

For other companies in the region, co-produced hydrogen is usually contained in a gas stream along with other chemical components. These co-product streams are usually used as fuel. The reasons why this hydrogen is not purified and gathered for its chemical value are:

- ✓ The co-product nature of the production implies a lack of reliability as to availability and quality users on hydrogen that need a reliable source such as shell have built their own hydrogen plant using natural gas.
- ✓ The infrastructure required to purify and store hydrogen is expensive. A salt cavern would have to be built to store hydrogen. Pipelines would have to be constructed to distribute hydrogen.

Other applications for hydrogen and fuel cell technology in Alberta include hydrogen sulfide and syngas. New technology is being developed to convert hydrogen sulfide into electricity. With the large amount of hydrogen sulfide available in Alberta, this technology may have promising the economic benefits. Syngas can be produced by gasifying coal or petroleum residues. If syngas can be converted to electricity using fuel cell this would open new economic possibilities in Alberta

Automotive applications for fuel cells are not likely to find a competitive advantage in Alberta because of the absence of an automotive industry here. However, one should not discount fuel cell applications for the electronic and wireless industries in Alberta. The Province is a low cost jurisdiction for manufacturing industries and Edmonton and Calgary have diversified there industrial base in recent years. Therefore economic and technology opportunities based on manufacturing and advanced materials are a focus for the future economic development of Alberta.

Research and Development Needs for Hydrogen and Fuel Cells:

They demonstration program for hydrogen vehicles would be a good idea in the industrial heartland. A source of high purity hydrogen is available from Alberta Envirofuels. But cars or intercity buses fuel to buy hydrogen could be demonstrated here

Government support for the development of new technology is important. Government acts as a catalyst for new opportunities. It is important that development programs be generally accessible without onerous paperwork. A program supporting the exploitation of hydrogen sources available in the industrial heartland would be a benefit

Marc Godin

Alberta Ingenuity Fund
Interview Report

Organization: Alberta Ingenuity Fund
Edmonton, AB

Date: June 5, 2003

Representative: Wendy Lam
Director – Grants and Awards

Description:

Alberta Ingenuity is the trade name of the Alberta Heritage Foundation for Science and Engineering Research. The fund was established by the Government of Alberta in 2000, with an endowment of $500 million. Interest from the endowment is used to support a balanced, long-term program of science and engineering research based in Alberta. The mandate of the fund is to nurture the discovery of new knowledge and encourage applications that benefit Albertans. It provides support for world-class research that will advance science and engineering.

Views on the Hydrogen and Fuel Cell Sector

Albert Ingenuity supports science and engineering research and development in Alberta. The fund views climate change as an issue of relevance to Alberta. In 2002, the funded sponsored a conference on climate change. Scientist and experts explored the scientific basis for concern about climate change and examined ways to address the situation. Hydrogen and fuel cell technology areas have the potential to make a significant contribution to reducing the impact of human activities on climate change.

Opportunities for Alberta in Hydrogen and Fuel Cells

Hydrogen and fuel cell research is emerging in Alberta. Research groups are active at the University of Alberta in the Faculty of Engineering and at the University of Calgary in the Faculty of Science. The industrial sector in Alberta includes companies such as Global Thermoelectric and Dynetek.

Hydrogen and fuel cell technologies have the potential to address key needs of the energy sector in Alberta. It is not clear to Alberta ingenuity what should be the Alberta niches in the area of hydrogen and fuel cell. Alberta is not yet a research leader in this area.

Research and Development Needs for Hydrogen and Fuel Cells

A potential focus area appears to be solid oxide fuel cells. Alberta Ingenuity has encouraged Alberta research groups to build up their reputation and to demonstrate collaboration with other research groups worldwide. Options include attracting to Alberta researchers with a global reputation in the area of hydrogen and fuel cells. To be successful in obtaining AIF funding, emerging research groups in Alberta need to show awareness and collaboration with other groups internationally.

SOFC would probably be a good niche for Alberta, particularly when using hydrocarbon fuels. In the area of hydrogen, there are clear links between hydrogen research and the Alberta energy sector. Hydrogen is used for upgrading bitumen into synthetic crude oil. Increased R&D into production of hydrogen from non conventional sources such as bitumen would be a good fit with the Alberta situation. However this must be done with a focus on building up the international reputation of Alberta research group and increasing collaboration with other centers of expertise worldwide.

Marc Godin

Alberta Research Council
Interview Report

Organization: Alberta Research Council
Edmonton, AB

Date: May 21, 2003

Representative: Karen Beliveau

Description:

The Alberta Research Council (ARC) develops and commercializes technology in the areas of energy, life sciences, agriculture, environment, forestry and manufacturing.

ARC performs applied research and development on a contract basis. ARC also co-ventures with clients to develop new technologies and earns a return on investment from the commercialization of products and processes. ARC has world-class resources at facilities in western Canada, and a team of six hundred experienced scientists, researchers and business experts.

Opportunities for Alberta in Hydrogen and Fuel Cells

ARC is active in the area of fuel cells with a project with EVI and some early research and development in micro solid oxide fuel cells (SOFC). With respect to the EVI venture, ARC is jointly working with them on the development of a direct alcohol fuel cell. The micro-SOFC project is at an early stage. The next step will be to identify a partner to leverage ARC's investment in this project. The partner would bring the skills and market presence required to commercialize this technology.

Research and Development Needs for Hydrogen and Fuel Cells

ARC is conducting research and business development in fuel cells with limited resources and a modest budget. ARC does not focus on basic research and knowledge creation. ARC occupies the middle space between fundamental research and commercial applications. All research needs to be applied. ARC would like to see a greater share of government funding on innovation to be directed to commercialization and business development efforts. In the area of fuel cells, it would be useful to see increased funding and investment in early commercialization and demonstration projects.

Marc Godin

Alberta Research Council
Interview Report

Organization: Alberta Research Council
Edmonton, AB

Date: May 21, 2003

Representative: Dean Richardson
Project Leader

Description:
The Alberta Research Council (ARC) develops and commercializes technology in the areas of energy, life sciences, agriculture, environment, forestry and manufacturing.

ARC performs applied research and development on a contract basis. ARC also co-ventures with clients to develop new technologies and earns a return on investment from the commercialization of products and processes. ARC has world-class resources at facilities in western Canada, and a team of six hundred experienced scientists, researchers and business experts.

Opportunities for Alberta in Hydrogen and Fuel Cells

EVI DMFC Project

- Doug James is EVI leader in Calgary.
- EVI has the crucial early patents for flowing electrolyte that increase service life and allow higher power densities.
- EVI is driving the venture.
- ARC is providing lab space, engineering and scale-up support;
- ARC has EVI equity and board membership
- Fuel cell markets have been segmented as follows by ARC:
    - Stationary
    - Portable (e.g. laptops and battery replacement)
    - Transportable (e.g. portable generator, fork lifts, etc)
    - Transportation (automotive)
- DMFC is for transportable segment; 1 to 5 kW devices, possibly hybrid devices.
- Benefits of DMFC are low temperature, low relative cost and availability of methanol distribution infrastructure.
- Challenges are that power density is not super high. The industry can achieve 50-100 mW/cm2; achieving 200 mW/cm2 would be cutting edge.
- Development stage is at the engineering prototype stage.

Micro SOFC Project

- Driven by internally generated technology.

- ARC has 6 patents.
- Key technology is hollow ceramic membrane technology.
- Markets extend from portable to stationary, but would be starting in portable and transportable segments.
- Focus on markets requiring smaller wattage and moderate volumes.
- Benefits of SOFC are fuel flexibility and tolerance, high temperature for producing high quality heat. The power density of SOFC is higher than DMFC. ARC has achieved 200mW/cm2 prototype.
- Key milestone is to develop an un-tethered prototype by year-end.
- Development stage is at the engineering prototype stage.
- Next steps are to find development partners with skills in balance of plant and power electronics and partners with market presence in targeted niches.

Research and Development Needs for Hydrogen and Fuel Cells

Industry Gaps and Barriers

- Matching capabilities with markets that will pay the higher cost of fuel cells
- Ramp up volume manufacturing
- Fuel infra-structure issues for methanol and hydrogen.
- Toshiba has announced a FC laptop available by late 2004.
- Stationary FC could be commercial by 2007-2009 and automotive applications by 2010-2012.

Marc Godin

Angstrom Power
Interview Report

Organization: Angstrom Power
North Vancouver, BC

Date: June 13, 2003

Representative: Ged McLean
Founder and CTO

Description:

Angstrom Power is a technology company that is developing technology for micro structured fuel cells. It is based on technology developed at the University of Victoria by Dr. McLean. It is applying micro fabrication techniques using novel architecture and fabrication techniques. Applications include battery replacement and portable power.

Views on the Hydrogen and Fuel Cell Sector:

Micro fuel cells use the same chemistry as other fuel cells. However the challenge lies in the architecture and fabrication technology for very small systems. In addition, testing and evaluation systems for micro fuel cells are different than those for larger fuel cells. NRC has an environmental chamber for testing large fuel cells for use in cars and buses. NRC would benefit from having an environment told chamber for evaluating micro systems.

Opportunities for Alberta in Hydrogen and Fuel Cells:

Angstrom is familiar with the micro fabrication expertise at the University of Alberta and could do more work using the capabilities of the Nanotechnology Institute that is being established in Edmonton.

Alberta is seen as a source of low cost hydrogen for the hydrogen economy and for automotive fuel cell applications.

Portable fuel cell application that could be applied in Alberta includes fuel cells for small utility trucks and fuel cells for radios used in remote locations. In addition, a local hydrogen refueling station could be built using hydrogen available from the oil industry.

Research and Development Needs for Hydrogen and Fuel Cells:

A key research need is metrology. There is a need for regional expertise in high resolution imagery for use in material characterization of porous media. Access to equipment is available at ICPET in Ottawa. However Ottawa is very far from Vancouver and the availability of similar equipment and expertise in Western Canada would be extremely useful. While equipment may be available in Western Canada, organizations which such equipment do not have the expertise required for characterizing fuel cell materials. In addition trust and a commitment to absolute confidentiality are paramount.

There is a need for an information clearinghouse on fuel cells. It is difficult for a small company to know who has what expertise and what equipment. The availability of such information would facilitate partnerships and joint developments.

Increased funding to universities with matching funds from industry is required to enable the level of research effort that is required.

Potential Interest in a R&D Consortium for Hydrogen and Fuel Cells:

Industry based consortiums are useful and can be seen as the validation of the need for research. However obtaining matching funds is always a problem.

Marc Godin

Ballard Power Systems
Interview Report

Organization: Ballard Power Systems

Date: June 5, 2003

Representatives: Sylvia Wessel
Vice President Research and Development

Description:

Ballard is recognized as the world leader in developing, manufacturing and marketing proton exchange membrane fuel cells (PEMFC). The company is commercializing fuel cell engines for automotive applications. Ballard has technology and demonstration alliances with several of the world's leading automotive companies.

Research and Development Needs for Hydrogen and Fuel Cells:

Research and development in fuel cells should be focused on cost reduction in all areas. In particular the development of non-noble catalysts for proton exchange membrane fuel cells would be an important research target.

Ballard would have the same views and research priorities as those of the institute for fuel cell innovation that is part of the national research council in Vancouver.

Marc Godin

Cellex Power Products
Interview Report

Organization: Cellex Power Products
Vancouver, BC

Date: June 17, 2003

Representative: David Pfeil

Description:

Cellex Power is a developer of a fuel cell based power products. Cellex is a technology integrator and an application developer. It is focused on developing products for powered industrial vehicles. It is involved in developing lift trucks for use in distribution centers. Other interests are scooters, mining vehicles and military applications. Cellex believes that these smaller markets may develop more quickly than cars and mainstream automotive applications. In these markets fuel cells compete with batteries.

Views on the Hydrogen and Fuel Cell Sector

The cost of fuel cell needs to be reduced for fuel cells to find widespread applications. In addition the durability or life expectancy of fuel cells needs to be increased. Fuel cells need to work well over many years of service life.

Hydrogen is an important area for the fuel cell industry. The availability of low cost hydrogen is key. The production of hydrogen can be done using known processes such as reforming and electrolysis. Hydrogen storage is a key issue. The density of storage and the safety of stored hydrogen need to be improved.

Methanol is an excellent fuel. It can be used directly in a fuel cell or can be reformed onboard. However for methanol to be used as a fuel, the direct methanol fuel cell will need to become more reliable and cost effective.

Research and Development Needs for Hydrogen and Fuel Cells

The critical need is to develop improved methods for the storage of the hydrogen. Compressed hydrogen can be stored into high pressure vessels such as those developed by Dynetek. Other approaches involved the use of metal hydride. It would be useful if NRC and Alberta could collaborate to develop improved methods for the storage of hydrogen.

Marc Godin

Fuel Cell Canada
Interview Report

Organization: Fuel Cells Canada

Date: April 22, 2003

Representatives: Ron Britton
President and CEO

Description:

Fuel Cells Canada a non-profit organization and the national industry association for the hydrogen and fuel cell industry. Its mandate is to promote the Canadian fuel cell industry in the global market; and encourage a national strategic approach to fuel cell industry development. It is involved in facilitating demonstration projects that allow fuel cell companies to test and perfect their pre-commercial fuel cell technologies.

Fuel Cell Canada believes that Canada has a unique opportunity to build on the presence of world-leading fuel cell technology developers. Through early adoption of fuel cell technology, Canada could retain and grow the fuel cell knowledge base, set new standards for the developing industry, lead in the supply of components, sub-systems, and services and attract complementary technology and capital and expertise that result in the development of new industrial clusters.

Views on the Hydrogen and Fuel Cell Sector:

Fuel Cell Canada contributes to the development of the hydrogen economy. Improved technology must be developed in order to provide abundant low cost hydrogen. And in addition a distribution infrastructure for hydrogen must be developed. Sources of hydrocarbons and hydrogen are not generally found near cities and issues related to transportation of hydrogen must be investigated

Opportunities for Alberta in Hydrogen and Fuel Cells:

Alberta is a region that is rich with hydrocarbon natural resources. Hydrocarbons can be used to produce hydrogen for the hydrogen economy. This is an important and key contribution that Alberta can make. Development in Alberta should therefore be focused on hydrogen. The oil and gas industry in Alberta should be engaged in research to convert hydrocarbons into hydrogen more effectively and at a lower cost. Transportation issues such as hydrogen embrittlement of pipelines also need to be researched. Reforming technology is used in the oil and gas sector can be applied to reforming hydrocarbons into high purity hydrogen for fuel cell applications.

Alberta should focus on hydrogen research rather than on fuel cell research. Improving fuel cell devices is already active in Vancouver and may shift in the future to industrially important areas such as Ontario where the automotive industry is located.

Research and Development Needs for Hydrogen and Fuel Cells:

Reforming technology for converting hydrocarbons to hydrogen is required. Improved methods for purifying hydrogen are also needed. Improve methods for transporting hydrogen either by pipeline or compressed tanks are also required. Issues related to hydrogen purity and fuel cells must be explored. The use of nuclear energy to produce hydrogen is also a topic of interest

Marc Godin

Greenlight Power Technologies
Interview Report

Organization: Greenlight Power Technologies
Burnaby, BC

Date: June 26, 2003

Representative: James Dean

Description:

Greenlight Power is a manufacturer of test stations for fuel cell stacks, components, fuel reformers, electrolyzers and fuel cell systems. The research activities of Greenlight are focused on onboard diagnostic equipment for fuel cell applications. Green light provides testing equipment for several fuel cell technologies such as PEMFC, SOFC, MCFC and DMFC. Markets served are automotive, stationary and micro fuel cells.

Views on the Hydrogen and Fuel Cell Sector

Greenlight is actively involved in the development of the hydrogen and fuel cell industry. They are working on the joint development of core technology with NRC in Vancouver. New products are under all going testing at the pre-commercial level. Greenlight is also involved in demonstration of fuel cell vehicles where some of their products are being used.

Opportunities for Alberta in Hydrogen and Fuel Cells

The opportunity for Alberta is to focus on the production of hydrogen for fuel cell applications. Alberta is a region that has significant amount of hydrocarbons that could be converted into hydrogen.

Research and Development Needs for Hydrogen and Fuel Cells

More research is needed to understand the failure modes of fuel cell. Uncovering how fuel cell fail will enable the development of sensors that can optimize fuel cell operations and avoid their premature failure. The development of improved equipment, sensors and diagnostic tools for fuel cell is an area of high importance.

Marc Godin

Methanex
Interview Report

Organization: Methanex
Vancouver, BC

Date: June 2, 2003

Representative: Dominique Kluyshens

Description:

Methanex is the global leader for production and distribution of methanol. Methanex has production facilities in North America, New Zealand and Chile. In addition to these manufacturing facilities Methanex also has marketing offices in the United States, Chile, New Zealand, Belgium, the United Kingdom and Korea. The extensive global marketing and distribution system of Methanex makes them the largest supplier of methanol to each of the major international markets. In 2002, Methanex sales accounted for approximately 24% of the total world market for methanol.

View on Hydrogen and Fuel Cells

The fuel cell industry is developing rapidly. The cost of fuel cells has come down significantly in the last fifteen years. In addition to automotive applications, new applications are being developed for fuel cells such as forklift trucks, wheel chairs, laptop computer and cell phones.

Hydrogen is a very difficult to transport, store and distribute. Delivered price of hydrogen can be as much as $4.00 per kilogram. Hydrogen can be produced by reforming natural gas. However only fifteen percent of developed areas are covered by natural gas distribution. In addition, natural gas prices are increasing sharply. Methanol is a better energy carrier and hydrogen for fuel cells. Methanol can be distributed in it in a safe convenient and low cost manner anywhere in the world. Methanex produces methanol from low costs stranded natural gas reserves.

Methanex is partnering with certain fuel cell developers for certain markets. Announcements have not been made yet. But products of interests to Methanex are fuel cells for forklift trucks and micro fuel cells for laptop computers.

Opportunities for Alberta in Hydrogen and Fuel Cells

Fuel cell developers and researchers in Alberta are not integrated with the global network. Alberta does not market its technology development efforts and its resources. Awareness is low about fuel cell developments in Alberta.

Research and Development Needs for Hydrogen and Fuel Cells

Proton exchange membrane fuel cells (PEMFC) are facing challenges. Durability is a major issue particularly beyond 2,000 hours of operating time. It is expected that a new generation of PEMFC will be developed to meet performance requirements. The direct methanol fuel cell (DMFC) on the other hand can reach 5,000 hours of operating time without problems. With new membranes, the DMFC could reach high power densities. Costs targets of $1,000 to $2,000 per kilowatt are within reach. A number of companies are developing direct methanol fuel cells in the smaller power categories. Applications include forklift trucks, scooters and wheelchairs. Automotive applications are at least fifteen years away. The solid oxide fuel cell (SOFC) has been plagued by constant delays. It is a good technology but it is not yet ready.

Potential Interest in a R&D Consortium for Hydrogen and Fuel Cells

Methanex may be interested in supporting research and development in the area of direct methanol fuel cells. DMFC have momentum at the present time particularly for smaller fuel cells. Methanex may be interested in demonstration projects and early commercialization efforts. There is not a lack of potential partners.

Marc Godin

National Research Council
Interview Report

Organization: National Research Council
Industrial Research Assistance Program
Vancouver, BC

Date: June 12, 2003

Representative: Olga Kargina
Industrial Technology Advisor

Description:

The National Research Council-Industrial Research Assistance Program (NRC-IRAP) is an innovation assistance program for small and medium-sized enterprises (SMEs). It is a component of the NRC overall program and a cornerstone in Canada's innovation system. IRAP's mandate is to stimulate wealth creation for Canada through technological innovation. It is accomplished by providing technology assistance and funding to SMEs at all stages of the innovation process and by helping them build their innovation capacity.

View on Hydrogen and Fuel Cells

IRAP has provided assistance to companies in the Vancouver area for the development of hydrogen and fuel cell technologies.

Opportunities for Alberta in Hydrogen and Fuel Cells

In the area of hydrogen production, the Vancouver company Membrane Reactor Technology is developing a small scale reactor for reforming natural gas to hydrogen. The technology looks promising and is being developed in partnership with the Institute for Fuel Cell Innovation. The company is a spin-off from research conducted at the University of British Columbia. There could be some opportunities to develop this technology further in Alberta.

Marc Godin

National Research Council
Interview Report

Organization: National Research Council
Industrial Research Assistance Program
Calgary, AB

Date: May 27, 2003

Representative: Michael Hayes
Industrial Technology Advisor

Description:

The National Research Council-Industrial Research Assistance Program (NRC-IRAP) is an innovation assistance program for small and medium-sized enterprises (SMEs). It is a component of the NRC overall program and a cornerstone in Canada's innovation system. IRAP's mandate is to stimulate wealth creation for Canada through technological innovation. It is accomplished by providing technology assistance and funding to SMEs at all stages of the innovation process and by helping them build their innovation capacity.

View on Hydrogen and Fuel Cells

IRAP provides assistance and funding for proof of concept to prototyping and commercialization. Programs can be in the $1 million range. An example of an IRAP program is testing of proton exchange membrane fuel cells (PEMFC) in forklift engines and using them in service. Another example could be the demonstration of a fuel cell bus.

The Institute for Fuel Cell Innovation in Vancouver does contract research. The Institute examines fuel cell projects for IRAP as a technical consultant. NRC laboratory ICPET in Ottawa also does consulting work, as well as IMRI, the Industrial Materials Research Institute in Montreal. ICPET focuses on the development of membranes. The Institute for Fuel Cell Innovation in Vancouver coordinates the fuel cell programs of the various laboratories. The Institute has testing facilities for fuel cells as well as hydrogen capable laboratories. It is in the process of installing a solid oxide fuel cell (SOFC) tests stand. The Vancouver facility started focusing on fuel cells one to two years ago.

Opportunities for Alberta in Hydrogen and Fuel Cells

Alberta is home to fuel cells companies such as Global Thermoelectric, EVI and Snowleopard. Advanced Measurements is involved in the development and production of test stands for fuel cells. There are about 500 people in the fuel cell area in Calgary. IRAP is funding research on two or three projects involving fuel cells in Alberta. In the past, Global Thermoelectric has benefited from an IRAP funding. Global Thermoelectric is being acquired by the American company Quantum. There is a 50 percent chance of Global Thermoelectric moving out of the Province to the United States. In the past, the Canadian company H Power was bought by the U.S. company Plug Power and within two years H Power had been moved to the United States.

There is no hydrogen expertise in Alberta for fuel cell applications

The Northern Alberta Institute of Technology (NAIT) is installing 2 fuel cells with assistance from AERI. The University of Calgary has a small research group focused on fuel cells. The areas for research include catalysts, materials and electrochemistry. It is in the process of obtaining additional facilities. Ballard in Vancouver has done some work with the University of Calgary. However the University of Calgary is not a world leader in terms of fuel cells. There is some research work happening at the University of Alberta in the area of fuel cells.

Research and Development Needs for Hydrogen and Fuel Cells

In British Columbia, the Province has a program to support to the demonstration of fuel cells. Fuel Cell Canada is the administrator of the program. Western Economic Diversification is also providing support. Alberta could consider initiating a similar program here.

There is a need to reduce the cost of hydrogen production. Micro-sized reformers for producing hydrogen on-site or on-board also need to be developed.

SOFC demonstrations could be implemented in one of the major cities in Alberta. Ecologically sensitive areas such as Banff, Jasper or Kananaskis may also benefit from stationary power SOFC. For example, Jasper would need more electric power that can be provided through the grid.

Marc Godin

National Research Council
Interview Report

Organization: National Research Council
Industrial Research Assistance Program
Edmonton, AB

Date: May 29, 2003

Representative: Kashmir Gill
Industrial Technology Advisor

Description:

The National Research Council-Industrial Research Assistance Program (NRC-IRAP) is an innovation assistance program for small and medium-sized enterprises (SMEs). It is a component of the NRC overall program and a cornerstone in Canada's innovation system. IRAP's mandate is to stimulate wealth creation for Canada through technological innovation. It is accomplished by providing technology assistance and funding to SMEs at all stages of the innovation process and by helping them build their innovation capacity.

View on Hydrogen and Fuel Cells

IRAP provides assistance and funding for proof of concept to prototyping and commercialization in the area of fuel cells. IRAP has worked in the past with Global Thermoelectric.

The IRAP program is designed for small and medium enterprises under 500 people. Grants can be up to $250,000.00 per project. Larger scale projects would fall in the Technology Partnership Canada program of the National Research Council. This program is for pre-commercial technology and involves repayable loans based on future revenues.

Opportunities for Alberta in Hydrogen and Fuel Cells

Stationary power fuel cells that can use natural gas would make sense. The suggested size is 5kW for a typical North American home. However the technology needs to be adapted to the market. In Europe, 5kW fuel cells would be used to supply power to an apartment building.

The fuel cell technology that was developed by Indexable Cutting Tools has now moved to Fuel Cell Technologies in Ontario. This technology was part of Thermic Edge which was a spin-off from Westaim. Snow leopard and the University of Alberta are conducting research in the utilization of hydrogen sulfide by fuel cells.

Research and Development Needs for Hydrogen and Fuel Cells

One possibility for supporting Alberta research in fuel cells would be to provide financial support for an Alberta delegation to attend the European fuel cell conference in September, 2003. This technology partnership mission is sponsored by IRAP and Fuel Cell Canada.

Marc Godin

National Research Council
Interview Report

Organization: Institute for Fuel Cell Innovation, National Research Council Canada

Date: June 13, 2003

Representatives: David Wilkinson
Principle Research Officer

Description:

The Institute for Fuel Cell Innovation is located in Vancouver and is part of the National Research Council. It is a research laboratory and innovation center focused on hydrogen and fuel cells. Its mission is to develop core competencies relevant to the long term strategic technology needs of Canada with particular emphasis on engagement of stakeholders and cluster development.

The Institute for Fuel Cell Innovation has a national mandate in the area of hydrogen and fuel cells. It coordinates the activities of several NRC laboratories across Canada on the subject of hydrogen and fuel cells. The Institute is active in PEMFC and other fuel cell technologies such as SOFC and direct methanol fuel cells. It has hydrogen safe laboratories and fuel cell testing stations. It conducts collaborative research with companies in the Vancouver area.

Views on the Hydrogen and Fuel Cell Sector:

Fuel cells are a technology to develop sources of clean energy. Dr. Wilkinson is involved with the systems aspects of fuel cells, particularly for proton exchange membrane fuel cells (PEMFC). The areas of interest include cells and cell stacks design, controls and integration.

Low temperature fuel cells such as PEMFC operate on hydrogen but can also utilize hydrocarbons directly.

Reducing the cost of fuel cells is a critical issue. Fuel cells are within contact of the cost target. Mass production of fuel cells is required to reach cost targets and to lower the cost per unit. About 50 percent of the cost comes from the fuel cell stack while the balance is contributed by the other components. An approach to reduce cost is to reduce the total number of supporting components.

Opportunities for Alberta in Hydrogen and Fuel Cells:

Alberta should become a source for abundant and low cost hydrogen for the hydrogen economy because of the presence of vast hydrocarbon resources.

Research and Development Needs for Hydrogen and Fuel Cells:

Material characterization is a very important issue. Sophisticated equipment is used in government laboratories such as NRC in Ottawa and at local universities. Software and computer modeling are also important

Marc Godin

National Research Council
Interview Report

Organization: Institute for Fuel Cell Innovation, National Research Council Canada

Date: June 6, 2003

Representatives: Maya Veljkovic
General Manager

Description:

The Institute for Fuel Cell Innovation is located in Vancouver and is part of the National Research Council. It is a research laboratory and innovation center focused on hydrogen and fuel cells. Its mission is to develop core competencies relevant to the long term strategic technology needs of Canada with particular emphasis on engagement of stakeholders and cluster development.

The Institute for Fuel Cell Innovation has a national mandate in the area of hydrogen and fuel cells. It coordinates the activities of several NRC laboratories across Canada on the subject of hydrogen and fuel cells. The Institute is active in PEMFC and other fuel cell technologies such as SOFC and direct methanol fuel cells. It has hydrogen safe laboratories and fuel cell testing stations. It conducts collaborative research with companies in the Vancouver area.

Views on the Hydrogen and Fuel Cell Sector:

The vision of the Institute for Fuel Cell Innovation has two areas of focus. A high priority is to support the BC fuel cell cluster. The Institute also provides leadership across Canada for the NRC fuel cell program. The institute is the only NRC Institute that is focused on fuel cell technology. It is a good catalyst to bring together partners in order to build provincial clusters across Canada for development of the hydrogen and fuel cell industry.

NRC has nine hydrogen safe laboratories and could work in partnership with the Alberta Research Council in providing a conduit for research to move from university laboratories to industry.

Opportunities for Alberta in Hydrogen and Fuel Cells:

Alberta and British Columbia are two energy rich provinces. They should join forces to also become the alternative energy engine of Canada. Dr. Veljkovic is very familiar with the Alberta industry and universities. The Institute for Fuel Cell Innovation could play a facilitating role to overcome some of the rivalry that exists between the University of Alberta and the University of Calgary. The Institute could be a partner and a conduit for collaboration in Alberta.

The Alberta fuel cell niche should be energy sector SOFC. An emerging cluster already exists in this area in Alberta.

Abundant natural resources in Alberta could lead to the production of excess hydrogen that could be exported to fuel cell applications in other jurisdictions. Fuel cell increase energy efficiency and provide a cleaner energy source. Other areas of interest include coal gasification and fuel cell systems that utilize hydrocarbons.

NRC has expertise in micro fuel cell technology and could provide assistance and partnership to micro fuel cell programs at the Alberta Research Council.

Potential Interest in a R&D Consortium for Hydrogen and Fuel Cells:

The key message is that organizations developing hydrogen and fuel cell technology should join forces and work together. Partnerships between industry university and government laboratories are excellent conduits for collaboration and NRC is well placed to play a facilitating role.

Marc Godin

National Research Council
Interview Report

Organization: Institute for Fuel Cell Innovation
National Research Council
Vancouver, BC

Date: June 17, 2003

Representative: Kevin Stanley

Description:

Kevin Stanley is responsible for the micro fuel cell research program at NRC. The program is based on PEMFC. and will likely use methanol as the fuel. The emphasis is on long term research.

Micro fuel cells are used for portable devices such as cell phones and laptop computers. The developers of micro fuel cells fall in one of three categories:

- ✓ But pure technology development companies such as an MGI. and Manhattan
- ✓ Battery companies
- ✓ Large electronic companies such as Motorola and Toshiba.

Other applications for micro fuel cells include battery chargers for utilization away from the electrical grid. Fuel cell battery chargers may be of value for search and rescue operations, forestry companies and oil and gas exploration activities.

Opportunities for Alberta in Hydrogen and Fuel Cells

Not discussed.

Research and Development Needs for Hydrogen and Fuel Cells

Micro fuel cell technology is an area that is developing rapidly. R&D is needed for improved catalyst with a better dispersion and new materials. Fabrication and mass production technologies need to be developed in order to reduce the cost per kilowatt of fuel cells. New geometries for membrane electrode assemblies are being developed to facilitate sealing and assembly.

Marc Godin

National Research Council
Interview Report

Organization: Institute for Fuel Cell Innovation,
National Research Council Canada
Fuel Cells Canada

Date: April 22, 2003

Representatives: Des Mullan
Director, B.C. Regional Innovation
National Research Council Canada

Ron Britton
President and CEO
Fuel Cells Canada

Description:

The Institute for Fuel Cell Innovation is located in Vancouver and is part of the National Research Council. It is a research laboratory and innovation center focused on hydrogen and fuel cells. Its mission is to develop core competencies relevant to the long term strategic technology needs of Canada with particular emphasis on engagement of stakeholders and cluster development.

The Institute for Fuel Cell Innovation has a national mandate in the area of hydrogen and fuel cells. It coordinates the activities of several NRC laboratories across Canada on the subject of hydrogen and fuel cells. The Institute is active in PEMFC and other fuel cell technologies such as SOFC and direct methanol fuel cells. It has hydrogen safe laboratories and fuel cell testing stations. It conducts collaborative research with companies in the Vancouver area.

Views on the Hydrogen and Fuel Cell Sector:

The institute is interested in contributing to the development of the hydrogen economy. Improved technology must be developed in order to provide abundant low cost hydrogen. And in addition a distribution infrastructure for hydrogen must be developed. Sources of hydrocarbons and hydrogen are not generally found near cities and issues related to transportation of hydrogen must be investigated

Opportunities for Alberta in Hydrogen and Fuel Cells:

Alberta is a region that is rich with hydrocarbon natural resources. Hydrocarbons can be used to produce hydrogen for the hydrogen economy. This is an important and key contribution that Alberta can make. Development in Alberta should therefore be focused on hydrogen. The oil and gas industry in Alberta should be engaged in research to convert hydrocarbons into hydrogen more effectively and at a lower cost. Transportation issues such as hydrogen embrittlement of pipelines also need to be researched. Reforming technology is used in the oil and gas sector can be applied to reforming hydrocarbons into high purity hydrogen for fuel cell applications.

Alberta should focus on hydrogen research rather than on fuel cell research. Improving fuel cell devices is already active in Vancouver and may shift in the future to industrially important areas such as Ontario where the automotive industry is located.

Research and Development Needs for Hydrogen and Fuel Cells:

Reforming technology for converting hydrocarbons to hydrogen is required. Improved methods for purifying hydrogen are also needed. Improve methods for transporting hydrogen either by pipeline or compressed tanks are also required. Issues related to hydrogen purity and fuel cells must be explored. The use of nuclear energy to produce hydrogen is also a topic of interest

Potential Interest in a R&D Consortium for Hydrogen and Fuel Cells:

The Institute for Fuel Cell Innovation will collaborate with Alberta in the strategy that is chosen by Alberta. IFCI recognizes is that SOFC research and business development is already active in Alberta. Should the Alberta emerging cluster continue to grow the Institute will support that growth.

Marc Godin

National Research Council
Interview Report

Organization: Institute for Fuel Cell Innovation
National Research Council
Vancouver, BC

Date: June 16, 2003

Representative: Dave Ghosh

Description:

Dave Ghosh has been involved in the early developments of fuel cell research in Alberta. He worked nine years ago at the Alberta Research Council and was instrumental in developing fuel cell research at ARC. He was the head of the manufacturing technology department that assisted Global Thermoelectric in developing solid oxide fuel cell technology. Dave Ghosh then worked for Global as vice president of technology. At Global, he developed manufacturing technology for planar SOFC. Global's pilot plant is capable of producing 1,000 fuel cells per week but could be expanded to 2,500 fuel cells per week. Dave Ghosh is now involved with setting up the SOFC program at the Institute for Fuel Cell Innovation in Vancouver. Like ARC, NRC occupies the space between university research and corporate research. NRC works together with universities for idea generation and fundamental research. NRC is hiring researchers with joint appointments with SFU and UBC.A similar approaches could be undertaken with the University of Calgary and the University of Alberta. NRC also works with industry for application development and industry growth. NRC is setting up the Institute for Fuel Cell Innovation in Vancouver to accelerate the commercialization of fuel cell technology in Canada. The institute has been very active with Ballard in Vancouver but is also involved in other areas of fuel cell development. The institute coordinates all NRC fuel cell activities. For example ICPET has a $1 million program to develop electrode materials and alternate interconnect materials.

Opportunities for Alberta in Hydrogen and Fuel Cells

Dave Ghosh is very familiar with fuel cell research in Alberta. At the University of Alberta there are two research groups active in fuel cells. Tom Etsell is active in high temperature electrochemistry and is developing novel catalysts and sensors. Karl Chuang is developing novel PEMFC for hydrogen sulfide applications. At the University of Calgary Viola Birss does research in low temperature fuel cells exploring fundamental electrochemical processes. She also is active in high temperature fuel cells. Global Thermoelectric has a focused program on planar SOFC. Their work in is very focused on the development of commercial technology. NRC is interested in developing a working relationship with ARC on fuel cells. If it would be useful to better focus research work in common directions rather than fragmentation in different directions

Research and Development Needs for Hydrogen and Fuel Cells

The Institute for Fuel Cell Innovation will focus on PEMFC and SOFC, including direct methanol fuel cells. One of the goals is to be the R&D department for industry and to conduct contract R&D for companies with a one to two year time frame. The Institute also has benched testing equipment and application development skills that are of value to industry.

Marc Godin

Natural Resources Canada
Interview Report

Organization: Natural Resources Canada
Ottawa, ON

Date: June 4, 2003

Representative: Vesna Seapanovic

Description:

Natural Resources Canada (NRCan) and the CANMET Energy Technology Centre (CETC) are leading Federal science and technology organizations that are involved in the development and deployment of energy efficient, alternative energy and advance technologies. NRCan has initiated the Canadian Transportation Fuel Cell Alliance to champion fuel cell technology in Canada and to further the development of the fueling infrastructure required for fuel cell vehicles. NRCan is also involved in the demonstration of new fueling systems, technical standards, training, certification and safety issues with respect to do utilization of fuel cells in transportation applications.

View on Hydrogen and Fuel Cells

NRCan has been involved in hydrogen and fuel cells for the last twenty years. Its program has a national scope. Program elements include hydrogen production, distribution and storage, fuel cells, safety codes and outreach. With respect to hydrogen production, the program is focused on electrolysis as a production method for hydrogen from renewable energy sources. Integrated hydrogen systems, including distribution and storage are also a key area for technology development. In particular NRCan is supporting technology development that would avoid multi-stage compression. Technology areas such as metal hydride and carbonate nano-structures appear promising.

With respect to safety codes and standards, hydrogen and fuel cell will require that new codes and regulations be established. Work is being done on the modeling of hydrogen releases in order to determine explosion potential. The safety of hydrogen systems associated with fuel cells is a key issue. NRCan is supporting the BNQ in Quebec in its work to support the development of the standard ISO TC 197. With respect to outreach, NRCan has training videos, as well as information and books regarding hydrogen safety and fuel cell applications.

Opportunities for Alberta in Hydrogen and Fuel Cells

Over the last few years, NRCan has worked with Global Thermoelectric and with Dynetek. The program with Dynetek involved the development of 10,000 psi storage tanks for hydrogen. With Global Thermoelectric, NRCan has funded the development of stationery fuel cell systems for use as backup power and auxiliary power units [APU] in large vehicles such as trucks.

There is a lot of activity in Alberta in the area of solid oxide fuel cells (SOFC). One of Alberta's strengths should be the production of hydrogen. In particular, Alberta should lead in and the production of hydrogen from fossil fuels. Improvements to reforming technology should be an area for research and development in Alberta.

Research and Development Needs for Hydrogen and Fuel Cells

Alternative energy technologies such as wind, turbines and fuel cells are all part of the solution. Wind is an intermittent source of energy that could be used to produce hydrogen. The benefits of fuel cells are:

- ✓ There are no moving parts and therefore they require less maintenance and have higher reliability.
- ✓ Higher theoretical electrical efficiency
- ✓ Fuel cells do not make any noise.

However more research and development is required to bring fuel cells to the required level of performance. In particular, increasing reliability and lowering costs should be objectives for additional research.

Marc Godin

Northern Alberta Institute of Technology
Interview Report

Organization: Northern Alberta Institute of Technology
Edmonton, AB

Date: August 20, 2003

Representative: Richard Caldwell

Description:

The Northern Alberta Institute of Technology (NAIT) in Edmonton is one of Canada's largest institutes of technology. It has approximately 17,000 full-time and apprenticeship students, and about 42,500 continuing education registrations. About 2,400 people work at NAIT's four campuses. NAIT confers certificates, diplomas, and applied degrees. The Institute offers over 190 programs including 32 apprenticeship offerings. Over 1,200 continuing education courses are also available.

Views on the Hydrogen and Fuel Cell Sector

NAIT is heading a recently announced $3.3-million public/private partnership to study the use of high-voltage fuel cell technologies. The partnership is composed of AERI, Western Economic Diversification Canada (WEDC), ATCO Gas and Climate Change Central.

NAIT will install a 200-kilowatt PAFC from UTC Fuel Cells. This fuel cell installation will be Canada's first high voltage, fully operational fuel cell. In addition to electricity, the PAFC will produce useable heat energy in the form of hot water. The NAIT PAFC will produce 50% hot water and 50% warm water. The combined heat and power feature of the PAFC will result in 50% fewer greenhouse gas emissions and 99 per cent less pollutants.

Opportunities for Alberta in Hydrogen and Fuel Cells

NAIT's applied research project team will investigate ways to use the clean energy produced by the 200 kW phosphoric acid fuel cell, such as heating the swimming pool in winter and cooling buildings in summer. The team will also collaborate with other western Canadian research institutions to continue work on improving environmentally friendly fuel cell technologies through research partnerships.

The project team will also look for innovative uses for fuel cells and focus on public awareness and education about the benefits of fuel cell technology from a consumer's point of view. An interactive interpretive centre-incorporating the 200kW fuel-cell will open at NAIT in early 2004 making information about the technology more accessible to the public and explaining the environmental benefits of fuel cells.

The project will also place NAIT's Power Engineering program at the forefront of international fuel-cell education, creating a growing trained workforce capable of applying the emerging technology worldwide. NAIT technology graduates will be able to enter the workforce with a working knowledge of fuel cell technology. Alberta will be well positioned to commercially adopt the new technology and provide a well-trained workforce for the global fuel cell market.

This project is the first of a number of projects in the fuel-cell area. The second project is the installation of a 5 kW SOFC in the Power Engineering Laboratory. A potential third project would be the installation of a PEMFC in the same Laboratory. The purpose is to expose students to the leading fuel-cell technologies in order to give them a broad background and for understanding of the strengths and weaknesses of each technology.

NAIT also plans to experiment with different fuels for the SOFC.

Research and Development Needs for Hydrogen and Fuel Cells

Demonstration projects such as the fuel-cell project at NAIT are an excellent vehicle for the promotion of energy efficient technologies such as hydrogen and fuel-cells. Another example for a demonstration project would be the installation of a fuel-cell at community centers in Alberta. It would allow the community center to stand on its own in the event of a power blackout. The community center would become a shelter and emergency center available to the community. This would particularly be valuable if a blackout were to occur in very cold weather.

Marc Godin

Palcan Fuel Cells
Interview Report

Organization: Palcan Fuel Cells
Burnaby, BC

Date: June 13, 2003

Representatives: Jeremy Tomlinson
Production Manager

Description:

Palcan is a technology company that is developing technology and applications for proton exchange membrane fuel cells (PEMFC). The flagship product of Palcan is a scooter powered by a fuel cell. Asia, particularly China and Taiwan, would be large markets for scooters powered by fuel cells. Palcan has development joint venture in Asia.

Views on the Hydrogen and Fuel Cell Sector:

Transportation and automotive applications of fuel cells are likely to use hydrogen as the fuel. A hydrogen fueling infrastructure is needed. Transportation applications of fuel cells will require a distribution network for high purity hydrogen.

An important issue is the certification and standardization of fuel cell systems. Hydrogen storage is a key issue. Palcan is part of an ISO committee for metal hydrides portable canisters for storing hydrogen. Re-usable canisters are the storage solution that fit best with Palcan's fuel cell scooters. Exchangeable canisters based on metal hydrides offer a low pressure and safe solution for transportation of hydrogen. It is important to develop a certification and standardization procedure and too fast track approvals. Transport Canada and NRCan are working on the issue.

Opportunities for Alberta in Hydrogen and Fuel Cells:

At the moment, Alberta would be a region that is too cold for demonstrating fuel cell vehicles. Proton exchange membrane fuel cells freeze and are damaged by freezing temperatures.

Research and Development Needs for Hydrogen and Fuel Cells:

More research is required on metal hydride storage solutions for hydrogen. In particular, methods need to be developed on how to fill a metal hydride canister with hydrogen. Another issue is how out to get the metal alloy into the canister while maximizing the surface area.

High purity hydrogen is required for fuel cells. A better understanding of contaminants and purification technology is required. In addition there is a need to understand the effects of air quality on fuel cells. Contaminants presents in the air such as fluorocarbons and phenols have an affect on the long term life of fuel cells.

New alternative materials need to be developed for fuel cells. There is a need for better performing conductive materials.

New storage solutions for hydrogen should be explored such as the use of carbon nanotubes and polymer encapsulated rare earth alloys.

The recently announced trial of six fuel cell cars in Vancouver puts Canada into the forefront. The hydrogen refueling station will be an important development. A beta test site for refueling scooters powered by fuel cells would also be a valuable demonstration.

Potential Interest in a R&D Consortium for Hydrogen and Fuel Cells:

Palcan believes that collaborative R&D is an effective approach. It allows small companies to benefit from research while spreading the cost over several organizations. However the intellectual property aspects must be properly addressed. University research is also valuable on fundamental science issues.

Marc Godin

Syncrude
Interview Report

Organization: Syncrude
Edmonton, AB

Date: May 12, 2003

Representative: Wayne McKee
Research Director

Description:

Syncrude Canada is the world's largest producer of crude oil from oil sands and the largest single source producer in Canada. Syncrude currently supply 13 percent of Canada's petroleum requirements Syncrude operate a large oil sand mine, utilities plant, bitumen extraction plant and upgrading facility that processes bitumen and produces value-added light, sweet crude oil for domestic consumption and export.

View on Hydrogen and Fuel Cells

Syncrude does not currently conduct research and development in the areas of hydrogen and fuel cells. Hydrogen is not currently on the technology development radar screen. Hydrogen can be produced by reforming natural gas in a manner that is technically and commercially acceptable.

Research and Development Needs for Hydrogen and Fuel Cells

Eventually, natural gas reserves in Alberta will be depleted. New production techniques for hydrogen will then be needed. Syncrude has studied the gasification of petroleum coke and of heavy bitumen that could result in the production of hydrogen. However it has found that this technology is very expensive. However this is not an immediate need and it will take its least ten years before the subject of alternative methods for hydrogen production becomes a priority

Marc Godin

TransCanada Pipelines
Interview Report

Organization: TransCanada Pipelines
Calgary, AB

Date: August 19, 2003

Representative: Hasan Imran

Description:

TransCanada operates a network of about 38,000 kilometers of pipeline that transports most of Western Canada's natural gas production to markets in Canada and the United States. TransCanada also own, control or are constructing power plants that produce more than 4,500 megawatts of power.

Views on the Hydrogen and Fuel Cell Sector

TransCanada pipeline is not a fuel-cell company and is not involved in the development of fuel cells. TransCanada is a pipeline company concerned with the transmission of natural gas from Western Canada to Eastern Canada and the United States. Is also a power company that operates cogeneration power plants in Canada that are fueled with natural gas. TransCanada is always looking for opportunities to reduce greenhouse gas emissions. In this respect the company would be interested in fuel cells for remote areas in order to reduce environmental emissions and increase efficiency.

Potential Interest in a R&D Consortium for Hydrogen and Fuel Cells:

TransCanada is not interested in participating in the research and development of fuel cells. However it could be interested in the operation of commercial fuel-cell systems or in the demonstration of emerging fuel-cell systems that would be of value to TransCanada, particularly in remote operations. One specific application would cathodic protection of natural gas pipelines. The units involved would be small and less than 5 kW.

Marc Godin

University of British Columbia
Interview Report

Organization: University of British Columbia
Department of Chemical and Biological Engineering
Membrane Reactors Technology

Date: June 5, 2003

Representatives: John Grace
Professor – UBC
Chairman – MRT

Description:

Membrane Reactor Technology is a technology development company in Vancouver. It is built around a patented fluidized bed membrane reactor for producing hydrogen from hydrocarbons such as natural gas. Dr. John Grace of UBC is one of the inventors of the fluidized bed membrane reactor.

Views on the Hydrogen and Fuel Cell Sector:

Research into hydrogen production is key for the hydrogen economy. Of particular importance is the production of high purity hydrogen. MRT has developed a novel reforming reactor. They have done laboratory work with natural gas and converted it to hydrogen. They want to work with other hydrocarbon fuels such as propane, LPG and diesel. MRT is also active in the area of gasification.

Opportunities for Alberta in Hydrogen and Fuel Cells:

MRT is working with Westaim in Alberta for the development of catalysts. The membrane reactor uses a palladium alloy a catalyst on a thin porous membrane. One part of the reactor is used for reforming while and other part is used for shift conversion.

John Grace has worked with Syncrude in the past. He has also been funded by Suncor.

Research and Development Needs for Hydrogen and Fuel Cells:

MRT has a good cooperation with IRAP regarding funding. They are also involved in building a pilot plant at the Institute for Fuel Cell Innovation.

Marc Godin

Western Economic Diversification Canada
Interview Report

Organization: Western Economic Diversification Canada
Edmonton, AB

Date: August 13, 2003

Representative: Doug Chambers
Project Officer

Description:

Western Economic Diversification Canada is a department of the Government of Canada. Its purpose is to stimulate the development and diversification of Western Canada's economy and to advance the interests of the West in national economic policy.

WEDC is supporting programs and activities that advance innovation, encourage entrepreneurship and build sustainable communities. WEDC promotes the commercialization of technology; leverages new funding; brings together companies and other partners to work jointly on projects; and supports the development of clusters in key sectors of the Western economy.

View on Hydrogen and Fuel Cells

Doug Chambers is part of the innovation group at Western Economic Diversification Canada. The innovation group has identified 10 priority areas. Fuel cells are a priority area. Greenhouse gases reduction is another priority area. The Vancouver office of WEDC is the lead office regarding fuel cells. WEDC is also heavily involved with Fuel Cells Canada and recently WEDC extended additional funding to FCC. WEDC has also helped funding for one of the hydrogen safe laboratory at the Institute for Fuel Cell Innovation in Vancouver. In Manitoba, WEDC has supported a fuel-cell project involving buses powered by fuel cell engines.

Opportunities for Alberta in Hydrogen and Fuel Cells

In Alberta, WEDC is a partner with the Alberta Energy Research Institute [AERI] in the project to install a fully operational fuel-cell at the Northern Alberta Institute of technology {NAIT}. WEDC has also funded strategy development at the University of Calgary for the Western Canada Fuel-Cell Initiative. WEDC has provided financial support for fuel-cell conferences in Alberta held in 2003 at the University of Calgary and in 2001 at the University of Alberta.

Potential Interest in a R&D Consortium for Hydrogen and Fuel Cells

WEDC is considering participating in a potential project for a hydrogen fueling station in the Alberta Industrial Heartland with AERI. Hydrogen and fuel cells are a priority area for WEDC and projects proposed by AERI are technically strong and well justified. WEDC has worked well with AERI in the past and looks forward to continuing this fruitful relationship in the future.

Marc Godin