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FUEL CELLS - THE CANADIAN EXPERIENCE

DTI International Technology Service Mission Report
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EXECUTIVE SUMMARY

David Hart, Imperial College of Science, Technology and Medicine

Canada is viewed as a world-leading developer and supplier of fuel cell and hydrogen related technologies, with over 60 companies working in the sector. The focus of activity is British Columbia, with 30 plus companies, although Ontario has over 20. Québec and Alberta are also represented, with 6-8 companies in each. 1,800-2,000 people are employed in the sector, and, if growth trends continue, levels will rise to ~2,500 in 2003. Again, British Columbia is the focus of employment, with 1,200 jobs in Vancouver alone.

The key aim of the DTI International Technology Service sponsored Mission to Canada was to foster the development of the UK fuel cell industry through exposure to what is probably the most successful example of a fuel cell industry to date, albeit still in a nascent state. Specific objectives included improving UK awareness of Canadian fuel cell developments; developing an appreciation of markets, applications and drivers; and understanding the nature and support structures of the Canadian industry, especially with regard to Government policy. Further objectives were in developing opportunities for collaboration and technology transfer, and highlighting opportunities for fuel cells in the UK.

A wide range of companies representing the Canadian fuel cell and hydrogen industry was visited, taking in most elements of the supply chain. Stack and system technology developers, materials and component suppliers, balance of plant, fuel and testing equipment suppliers were all represented, in addition to Government bodies and financiers. The primary focus in Canada is on Proton Exchange Membrane (PEM) fuel cell and Solid Oxide fuel cell (SOFC) related technologies, including some research on Direct Methanol fuel cell (DMFC) technology.

A number of themes emerged during the Mission; these are discussed below.

Strong and co-ordinated Government support has enabled the industry to develop at a rapid pace. This support has partly been in the form of Government funding injections for corporate or entrepreneurial R&D, as well as in wider co-ordination and support, such as education funding and provision of facilities. Government funding has achieved high 'leverage' of about 6:1 overall (4:1 on average in R&D activities), enabling significant developments with limited investment, and shared risk-bearing. It is recognised that fuel cell companies tend to be early-stage and thus have less ability to match funding than established industry.

To help focus effort and achieve early commercialisation of products, road-mapping has formed and is forming an important part of Government and industry strategy development. A major worry at present is that Canada will not have the resources to compete with the USA and Japan, in particular, as they begin to invest heavily in this area, and will lose its current leading position – and perhaps some of its companies and expertise.

The development of fuel cell and hydrogen related industries is facilitated by the formation of 'industry clusters', where support services from fundamental research to components production and supply are available to the stack and system manufacturer. Equally, the development of a successful company in the area of fuel cells or broader hydrogen technologies may instigate the evolution of a cluster, formed either by new firms entering the market locally or by enhanced local awareness of potential leading to development of new products within existing companies.

No easy win situations exist for fuel cells, and the early markets are expected to be in specialised areas with particular economic drivers, such as remote power for telecommunications. In fact, some systems are already being sold into this area. However, confidence is high that products can be developed to meet more demanding cost and performance targets.

From the Canadian Government perspective, two specific drivers for fuel cells appear to dominate. One of these is clearly the benefit to Canada of developing a leading-edge industry that can grow as older, mature industries decline. The second is the potential for fuel cells to be adopted in Canada to meet Greenhouse Gas emissions reduction agreements, especially in the transport sector. To this end, a plan is being developed for the introduction of limited hydrogen refuelling infrastructure, partially in partnership with US organisations, to enable fuel cell vehicles to be sold into these areas. Infrastructure is seen as an area where specific Government support is required, to spread risk and enable a long-term perspective to be taken.

Market drivers for fuel cell and hydrogen technologies in general are broader, and include:

- the partial liberalisation of the Canadian energy market and a concomitant increased interest in decentralised generation;
- security of energy supply in the sense of ‘keeping the lights on’ in extreme weather conditions; and
- air quality improvements.

The USA, Japan and, to a lesser extent, Germany are generally considered the leading markets (and competing technology developers) for Canadian companies. The UK is currently not seen as an important or valuable market opportunity, although there is nevertheless very strong interest within Canadian companies and Government to forge and develop links with the UK. “[The UK] could be made into [an attractive market], given similar support to the German market”.

From a fuel cell and hydrogen technology perspective, Canada has developed impressive strengths in a range of areas, including:

- Hydrogen:
    - Production – electrolysis, gas separation, methanol reforming
    - Storage and supply – cylinders, tube trailers, hydrides, nanotubes
    - Fuelling – regulators, reforming, infrastructure
    - Safety – sensors, modelling, Codes and Standards

- Fuel cells:
    - PEM and SOFC – mobile, portable, stationary, APUs
    - Materials – flow plates, heat exchangers, catalysts
    - Balance of Plant – inverters, integration, controls
    - Test Stations – PEM, SOFC
    - Integration i.e. fuel cell/hydrogen “systems”

Canada has highly developed fuel cell technology and stack capability in the PEM area, with initial products on limited commercial sale from Ballard Power Systems Inc., H Power Enterprises of Canada Inc. and Hydrogenics Corporation. Each has strong strategic links with major companies, such as DaimlerChrysler (Ballard), GM (Hydrogenics) and Osaka Gas (H Power). Only Ballard is developing stacks for the automotive market, although Hydrogenics has access to GM stack technology. Each has some manufacturing capacity already in place.

From an SOFC perspective, expertise has also been developed. Some of this is using external technology, such as Fuel Cell Technologies' agreement with Siemens-Westinghouse to use 5kW SOFC 'bundles' in its systems, but indigenous expertise also exists. Novel applications including sulphur-resistant designs are under investigation for use with sour gas wells (i.e. Snow Leopard), and could be extended to PEM fuel cell systems. Small-scale tubular systems are also being developed (i.e. Energy Visions Inc.).

Fuel production and purification is advanced, with two world-class companies in the field of small-scale electrolysis (Stuart Energy Systems Corporation and Hydrogen Systems Inc.), and one in high-speed gas clean-up (QuestAir Technologies Inc.). Each is aggressively pursuing the hydrogen energy market, although QuestAir technology is applicable to a wide range of gases.

Hydrogen storage is a key component of the overall energy system and is being pursued, again, by two globally competitive companies. Dynetek Industries Ltd manufactures high-pressure gas cylinders using an aluminium liner and carbon-fibre wrap, while HERA Hydrogen Storage Systems Inc. is developing advanced metal and chemical hydride storage systems. Each is recognised to have a significant global brand.

Other support for the industry comes in the form of materials and components supply, with Dupont Canada Inc. an important player in the design of bespoke membranes for PEM, in particular. Fuel reforming technologies exist in-house at Ballard and H Power, while academic work on methanol reforming is being done at the Institute for Integrated Energy Systems at the University of Victoria (IESVic) in British Columbia with Methanex Corporation, and on a variety of reforming techniques at the Royal Military College of Canada in Ontario.

Testing and evaluation is a crucial factor in the value chain, and provides one of the few areas of consistent revenue for fuel cell companies. Both Hydrogenics and Greenlight Power Technologies Inc. have automated test stands for sale, whether off-the-shelf or bespoke, for fuel cell cell, stack or system tests and diagnostic work. BC Hydro/Powertech has large-scale testing facilities for hydrogen safety experiments, for example, and Kinectrics Inc. can conduct large-scale fuel cell system testing in internal controlled environments. BC Hydro is also investing in hydrogen infrastructure.

At the far end of the supply chain, Chrysalix Energy provides venture capital funding, enabling finance that might otherwise be unavailable. Dealflow is primarily concentrated in the Pacific North-West.

The overall picture from Canada is impressive. A complete supply chain has come into existence around several specific technologies – driven primarily by PEM fuel cell and SOFC development. Clusters of companies from the materials and component supply level to the end-user have formed in several Provinces. Significant assistance has been given by Government programmes, some of which has been strategic, and some opportunistic. Additionally, private and corporate finance has been available to help balance the Government input. However, concern has developed that the position achieved by Canadian companies may be overtaken by the USA and Japan deploying greater financial resources. At the present time, strong interest exists in Canada to form or strengthen connections with the UK, including technical, industrial or academic exchanges. This may offer an opportunity for the UK to benefit from learning from a comparatively mature fuel cell and hydrogen industry, while assisting Canada to stabilise its position as a global player.

In visiting the 25 companies and Government organisations during the course of this Mission, the team developed a number of recommendations for the UK fuel cell and hydrogen industry, UK Government and its agencies and UK academic institutions. These recommendations are summarised below:

- It is recommended that consideration be given to developing an integrated approach (based on the Canadian "industry clusters" model) to assist companies to collaborate and develop the products that the market needs, with public funds and facilities channelled accordingly.

- It is recommended that significant and sustained public investment should be made in the industry in order for the UK to be a "player" in this emerging market (which is not too late).

- It is recommended that consideration be given as to the barriers that exist in obtaining finance for projects that are perceived as "high risk" by private finance sources, and for SMEs. Innovative finance mechanisms should be developed to enable demonstrations to take place with SME participation.

- It is recommended that liaison and co-ordination between Government Departments and agencies supporting fuel cell and hydrogen activities in the UK be strengthened through the establishment of a co-ordinating body providing a focus for communication, and the development of joined-up and consistent policy and innovation-friendly regulation.

- It is recommended that opportunities to form or strengthen connections with Canada (including technical/industrial/academic exchanges) be investigated with the DTI's ITS Secondment Programme and EPSRC.

- It is recommended that the internationally respected UK academic base for fuel cells and hydrogen be nurtured and developed. A capabilities report/directory should be produced for the universities and research institutes.

- It is recommended that consideration be given to establishing a DTI-EPSRC LINK Programme for fuel cells and hydrogen to provide a vital linking role between fundamental science activity and industrially-led applied R&D and demonstration.

- It is recommended that the benefits of publicly supported R&D and testing facilities in the UK that would provide incubator support services for small and start-up companies be evaluated.

- It is recommended that a new, integrated, industry-led technology and commercialisation road mapping activity be conducted and that this be used to develop implementation strategies and guide public funding so as to position the UK in the vanguard of countries in these areas.

- It is recommended that a UK fuel cell industry association (along the lines of Fuel Cells Canada) be established as a priority.

- It is recommended that greater consideration be given to the importance of hydrogen infrastructure, fuel cells and associated opportunities, as part of a balance portfolio of measures to achieve reduction of Greenhouse Gas emissions, and mechanisms for achieving this.

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ACKNOWLEDGEMENTS

Many organisations and individuals contributed to the success of this technology Mission. The Mission organisers and participants wish to extend particular thanks to:

- The Department of Trade and Industry's International Technology Service
- The Canadian High Commission in London
- The British High Commission in Ottawa, the Consulates-General/Consulates in Montreal, Toronto and Vancouver, and the British Trade Office in Calgary
- Fuel Cells Canada
- The National Research Council's Innovation Centre in Vancouver
- The 25 Canadian companies and Government organisations that hosted the Mission team.

1. INTRODUCTION

Celia Greaves, Synnogy

1.1 Background to the Mission

Canada is the world's leading country in the commercialisation of fuel cells. Canadian companies are regarded as being in the vanguard of developing stack components, materials, manufacturability, fuel reforming / handling/ storage technologies, air handling capability, power conditioning and integrated systems for both Proton Exchange Membrane (PEM) fuel cells and Solid Oxide fuel cells (SOFC). All of these are of considerable interest to UK companies.

Given Canada's leading position in the fuel cell industry, there was considerable enthusiasm for a Mission amongst organisations such as leading UK companies and academic institutions, the Department of Trade and Industry, the Foreign and Commonwealth Office's Posts in Canada and the British High Commission in Canada. The Mission was developed in response to this enthusiasm and with the objectives described below.

The DTI's International Technology Service (ITS) backs short fact-finding overseas visits by small groups of technical experts from UK companies, to identify and learn from the best practice and technological developments in leading companies overseas. ITS funds the travel costs and helps towards the sponsoring body's costs of organisation and promotion. Full details of about DTI missions and other activities of the International Technology Service can be found at www.globalwatchonline.com

1.2 Overview of the Canadian Fuel Cells and Hydrogen Industry

<u>The Market</u>

The drivers behind the growth of the "hydrogen economy" appear to be universal. In the power generation market the growing demand for power, coupled with more stringent environmental constraints and limited capacity for additional transmission of power, are creating an opportunity for clean, quiet, distributed generation technologies. Transportation is arguably the single largest contributor to atmospheric emissions. Highly efficient fuel cell and hybrid powered vehicles offer a clean alternative to traditional internal combustion engines. In addition, certain fuel cell technologies have attributes such as long-life, that will make them ideal to replace existing battery technologies. The Canadian Government (Federal and, in some cases, Provincial) and industry are approaching the hydrogen economy in a collaborative manner to create a relatively comprehensive and competitive fuel cell industry. Through this collaboration, technologies are evolving that appropriately address the potential of a future hydrogen economy.

Key Features of the Industry

Key features of the Canadian fuel cells and hydrogen industry are as follows:

- The industry currently employs 1,800-2,000 people - this number has grown rapidly from a low level in the mid-1990s and is continuing in an upwards trend. (In 1995/96 the headcount was ~200; 2000/01 ~1,700; 2002/03 ~2,500 estimated). Approximately 1200 of these are employed in Vancouver alone.

- Total R&D expenditure in the fuel cells and hydrogen industry has grown dramatically since the mid-1990s and currently exceeds C$200 million/year. (In 1995/96 total R&D expenditure was ~C$20m; 2000/01 ~C$180m; 2002/03 ~C$360m estimated).

- R&D "intensiveness" is very high in the Canadian fuel cells and hydrogen industry, running in excess of C$100,000/person/year – a much higher figure than for other major Canadian industries such as the aerospace and automobile industries.

- As a result of product development, the Canadian fuel cells and hydrogen industry has started to generate revenue from sales - currently, this annual revenue exceeds C$100 million/year. (In 1995/96 no revenue was generated; 2000/01 ~C$95m; 2002/03 ~C$360m estimated).

- Much of the revenue generated is through sales exports - these are currently valued at around C$100 million/year. (In 1995/96 no exports were generated; 2000/01 ~C$80m; 2002/03 ~C$130m estimated).

- Investment by the Federal Government and several Provincial Governments (mainly British Columbia, Québec and Alberta) in the Canadian fuel cells and hydrogen industry to the end of 2001 totalled over C$150 million. This enabled Canadian Fuel Cell companies to generate close to C$1 billion in public markets in 2000 – a leverage effect of over 6:1, giving a total investment over the decade of approximately C$1.1 billion. Funding levels have declined recently.

- The Canadian fuel cells and hydrogen industry has developed world-leading strengths in:

  Hydrogen:
  - Production – electrolysis, gas separation, methanol
  - Storage – cylinders, tube trailers, hydrides, nanotubes
  - Fuelling – regulators, reforming, infrastructure
  - Safety – sensors, modelling, codes and standards

  Fuel cells:
  - PEM and SOFC – mobile, portable, stationary, Auxiliary Power Units (APUs)
  - Materials – flow plates, heat exchangers, catalysts
  - Balance of Plant (BOP) – inverters, integration, controls
  - Test Stations – PEM, SOFC
  - Integration i.e. fuel cell / hydrogen "systems".

Canadian Fuel Cell Companies

From a geographical perspective, the location of Canadian fuel cell companies generally reflects the immature nature of the industry and the Canadian topography; companies tend to form in groups centred around areas associated with high tech industries. Specifically, the industry comprises over 60 companies, mainly focused in British Columbia (30+), Ontario (20+), Québec (7+) and Alberta (6+). This clustering supports the necessity for collaboration to derive maximum benefits from technology development, and the transfer of best practices amongst the participants.

Select companies are developing the hydrogen infrastructure (including production, transport and storage technologies) necessary to support broad fuel cell applications. A smaller group of companies is developing core fuel cell technologies, generally PEM and SOFC, for three broad categories of applications: transportation, stationary power and portable power.

Canadian companies demonstrate the range of commercial applications that will arise as the hydrogen economy continues to mature. They also show the diverse nature of the technologies that are being created to address it. It is reasonable to assume that there are innate efficiencies in the development of both upstream and downstream technologies in the fuel cell value chain.

1.3 Mission Objectives

<u>High Level Aim</u>

The key aim of the Mission was to foster the development of the UK fuel cell industry. This was to be achieved by:

- improving UK awareness of fuel cell developments in Canada;
- developing opportunities for collaboration and technology transfer to help develop the UK fuel cell industry, for stationary power, transportation and portable power applications;
- highlighting opportunities around fuel cells for the UK; and
- enhancing awareness of new markets and applications.

<u>Specific Objectives</u>

The specific objectives were:

- To facilitate new relationships of potential value to UK industry.
- To support the development of the UK fuel cell industry through dissemination of Mission findings.
- To expose UK organisations to leading edge thinking and activity around fuel cell commercialisation, thus supporting their own development.

1.4 Participants

The Mission was organised and managed by Synnogy (Celia Greaves). Other participants comprised:

Alastair Rennie	AMEC
David Wright	Core Technology Ventures
Kevin Pointon	Defence Science and Technology Laboratories (DSTL)
Ray Eaton	Department of Trade and Industry (DTI)
Philip Sharman	DTI - International Technology Promoters
David Hart	Imperial College of Science, Technology and Medicine
Dennis Hayter	Intelligent Energy
Alan Chapman	Morgan Materials Technology
Dave McGrath	Regentech
Alan Spangler	Rolls-Royce Fuel Cell Systems

Further details are provided in Appendix A and B.

The Mission team visiting QuestAir: from left to right - Dennis Hayter, Intelligent Energy; David Wright, Core Technology Ventures; David Hart, Imperial College; Celia Greaves, Synnogy; Alastair Rennie, AMEC; Ray Eaton, DTI; Alan Chapman, Morgan Materials; Alan Spangler, Rolls-Royce, Kevin Pointon, DSTL.

1.5 Itinerary

The Mission took place between September 11 and September 18 2002. During that period, the group met with 25 private and public sector bodies, along the full length of the fuel cell supply chain, and across Canada. The schedule was as follows:

Date	Location	Visit / meeting
12 September	Montreal	Natural Resources Canada (NRCan) HERA Hydrogen Storage Systems Inc. Hydrogen Systems Inc. H Power Enterprises of Canada Inc.
13 September	Toronto	Fuel Cell Technologies Ltd. Dupont Canada Inc. Kinectrics Inc. Hydrogenics Corporation Stuart Energy Systems Corporation
14 September	Vancouver	Fuel Cells Canada National Research Council of Canada (NRC) Industry Canada Government of British Columbia Institute for Integrated Energy Systems (IESVic) Chrysalix Energy Azure Dynamics Corporation Methanex Corporation
		Reception hosted by the British Consulate, Vancouver
17 September	Vancouver	BC Hydro Ballard Power Systems Inc. QuestAir Technologies Inc. Greenlight Power Technologies Inc.
18 September	Calgary	Dynetek Industries Ltd. Energy Visions Inc. Alberta Economic Development Snow Leopard

Indicative capabilities are shown overleaf.

Contact details can be found in Appendix C and a full list of topics for discussion at the various visits and meetings is provided in Appendix D.

1.6 About this Report

This Report summarises the learning from the Mission and considers the implications for the UK. The Chapters which follow have been produced by individual members of the group, in line with specific areas of expertise.

	PEM		SOFC		DMFC		Hydrogen		System Integration	Hybrid Engines	Basic Research	Venture Capital / Funding / Other Support
	Units	Supply / Test	Units	Supply / Test	Units	Supply / Test	Production	Storage				
Azure Dynamics										X		
Ballard	X											
BC Hydro / Power Tech	X						X		X			
Chrysalix												X
Dupont		X										
Dynetek								X				
Energy Visions					X							
Fuel Cells Canada												X
Fuel Cell Technologies			X									
Greenlight Power		X		X								
H Power	X											
HERA								X				
Hydrogen Systems							X					
Hydrogenics	X	X										
Industry Canada												X
IESVic											X	
Kinectrics				X					X			
Methanex							X		X			
NRC											X	X
NRCan											X	X
QuestAir							X					
Snow Leopard		X		X								
Stuart Energy							X		X	X		

2 FUELS: PRODUCTION AND STORAGE

Kevin Pointon, DSTL

2.1 Introduction

As mentioned earlier, a number of Canadian organisations are embracing the concept of the hydrogen economy and participating in its development. Since free hydrogen is not found in significant quantities on the Earth, production of hydrogen, together with compact and safe storage of hydrogen, represent key enabling technologies for the development of hydrogen infrastructure. Use of sustainable hydrogen sources will aid in meeting social and environmental targets. In many applications, successful hydrogen production from existing fuel stocks (fuel reformation) will be also be fundamental to the emergence of hydrogen technologies such as most fuel cells, during what will certainly be an extended transition period to a sustainable hydrogen economy. This Section examines the status of these technologies in Canada and the activities of those key developers visited during the Mission.

2.2 Fuel Reformation

The Stack Developers' Perspective

A natural starting point for discussion on fuel reformation in Canada is to consider the activities of its small number of stack developers/manufacturers. Among others, the Mission visited H Power, Ballard Power Systems, Fuel Cell Technologies and Hydrogenics.

H Power is currently pursuing propane and natural gas reforming for its residential co-generation units (RCU) and premium power products. Products fuelled in this way are to follow its current hydrogen-fuelled product line in 2-3 years. Its longer-term vision is for renewable energy sources, possibly coupling its products with a biomass reactor. However, it is not currently working on reforming these types of fuels.

H Power has its own proprietary steam reforming fuel processing technology, which it has been installing in development versions of its RCU. In addition, it has recently entered into a licensing agreement with Osaka Gas Co. of Japan, under the terms of which it has the right to manufacture, integrate, use and improve upon Osaka Gas's fuel processor for use in H Power systems. This processor is based on steam reforming and is more applicable to small-scale systems than H Power's, the break point being around 1.2kW$_e$.[1] Other manufacturers would also be considered if they offered an advantage.

A tour of H Power's manufacturing facility revealed several 4.5kW$_e$ RCUs being readied. The units were large (around 1.4m x 1.4m x 1.5m), with the fuel processor accounting for around 50% of the volume. H Power sees reliability and cost as key R&D issues; reducing the footprint of the fuel processor is of secondary importance. Nevertheless, the degree of consumer acceptance required to generate volume markets is likely to require considerably less cumbersome units than that demonstrated, the fuel processor being a key area for miniaturisation. The current

[1] W$_e$ refers to a specific electrical output from a unit or system. This level of detail was not available in all discussions / visits.

performance of H Power's fuel processor in terms of power density is only around 3W/l (c.f. 50W/l achieved by the Tokyo Gas 1kW$_e$ fuel processor).

Ballard, too, is concerned with reforming natural gases. It has been incorporating Tokyo Gas' fuel processors into its Ebara Ballard 1kW$_e$ domestic combined heat and power (CHP) units for the Japanese market. This is a high efficiency integrated natural gas steam reformer. Its agreement with Tokyo Gas allows it to distribute products incorporating the technology throughout the world. Ballard has also agreed to collaborate with Osaka Gas in developing Osaka's low temperature compact fuel processing sub-system for the Japanese residential market.

Ballard has its own proprietary natural gas steam reformer technology. This has been incorporated into its 250kW$_e$ field trial units. Ballard considers performance data on this reformer to be confidential until completion of its field tests. However, it is known that the fuel processor occupies around 40% of the 2.4m x 2.4m x 6.1m package. Although the main thrust of Ballard's fuel processing activity for stationary generation is focused on natural gas, its reformer (with enhanced gas clean-up) can also be operated on biogas. Indeed, one of the field trial units was delivered to a biogas application at a sewage treatment plant in Japan.

In addition, Ballard possesses internal technology for reforming methanol and synthetic fuels such as dimethyl ether. Although details of these were not released during the visit, Ballard has recently patented technology based on auto-thermal reforming which can be used for reforming such fuels.

Fuel Cell Technologies (FCT) fuel reforming approach is based firmly around internal reforming of natural gas for its 5kW$_e$ CHP systems in order to achieve system simplicity and maximise the efficiency of its SOFCs. Its system design achieves desulphurisation using an activated carbon adsorbent together with a chemical step to remove more problematic sulphur compounds. Pre-reforming is achieved using a small reactor integrated in the stack.

FCT is collaborating with the Electrochemical Power Sources Group at the Royal Military College of Canada, which has expertise in catalyst development, methanol reforming, high-temperature reforming and membrane reformers. Their role in FCT's programme is in pre-reformer development.

The System Integrators' Perspective

The Mission visited Kinectrics and Hydrogenics. A major current project by Kinectrics is a demonstration of Siemens-Westinghouse's 250kW$_e$ CHP unit. Kinectrics' role in this project includes Balance of Plant (BOP) engineering and assembly, fuel system evaluation, site engineering, system integration, permitting and approval, grid connection, CHP system, start up, testing and reliability analysis.

The visit to Kinectrics included a tour of its facility. On show was a 250kW$_e$ Siemens-Westinghouse unit being readied for deployment in the field. The unit is large, filling the whole of a 12m x 3m x 2.5m container. Roughly half of this is the stack and fuel processing system; the remainder is the BOP. The fuel processing system is a standard internal reforming front-end, employing adsorbent for de-sulphurisation and pre-reformer integrated with the stack. The adsorbent is non-standard and was sourced from a Japanese supplier. It occupies significantly less volume than activated carbon and can remove problematic species such as diethyl sulphide and thiophenes. The stack and fuel processing system run on natural gas at atmospheric pressure.

Kinectrics see optimal integration of the stack and BOP items such as the fuel processing system as one of the key challenges for the development of competitive fuel cells.

Partly funded by NRCan, Hydrogenics is developing a $50kW_e$ natural gas-fuelled unit for multi-unit dwellings and small commercial sites (to be known as HySTAT™). The reformer is based on steam reforming in conventional packed catalyst beds and is being supplied by a third party. The reformer system measures approximately 2.1m(H) x 1.8m(L) x 1.5m(W), i.e. it operates at a power density of around $8W_e$/l. The company sees reduction of the reformer volume and the integration of its controls to the fuel cell module as being the most pressing development issues.

The Government Perspective

The NRC has a carbon dioxide neutral fuel production project i.e. production of hydrogen from hydrocarbons without a net release of CO_2. This includes developing highly efficient hydrogen storage materials and demonstrating/evaluating reforming technologies.

A significant vehicle by which Federal Government is supporting fuel-reforming activities is the Canadian Transportation Fuel Cell Alliance (CTFCA) (See also Section 7). This is a five-year, approximately CD$69m (including leveraging) programme focusing on hydrogen fuelling infrastructure development for fuel cell vehicles. Reforming options that will be demonstrated include natural gas reforming to hydrogen at distributed stations and methanol stations for vehicles with on-board fuel reformation to hydrogen.

As part of the CTFCA programme, NRC, BC Hydro and Methanex are in the process of developing a proposal for a “hydrogen highway”, a refuelling station demonstration project involving a total capacity of 2,000 kg/day split amongst six stations along a specific route in British Columbia. Three stations are planned to feature methanol reforming and one will be equipped with a natural gas reformer. Methanex is a partner in the project and will supply reforming technology. It is providing a complete fuel supply package and is able to deliver methanol or hydrogen on site depending on the wishes of the customer. Methanex plans on drastically changing its reformer and purification units to cut their costs in the next year. They are much cheaper than natural gas based reformers for up to 1,000kg of hydrogen per day.

Overview

Because the PEM sector of the fuel cell industry is focusing its efforts on driving hydrogen-fuelled devices into niche markets in order germinate a wider fuel cell market that can grow, it is not overemphasising fuel reforming for fuel cell systems. As evidenced by H Power’s and Hydrogenics’ declared intent, together with Ballard’s initial product orientation, systems fuelled with methanol or traditional fuels, such as natural gas, are seen more as future products. The overall Canadian approach to fuel reformation appears to mirror this pragmatism – generally fuel reformation appears to centre around packaging more or less conventional technology without outstanding performance, but which is likely to work and is comparatively less expensive than more sophisticated alternatives. Where any information concerning the conversion technology was forthcoming, it usually related to steam reforming.

The SOFC developers visited by the Mission were exclusively concerned with internal reforming. However it is known that Global Thermoelectric’s approach is basically one of external reforming - developing propane and natural gas reforming at the 5 kW_e scale and also a low temperature adsorbent-based desulphuriser. This fuel focus is consistent with the SOFC developers visited i.e. natural gas/propane for stationary power generation.

Given that the approach to applying fuel reformation in Canada is largely standard, the question arises: what more advanced technology is being researched that may be available for implementation in the future? The Mission was briefly exposed to the following projects:

- *Enzymatic reforming of methanol (IESVic/Methanex)*
  This is and early stage project to develop an *in vitro*, enzymatic pathway to convert methanol to hydrogen. This will be a low temperature (<50°C), low pressure process for converting methanol to formaldehyde and hydrogen. Produced hydrogen will be pure and no greenhouse gas emission will occur.

- *Microscale reforming (NRC).*

- *Electrochemical reforming in SOFCs (Eltron Research Inc/Snow Leopard)*
  Eltron Research has developed a catalytic membrane reactor based on solid oxide technology for partial oxidation of sulphur containing liquid fuels. This uses a mixed conducting solid oxide membrane, effectively being a short-circuited fuel cell. The fuel side has a partial oxidation catalyst and the oxidant side an oxygen reduction catalyst. When steam (to eliminate carbon deposition) and fuel are added, oxygen ions partially oxidise the fuel:

  $$C_nH_{2n+2} + nO^{2-} \rightarrow nCO + (n+1)H_2 + ne^-$$

  Based on Eltron's performance achievement of $12cm^3$ oxygen transfer per minute, the technology should fairly readily allow reactor sizes of the order of $5kW_e/l$ (not including shift and the rest of the system).

2.3 Electrolysis

Two organisations visited on the Mission are participating actively developing and marketing in-house fuel production technology utilising electrolysis, in order to compete in the approximate £20M/year world-wide electrolyser market. Hydrogen Systems has technology aimed at on-site and on-demand hydrogen production and claim the highest efficiency commercially available. Also, it is developing a unitised regenerative fuel cell (integrated and reversible electrolysis technology and fuel cell in one electrochemical stack) based on its core technology.

The core technology is the Inorganic Membrane Electrolysis Technology (IMET™). The module consists of a number of circular electrolysis cells. It is bipolar with a parallel-connected electrical system and series connected hydraulic system. The unit requires process water (<1l per Nm^3 of hydrogen produced) and cooling water for the cells. Anode and cathode aqueous electrolytes and gaseous products are kept separate by a membrane. This membrane is the key innovation at the heart of the electrolyser and it is this that Hydrogen Systems claim is the main element that differentiates its technology. It is an inorganic alkaline ion exchange membrane that Hydrogen Systems has patented in 114 countries.

When operating, generated hydrogen and oxygen bubbles are carried along with the electrolyte to the top of the cells and collected in two separate headers in the module. The gas flows into the gas separator and is removed from the electrolytic solution.

From the gas separator, the hydrogen is passed through a rinser integrated in the electrolyser, where the last traces of potassium hydroxide are removed. Finally, the gases flow to the outlet connections via separate coolers and de-mister columns.

Since the process employs gravity to drive the electrolyte through the module, no pump is required in the unit. With the exception of valves and exhaust fan, the electrolyser uses no moving parts. There is also no external or internal electrolyte tank and there is no requirement for an electrolyte filter.

The efficiency of the electrolyser is claimed to be high and requires 4.8kWh per Nm^3 of hydrogen (4.2 from the electrolyser and 0.6 from the peripherals). The unit can produce hydrogen at 25 bar without a compressor. Higher pressures require a compressor due to materials issues. Hydrogen Systems claims its electrolyser can produce hydrogen at 35 US cents/Nm^3, i.e. about US$4/kg, excluding capital and maintenance costs.

Stuart Energy's core technology is also based on proprietary alkaline water electrolysis. Stuart is concentrating on producing hydrogen in three markets:

- its current market of industrial hydrogen plants and other large projects;
- a near term market of back-up and off-grid power, which it sees as becoming significant after 2003; and
- a longer-term transportation market, i.e. fuelling infrastructure.

Stuart is integrating its own technology with hydrogen generation and storage solutions, power conversion, packaging, controls and dispensing to produce complete systems, of which it has already sold over 1000. It supplies a variety of electrolyser plants from $1Nm^3/h$ to over $20,000Nm^3/h$. (To put this into perspective, the latter would meet the refuelling needs of around 20,000 fuel cell cars.)

Stuart's power products typically feature electrolyser production, storage in hydride or conventional cylinders and internal combustion engine electrical generator sets. Its initial products will be at the $250kW_e$ scale.

All Stuart's products are based on its proprietary technology. It has 15 issued patents and more than 100 additional applications on file. Its DEP™ electrolyser, using newly developed electro-catalysts, has demonstrated energy efficiency greater than 90% in multi-kilowatt electrolysis cells. Fundamentally, the technology is based on alkaline water electrolysis. Stuart sees electrolysers based on PEM as slick but expensive and competitive only at small scale. Alkaline is better at large scale (break point roughly $0.5Nm^3/h$).

The visit included a tour of Stuart's plant. The delegation saw a $12Nm^3/h$ electrolyser coupled to a high-pressure storage system comprised of 12 x 5kg tanks. The electrolyser is modular with each module providing $6m^3/h$. Up to six modules could be supplied, giving a total of $36m^3/h$. When power is needed, an internal combustion engine generator starts up in 15 seconds (there is a battery for ride through) and provides $120kW_e$ for up to six hours. The storage tanks discharge sequentially. The electrolyser can be run indefinitely with minimal maintenance (mostly filter replacement).

Stuart admitted that, as a value proposition, this form of Uninterruptible Power Supplies (UPS) doesn't stack up economically. To maximise the economic case, an additional use for produced hydrogen is required (e.g. refuelling the organisation's vehicles). The electrolyser is the highest cost component of the system.

Canadian electrolysers have been and are being incorporated into a number of key demonstration projects, the majority outside Canada. Stuart has orders for or has delivered eight hydrogen fuelling stations. This includes a bus fueller for heavy-duty hydrogen supply to buses and trucks, which is capable of delivering 35 – 3,500Nm^3/h at up to 408 bar. There is a smaller scale (450 or 1,350Nm^3/h also at up to 408 bar) community fueller for automobiles.

Hydrogen Systems' IMET™ technology is currently being installed in filling station demonstrations. Under the EU-supported Clean Urban Transport Europe (CUTE) programme, the company is supplying electrolysers to a filling station in Amsterdam. The design criteria for this are for 120kg/day production of 99.95% pure hydrogen with continuous operation at an availability of 95%. This will be sufficient to refill one bus with 40kg of hydrogen per eight-hour period. Hydrogen Systems also has demonstrations under construction in the USA (with Quantum), Canada (with General Hydrogen), the UK (with Cambridge University) and Sweden at Gotland and in operation at the Japan Auto Research Institute.

2.4 Fuel Storage

High Pressure Cylinders

Canadian development in this area is represented by Dynetek. Dynetek manufactures and markets lightweight high-pressure gas storage tanks that have application in on-board storage or filling station storage of hydrogen or natural gas for vehicles or for bulk hydrogen transport. Currently, Dynetek's business is mainly in natural gas cylinders.

The company's core technology, DyneCell, is a seamless, thin-walled aluminium liner with a carbon fibre overwrap. Features claimed by Dynetek for this technology are:

- *Corrosion resistance in harsh road vehicle environments* - this is a consequence of the materials choice.
- *Highest internal volume for any given diameter of any lightweight cylinder on the market* - the difference in wall thickness of only 5-6mm, means that competitors need to install nine cylinders per bus to Dynetek's seven.
- *Greater cylinder heat dissipation* - this results in a greater fast fill capability. For example, some competing cylinders require 5-8 minutes for filling to 5,000psi; DyneCell can be filled in around 1 minute.

The tanks are manufactured by stretching a rotating cylindrical aluminium tube, heated strongly along its centre (the end sections are left full thickness since they must be moulded into the cylinder ends). The ends are then closed and the cylinders annealed and quenched. With three cylinders on the jig at the same time, the cylinders are wrapped with epoxy resin-coated carbon fibre, a process that takes 20 minutes (Dynetek are close to perfecting a much faster system that will require only two minutes). After curing the resin for five hours, the cylinders are pumped up well beyond their design specification. This has the effect of plastically stretching the liner. When the cylinder is emptied, the liner is then under compression by the carbon fibre. Now, on refilling, the first 100 bar simply counteracts the compression.

Dynetek manufactures squatter containers by a process very similar to that used to manufacture "drawn and ironed" beverage cans. A thick circular blank is pressed out into a cup shape. This is then forced through a slightly narrower die, ironing the cylinder out to a longer shape. Subsequent steps are as described above to obtain the finished tank.

The largest competitive disadvantage for composite cylinders is their cost. For example, steel tanks, whilst being considerably heavier, cost only 30-40% of composites. This issue, together with the optimisation of the carbon fibre for the highest pressures, is the major R&D hurdle. High cost arises fundamentally from the choice of materials. Carbon fibres are intrinsically expensive, but are decreasing in cost. Dynetek believes that the cost of its cylinders will reduce fairly readily to 50% of its current level, but will always be much more expensive than a conventional gasoline tank.

Dynetek cylinders have been demonstrated in a number of storage applications such as fuel cells vehicles (e.g. Ford Focus FCV, Toyota FCHV-4 and Nissan XTERRA FCV), fuel cell buses (ZEbus), stationary hydrogen storage (such as filling stations) and bulk hydrogen transportation. Japanese manufacturers tend to build vehicles around the available storage technology; others require specialist technology to be developed.

In the near term (1-3 years), Dynetek plans to continue its involvement in fuel cell demonstrations such as the California Fuel Cell Demonstration, and will continue to work with its current nine OEM collaborators. It expects commercial sales from automotive OEMs to follow in the longer term.

<u>Hydrides</u>

HERA is building a business around hydrogen storage. HERA's products are centred on hydrogen storage materials, tanks and tank materials based on metal hydrides such as AB_2 and AB_5. With metal hydride storage, tank pressures can be low, allowing HERA to design tanks that do not conform to the standard cylindrical design. This provides design flexibility when applying the technology. The benefit offered by the technology is reduced volume relative to hydrogen storage in high-pressure cylinders (but not reduced weight).

HERA believes that materials development represents the key to achieving success in hydrogen storage and maintains an R&D programme aimed at increasing storage capacity and reducing costs. Materials under development include:

- magnesium-based hydrides, operating at high temperature and storing up to 6.5wt% of hydrogen;
- irreversible chemical hydrides, storing over 10wt% hydrogen; and
- medium temperature alanates.

The principal benefits and characteristics of these approaches are summarised below:

Mg-based high temperature hydrides	• 6.5% storage capacity • Desorbs at higher temperature • Materials available in pre-production quantities
Chemical hydrides	• 10% storage capacity • Patent pending on new family of low-cost chemical hydrides
Medium temperature alanates	• Potential for higher hydrogen storage capacity than conventional hydrides and for operation at lower temperatures than Mg-based hydrides;

	• Early R&D stage.

The company firmly believes that hydrides are the storage technology of choice for many applications and are unconcerned about carbon nanotechnology: yhis is not considered to represent a threat to the business.

Hydrogenics has a hydride storage system based on irreversible hydrolysis of sodium borohydride. This was developed under military contract to the Department of National Defence (DND). In its proprietary process, hydrogen is generated from sodium borohydride tablets dissolved in water and consumed as demanded by the fuel cell module. The storage achievement is around 1kWh/kg and 1kWh/l. This corresponds to approximately 4.5wt% of hydrogen (note that this is for a system, not just the hydride material). The unit is around 20cm x 30cm x 15cm in size for a sub-system to fuel a $1kW_e$.

This fuel sub-system has been incorporated into Hydrogenics' HyPORT C™ 500W portable power generator. The system is aimed at application such as field battery chargers or directly powering electronic instrumentation.

Carbon Nanofibres

The Mission encountered only one research project on carbon nanofibres. In collaboration with the University of Quebec and the DND, the NRC is conducting a project entitled Hydrogen Storage in Carbon Nanostructures. The focus is on developing materials with high hydrogen storage that can be manufactured in a cost-effective process. The NRC is making metal-doped carbons, the University of Quebec is making hydrogen uptake measurements and the DND is responsible for materials characterisation. The project is in its early days and so far hydrogen storage is only 1% by weight.

The NRC is conducting the research to identify whether carbon really is a viable storage medium for hydrogen, and if it is, to develop a 6 - 10 wt% hydrogen storage material.

2.5 Lessons for the UK

Some of the most significant players in the fuel cell industry are looking to enter fuel cell markets with their first generation of hydrocarbon-fuelled units equipped with fuel processors of very modest performance. This approach is entirely warranted given the pressing need for the fuel cell industry to begin building a market sooner rather than later, and sends some important messages for the small number of UK companies looking to exploit fuel processor technology for fuel cells:

- Leading developers are happy to focus their limited resources on their core stack and systems technology, maintaining only a small fuel processing programme and/or buying in technology where needed. Thus, there is a market for suppliers of fuel processor systems and components.

- Many stack/processor alliances have already been forged and UK developers without existing alliances can expect to find it increasingly difficult to find viable routes to market without a product so markedly superior both technically and practically that it will "turn heads".

- At the same time, there will be a need for improved products for future generations of systems. Radically different approaches are likely to provide such products more readily than incremental development of existing packed catalyst bed systems. The UK may be able to compete in this arena.

It is clear that Canada benefits from an integrated approach. Companies offering state-of-the-art fuel cell technology, fuel production, fuel storage solutions and systems integration, collaborate to develop the products that the market needs to realise its vision of the hydrogen economy, with public funds and facilities channelled accordingly. Emulation of this approach, which does not currently exist in UK, would require a positive approach by the DTI in order to foster development of the necessary critical mass.

3 SOLID OXIDE FUEL CELLS (SOFC) COMMERCIALISATION

Alan Spangler, Roll-Royce Fuel Cell Systems

3.1 Introduction

While much of the Canadian fuel cell industry is focused on Proton Exchange Membrane (PEM) related activities. (driven by the market outlook for PEM technology as it relates to the automobile industry and residential CHP applications), SOFC technology, which is generally thought to be a more suitable technology for large, stationary applications such as power generation, is being pursued by a narrower group of companies.

According to the Canadian High Commission in the UK, the SOFC industry in Canada generally consists of:

- 45 Canadian companies which claim to be in business or supply-chain,
- 13 which advertise a prototype technology, and
- 4 which claim a production product.

The Mission visited two companies with prototype SOFC products and a number of companies that may fit into the SOFC supply chain. Of the two companies with products, one was pursuing SOFC applications primarily targeted at the stationary power generation market, i.e. generally greater than 200kW applications. The second was using SOFC technology in residential CHP applications at approximately 5kW. The SOFC technology appeared to be promising in both applications with a number of apparent benefits including fuel flexibility and high efficiencies. The most important single challenge for sustained competitiveness was reduction in capital cost.

Supply chain companies for the SOFC technology were focused on capabilities such as testing services, packaging and system integration, reforming technologies and sulphur-compliant anode technologies.

The following reviews the activities of the two SOFC manufacturers and other supply chain companies in terms of products, market focus and approach to commercialisation. It concludes with a comparative overview and considers the extent to which there are lessons to be learnt by the UK.

3.2 SOFC Products and Market Focus

SOFC technology has certain inherent advantages for power generation applications. These include high efficiencies (up to 70% in simple-cycle hybrid configurations), internal reforming of fuels lessening the need for fuel infrastructure, greater fuel flexibility and tolerance, and the production of high-grade waste heat for co-generation applications. The Canadian companies visited perform a variety of value-added testing, packaging and integration services in order to improve the stack and system performance. For the most part, they source the core stack technology from a third party.

As is indicative of the evolution of cottage industries around a technology hub, a network of Canadian companies have been formed that serve as value-added suppliers to global SOFC core stack technology companies. SOFC systems, when applied in either central power generation or residential CHP configurations, are supported by a multitude of peripheral materials and services suppliers striving to enhance the competitiveness of the product and create sustainable business models in their own right. Typical development challenges include improving the cost-effectiveness of core fuel stacks, increasing overall stack power densities and efficiencies, expanding the fuel tolerance capabilities and understanding fundamental stack and system characteristics under transient operating conditions.

A brief description of the companies visited as they relate to SOFC applications follows:

Kinectrics

Kinectrics is a former research arm of Ontario Hydro. It leverages its electric utility heritage by providing package / system integration and testing services to Siemens-Westinghouse SOFC technology. Its capabilities also extends to PEM and Phosphoric Acid Fuel Cells (PAFC) technologies. As a demonstration of its capabilities, it is currently performing in-house testing of a complete 220kW SOFC system. The testing regime includes:

- Stack and fuel testing;
- Interconnection of distributed generation systems to grid;
- Load following tests; and
- Islanding capability.

Fuel Cell Technologies

FCT develops 1kW to 50kW systems for residential and small commercial applications based on the Siemens-Westinghouse tubular SOFC stack technology. The package consists of fuel cells and interconnect capability to run in a grid parallel application. The controls have grid fault-sensing capability and with the assistance of batteries, can rapidly pick-up local loads and peak-shave. The system provides hot water / steam suitable for residential use. SOFC has inherent fuel flexibility and potential fuel inputs include hydrogen, natural gas and propane. In addition to the provision of residential CHP systems, FCT also engages in the testing of fuel cell stacks.

QuestAir

QuestAir products purify gases - primarily hydrogen and oxygen - for a wide range of applications, including large industrial facilities. Oxygen enrichment provides advantages for fuel cells, while hydrogen purification enables fuel reformers and hydrogen refuelling stations to meet stringent fuel-cell related specifications. As it relates to SOFC, oxygen and hydrogen enrichment are thought to offer efficiency advantages with the SOFC system.

Snow Leopard

Snow Leopard is currently in the process of developing proprietary hydrogen sulphide (H_2S) fuel technology primarily for the oil and gas industry. The company's industrial fuel cell will process H_2S to produce sulphur, electrical energy and water. In the broadest sense, this technology could replace the Claus Kiln section of a sour gas processing plant and convert the hydrogen in H_2S to electrical energy. As it applies to other SOFC stack manufacturers, the technology could be used as a basis for sulphur-tolerant anodes.

Greenlight Power

The Greenlight Fuel Cell Production Test Station is a performance test tool for fuel cell stack manufacturers, either PEM or SOFC. Stack manufacturers can simulate and control operating conditions, using gas mixing modules, humidifiers, water management systems, control software and load banks. Using data acquisition software, the test station assesses whether the stack meets test criteria and reports performance and failure data.

3.3 SOFC Commercialisation

Stationary power applications (central stations) for SOFC technology are expected to be a competitive commercial product within the next five years, and pre-commercial products are gaining valuable operating experience. Current 200kW prototype (pre-commercial) plants are thought to be in the C$5,000 to C$6,000 / kW range on a first-cost basis. The goal is to become competitive on a life-cycle basis with other distributed generation technologies, i.e. small turbines and reciprocating engines, especially when the SOFC systems are configured as hybrid and cogeneration power plants. There is an ongoing debate as to whether current SOFC technology for large stationary applications will achieve the necessary life-cycle costs to become viable, but there are at least a few reasons to be optimistic, including the addition of turbine generators to create SOFC hybrid systems.

It is generally recognised that the core SOFC stack contributes approximately 30% to the total power plant installed cost on a simple-cycle basis. Therefore system packaging, installation and integration are critical components of the power plant equipment purchase price. In addition, the performance of the stack over time, including stack degradation and mean-time-between-failures, is a large contributor to life-cycle competitiveness of the power plant. The skill-sets and support infrastructure developed by Canadian companies are providing valuable inputs into the SOFC power plant development cycle. It has yet to be proven that these contributions to core technology will provide a sustainable business model for Canadian companies themselves. However, it is not unreasonable to believe that should SOFC continue to improve its competitive position as a power generation alternative, then specialist services for packaging, system integration, stack testing and related services will be specialist functions that evolve in the industry and hold a niche role in support of core SOFC stack developers.

Current prices for SOFC-based residential CHP systems are an order of magnitude higher than traditional home heating systems, an issue similar to that faced by PEM fuel cell suppliers. To become cost competitive, the power density of the stack needs to improve and the packagers need a substantial benefit of scale. Current estimates regarding scaling to improve costs are thirty to fifty thousand units per year to reach competitive prices and sustainable margins. Early markets for prototype units include California, Japan and Germany. Not surprisingly, there is a direct correlation between markets with inherently expensive residential electricity prices and the desire of those markets to consider residential CHP units.

QuestAir is offering efficiency enhancements to SOFC technologies through purification of the hydrogen and oxygen streams in the fuel cell. If a baseline efficiency of an SOFC system used in a power generation application is approximated at 50%, then projected improvements in fuel burn are of the order of 20%. In addition to this, there is an estimated output improvement of the order of 25%. This is a significant improvement but requires more detailed analysis. In addition, the output and efficiency increases must be accompanied by reasonable first cost, such that the overall system remains competitive on a life-cycle evaluation basis.

There are a number of companies working on reformer and related technologies to improve the fuel flexibility of SOFC systems. SOFC systems are generally tolerant to pipeline natural gas but are susceptible to reduced anode life based on small traces of sulphur in the fuel. One company has developed prototype sulphur-tolerant anodes for SOFC applications. The system would be able to collect sulphur in solid form, separated from the hydrogen stream. This would allow SOFC technology to move closer to the well-head and create additional benefits, such as hydrogen and sulphur separation, to the core off-take of electricity.

3.4 Common Experiences and Issues for SOFC

The companies mentioned above are generally value-added suppliers for SOFC systems. In general, they offer a variety of products and services that complement core SOFC stack technology.

- Kinectrics and FCT offer packaging and testing services to core Siemens-Westinghouse tubular stack technology. Kinectrics offers packaging and integration expertise to large, central power plants, (i.e. 200kW, and Fuel Cell Technologies provides packaging for 5kW residential applications as well as fuel testing expertise.

- These companies historically received funding through the US Department of Energy's Solid Electrolyte Conversion Alliance (DoE SECA) programme and are currently either looking to extend that arrangement or provide services to other fuel cell companies in order to supplement the revenue stream.

- Products are generally at the "pre-commercialisation" phase. Current customers include strategic partners and other firms that have incentives to enter into fuel cell use in an early stage.

All of the firms have experienced or are continuing to face issues with:

- Profitable commercialisation of products - recognising that scaling benefits will not be realised in the near-term;
- Sustaining revenue streams - as historical funding schemes are reducing or coming to a close; and
- Developing consistent Codes & Standards in an evolving industry - there has been mixed experience and commercialisation implications in dealing with non-existent or emerging standards.

Generally, the companies have focused their efforts to date on a limited number of markets. North America and Japan have been the primary focus, with Germany as the only European centre of opportunity. This is primarily due to the existence of early demand associated with military and government programmes, or a reflection of R&D and demonstration programme funding together, in the case of the USA, with a relatively low quality power supply infrastructure and relatively extensive off-grid power needs for remote communities. Security of supply is increasingly being mentioned as a driver of demand.

3.5 Lessons for the UK

Key learning experiences for the UK from the Mission from an SOFC technology perspective are:

- The future success of fuel cells is not solely intertwined with a hydrogen economy. SOFC technology is proving that current hydrocarbon-based fuels can be used efficiently and with minimal resulting emissions.

- SOFC technology is in a pre-commercialisation phase and may have reasonable and achievable commercialisation time-frames, i.e. within the next five years.

- Government funding is essential to bridge the gap between the development of intellectual property and the commercialisation of products. The SOFC-related companies visited to a large extent evolved, and are sustained in the near-term, as a function of government funded development programmes. With this as an impetus in terms of physical infrastructure and skill-set development, a supplier infrastructure of related technologies is also evolving, creating useful technology hubs.

- Government, industry and university collaboration is required to set consistent standards for the technology and to raise consumer awareness concerning the benefits of the technology. These groups are taking on the challenge of creating Codes and Standards, raising public awareness and providing a general framework for the sustainability of SOFC (and PEM) technologies.

4 PROTON EXCHANGE MEMBRANE (PEM) FUEL CELL COMMERCIALISATION

Dennis Hayter, Intelligent Energy

4.1 Introduction

PEM fuel cells are based around an electrochemical process to generate electricity and heat by passing hydrogen and air through a catalytic membrane. They are relatively small, lightweight and operate at low temperatures (up to 85°C), and emit heat, power and water as the only products of their electrochemical process. The hydrogen used in the process is derived from electrolysis of water or from hydrocarbons.

PEM technology is relatively mature, in stack design at least, and has been under serious development for nearly forty years, with much of that development taking place in Canada and the USA. Varying approaches to stack design, use of metallic plates and other available materials and scale advantages, have attracted a significant number of companies to PEM development.

The current technology allows for power generation from around 20W up to 100kW and exceptionally up to 250kW, although the higher power ranges will consist of stack arrays based, for example, on multiples of a 20-50kW stack that are close coupled and manifolded to form a power unit. Depending on whether heat is recovered, PEM applications include portable, stationary and motive power generation based on direct current (DC), or CHP for domestic or commercial requirements.

Of the companies visited in Canada, Ballard, H Power and Hydrogenics are senior players with well established activities and probably the most advanced market positions in the world. They are either close to commercialisation or already have one or more products in their line-up that are commercially available today. Subsequent to the Mission, H Power was acquired by Plug Power Inc. of the USA.

The Mission also met with Snow Leopard, a new firm with a relatively unique technology approach. This is focused on hydrogen sulphide removal from sour oil and gas, with the resultant streams used to power both PEM and SOFC systems for power generation. This firm is still in start-up and does not yet have more than a "proof of concept" position in the market. It is, therefore, not included in this review.

It is noted that there was no apparent crossover of PEM and SOFC technologies and, with the exception of Snow Leopard, none of the mainstream PEM firms appear to have contemplated the addition of solid oxide technology to their product and technology portfolios. Nor do they indicate a particular concern with SOFC as a competitor in the PEM power range (up to 100kW) and main PEM application markets.

The following reviews the activities of the three PEM firms in terms of products, market focus and approach taken to commercialisation. It concludes with a comparative overview and considers the extent to which there are lessons to be learnt for the UK.

4.2 PEM Products and Market Focus

PEM fuel cell technology has a number of key attributes in terms of mass, power density, efficiency, start-up time and ability to load follow that makes PEM systems highly suited to automotive and motive power applications together with a range of stationary power applications. These are typically focused around the 1kW to 80kW power range. Systems have also been developed for portable and 'personal power' applications at the sub 1kW power range.

A brief description of the companies visited, their products and PEM applications follows.

Ballard

Ballard began work on PEM fuel cells 18 years ago in Vancouver, Canada and is now generally recognised as the industry leader in PEM systems. The firm has gone through a number of corporate transitions over time, including IPO, and has significant equity holdings by two automotive OEM's: Ford Motor Company and Daimler Chrysler AG. Ballard was recently restructured and as of May 2002 Ford had a 20% stake in the newly combined business and Daimler Chrysler 24.2% with the balance of 55.8% in public stock. Four divisions have been created:

- *Transport*: This division acts as a focus for fuel cell engines for transit buses and other Public Service Vehicles and passenger vehicles based on 220kW systems for transit buses and 85kW pressurised power modules for passenger vehicles. The company has an exclusive 20 year non compete supply agreement with Ford and Daimler. It works with gaseous hydrogen, liquid hydrogen, sodium borohydride – hydrogen (the Daimler Chrysler Natrium hybrid car) and methanol reformate fuel sources (the Daimler Chrysler Necar, Mazda Premacy GM Zafira and Nissan R'nessa hybrid cars). However, Ballard expect that on-board reformation will be bypassed and its focus will increasingly be on gaseous hydrogen systems.

- *Power Generation*: Ballard Generation Systems (BGS) was formed in 1996 with Alstom, First Energy and Ebara as partners. The focus is on stationary power generation products. The first commercially available portable generator, based on the Nexa Power Module, a 1.2kW ambient system has already been released. The generator is being supplied to Coleman Powermate for integration into an 'Airgen' system (with hydride fuel canisters) and Idatech (with a methanol fuel reformation system), and is also available generally for public purchase. It is intended for use in Uninterruptible Power Supplies (UPS), standby, and related applications. Through Ebara and in association with Tokyo Gas, 1kW cogeneration units based using Ebara's NG fuel reformer are being developed for the Japanese market. These are grid-connected with additional power, beyond 1kW, being drawn from the grid. At the higher end of the power spectrum, Ballard has prototypes for 10kW natural gas units and 60kW hydrogen units. Ballard is presently testing a demonstration 250kW generator using natural gas with the utility company Cinergy in Indiana (USA). It is also offering natural gas and hydrogen powered conventional Ford internal combustion engine for low carbon stationary generators.

- *Electric Drives & Power Conversion*: This division develops and supplies electric drives for fuel cell and battery vehicles together with power electronics for vehicle and other applications.

- *Material Products*: This division supplies carbon fibre products for automotive fuel cell applications and develops gas diffusion electrodes for PEM fuel cells.

Ballard has main locations at Burnaby (Vancouver BC), Dearborn (Michigan, USA), Lowell (Massachusetts, USA) and Naborn (Germany). The Vancouver location includes the world's first PEM volume process manufacturing facility, with 110,000 square foot. The company currently has approximately 1400 employees worldwide.

<u>H Power</u>

H Power was started in 1989 in Delaware in the US. In 2002, it formally announced a move from being a development company to a manufacturing company for PEM products for stationary and portable applications. The company has facilities in Monroe (North Carolina) (90,000 square foot), St Laurent (Montreal) (28,000 square foot) and Bellville (New Jersey). At mid 2002 H Power had 183 staff, of which some 60-75 are located in Canada.

H Power has entered into a variety of formal agreements, MOU's and distribution arrangements with firms in North America, Japan and Europe. A number of these provide significant product development funding or advance order payments; for example, the agreement with the Energy Co-Opportunity Inc. (ECO) provides for ECO to purchase US$81 million of H Power's fuel cell products between 2002 and 2008. ECO is also an equity holder in H Power Corp.

H Power has developed proprietary technology around lower power PEM stacks (<5kW), the thermal management of stacks (H Power designs include both air and liquid cooling of stacks), controllers, ancillary systems / BOP and fuel processors. H Power has 22 patents on its PEM fuel cell technology, with a further nine pending.

A comparative technology advantage of the H Power products is that they operate at near atmospheric pressure, allowing for use of an air blower rather than compressor, with benefits in reduced parasitic losses and lower noise in full power operation.

At present, the company's product portfolio covers:

- 'lower power', direct hydrogen, air cooled systems of <1kW; and
- 'higher power' systems of >1kW based on either direct hydrogen or including fuel processing to allow use of fossil fuel sources , typically natural gas or propane.

The marketed product lines include:

- *EPAC 500*: A pure hydrogen system at 500W nominal power and an output range of 25W to 500W with hydrogen obtained from standard industrial gas bottles. It is intended for back-up and standby power and is designed to self start in the event of grid failure (from start up to full load within five minutes). The EPAC can be racked and integrated to provide up to 2kW of power requirement. It is packaged for either indoor or outdoor placement in relatively harsh conditions. The EPAC 500 is offered as maintenance free for 3500 to 4000hrs and is guaranteed for one year in service.

- *HCore 500*: a 500W direct hydrogen power generator intended as a battery charger or for standby power. It has been tested in applications for power supply to Telco towers, data centres and for powering construction and power tools, reefer trucks and recreational vehicles. It is modular and can be racked to provide up to 2kW of power.

- *RCU4500*: a residential CHP unit. It combines:
  - a fuel processor for conversion of natural gas or propane to hydrogen;
  - fuel cell of 4.5 kW and related sub-system;
  - power conditioning and power management;
  - heat recovery for domestic hot water heating purposes.

  The system includes battery storage to meet short term peak power need of 10kW for up to 15 minutes and 20 kW for momentary spikes.

- *RCU500*: a lower powered CHP unit designed for the Japanese market in conjunction with Osaka Gas, who supply associated fuel processing technology. Testing of these pre-production units is now underway in Japan

A variety of other low power systems have been developed or are in the course of development with strategic partners. They are intended to be made available via new distribution and development agreements with these partners (see Section 4.3).

The RCU 4500 is the product supplied under the Joint Agreement with ECO. There are 900 rural electric co-operatives in the US, of which 300 are members (and owners) of ECO. These co-operatives have an obligation to provide power and have found that, for properties further than 25 miles away from a grid connection, it is potentially more cost effective to run a grid independent CHP unit. H Power, through ECO Fuel Cells LLC, currently has 20 pre-production units on testing (including a unit at Yellowstone National Park). However not all units are expected to be grid independent and further development of the RCU4500 units will include net metering to allow power to be sold back to the grid. The majority of fully developed units to be supplied by H Power under the ECO Agreement will be delivered between 2005 and 2008.

Hydrogenics

Hydrogenics is located in Mississauga, Ontario, and commenced fuel cell business operations in 1995. Initially a private company, it moved to an IPO in January 2000. In October 2001 a corporate alliance was signed with General Motors, providing the basis for technology transfer and joint development, engineering, branding and marketing of fuel cells. The majority of activity is located at Mississauga (Toronto) (95,000 square foot). In mid 2002, the company had around 220 employees.

Hydrogenics has three product and service lines:

- Test stations for PEM stacks and systems;
- Power products and energy solutions; and
- Systems integration and engineering services.

The company's early focus was on its Fuel Cell Advanced Test Systems (FCATS). FCATS provide test and diagnostics capability for PEM fuel cell stack developers and fuel cell systems and materials suppliers. They are produced in sizes from sub 1kW up to 120kW and are sold globally, with 106 systems installed to date.

Hydrogenics have been working on their own PEM stack and sub system technologies in the 5-25kW range since 1995. An alliance made with General Motors in October 2001 has provided it with a the rights to use General Motors' PEM stack technology for 25 and 50kW units. There are currently have four PEM product groups:

- *HyPORT C*: portable power generator with <1kW output range and proprietary chemical hydride hydrogen source (using sodium borohydride tablets dissolved in water to provide power on demand).

- *HyPORT*: portable power generator with multi kW range (up to 5kW). Fuelling by either a metal hydride hydrogen source or hydrogen in compressed gas cylinders.

- *HyPM*: power module with options of 10kW, 25kW or 40kW output, and based on either a Hydrogenics stack design or GM stack design. Developed for direct hydrogen operation only, and intended for adaptable use across stationary and automotive markets. By moving from high pressure to low pressure stack and system design, significant gains have been made in reducing system mass from 290kg to 100kg, volume from 365l to 180l. Peak efficiency has increased from 48% to 54%.

- *HyUPS*: fully integrated re-generative 25kW back-up system combining fuel cell and sub-systems, hydrogen generation by electrolysis, hydrogen storage and power management systems

A variation of the HyPM comprising a 50kW power unit, combined with a natural gas fuel reformer is to be offered shortly. This is being developed for stationary markets with light industry and residential complex distributed generation applications.

4.3 PEM Commercialisation

Each of the three firms has developed differing strategies for commercialisation and has a different perspective on timing and focus. This is described below.

<u>Ballard</u>

Ballard considers that it has already received its first commercial order for heavy duty fuel cell engines. These will power 30 buses to be supplied by Daimler Chrysler for the European Cleaner Urban Transport Europe (CUTE) programme. It also considers that the Nexa power module is its first commercially available product. Its overall expectation for commercialisation is:

- Portable generators: 2002/3 onwards;
- Uninterruptible Power Supplies (UPS) systems: some systems already ‘commercial’ in the 10-60kW range and mainstream from 2005 onwards;
- Transit buses: 2005 onwards;
- Domestic CHP: 2004 onwards for the Japanese market; and
- Passenger car engines: 2005 onwards – depending on the rollout plans of carmakers and vehicles not necessarily available in showrooms.

Ballard has taken the approach of supplying predominantly to OEMs PEM fuel cells and key sub-systems (including fuel processing) and components based on technologies developed in-house to maintain competitive advantage and protected by patents. Significantly, the company has relatively few customers (for example, only 13 customers on a world-wide basis for Power Generation) and the relationships with these customers have formed and will continue to form the basis for commercial supply agreements.

Manufacturing capability is considered a key factor in achieving improvements in quality and reducing costs. Long term relationships have been developed and will be extended with suppliers of raw materials and sub-components. Equally, where

Ballard has identified a material, process or component that could accelerate cost reduction or add value to products/access to markets, it has entered into joint development agreements or/and taken an equity stake in other firms (examples include: with Victrex and Dupont for development of membranes; with MicroCoating Technologies for catalyst coatings; with Graftech for graphite based flow field plates and gas diffusion layers; and with QuestAir for hydrogen purification and oxygen enrichment technologies).

Fuel flexibility is seen as a strategic advantage and Ballard consider that its products will be compatible with any form of fuel infrastructure that develops – whether based on hydrogen, natural gas, methanol, naphtha or other petroleum fuels.

In terms of geographic focus, North America and Japan are considered the best markets for product roll-out and potential commercialisation. This is due to the availability of government support and the presence of demonstration programmes. Ballard considers the latter to be critical to enhancing product performance, gaining customer acceptance, validating the product against safety and other Codes and Standards requirements, and helping to develop the infrastructure for future volume supply.

An additional commercialisation approach will be via the licensing of the company's technology. Further cross-licensing to technology partners (such as Tokyo Gas) is expected from 2002 onwards.

The outstanding barriers and issues to be addressed in commercialisation were stated to be materials related (particularly the availability and performance of membranes, seals and sealants), and costs. It was also acknowledged that the stranded cost and residual technology 'overhang' from transport and utility markets will hinder the pace and pattern of commercialisation.

<u>H Power</u>

H Power made its first 'commercial' sale by providing the New Jersey Department of Transport with 65 back-up power units for its variable messaging boards on a competitive bid basis with warranty on the delivered units – most of which are still in operation. Its strategy has been based around:

- initiating and maintaining a set of key marketing and technology development alliances and using these for funding support, for prototype demonstration and product refinement to meet commercial targets; and
- focusing on a limited number of product platforms using direct hydrogen for small portable and stationary applications.

This has resulted in key relationships covering:

- ECO: for the supply of residential co-gen units in rural North America;
- Mitsui: a joint venture creating H Power Japan for sales in Japan;
- Ball Aerospace & Technologies Corp: for the supply of low power portable fuel cell systems for the US military;
- Osaka Gas Co.: for the development, demonstration and sale of 500W co-gen units for the Japanese market;
- Gaz de France: for the development, demonstration and sale of residential co-gen systems for France, including obtaining necessary certification and standards approvals for France and the EU;
- Naps System Oy: a distribution and development agreement for supply of standard and customised off-grid systems in Finland; and

- PSA Peugot Citroen: joint development agreement for use of low power systems as range extenders in battery/electric light duty vehicles.

It has also meant a product focus at 500W for low power and around 4.5kW for higher power, using direct hydrogen rather than fuel processing for the lower power products - that is ‘use what’s available’ in bottled gas and ‘rack and stack’ for the needed storage capacity as the size of plant is not the critical issue for most markets at the moment, except for military portable equipment.

Because they are regions where there is demand due to a lack of reliable, good quality power, the USA and Canada will remain H Power’s geographic focus; it will be looking to attract industrial users to consider fuel cell products where they have already invested in UPS or standby systems and are well aware of the implications of power outages on their business. Elsewhere, Japan is considered attractive, and high value applications and situations where environmental issues are a priority are the key markets in Europe. The UK is not currently seen to provide significant premium power opportunities.

The automotive sector is not seen as a market for the near- to medium- term. The intention, instead, is to access automotive via stationary markets once technology enhancement, reliability and costs have been addressed.

The outstanding barriers and issues to be addressed in further commercialisation are considered to be:

- There is a need to move quickly beyond the prototype development and testing stage to achieve economies of scale and to drive the volume/cost relationship to drive down system capital costs.

- Design for manufacture is important in managing costs and is critical to improving the quality of sourced products – particularly power electronics, valves and pumps. H Power has been using auto product material but has found that it does not have the longevity of the materials required for stationary applications to be competitive with conventional diesel gensets.

- Codes and Standards need to be addressed and dealt with. However, for H Power, close alignment with strategic partners has meant that the partners are more attuned with product compliance issues and ensure that they are resolved for their specific application in residential, telecoms, UPS and related functions. Nevertheless, the company is well aware of Codes and Standards issues relating to fuel cells (construction, performance and safety, siting, installation, etc.) and is represented on key North American / international committees and working groups dealing with the development or modification of Codes and Standards.

<u>Hydrogenics</u>

The path taken by Hydrogenics for its PEM fuel cell systems is to:

- establish and capitalise on strategic alliances; such as that with General Motors for technology sharing and market reach and with Dow Corning for the use of injected silicone materials for stack sealing;
- access government funding sources to demonstrate fuel cell technologies and expand development efforts with minimal impact on cash position;
- undertake early stage product development and rapid prototyping based on significant reduction in weight and mass with performance gain and the use of

'best' available materials (typically from the automotive and aerospace sectors) or proprietary designs and processes; and

- focus on premium power applications for a limited number of early adopting customers in military, telecom, aerospace and materials handling sectors who were 'knowledgeable and fully aware' of product objectives and performance.

In market and customer approach the company's current position is:

- *Military*: Hydrogenics has supplied to both Canadian and US military programmes for portable field units where power needs are considered 'mission critical'. Applications include battery re-charging, auxiliary power unit systems (APU) in light armoured vehicles, and reliable power supply for powering digital equipment and extended 'silent watch' functions.

- *Aerospace*: Hydrogenics has supplied fuel cell modules for relatively unusual applications in unmanned aircraft, with a first unit being recently delivered to AeroVironment.

- *Uninterruptible Power Supplies (UPS)* - primarily for the telecom sector: Fully integrated systems are designed to keep a telecoms mast in operations for up to 4 hours (this includes running air-conditioning or heating where appropriate). These are currently grid connected but could use a renewable power source for electrolysis. The aim is to replace diesel gensets and lead-acid battery packs across the entire North American market (based on 130,000 telecom towers at present with many more planned). This system has recently been demonstrated with Nextel Communications in California.

- *Domestic and industrial premium power*: These systems are being developed for power supply up to 50kW based on gaseous hydrogen. They are presently at the prototype or demonstration stage. One potential CHP product has been partly funded ($Can2 million awarded in April 2002) by Natural Resources Canada (NRC) and the Climate Change Action Fund. This comprises a 50kW CHP system to be fuelled by natural gas, with benefits to be achieved in CO_2 emission reductions.

Automotive markets are not being targeted, although the use of Hydrogenics' systems for military APUs and propulsion power for underground mining vehicles suggest that hybrid electric vehicles may be a future application. It could be expected that the relationship with General Motors would result in a division of interests, with General Motors maintaining the focus on automotive and Hydrogenics on portable and stationary markets.

Future PEM system commercialisation is expected to continue to target premium and Uninterruptible Power Supply (UPS) markets. Available price differentials (in terms of USD cost/kW) range from US$30k for aerospace, US$20k for R&D equipment, US$3-7k for military and US$2-5k for telecoms and utility markets. Hydrogenics acknowledges that its PEM systems are more expensive than incumbent technologies and will remain so for all sectors (except specialist R&D equipment) for between two and four years.

For Hydrogenics' PEM products, North America has been and is expected to be the primary geographical focus for the near term. Beyond that the access gained to GM distribution systems and market coverage is anticipated to generate growth in Asia in particular and in Europe. FCATS sales have been made on a global basis and a relationship with FCATS customers is considered to be a basis for extending future geographic coverage.

Product and system certification is not considered an issue for the company today; instead it relies on the moving through product iterations quickly - having a prototype or early demonstrator fully certified would waste time/resources that could otherwise be deployed on developing new materials, reducing costs or packaging the next product variant.

4.4 Common Experiences and Issues for PEM

Ballard, H Power and Hydrogenics are three of the world's leading players in PEM with relatively mature technologies, established development, prototyping, manufacturing and roll-out/demonstration processes. They also have a reasonably wide product and application portfolio mix made available to/through OEM's and strategic partners. There are, however, some differences:

- H Power has stayed quite close to a core technology focused on 500W to 5kW PEM fuel cells and BOP integrated into products with portable and stationary power applications. They have added only reformer technology to their offering, albeit by licensing from a partner, Osaka Gas co., and source much of their additional components and materials from a network of suppliers.

- Hydrogenics started with a core business in the global supply of fuel cell testing equipment and has moved to PEM products relatively recently. Following an initial focus on portable and stationary power for up 5kW, the alliance with GM has allowed a rapid 'catch-up'. Access to GM's stack technology has enabled the company to now offer systems of up to 50kW. Target markets continue to be premium power segments of portable and stationary power markets, rather than automotive applications.

- Conversely, Ballard initially had a core focus on PEM for motive power and related powertrain and power management systems, and has added portable and stationary power products and applications quite recently. Ballard now has the widest diversity of activities, apparently driven by a need to establish new market entry and supply capabilities for core PEM systems derived from their automotive development programmes.

Each of the three firms has driven early stage product development, prototyping and product enhancement through public and private sector support mechanisms including:

- Government grants and tax incentives (in Canada, the USA and via alliances or joint ventures in Japan);
- Military programmes (in Canada and the USA);
- National Research & Development funds/programmes (in Canada and the USA);
- Strategic partnering, alliances, joint venturing based development and supply agreements;
- Licensing; and
- Initial Public Offering (IPO) and public share placement.

All of the companies have experienced or are continuing to face issues with:

- Quality, cost and performance of materials for stack and BOP input - the most critical of these were referred to as membranes, sealants/seals, power electronics and valves/pumps.

- Fuel source and fuel infrastructure - gaseous hydrogen has been and remains the primary fuel approach, although all three companies have developed proprietary technology or have licensed fuel processing technology for integrated power supply products, primarily using methanol, natural gas and propane as reformate fuel sources.

- Systems integration (assembling packaged system for prototype, demonstration or 'commercial' product) - own development, cross-licensing and supplier development has been required to obtain inputs, and the growth of the three firms has spawned the creation of a materials, component and technology supplier network in Canada and the USA to feed systems requirements. System integration and product packaging is now a core expertise of the PEM majors.

- Codes and Standards - there has been mixed experience and commercialisation implications in dealing with non-existent or emerging Standards, but this has not prevented product development or significantly hindered product demonstration and application so far. It is, however, expected to impact on wider roll-out to commercial markets in the near- to medium- term.

- Costs - product cost competitiveness is now and will remain a key issue for wider commercialisation. It is commonly seen as an 'economy of scale' and volume driven matter, with the implication that the wider the mix of applications achieved with common PEM systems (e.g. using a stack and core sub-systems from an automotive application as a stationary power generator) the quicker a downturn in unit costs can be achieved. This is logical for many, but not all, of the key components used in PEM systems construction. (In a PEM stack the majority of cost (in the order of 60-75%) is accounted for by membranes, which do not decline with volume at the same rate as, say, metal or graphite plate.)

All three of the companies have focused their efforts to date on a limited number of markets. North America and Japan have been the primary focus, with Germany perceived as the only European centre of opportunity. This is primarily due to the existence of early demand associated with military and government programmes or a reflection of R&D and demonstration programme funding together, in the case of the USA, with a relatively low quality power supply infrastructure and relatively extensive off-grid power needs for remote communities and for telecoms and similar applications. Fuel security is a more recently mentioned driver of demand.

Paths to commercialisation have varied somewhat (particularly in the case of Ballard with its primary drive for automotive fuel cell engines and related systems) but have generally focused on either UPS applications and/or Premium power, where the economics of the new technology supply is not based on a 'head to head' price comparison with existing products. Each of the companies has, however, emphasised the significance of demonstration projects – funded or otherwise – as a route to product roll-out. The predictions for commercialisation time-scaled varied by company with general consensus around:

- 2003 for portable and UPS related power generators;

- 2005/6 for first commercial automotive products;
- 2004 for remote domestic power with reformate fuel, natural gas or propane;
- 2005 for domestic CHP and distributed generation; and
- beyond 2005 for fuel cell passenger cars – and still hybrids for some years thereafter.

4.5 Lessons for the UK

PEM technology is particularly suited to lower power applications for portable, stationary and motive power purposes, with either direct hydrogen or a hydrocarbon fuel source to provide electricity and where required, heating (CHP/co-generation) and cooling (tri-generation).

The key lessons for the PEM industry and potential users of PEM products are:

- Developing a PEM capability is costly - the combined accumulated deficits for just the three companies (Ballard, H Power and Hydrogenics) amounted to approximately US$300 million, after allowance for receipt of government grants, tax incentives, military programmes and revenues from early sales.

- PEM design and stack technology is relatively mature - the focus of development effort now is on fully integrated systems that are lighter, achieve better performance and have higher power densities than in the past, together with enhancement of associated systems for the storage and supply of hydrogen (gaseous or in hydrides) or via fuel reformation.

- Development is also targeted towards improving material and component supply, (particularly membranes, sealants/seals, power electronics and valves/pumps) to achieve reduced cost and extended durability and operational reliability.

- A number of market segments are approaching the point at which PEM systems can be commercially competitive – these include remote power supply for non-grid connected users, standby power and UPS. The price differential for military and aerospace applications also makes these early adopter markets.

- Prototype development and demonstration programmes are important instruments for achieving product validation and next stage product enhancement – they also serve to increase customer and public awareness and facilitate the development of supporting infrastructure and appropriate Codes and Standards. However, for optimal outcomes demonstration programmes need to be ‘looped’ back into continuing R&D, product and materials performance, and cost improvement, rather than end with the demonstration alone.

- Publicly supported R&D and testing facilities (and/or university centres) that provide space (leased) and support services, such as hydrogen and other fuel supply, computer simulation, non destructive testing, etc. (on a lease or fee for services basis), and are open to small and large firms alike, have been a vital feature in Canada; there are no similar facilities in the UK.

- Codes and Standards have not been a significant barrier to commercialisation to date – but they could become so if national and international institutions are not aware of the extent to which market barriers may be created or reinforced.

- Private sector firms have been willing to fund PEM development, and access to venture capital and private funding has not been a significant issue. This may not be the case at present, and for the near- to medium- term additional market entry support and programmes to move PEM products into wider use may be critical. Use of government purchase of fuel cell systems to emphasise acceptance of the technology could be an important stimulus as part of support initiatives.

5 BUILDING FUEL CELL SYSTEMS

Dave McGrath, Regentech, and Alastair Rennie, AMEC

5.1 Introduction

This Section draws together the lessons learned from the Mission across areas relating to the full fuel cell system, including Balance of Plant (BOP) and systems integration. It also explores the broader range of opportunities which will emerge in association with the fuel cells sector as it moves forwards.

Many suggest that the development of a hydrogen infrastructure is critical to the successful growth and development of the fuel cell industry. Whilst this is true, the establishment of the entire industrial infrastructure to support the industry is potentially even more important. The following are some of the issues emerging from the Mission as of concern to the development of the industry in Canada and, by example, the UK:

- Fuel cell systems R&D (e.g. materials etc.)
- Fuel cell systems production technologies, including machining, assembly and testing
- Fuel cell manufacturing supply chain
- Fuel cell systems production (in volume)
- Systems certification, industry Codes and Standards
- Distribution, installation and servicing
- Fuel production and distribution
- Specialist advice for systems development and deployment in specialist sectors
- Education and training at universities through to field technicians
- Development of industry, political and public awareness.

Although Canada is, arguably, the leading country in the commercialisation of fuel cells, the industry is only just emerging from the concept / applied research stage. Efforts are beginning in earnest to service the broader industrial needs of the sector. What quickly became evident, confirmed and amplified by the Mission, is that the needs of the industry and, thus, opportunities are very much greater than first seems apparent.

The above activities need to develop in parallel for the full emergence of the industry. The weight of effort is currently focussing on the R&D side, with spending priorities in Canada beginning to shift towards the actions required for early field demonstration leading to commercialisation. Early commercialisation was anticipated in identifiable niche markets where capital costs were less of an issue than operational needs, which translate into lifetime operating costs.

The industry is multi-dimensional and can be represented in a number of ways. In evaluating the business opportunities in the industry it is useful to map out the activities and structure of the industry. The following Sections highlight some of these. By way of background, Appendix E and F provide a typology of fuel cell technologies and discuss how a fuel cell “system” comes together in general terms.

5.2 Development Status and Implications

The development status (i.e. positioning on the "concept – prototype – pre-production - production" spectrum) of the companies visited during the Mission is illustrated in the matrix below. This reflects the levels of activity for product the various companies have for sale. For example, H Power is researching stacks but will not sell a stack; it has generator and system products available for sale and is also actively involved in R&D for new generator and system products.

	Concept / R&D	Prototype	Pre-production	Production
Base chemicals / Materials	Dupont	Dupont	Dupont	Dupont
Membrane Electrode Assemblies	Dupont	Dupont	Dupont	Dupont
Stacks	Ballard Energy Visions Snow Leopard	Ballard	Ballard	Ballard
Fuel Cell Generators	 FCT Hydrogenics Ballard Energy Visions Snow Leopard	H Power FCT Hydrogenics Ballard Snow Leopard	H Power FCT Hydrogenics Ballard	H Power Hydrogenics Ballard
Systems	H Power FCT Hydrogenics	H Power FCT Hydrogenics	H Power FCT Hydrogenics	
Peripherals	HERA H. Systems Stuart Azure QuestAir Greenlight Dynetek	HERA H. Systems Stuart Azure QuestAir Greenlight Dynetek	HERA H. Systems Stuart Azure QuestAir Greenlight Dynetek	 H. Systems Stuart QuestAir Greenlight Dynetek

The companies active in the base chemicals / materials and membrane electrode assemblies (MEAs) have a quite different range of requirements from those of the systems integrators.

What was clear from the Mission, as may be anticipated, was that there are no commercially available fuel cell systems in the mature production phase. All companies who reported products in the field indicated that pre-production systems were available and being tested. Phosphoric Acid Fuel Cell (PAFC) systems were not explored during the Mission but could claim advanced commercialisation.

The key messages relating to product development status derived from discussions with Mission hosts were as follows:

- The choice, composition and characteristics of the chemicals used in the MEAs are all areas receiving significant attention.

- Considerable work still needs to be done on optimising flow plate design and, more crucially, on the production techniques to be used.

- Norms for control coding etc. are not yet apparent, and could help to bring down costs for component suppliers.

- The materials supply industry is mature, but considerable further scope for development exists.
- There is not yet a fully production version of a PEM MEA, and it is debatable whether there is a production version of a SOFC stack.

- Almost all of the fuel generator manufacturers expressed keen interest in securing access to better or cheaper BOP components across the board. Technologies are sought from established product lines adapted for use in the fuel cell systems.

- It is not clear at this stage whether specialist applications of fuel cells will have common BOP issues.

- The stacks closest to production status are available are those from H Power, Ballard and Hydrogenics. However, these are not available for sale as sub-units.

- There are very few fuel cell generators available, the Ballard Nexa being the most readily available.

- There are a limited number of complete integrated systems available (e.g. from Hydrogenics and H Power), although these are essentially pre-production systems.

- Demonstration / pre-production systems that are available are expensive.

- It is likely to be some 3-5 years before any mature production becomes evident.

During the Mission, some organisations thought that gas supply pumps for PEM fuel cells were an area for improvement, and some mentioned that they wanted better humidity control (this is to prevent membrane damage).

Companies manufacturing peripheral equipment could be regarded are closest to commercialisation and it is worth noting their particular product offerings:

• HERA	Metal hydride hydrogen storage cylinders
• Hydrogen Systems	Electrolysers (in commercial production)
• Stuart	Electrolysers (in commercial production)
• Azure Dynamics	Hybrid ICE/Electric vehicles
• QuestAir	Gas purification systems
• Greenlight	Fuel cell test stations for MEAs, Stacks and systems (over 300 systems)
• Dynetek	Low / high pressure gaseous hydrogen storage cylinders

Whilst this is not a representative sample of the industry, it is interesting (although perhaps not surprising) that the support technologies are the ones fastest to market.

There were mixed messages from the differing companies as to when we will see commercialisation in production models of fuel cell systems - H Power claiming year 2002 and HERA suggesting five years from now.

5.3 Emerging Opportunities

Consideration of each type of organisation that is, and will, become involved in the fuel cell business reveals that there are considerably more opportunities to service the needs of the industry than may at first be apparent. Each have differing requirements and demands. In the early stages, the bulk of business is coming from and will come from the research centres and development companies, with the balance shifting to the volume manufacturers as the industry matures and develops.

The Table below shows the needs of each organisation type. This, in turn, highlights where early opportunities already exist.

Organisation type	Activities	Needs
Research Labs (Commercial and academic): • NRC • Kinectrics • IESVic • University of Victoria (Manufacturers like Dupont and Ballard have internal R&D but their focus is on manufacture)	Research organisation involved in fundamental research, analysis, characterisation and testing from materials right through to complete energy systems.	Equipping of the labs involves: • Gas supply and control systems • Test stations • Emergency detection and control systems • Gas/fire sensors • Software modelling tools. This alone offers significant sales opportunities to companies in a position to establish these labs. The NRC facility in Vancouver alone has 10 “hydrogen safe” labs.
Development Companies • Kinectrics	Commercial companies commissioned to execute product and system design from fundamental research and characterisation to industrial design. This service is provided to the fuel cell generator manufacturer (or done in-house).	These companies require: • Hydrogen safe labs • Gas supply installations • Gas safety and alarm systems • Fuel cell test systems (MEAs to complete systems) • Software modelling tools • Data acquisition systems • Data processing • Load banks.
Manufacturers (fuel cell): • Dupont • Ballard • H Power • Greenlight • FCT • Snow Leopard	Manufacturers of actual fuel cell components and sub-assemblies, generators systems and test systems.	Most manufacturers will execute much that the development companies do in-house and will require much the same facilities. In taking over the facilities of Ballard in Vancouver, Greenlight inherited some C$3-4m of hydrogen safe labs and test station facilities.
Manufacturers (peripherals): • HERA • Dynetek • QuestAir	Traditional industries will supply standard and custom designed products for generator and system manufacturers.	
Specifiers:	People and companies who are	They need basic understanding

• Kinetrics	in a position to influence purchasing decisions.	of fuel cell systems as systems. They will require training in fuel cell generators and systems and certification requirements.
Training Providers: • Education, academic • Field service staff • Manufacturing and design technicians • Certifiers	The industry will require significant training from the handling and safety of hydrogen through to field technicians.	
Service Providers: • Infield maintenance, service and repair.	Companies and individuals maintaining systems in the field.	
Codes and Standards Developers: • Certification • Development of standards and certification rules	All products that achieve commercial sales must have some form of certification. Installations require compliance with Standards and certification at a local level. These Standards have to be designed and developed.	This is major issue facing all of the companies visited.
Certification specialists: • Execution of certification.	Once Codes and Standards have been developed and adopted, these need to be applied and will be implemented on the ground by local agents and inspectors.	

A common theme with every company visited was the need to get fuel cell systems into the end-user market place. Activities down-stream of R&D are gaining increasingly urgent attention for two reasons:

- to begin to show some revenue from sales to satisfy investors (particularly relevant for those who may need to return to the markets for cash in the near term future - say 6-18 months); and
- to demonstrate the viability of the technology and to help stimulate product acceptance and market penetration – the CTFCA, for example, (see Section 7) has allocated 70% of its budget for fuelling demonstration and evaluation.

Of the earliest markets identified, the most commonly cited systems were for Uninterruptible Power Supplies (UPS) and standby power, closely followed by stationary high value installations where capital cost is less of an issue than technical advantage over incumbent technology. This was emphasised especially by H Power and Hydrogenics. Projects were being carefully scrutinised and selected for these purposes. Common characteristics were:

- Hydrogen infrastructure required
  - Government support can assist
- Initial applications to deliver value and reliability
  - Clear value proposition
  - Targeted markets
  - Markets matched to capabilities of company and technology
- Cost reduction is paramount
- Focus on short term realistic and achievable opportunities
- Address whole value chain
  - Standardisation
  - Certification

- Manufacturing
- Refuelling

- Deliver early wins and do not over sell
- Local/national Codes and Standards

It was a commonly held view that industrial applications would lead the commercialisation process.

Batteries remain a feature of fuel cell generators – needed for immediate power response and for meeting peak load requirement. Opportunities exist for companies able to supply high quality rechargeable batteries (e.g. Ni-Zn in place of Pb-acid)/

With the industry in its current state of development, there has not been very much standardisation of control and monitoring equipment and coding; nearly all systems are bespoke. In due course, it can be expected that rationalisation and standardisation will occur, helping to reduce costs for component suppliers. This transition will present opportunities for companies that can respond to these needs.

5.4 Lessons for the UK

Canadian Priorities

The following priorities were noted by the Canadian Government agencies and companies visited:

At a Strategic level:

- Co-ordination of activities.
- Coherent National and local strategies.
- Development of clusters of expertise.
- Recognition of the importance of the academic sector as well as the industrial.
- Government to work closely with commercial organisations, both small and large.
- Requirements for wide ranging and comprehensive financial support.
- Stimulation of the Hydrogen infrastructure and provision of government support.
- Recognised the competitive threat from USA, Japan.
- Canada to be unfettered by externally defined trade support limitations.
- Strategies looking no more than 12-18 months ahead (as the ground is moving so quickly).
- Early demonstration funding support.

At a commercial level:

- Cost reduction throughout value chain – base chemicals / materials to integrated systems.
- Focus on realistic and achievable goals.
- Coverage of the entire value chain including standardisation, certification, manufacturing and refuelling.
- Extension of product lifetimes.
- Achievement of some significant early wins and avoiding over-selling.
- Stimulation of commercialisation.
- Recognition of the importance of broader issues around commercialisation such as infrastructure, codes and standards, supply chain management.
- Concentration on attributes of the fuel cell that make a compelling case for their use.

- Recognition that the industry cannot be subsidised into existence where it should not exist.
- Recognition of hydrogen infrastructure as an economies of scale issue not a technology issue.
- Product reliability, durability and costs as key drivers.
- Priority markets as industrial, power generation and transport in this order.
- Need for field data (insufficient units out there and not enough data to evaluate performance).
- Delivery of early wins.

At Investment level:

- Overcome high burn rates (i.e. capital expenditure rates).
- Generation of early sales and must begin focus on revenue.
- Recognition of need for soft cash for commercialisation (repayable).
- R&D focussed on short term horizons.

Likely developments in the near term include:

- Consolidation expected due to possibly too many entrepreneurial companies.
- A shift in focus from vehicles and buses to smaller, more tangible projects.
- Opportunities for clusters, technical and commercial collaborations and new innovators, including those external to the industry.
- Early breakthrough from smaller companies as larger ones struggle to pass investment tests.

Implications for the UK

These Canadian priorities, together with the other lessons from the industry, lead to the following recommendations for the UK:

- Improved co-ordination of funding programmes and R&D effort.
- Enhanced funding levels more in line with UK GDP.
- Avoidance of "picking winners".
- Greater focus on commercialisation.
- Greater support for SMEs.
- Faster response to commercial and technical developments.
- Greater recognition of the importance of the hydrogen infrastructure and associated opportunities.

6 FINANCING AND VENTURE CAPITAL

David Wright, Core Technology Ventures

6.1 Introduction

By any conventional financial measure, the global fuel cell industry is currently in an embryonic phase of development. Technologists and scientists within companies, academic institutions and research institutes have been researching and developing fuel cell technologies for the past forty years. As the industry approaches the early stages of commercialisation, the availability and the sources of funding become critical to its future development and will determine its scale.

Sources of Funding

The typical sources of external funding for a company or a sector at the various growth stages can be simplified as follows:

	Public Sector/ Grants	Equity		Debt	
		Private	Public Markets	Private	Public Markets
R & D	✔				
Pre-commercialisation	✔	✔			
Growth		✔	✔	✔	
Mature			✔	✔	✔

Companies and organisations involved at the early stages of research and development will rely heavily on either a direct and specific award of grant funding or will benefit from public sector funding to the institution in which they reside.

Once the technology has been developed to the extent that prototypes have been produced and tested, commercial applications identified and markets targeted, private investors will become interested. At this stage the company will still be viewed as very high risk in terms of the likelihood of future commercial success and only investors with appropriately high-risk thresholds are likely to invest. Typical investors at this stage are either “angels” (wealthy individuals) or early-stage specialist venture capitalists. It is highly unlikely that a company at this stage of development will be able to raise debt finance, as debt will only be provided to companies that can service the debt and ultimately repay the capital.

Once companies commence production and sales of commercial products, they are likely to require funding to develop production facilities, for working capital and to build a commercial infrastructure. Companies at this stage will be able to access equity funding from various sources:

- a larger number of later-stage private equity providers;
- debt from banks and asset financiers; and
- depending on the point in the economic cycle, public markets eg AIM, NASDAQ, Toronto Venture Exchange.

Mature companies are in the enviable position of being able to mix and match their funding types and sources of funding to suit their needs, optimise their capital structure and to minimise their funding costs.

6.2 Public Sector Funding in Canada

Canadian Governments, both federal and provincial, continue to actively support their domestic fuel cell industry although levels of funding have declined in the last two years. Investment has typically taken the form of direct funding for R&D projects, trials and demonstrations. The form and disposition of this funding is reviewed in Section 7.

In addition to direct funding, other programmes and incentives have been introduced. For example, funding has been provided to set up and support:

- Fuel Cells Canada - the Canadian fuel cells industry association;

- The Canadian Transportation Fuel Cell Alliance - set up in 2001 to focus on developing the hydrogen refuelling infrastructure for fuel cell vehicles;

- NRC Innovation Centre - dedicated to the continued research, development and promotion of fuel cells. The Centre, based in Vancouver, includes ten new fully equipped "hydrogen safe" laboratories that can be utilised for research and testing, and offers incubation and acceleration for fledgling businesses. In March this year the Canadian Minister for Industry announced that the National Research Council would increase funding at the Innovation Centre by C$20 million over the next five years thereby doubling its base annual budget *(Source: Fuel Cells Canada).*

Over the past 20 years Canadian Governments have invested over C$150 million (*Source: Industry Canada*) in the fuel cell industry and nearly every company involved in the industry that was researched for this report had benefited or is currently benefiting from Government funding in some form. In addition, the finance made available to companies by Government has attracted additional finance from the private sector. Providing funding in this way has been an essential means of leveraging additional money for projects from the private sector. These aspects are dealt with more fully in Section 7.

This investment by Canada must be put into the context of spending on fuel cells by other countries. For example, Japan's fuel cell research programme has tripled since 1995, reaching US$220 million in 2002; under the Framework 5 Programme, the EC provided up to Euro120 million to fuel cells R&D between 1999 and 2002; and the US Government's investment in fuel cell research is US$200 million per annum *(Sources: Fuel Cells and Hydrogen: The Path Forward)*. Annual global industry spend is estimated to be US$3 billion and the auto industry alone is estimated to have spent US$4.5bn to-date *(Source: Finance and The Fuel Cell Industry*).

6.3 Private Sector Funding in Canada

Funding from the private sector for an emerging industry will typically follow the trend outlined in the earlier table, with individuals and venture capitalists financing the early technology risk and institutional investors funding later stage businesses.

Public Markets

This pattern, however, was changed during the late 1990s and in 2000 when technology companies from a variety of sectors were able to list on stock exchanges around the world and raise considerable amounts of money. Previously it was uncommon for such early-stage companies to access the capital markets so early in their life and to raise such large amounts of capital.

The fuel cell industry in Canada appears to have benefited from the prevailing market conditions during this period and several fuel cell companies launched IPOs or secondary issues (follow-on issues) and raised equity capital.

The table below lists the main equity issues in Canada in 2000:

Date	Company	Amount	Type of Issue
March	Ballard Power Systems	C$ 505m	Secondary
August	Global Thermoelectric	C$ 95m	Secondary
September	Dynetek	C$ 40m	IPO
October	Stuart Energy Systems	C$ 150m	IPO
November	Hydrogenics	US$ 76m	IPO

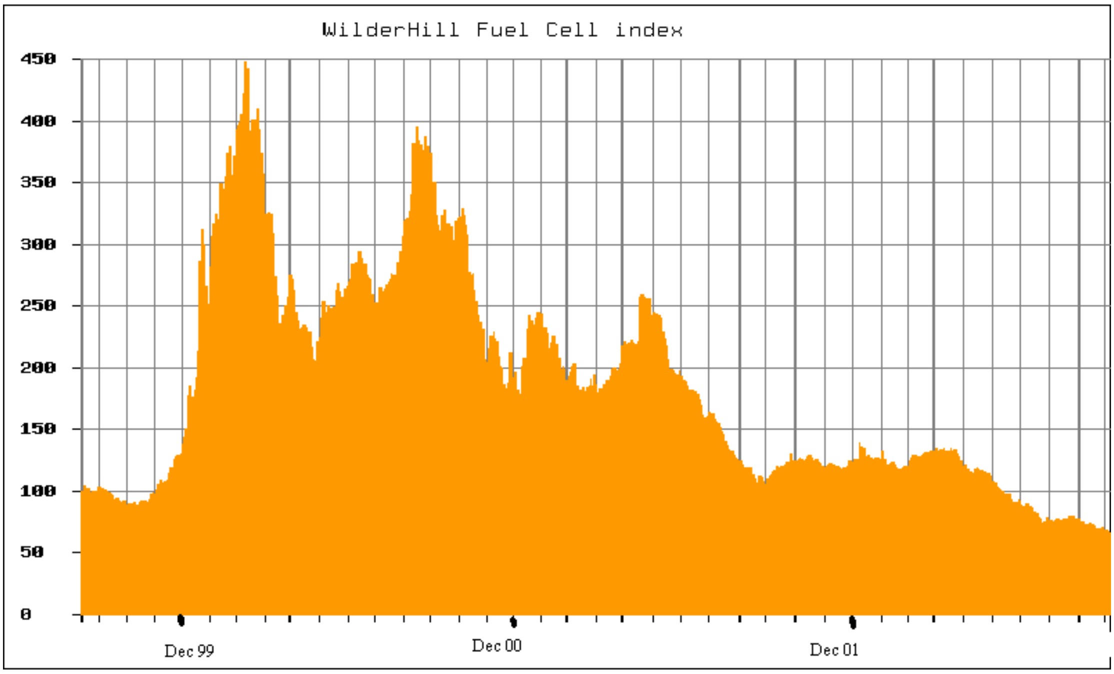
Sources: Annual company accounts

The companies above raised nearly C$1billion during 2000, taking advantage of the extremely receptive market conditions that prevailed in worldwide equity markets. Both Ballard Power Systems and Global Thermoelectric have been listed for a number of years and the finance raised in 2000 was from secondary public offerings.

Since the technology-led “bubble” burst in 2000, global financial markets have plunged and currently show little sign of any recovery in the near-term. A number of major corporations stand accused of all manner of malpractices, including fraudulent accounting and dubious transactions on the part of company directors. At the same time, some external advisors stand accused of having a ‘conflict of interest.’ These issues could take some time to resolve.

Meanwhile many of the world’s largest investment banks are being pursued by US regulators and public prosecutors. Equity analysts’ independence is under review and is likely to lead to changes in how corporate finance departments interact with equity research departments. At the same time, some of the largest investment banks stand accused of knowingly selling over-priced technology companies at the height of the boom. This has led to calls for changes in how banks are regulated and has dealt a severe blow to financial markets. Indeed, secondary market activity is severely depressed, while primary market activity has virtually collapsed.

The fuel cell industry has not escaped this loss of confidence by investors, as shown by the chart below, the WilderHill Fuel Cell Index, an index charting the combined market capitalisation of the publicly listed fuel cell companies. The chart clearly shows that stock values have fallen dramatically from their peaks in 2000, with the Index currently standing at 68.1, a fall of 85% from its high.



Source: H2FC website

The net effect of depressed public financial markets and certain corporate sectors racked by scandal is to squeeze the flow of financial and corporate investments. On the one hand, financial investors are engaged in a 'flight into quality', (i.e. are investing in traditional and well established sectors) while on the other, executive boards are significantly more risk averse than previously, and are concentrating their efforts on revenue generating activities. With the eyes of public prosecutors, investors and politicians trained on the corporate sector, marginal propositions with ill defined pay-back periods are swept off the corporate table without a second thought. A less obvious source of difficulty for 'New Technology' companies resulting from the current climate may well be a slowing down in order flow as executives seek to cut costs wherever possible.

The implications for the fuel cell industry are significant. There are companies that have not spent the money they raised and will not need to raise money for a number of years. However, there are others that raised money at the height of the boom having made ambitious statements and forecasts to underpin highly-inflated valuations; some are now returning to the capital markets for additional funding. These companies are facing a massive task to convince investors that their money has been well-spent and that the fuel cell industry has made demonstrable progress towards commercialisation.

What is clear is that progress has been made in certain areas such as:

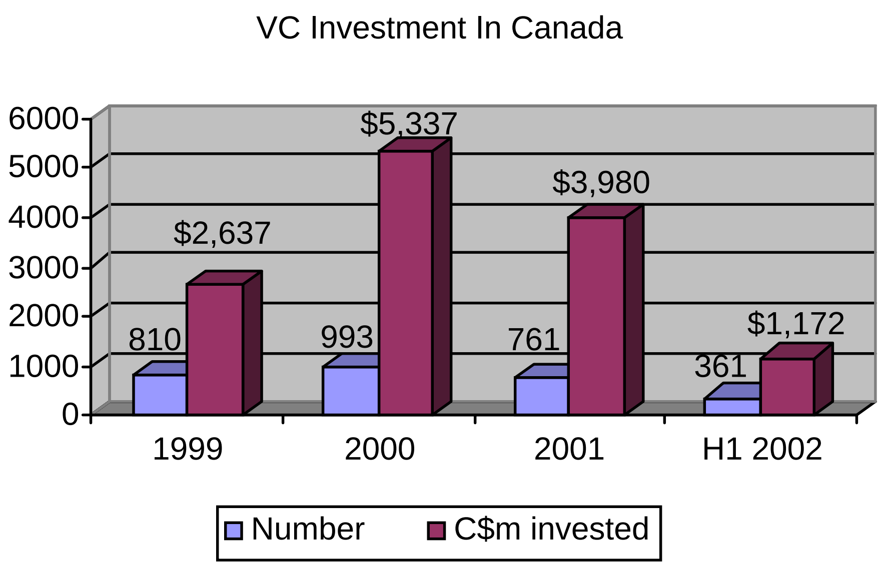
- forging commercial partnerships within end-user markets;
- technological and engineering advancements; and
- identifying near-term commercialisation opportunities.

Revenues from product sales, however, are currently in short supply and investors will soon decide whether their initial support for the industry was misplaced. Investors' failure to support the industry by providing the much needed funding for future growth will inevitably have an adverse effect on the pace of development of the industry.

Venture Capital

An emerging industry such as the fuel cell industry requires the support of venture capital finance to fund companies through the early-growth stages of development. Venture capital finance provides immature fledgling companies with a bridge until they have developed into companies that can attract institutional finance and withstand the rigours that a listing entails.

The table below shows the venture capital investment in Canada into all sectors:



Source: Canadian Venture Capital Association

This trend is typical of the global investment pattern during this period, with record investment levels in 2000 declining sharply to current levels. Average amounts invested have also fallen from C$5.4 million per investment in 2000 to C$3.3 million in H1 (first half) 2002. Investment in early-stage companies has also fallen both in absolute terms and as a proportion of the total invested *(Source: Canadian Venture Capital Association)*. Whilst no conclusions can be drawn from these statistics for the fuel cell industry specifically, they provide the backdrop to the venture capital market in Canada of which the fuel cell sector is a small sub-set.

Companies in Canada have benefited from venture capital, from strategic investors, Angels and, more recently, specialist venture capital funds funding for a number of years. Research indicates that the number of venture capital funds that focus specifically on fuel cell companies is very limited, with only one, Chrysalix, set up in Canada to address this industry. There are several other funds that have invested in fuel cells but have a mandate to invest with a wider remit eg Venture West, Hydro Quebec Capitech, OPG Ventures. Companies that have received venture capital funding include Cellex Power Products, Greenlight, QuestAir, HERA and Angstrom Power. Dates and amounts invested are not publicly available.

The lack of specialist venture capital funds in Canada focusing on the fuel cell industry is surprising given the number of fuel cell companies, the growth potential of the industry and the existence of a quoted sector in Canada (the existence of a quoted sector provides comfort to venture capitalists that an alternative exit route is available and successful exits are not wholly reliant on trade sales. It also gives the industry in Canada a distinct advantage over those countries that do not yet have a quoted fuel cell sector.). However, the downward trends in venture capital investment in Canada and stock market prices goes some way to explaining the slow development of a specialist venture capital community in Canada.

6.4 The Future

The availability of finance from both the public and private sector is key to the future success of the industry. Governments in Canada have to-date made available over C$150 million, although annual expenditures have declined recently. Fuel Cells Canada, the industry association formed to promote the Canadian fuel cell industry has requested C$[1.0]bn for fuel cell investment by the Canadian Government over the next 10 years *(Source: Fuel Cells Canada)*. This compares with a similar request for a ten year research and commercialisation budget of US$5.5 billion from the US Government *(Source: Fuel Cells and Hydrogen: The Path Forward)*.

Venture capital funding for fuel cell companies in Canada is currently available in relatively small amounts and from a surprisingly small number of sources. Furthermore, it is believed a number of other funds are in the process of being closed.

Whilst funding is available, the pace of future growth of venture capital funding will depend on a number of factors, such as the number of high profile venture capital realisations from IPOs and trade sales over the next few years. Conversely, high profile venture capital backed failures would inevitably slow the pace of growth and hinder the arrival of new entrants.

A number of Canadian fuel cell companies raised public equity during a boom period for a wide range of technology companies. Press releases and quarterly earnings statements from those companies are being scrutinised by investors for indications that products are selling and that the technology is being commercialised as promised.

Several private and listed companies are currently preparing to ask investors for additional funding. These companies have in more recent times, focussed their own attention and resources on strategies and markets that will yield revenues in order to demonstrate commercialisation. Investors will decide over the next few years whether their support has been justified or whether the industry still has some way to go and the industry has been premature in coming to the markets for cash.

6.5 Lessons for the UK

Finance for the Canadian fuel cell industry has been available for some time. Canada appears to have a significant number of funding programmes in place for R&D, trials and demonstrations, and Government departments and agencies appear to be co-ordinated and focused. The investment has been made available for several years and has been sustained.

The venture capital investment community in Canada consists of one specialist fund and half a dozen general energy funds. Whilst there appears to be room for more funds to enter the sector, there is a need for the breadth to allow co-investment and the sharing of risk amongst investors. In addition, and crucially, there is a quoted fuel cell sector that provides an alternative exit route, something that is currently a barrier to the pace of growth of the venture capital sector in the UK.

Governments world-wide are aware of the significant economic benefits that can be generated from the growth of an industry sector in the form of new employment opportunities and improved balance of payments given the projected size of the fuel cell market. Governments are setting out their future spending plans and in some cases are pushing fuel cell technology via regulation, procurement and fiscal incentives to ensure that they capture their share of the benefits that will be generated from a successful fuel cell industry.

The availability of funding, whether from public or private sources, is important. However, it is not the only factor determining both the future development of the industry and those countries that will be at the forefront of its development. The geographic evolution of the industry will be determined by participants and investors selecting to operate in countries where there is the most favourable combination of regulatory policy, fiscal policy and funding. Financial markets will take account of the framework within which these policies are executed and allocate capital accordingly. Other countries (US and Japan) currently appear to be taking the lead on these issues. On present trends, this will attract greater quantities of capital from countries with less favourable frameworks.

7 GOVERNMENT SUPPORT FOR FUEL CELLS

Philip Sharman,DTI - International Technology Promoters

7.1 Introduction

In addition to meeting many companies in the Canadian fuel cell and hydrogen industry, the Mission team met with representatives from several key parts of the Federal and Provincial Governments actively involved in supporting the development of this industry in Canada:

- Natural Resources Canada (NRCan) – particularly the CANMET Energy Technology Centre in Ottawa (CETC-Ottawa);
- Industry Canada (IC); and
- National Research Council (NRC).

In addition, discussions were had with the highly visible and active industry association, Fuel Cells Canada (FCC).

These meetings provided a valuable insight into the co-ordinated and effective Government support to this industry, now arguably the leading fuel cell/hydrogen industry in the world (although this situation is likely to change in the short term owing to the major investment of the governments of USA and Japan in their respective national RD&D programmes and hence industries).

This section of the report pulls together information on the Canadian Federal (and to some extent, Provincial) Government support.

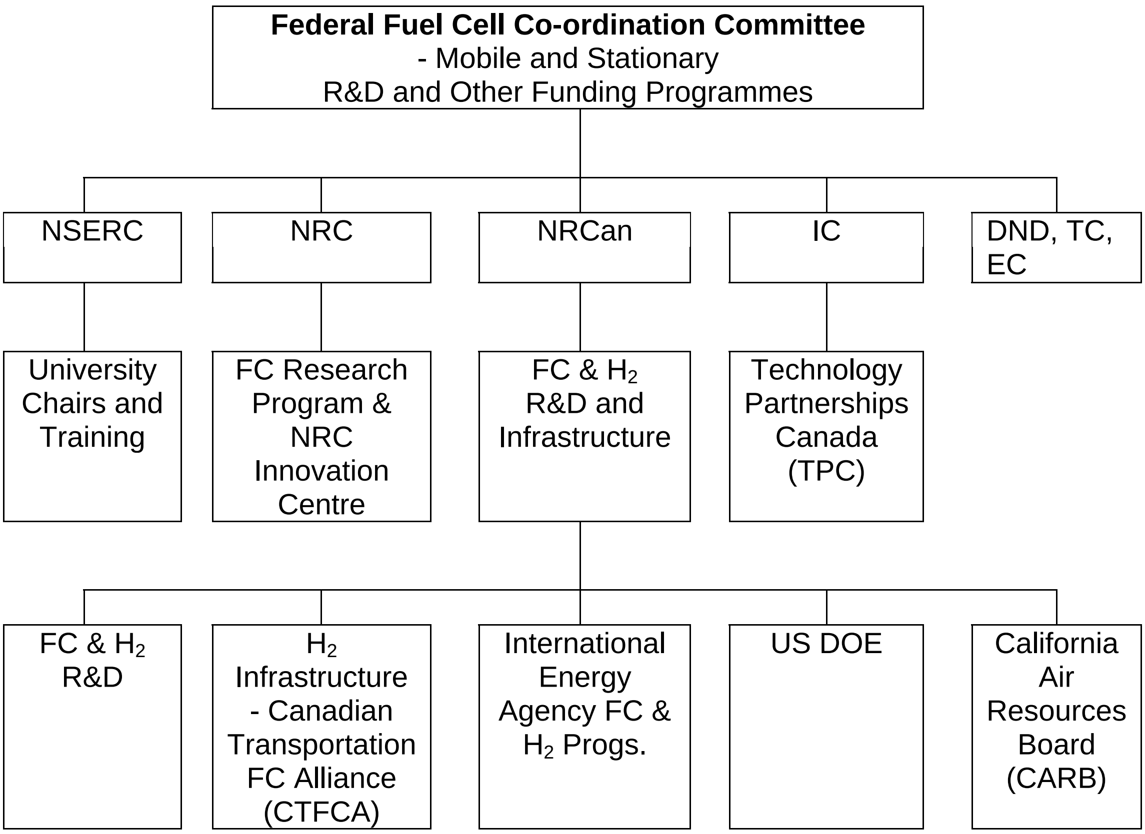
7.2 Industry Clusters - Co-ordinating Government Support

Federal Government support for fuel cells and hydrogen is provided by a significant number of Government Departments and agencies:

- Natural Sciences and Engineering Research Council (NSERC)
- National Research Council (NRC)
- Department of National Defence (DND)
- Natural Resources Canada (NRCan)
- Industry Canada (IC)
- Transport Canada (TC) – very little activity
- Environment Canada (EC) – very little activity.

In spite of the range of organisations involved, Federal support is very well co-ordinated both in terms of the different agencies focusing on (and partnering in) different stages of the "concept-prototype-pre-production-production chain" (through so-called "Industry Clusters"), and in terms of overall administration and liaison through an inter-Government "Federal Fuel Cell Co-ordination Committee" (FFCCC). These aspects of co-ordination are illustrated below:

Industry Clusters NSERC NRC DND NRCan IndCan TC EC HC			
Concepts	**Prototypes**	**Pre-production**	**Production**
Scientific investigations	Applied R&D Testing & evaln.: - specifications - performance	Applied R&D Testing & evaln.: - performance - reliability - costs - codes and standards	QA Demonstration Regulations Industrial R&D



The largest proportion of support to the fuel cells and hydrogen industry is provided by NSERC, NRC, NRCan, DND and IC. The programmes and budgets of these Federal Departments are summarised in the sub-Sections below.

7.3 Natural Sciences and Engineering Research Council (NSERC)

Budgets

While breaking out NSERC's funding specifically directed towards fuel cell and hydrogen R&D is not easy (as this forms just a part of a broad range of NSERC Programmes), the expenditure in this area is approximately C$3.4 million/year made up as follows:

- Discovery Grants Program: ~C$1m/yr
- R&D Projects in partnership with NRC and industry: C$0.34m/yr NSERC support (matched by NRC)
- Collaborative R&D Grants and Strategic Project Grants with industry partners: C$0.765m/yr
- Graduate Student Co-operative Work Terms in industry or Government : C$0.1m/yr
- Training (undergraduate student research awards, graduate student scholarships and post-doctoral fellowships): ~C$0.2m/yr
- University Fuel Cell Chairs (partnership with NRC): C$1m/yr.

Activities

NSERC's activities in the fuel cells and hydrogen area fall under the headings above.

A considerable amount of activity is taking place under the Discovery Grants Program, which supports investigator-driven basic science orientated activity, rather than project orientated R&D.

R&D projects have been/are being supported at a number of Canadian universities. Currently this includes at least fifteen projects, including five in partnership with NRC. Projects attracting industry sponsorship and collaboration are funded under the Collaborative R&D Grants and the Strategic Project Grants Programmes. Problems arising from confidentiality of R&D, and limited industry budgets for investment in longer term university based R&D, have tended to limit the leveraging (i.e. industry funding) available; this has led to a more relaxed approach towards required leveraging in some programmes.

NSERC funds a number of graduate student work terms in industry or Government laboratories each year in the fuel cells area and also supports a limited amount of undergraduate student research awards, graduate student scholarships and post-doctoral fellowships in this area. A number of students and post-doctorate students are supported under specific grants (typically 30% of a grant award goes towards training support).

In partnership with NRC, five Fuel Cell "Chairs" are in the process of being established. Currently, three have been chosen, although the locations and themes of these positions have not yet been announced. This will do much to foster the development of centres of excellence and a greater degree of co-ordination. A proposal for a "Network Centre of Excellence" for Sustainable Energy R&D (mainly fuel cell and hydrogen R&D) was declined in 1999 by the NCE program. (NB three were established: in aquaculture, vaccines and immunotherapeutics for cancer and chronic viral diseases, and stroke research). The 2000 NCE competition saw the introduction of a Network focussed on the Automobile of the 21st Century, which supports projects on reformer technology for fuel cells and hydrogen safety and infrastructure.

Canadian universities active in the fuel cell and hydrogen area include:

- University of Victoria, BC
- Simon Fraser University, BC
- University of British Columbia, BC
- University of Alberta, AB
- University of Calgary, AB
- University of Regina, SK
- Royal Military College, ON
- Queens University, ON
- University of Toronto, ON
- Ryerson, ON
- University of Ottawa, ON
- McMaster University, ON
- École Polytechnique, QC
- McGill University, QC
- Université de Montréal, QC
- Université de Québec, Trois-Rivières, QC
- Université de Québec, INRS – Energie, QC
- Memorial University, NF.

7.4 National Research Council (NRC)

Budgets

An extension of NRC's budget by C$20 million over five years – i.e. C$4m/year – and a refocusing of the original budget, provides approximately C$7m/year for fuel cell and hydrogen activities in total. This budget is allocated to the Innovation Centre in Vancouver (to become the centre of excellence in these technologies). The NRC Fuel Cell Program includes five other NRC National Laboratories/Institutes; these five institutes are contributing approximately C$2m/year, to give approximately C$9m/year for the NRC Fuel Cell Program in total.

The aim is to leverage NRC's resources in partnership with industry, academia and other Government funds.

Activities

NRC focuses on applied R&D/technology transfer (75% of effort/spend), often acting as a link between the more scientific investigation orientated activity of NSERC and the more industrial R&D activities involving NRCan, DND and IC. In this role, NRC forms a vital linkage between universities and industry, often working in partnership with NRCan, military organisations, Fuel Cells Canada, etc, to maximise benefits and minimise risk of public investments. NRC is also involved in investigative basic science R&D (25% of effort/spend), where it is considered necessary to achieve key technological break-through and build intellectual capital.

NRC helps to build globally competitive industry clusters by harnessing the capabilities of its 43,000 employees and 18 National Laboratories/Institutes (13 R&D, five engineering/technical – mainly around Ottawa), and its Industrial Research Assistance Program (IRAP), which offers assistance to Canadian SMEs through a network of Industrial Technology Advisors. It's role in cluster development includes:

- Undertaking strategic R&D to fill technology gaps (through the Science and Technology R&D Program and Cross-NRC Institute collaboration);
- Helping to establish public/private partnerships (local cluster stakeholders, national stakeholders and international organisations);
- Building relationships (fuel cells and hydrogen industry, OEMs, potential end-users, universities, suppliers, etc);
- Fostering new enterprises (incubation/acceleration functions);
- Fostering early adoption in Canadian niche markets;
- Undertaking prototyping, integration and evaluation activities;
- Creating industry intelligence (i.e. by linking economic/market/technology intelligence to R&D);
- Forming Stakeholder Working Groups which assist in defining R&D projects;
- Building capacity – personnel (training/mentoring and co-hiring new scientists and engineers), plant and equipment;
- Ensuring appropriate technology transfer;
- Encouraging international collaboration (partnerships/exchanges); and
- Assisting in public education.

NRC plays a significant role in support of the Canadian fuel cell and hydrogen industry, assisting the competitiveness of fuel cells with internal combustion engines and batteries in terms of performance, reliability and costs.

The focus is on PEM fuel cells (including DMFC), SOFC, fuels, oxidants and prototyping, integration and evaluation (PIE) and encompasses:

- Hydrogen storage (efficient, safe, compact)
- Higher temperature PEM, lower temperature SOFC
- DMFC electrocatalysts (prototyping into fuel cells in range 500W to 1kW)
- Systems reliability and life cycles
- Accelerated testing
- Micro-fuel cells
- Advanced materials
- Evaluation of performance.

Major fuel cell and hydrogen initiatives and partnerships achieved by NRC include:

- 15 R&D projects underway across Canada to fill technology gaps – PEM, SOFC, testing and evaluation, fuels, oxidants.
- Industry collaboration – eight firms co-located at NRC Innovation Centre, Vancouver. Shared facilities, equipment and personnel provide economies of scale and a revenue source for Fuel Cell Program expansion.
- Partnership with Fuel Cells Canada – 2,500 sq. ft. of "hydrogen safe" demonstration laboratory space at Innovation Centre.
- Partnership with Fuel Cells Canada, Western Diversification, BC Provincial Government - C$6 million demonstration project.
- NRC/industry secondments – energy and transportation sectors.
- Partnership in CTFCA (NRCan-led, see Section 7.5), e.g. developing "Hydrogen Highway" proposal with Methanex and BC Hydro.
- Five NSERC/NRC funded university projects (N.B. this scheme is very under subscribed – possibilities for UK universities to collaborate?)
- Partnerships with NRCan – PERD, CANMET, Technology Early Action Measures (TEAM), Climate Change Action Fund (CCAF), work on international standards.
- Partnership with DND – research MoU.
- Partnership with NSERC and universities:

  - NSERC/NRC Fuell Cell Chairs (initially five planned);
  - Graduate Fellowships;
  - NRC/university MoUs;
  - Co-hiring senior research staff with universities.
- Six NRC Institutes engaged in programme across Canada:
  - Innovation Centre, Vancouver;
  - Institute for Chemical Process and Environmental Technology, Ottawa
  - Steacie Institute for Molecular Sciences, Ottawa
  - Industrial Materials Institute, Boucheville
  - Integrated Manufacturing Technologies Institute, London, Ontario
  - Institute for Research in Construction, Ottawa (has two test houses, one with residential fuel cells).
- Partnership with Provinces on IRAP – BC, Alberta, “Prairies”, Ontario, Québec, “Atlantic”.
- Partnership with Province of Alberta (Alberta Research Council and University of Calgary) – Alberta Fuel Cell Initiative.

Fuel Cell and Hydrogen R&D:
Market forces drive NRC’s fuel cell Applied R&D projects (i.e. potential market applications provide engineering specs, creating opportunities for fuel cell and hydrogen technologies/systems, raising technological and scientific challenges that establish R&D project goals to enable gaps to be filled).

Key objectives include:

- Increase reliability and performance and lower cost of fuel cell systems
- Develop highly efficient hydrogen storage materials and systems and hydrogen production in a carbon dioxide neutral manner to lower Greenhouse Gas emissions
- Evaluate residential and industrial fuel cell systems
- Develop higher temperature, lower cost, highly reliable PEM fuel cells (e.g. in pulp plants)
- Develop high performance DMFCs
- Develop lower operating temperature SOFCs.

PEM projects comprise:

- Towards extruded Membrane Electrode Assemblies (MEAs) – lower manufacturing costs
- Adaptive multivariable control of fuel cell engines – fuel source, enhanced performance, diagnostics
- Photothermal probes for in situ investigation of MEAs – real time diagnostics
- Modelling of fuel cell stacks/systems – sealing structures, heat/mass flow
- Quality control systems – on/off-line to lower manufacturing costs
- Electrocatalysts for DMFCs – enhanced performance.

SOFC projects comprise:

- Advanced materials for intermediate temperature – anode, cathode, electrolyte, interconnects
- Environmentally safe electrode manufacturing – without volatile organic solvents
- Degradation of cell materials – failure mechanisms (U. Calgary & McMaster)
- Multifunctional reactors for co-production of chemicals and power – hydrocarbon feed (CANMET).

Fuel and oxidant system projects comprise:

- Carbon dioxide neutral fuel production – zero emission hydrogen production from hydrocarbons
- Hydrogen storage in nano-structured carbon – viability
- Evaluation of co-ordinated fuel cell systems for remote and northern communities – co-ordination of power sources and fuel cell grids, infrastructure, simulation and system development, harsh environment.

Prototyping, integrating and evaluation (PIE) projects comprise:

- Performance, reliability and failure analysis of PEM and SOFC systems under all climatic conditions – simulation and modelling
- Evaluation of fuel cell systems – stack/system platform tools, fuel/oxidant systems
- Evaluation of residential fuel cell power systems – controlled testing
- Fuel cell technology in industry – pulp and paper, waste biomass fuels
- Hydrogen sulphide fuelled SOFC – scale-up (e.g. Snow Leopard in Alberta).

These projects are managed by five Technical Groups within NRC: Materials Engineering and Development Group, Sensing and Microsystems Group, Fuels and Energy Infrastructure Group, Control and Diagnostics Group and Prototyping, Integration and Evaluation Group.

The Mission team tours the NRC Facilities in Vancouver

7.5 Natural Resources Canada (NRCan)

Budgets

The annual NRCan budget (FY2002/03) for fuel cells and hydrogen R&D and infrastructure is C$8.6 million, split as follows:

- Fuel Cells and H_2 R&D (C$4m/yr*)	- Hydrogen production	C$250k/yr
	- Hydrogen storage	C$725k/yr
	- Hydrogen utilisation	C$210k/yr
	- Hydrogen safety	C$250k/yr
	- Fuel Cells	C$2,485k/yr
	- Communications	C$80k/yr
- Infrastructure (Canadian Transportation Fuel Cell Alliance) (5 year av.)		C$4.6m/yr

***** funding from PERD (Program of Energy Research and Development).

Furthermore, the Technology Early Action Measures (TEAM) Program provides supplementary funds (up to 75%) for individual eligible projects (i.e. demonstrating substantial reductions of Greenhouse Gas emissions). This contribution to the funding platform of what are ostensibly close-to-commercial "showcase" projects, allows PERD funding to be reallocated. TEAM funding of fuel cell and hydrogen related activity amounts to approximately a further C$2 million/year.

Activities

Hydrogen and Fuel Cell R&D: (target leverage effect of 4:1, i.e. NRCan contributes 20% overall) covers five main areas:

- Hydrogen Production
  - research into hydrogen selective membranes
  - development of electrolysers from a "personal fuelling" size to large industrial units
  - demonstration of personal refueller (Stuart Energy)
  - steam reforming of ethanol.

- Hydrogen Storage
  - 10,000psi hydrogen storage cylinders (Dynetek)
  - magnetic refrigeration for hydrogen liquefaction (HRI, IESVic)
  - carbon nanotube R&D
  - mobile hydrogen fuelling stations.

- Hydrogen Utilisation (see under Fuel Cells)

- Hydrogen Safety, Codes and Standards, Testing
  - development of a hydrogen sensor
  - safety assessment of hydrogen fuel cell systems
  - finite volume simulation of hydrogen flares
  - support for international Codes and Standards work
  - production of a hydrogen safety video (cost shared with Hydrogen 2000 Inc.)
  - hydrogen fuel cell test station (Hydrogenics)
  - hydrogen safety book.

- Fuel Cells
  - fuel cell engine development for buses (Excellsis/Ballard)
  - development of a platform for fuel cell integration into homes (Global Thermoelectric)
  - development of software to optimise fuel cell systems for buildings
  - development and testing of a 250kW SOFC for industrial applications (Kinectrics)
  - use of fuel cells in chemical processing.

The Canadian Transportation Fuel Cell Alliance (CTFCA):
This new initiative (launched June 2001), focusing on developing hydrogen fuelling infrastructure for fuel cell vehicles, is funded to the level of C$23 million over five years through the Federal "Action Plan 2000 on Climate Change". The spend profile over the five years is C$1m, 3m, 5m, 8m, 6m (C$4.6m average). Leveraging of 2:1 is expected (i.e. C$46m from other sources to match the C$23m from Federal funds - C$69m in total over the period).

NRCan is the lead Federal department, with other participants being other Federal departments and agencies, industry, NGOs, Provincial Governments, utilities and universities.

These stakeholders participate in five Working Groups (Communications, Light-Duty Vehicles, Medium/Heavy Duty Vehicles, Codes & Standards, Assessments) under the management of a Core Committee which itself advises the NRCan Management Committee. A Project Advisory Committee evaluates proposals for the fuelling demonstrations and makes recommendations to the Management Committee as to whether the proposal should be accepted, accepted with changes, or rejected.

Programme elements comprise:

- Fuelling demonstrations and evaluations (70% of budget)
  - profiling different fuels (electrolytic hydrogen, methanol and natural gas reforming, others) and fuelling systems (light-duty vehicles, transit buses, other vehicles) by 2006.

- Fuelling pathway assessments
  - parallel, iterative activity with demonstrations
  - early focus on competitive Greenhouse Gas emissions to aid project evaluation
  - reporting on fuelling pathways using emission and cost data from the demonstrations.

- Standard and procedures development
  - developing Codes and Standards for fuelling systems
  - training and certification for installing and maintaining fuelling facilities
  - investigating safety issues and procedures
  - testing of advanced safety equipment
  - co-ordination with Canadian and International standards activities.

This activity has many linkages with ongoing industry activity in Canada (e.g. BC Hydro's HydroGEN activities), USA (eg CFCP's Sacramento fuelling station) and Japan (WE-net).

The strategy direction is largely provided by the 18-member Core Committee made up of representatives of industry and Governments.

7.6 Department of National Defence (DND)

Budgets

The annual budget for naval R&D only is C$0.8-1.1m/year (C$0.6-0.8m/year plus C$0.3-0.4m over two years on 50kW prototype development with Fuel Cell Technologies (FCT) of Kingston). This budget does not include activities of the Army (e.g. the "Soldier Power" program activity undertaken in collaboration with the US Army) or the Air Force.

Activities

DND is currently only involved in concept/prototype activity, and hasn't yet become involved in pre-production/production activity. Annual expenditure is therefore relatively modest at present, although this may change relatively soon as work on, for example, auxiliary power supply plant moves into the pre-production phase.

DND invested around C$10m over a number of years with Ballard developing a 50kW prototype fuel cell suitable for scaling-up to a 250-300kW "moveable" fuel cell system for use in submarines. Ballard demurred on this activity due to a re-focusing on fuel cells for automobile and small military applications.

Subsequently, DND developed a cost-sharing collaborative partnership with Fuel Cell Technologies of Kingston (who had been involved in the 50kW prototype activity) to develop a power sources for autonomous underwater vehicles. This activity is receiving DND support to the level of C$0.3-0.4m over two years.

Other current fuel cell activity includes developing concepts for fuel cell powered reconnaissance vehicles (switching from diesel powered drive trains to fuel cell systems for stealth), 0.5MW modular fuel cells for auxiliary power on all-electric warships (with US Navy Department), metal hydrides for hydrogen storage, lithium ion batteries for Australian Collins-Class submarines (with French and Australian partners), etc.

Other R&D partnerships exist with Hydrogenics and the Royal Military College.

7.7 Industry Canada (IC)

Budgets

The Technology Partnerships Canada (TPC) funding programme has allocated C$60 million to the Canadian fuel cells and hydrogen industry to date (specifically Ballard, Stuart Energy, QuestAir and Dupont Canada). TPC financing for FY2002/03 (currently being used to complete a three year investment at Dupont Canada) is estimated at C$7 million. Financing levels were considerably higher in this area two/three years ago when investments were being made in several companies simultaneously.

Investment by the Federal Government and several Provincial Governments (mainly BC, Québec and Alberta) in the Canadian fuel cells and hydrogen industry up to the end of 2001 totalled over C$150 million. This investment enabled Canadian fuel cell companies to generate close to C$1 billion in public markets in 2000 (i.e. Ballard C$500m, Global Thermoelectric C$125m, Stuart Energy C$150m, Hydrogenics C$117m, Dynatech C$40m) - a leverage effect of over 6:1 and giving a total investment over the decade of approximately C$1.1 billion. Total Federal and Provincial Government investments will exceed C$175 million by the end of 2003, although annual expenditure has been declining recently.

Activities

Industry Canada has a similar mandate (i.e. Mission and programmes) to the UK DTI aimed at fostering a growing, competitive, knowledge-based economy.

In the fuel cell sector, IC has focused on assisting the development of the Canadian fuel cells and hydrogen industry by:

- facilitating the preparation of an industry-led fuel cells "Commercialisation Roadmap" (see below);
- leading fuel cells industry sector Innovation Consultations;
- through TPC, supporting technology development undertaken by industry related to fuel cell and hydrogen systems;
- attracting foreign investment to Canada in the fuel cell sector by working in collaboration with investment agency partners in Canada;
- with industry/Provincial Government partners, supporting the development of regional fuel cell and hydrogen industry clusters;
- developing policies and programmes to enhance the economic climate for growth of the Canadian fuel cell and hydrogen industry;
- linking fuel cell opportunities with established industries such as through the development of a strategy for the Canadian automotive sector; and
- through the Federal Fuel Cells Co-ordinating Committee, working in conjunction with other Federal departments and agencies to develop a co-ordinated approach to fuel cell sector development.

Fuel Cells Commercialisation Roadmap:
While this is co-facilitated by IC and Fuel Cells Canada, this is an industry-led initiative, with representation from across the fuel cell value chain.

The objectives are to identify and analyse barriers to getting fuel cell products to market and provide recommendations on the actions that industry, Government and academia should take to best overcome these barriers.

In order to maintain a leadership position, Canada must address significant outstanding challenges (i.e. attaining cost reductions in fuel cell technology, building a fuelling infrastructure, developing Codes and Standards, accessing capital, developing a skilled workforce, demonstrating the benefits of fuel cell applications, etc).

The Fuel Cells Commercialisation Roadmap offers a timely opportunity to develop a national strategy to accelerate the full scale commercialisation of fuel cell technology by Canadian companies.

Five Working Groups have been established: Mobile, Stationary, Portable, Infrastructure, Skills.

These Working Groups have met from June to October 2002, with a Draft Roadmap Report to be produced by the end of December 2002.

The key findings to date are:

- Key challenges to commercialisation are:
    - defining and proving product performance, reliability, durability and lifetime;
    - reducing product costs;
    - developing Codes and Standards for hydrogen fuel sources;
    - building an appropriately skilled labour force; and
    - demonstrating the benefits of fuel cell applications.
- Building the right business environment in Canada to attract and retain investment to tackle these issues will require industry, Government and academia to work closely together.
- Identifying early adopters for fuel cell products, and collaboration with them, is critical to achieving market success.
- There is a strong desire for industry leadership – Fuel Cells Canada has the major role in this regard.

A number of "next steps" have been identified to follow-on from the preparation of the Commercialisation Roadmap. These are:

- Industry, academia and Government partnership is required to leverage strengths and to maintain Canada's global leadership position.

- Recommended strategies and actions arising from the Roadmap process need to be followed-through.

- There is a need for successful implementation by industry, academia and Government (following the development of a strategy for collaboration and implementation).

- It is recognised that an important link must be established into the Innovation and Climate Change agendas.

- Strong benefits derive from a strong fuel cell sector: knowledge-based; technology intensive employment; value added exports; enhanced innovation capacity; enhanced energy efficiency and energy diversity; reduced pollution; improved health; leadership in sustainable development; leadership in climate-change solutions.

7.8 Other Government Sources of Funding and Partnership Activities

Transport Canada – small amounts of activity only.

Environment Canada – small amounts of activity only.

Provincial Governments

Several collaborative activities involving Provincial Governments have taken place in recent years including:

- Alberta Province/NRC/University of Calgary – Alberta Fuel Cell Initiative
- Alberta Research Council/Western Economic Diversification – Micro-SOFC projects [C$1 million]

- BC Province/NRC/FCC/Western Economic Diversification: 2000 Western Economic Partnership Agreement [C$6.5m Federal funding; C$5.5-6.0m Provincial Government funding for a Demonstration Project] – funding completed
- Provinces/NRC – IRAP
- Québec Province – funding activities focused on hydrogen production/storage capabilities.

While much of this expenditure has been completed, the annual expenditure of the Provincial Governments in the fuel cell and hydrogen area is estimated to be in the region of C$2million/year.

Legislation, Incentives, etc.

Other mechanisms/drivers exist (or are likely to exist shortly) in Canada to promote the development, demonstration and deployment of fuel cells and hydrogen technology including:

- NRCan – Climate Change Action Fund
- BC Sales Rebate
- Purchase/lease of alternative fuel vehicles (C$1k) and buses (C$5k)
- R&D Tax Credits (Federal and Provincial)
- Kyoto Protocol Targets (when Canada ratifies the Kyoto Protocol – by end of 2002? – Greenhouse Gas reduction targets will need to be attained. Fuel cell and hydrogen technology will clearly be one focus for activity).

7.9 A Summary of Government Sources of Funding

The table overleaf attempts to summarise the various sources of Government (Federal and Provincial) and categorise them into R&D (basic science/applied), Demonstration and Legislation/Incentives/etc. This by no means gives a comprehensive picture but at least serves to illustrate the broad pattern of Government support.

SUMMARY OF CANADIAN GOVERNMENT INITIATIVES SUPPORTING THE FUEL CELLS AND HYDROGEN INDUSTRY

<table>
<tr><th rowspan="2">Stakeholder</th><th colspan="2">R&D Activities</th><th rowspan="2">Demonstration Activities</th><th rowspan="2">Legislation, Incentives, etc</th></tr>
<tr><th>Basic Science</th><th>Applied</th></tr>
<tr><td>NSERC
[C$3.4m/y]</td><td rowspan="6">• NSERC Discovery Grants Program [C$1m/y]
• NSERC R&D Projects [C$1.435m/y inc 5 projects below]
• NSERC/NRC - 5 Projects
• NSERC/NRC – FC Chairs (5) [C$1m/y]
• NSERC/NRC) - Graduate Student Work Terms in industry/Gov. [C$0.1m/y]
• NRC/university MoUs
• Universities/NRC - Co-hiring snr. research staff
• NSERC Training Programs
• DND/Royal Military College</td><td></td><td></td><td rowspan="3"></td></tr>
<tr><td>NRC
[C$9m/y]</td><td rowspan="7">• NSERC/industry – Collab. R&D [C$1m/y]
• NRC R&D Projects at Innovion Centre and 5 NRC Insts. (15)
• NRC/industry secondments
• NRC/NRCan – international stds.
• NRC/industry – Innovation Centre
• NRC/FCC – labs at Innovation Centre
• NRC/DND res. MoU
• NRCan – R&D (PERD/ CANMET) [C$4m/y]
• NRCan/NRC/… - CTFA [C$1.4m/y]
• Alberta/NRC/U. Calgary – Alb. FC Initiative
• ARC/WED – microSOFC projects [C$1m]
• NRC/FCC/WED – 2000 Western Economic Partnership Agreement [C$6.5m - Federal]
• DND/industry collaboration</td><td rowspan="7">• NRC/Provinces – IRAP (SMEs)
• BC/NRC/FCC/WED – 2000 WEPA: Demo Project [C$5.5-6.0m – Provincial funded]
• NRCan – Tech.Early Action Measures (TEAM) [C$2m/y]
• NRCan/NRC/Prov. – CTFCA (fuelling demos) [C$3.2m/y]
• IC/FCC – FC Commercialisation Roadmap
• WED Operating Support to FCC [C$1m]
• IC – TPC [C$30m/y]</td></tr>
<tr><td>(FCC)
[C$1m/y]</td></tr>
<tr><td>NRCan
[~C$10.6m/y]</td><td rowspan="5">• NRCan – Climate Change Action Fund
• BC Sales Rebate
• Purchase/lease of alt. fuel vehicles [C$1k] and buses [C$5k]
• R&D Tax Credits (Fed and Prov)
• Kyoto Protocol Targets (post-ratification)</td></tr>
<tr><td>DND
[C$0.8m/y]</td></tr>
<tr><td>Prov. Govt.
[~C$2m/y]</td></tr>
<tr><td>IC
[~C$7m/y]</td><td rowspan="2"></td></tr>
<tr><td><u>TOTAL
C$33.8m/y</u></td></tr>
</table>

7.10 Lessons for the UK

- Canada is, arguably, the world leader in the development and commercialisation of fuel cell technology. It is also pre-eminent in the development of concepts and technologies surrounding the idea of a "hydrogen economy", and the infrastructure issues associated with this. Through this broader vision, Canadian industry has developed world-leading strengths in Hydrogen (production, storage, fuelling, safety); Fuel Cells (PEM, SOFC, Materials, BOP, Test Stations); Integrated Systems. Canada has achieved this position due to a decade of considerable investment by the public sector of more than C$150 million (~£64 million), which has enabled finance to be raised in the markets approaching C$1 billion (~£400 million) - 6:1 leveraging. Current expenditure from public funds is approximately C$34m/year or C$1.1/capita annually (~£14.4 million/year or £0.5/capita annually).

- This historically high (although currently declining) level of public sector investment over the last decade, initially directed at conceptual (R&D) and prototyping activity, has stimulated a near-exponential growth in R&D expenditure and effort since the mid-1990s to the level of approximately C$360 million in 2002/03 – mostly funded by the industry itself. Product development and commercialisation has followed, with domestic and export revenues being generated from 2000/01.

- Compared to Canada, the UK fuel cell and hydrogen industry has had a very low level of public sector investment, and, as a result, has not developed sufficient concepts or prototype (and ultimately product) technologies that would enable it to compete effectively in the emerging world market for these technologies. UK companies have had difficulty raising capital and, as a consequence, have limited scope to invest their own resources in R&D. In order for the UK to be a "player" in this emerging market (which is not too late), significant and sustained public investment should be made in the industry.

- A significant number of Federal Government Departments and agencies (seven) are actively supporting fuel cell and hydrogen related activities in Canada: This support is very well co-ordinated both in terms of the different agencies focusing on different stages of the "concept-prototype-pre-production-production chain", and in terms of overall administration/co-ordination through an inter-Government Co-ordination Committee. Although a smaller number of Government Departments and agencies are supporting fuel cell and hydrogen activities in the UK, there is only very limited liaison and co-ordination between them. This situation should be remedied as a priority, and is a pre-requisite of any substantial public sector investment in the sector.

- Partnership between industry, Government and academia has been essential, and both the focusing of Government Departments, agencies, etc, and the Co-ordination Committee, described in the above point, have been key in enabling the very high degree of partnership achieved in Canada to date. The UK DTI's Advanced Fuel Cell R&D Programme has strived for a decade to build such a partnership - limited funding has restricted it's success.

- At the "concepts/prototyping" stages (ie basic science and applied R&D), NSERC (more-or-less equivalent to EPSRC in the UK) maintains a balance of activity between investigative-driven (non-project) science, basic science R&D projects and more strategic collaborative projects with industry partners in the fuel cells and hydrogen area. In addition, the establishment of five fuel cell "Chairs" in key universities/research institutes will help raise the profile and increase co-ordination. While it has been unsuccessful in attracting funding to date, it seems likely that a Network Centre of Excellence on fuel cells and hydrogen may well emerge in due course. As a result of these initiatives, a large number of universities are active in this area (18+). In the UK, a significant number of respected universities (more than eight) are active in the fuel cells and hydrogen area. Many of these universities have an excellent reputation overseas, including in Canada. This competence should be nurtured and developed as it is potentially a "way in" to more industrially driven activity in Canada and elsewhere. It was suggested on the Mission that a UK capabilities report/directory be produced for the universities and research institutes; such a report/directory does not appear to exist for Canadian universities.

- In Canada, NRC plays a vital role as a link between the more scientific investigation activity of NSERC and the more industrial RD&D activities involving NRCan, DND and IC. As such, it is highly involved in public-private (and other) partnerships, co-ordinating or undertaking itself strategic R&D. Of equal importance is the incubator role NRC has adopted, to foster early uptake of fuel cell and hydrogen technologies. One key way that NRC has addressed barriers facing start-up companies is to establish a suite of "hydrogen safe" laboratories and provide the hydrogen supply, storage, H&S services, etc on a contract basis. NRC also takes a strong lead in technology transfer and international partnership initiatives (usually with Fuel Cells Canada as a partner). While in the UK some of these roles are undertaken by EPSRC and DTI, many "fall between the stools" or are not co-ordinated. A possible early step that could be taken in the UK would be to establish a DTI-EPSRC LINK Programme for fuel cells and hydrogen. Should this prove successful, the Canadian model of an incubator site with hydrogen safe labs available to start-up companies would be a logical development.

- As well as administering a programme of fuel cell and hydrogen R&D through its Program of Energy R&D (PERD), NRCan leads a dedicated new initiative – the Canadian Transportation Fuel Cell Alliance (CTFCA) – focusing on developing hydrogen fuelling infrastructure for fuel cell vehicles. The CTFCA, which was launched mid-2001, has a budget of C$23 million (~£9.8 million) over a five year period, with an expected leveraging of 2:1 (i.e. total budget expected to be C$69 million (~£29 million)). This initiative was launched under the auspices of the Federal "Action Plan 2000 on Climate Change", indicating Canada's view of the role for reducing transport emissions in achieving Greenhouse Gas emission reductions.

- In the defence area – a likely early-adopter market for fuel cell and hydrogen technologies – activity is highly collaborative, with DND working in conjunction with NRC, industry partners and internationally (USA, France, Australia). While expenditure is currently modest, this is likely to change significantly as DND moves from concept/prototyping activities to pre-production partnership activity.

- Industry Canada, through it's Technology Partnerships Canada (TPC) funding programme, has historically been the largest funding source for fuel cell and hydrogen related work in Canada. Expenditure in 2002/03 is expected to be about

C$7 million (~£3 million). This programme supports technology development undertaken by industry and has enabled companies such as Ballard, Stuart Energy, QuestAir and Dupont Canada to leverage private finance.

- A Fuel Cell Commercialisation "Roadmap" is currently being prepared. This is an industry-led activity, co-facilitated by IC and FCC, aiming to identify and analyse the barriers to getting fuel cell products to market and provide recommendations to the actions that industry, Government and academia should take to best overcome these barriers. The Roadmap is addressing mobile, stationary and portable fuel cell systems, infrastructure and skills issues. A Draft Roadmap Report will be produced by the end of 2002, leading to a strategy for implementation: This strategy will be strongly linked to the Innovation and Climate Change agendas. The UK underwent its own (Government-led) "route mapping" activity for fuel cells and (separately) hydrogen in 2000/01 and it is recognised that this may need re-addressing from an industry perspective before long.

- In Fuel Cells Canada, Canada has a very strong national industry association with a membership of more than 50 companies/organisations in the fuel cells and hydrogen area (including two UK organisations). FCC, which has only existed for about two years, receives considerable operating support from Federal and Provincial (BC) Governments. FCC commissioned a study by PricewaterhouseCoopers in 2001/02 examining the status of, threats to, and opportunities for the Canadian fuel cell and hydrogen industry. This study reported in early 2002 and the results are being actively used by FCC to lobby the Canadian Federal and Provincial Governments to increase funding for this area. The UK does not have a similar industry association, relying instead on two "virtual" networks (the Fuel Cells Network and H2NET). The Mission team considered the establishment of an industry association (along the lines of FCC) a priority recommendation resulting from the Mission.

- Other market mechanisms to support, or act as "drivers" for, the development, demonstration and deployment of fuel cell and hydrogen technologies (to complement direct Government funding) are being established. These include NRCan's Climate Change Action Fund, a Sales Rebate available in BC, financial incentives for the purchase/lease of alternative fuel vehicles and buses and R&D Tax Credits (Federal and Provincial). When Canada ratifies the Kyoto Protocol – expected by the end of 2002 – Greenhouse Gas reduction targets will need to be established and attained; this will no doubt prompt further legislation/incentive mechanisms, with fuel cell and hydrogen technologies clearly a focus for activity. The UK, having already ratified the Kyoto Protocol, may need to look further than the move to lower carbon fuels, renewable energy and demand side measures to meet current and future Greenhouse Gas reduction targets, including transport and stationary power generation technologies offering "step-change" emission reductions and a move towards a "hydrogen society".

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Introduction

This fact-finding Mission, funded by the DTI's International Technology Service, had the primary aim of fostering the development of the UK fuel cell industry. This was to be achieved by:

- improving UK awareness of fuel cell developments in Canada;
- developing opportunities for collaboration and technology transfer to help develop the UK fuel cell industry, for stationary, automotive and portable applications;
- highlighting opportunities around fuel cells for the UK; and
- enhancing awareness of new markets and applications.

Given this clear technology transfer aim, the conclusions drawn by the Mission team are embodied in the parts of each of the preceding Sections of the report that draw out the lessons for the UK. This Section pulls these lessons together and draws out a number of recommendations. These recommendations are for the UK fuel cell and hydrogen industry, UK Government and its agencies and for UK academic institutes.

8.2 Conclusions – Key Lessons for the UK

General

- Canada is, arguably, the world leader in the development and commercialisation of fuel cell technology. It is also pre-eminent in the development of concepts and technologies surrounding the idea of a "hydrogen economy", and the associated infrastructure issues. Through this broad vision, Canadian industry has developed world-leading strengths in hydrogen (production, storage, fuelling, safety), fuel cells (PEM, SOFC, materials, balance of plant, test stations) and integrated systems.

- Canada's fuel cell and hydrogen industry is characterised by a high level of co-ordination of activities, underlined by coherent National and local strategies. This has led to the development of "clusters" of expertise which recognise the importance of the academic sector as well as the industrial. Federal and Provincial Government departments and agencies work closely with commercial organisations, both small and large, and academic organisations, and have stimulated, to a large extent, the early development of a hydrogen infrastructure.

- Governments world-wide are aware of the significant economic benefits that can be generated from the projected growth of the fuel cells industry in the form of new employment opportunities and improved balance of payments. They are setting out future spending plans and, in some cases, are pushing fuel cell technology via regulation, procurement and fiscal incentives to ensure that they capture their share of the benefits that will be generated from a successful fuel cell and hydrogen industry.

- The Canadian fuel cell and hydrogen industry clearly recognises the competitive threat from the USA and Japan, particularly given the much greater financial resources from public sources being deployed. This has accentuated strong interest in Canada to form or strengthen connections with the UK, including technical, industrial or academic exchanges. Such connections offer an opportunity for the UK to benefit from learning from a comparatively mature industry, while assisting Canada to stabilise its position as a Global "player".

- The future success of fuel cells is not solely intertwined with the concept of a "hydrogen economy". SOFC technology is proving that current hydrocarbon-based fuels can be used efficiently and with minimal resulting emissions.

- Government, industry and university co-ordination and collaboration is required to set consistent standards for the technology and to raise consumer awareness concerning the benefits of the technology. In Canada, these groups are taking on the challenge of creating Codes and Standards, raising public awareness and providing a general framework for the sustainability of fuel cell and hydrogen technologies.

Fuel Production and Storage

- Leading developers are happy to focus their limited resources on their core stack and systems technology, maintaining only a small fuel processing programme and/or buying in technology where needed. Thus, there is a market for suppliers of fuel processor systems and components.

- Many stack/processor alliances have already been forged and UK developers without existing alliances can expect to find it increasingly difficult to find viable routes to market without a product so markedly superior both technically and practically that it will "turn heads".

- There is a need for improved products for future generations of systems. Radically different approaches are likely to provide such products more readily than incremental development of existing packed catalyst bed systems. The UK may be able to compete in this arena.

Fuel Cell and Systems Commercialisation

- Government funding for R&D and demonstration has proved essential in bridging the gap between the development of intellectual property and the commercialisation of fuel cell products. The companies visited to a large extent evolved and are sustained in the near-term as a function of Government funded development programmes. With this as an impetus in terms of physical infrastructure and skill-set development, a supplier infrastructure of related technologies is also evolving, creating useful "clusters".

- Prototype development and demonstration programmes are important instruments for achieving product validation and next stage product enhancement – they also serve to increase customer and public awareness and facilitate the development of supporting infrastructure, appropriate Codes and Standards and supply chain management. However, for optimal outcomes demonstration programmes need to be 'looped' back into continuing R&D, product and materials performance, and cost improvement, rather than end with the demonstration alone.

- An absence of Codes and Standards has not been a significant barrier to commercialisation to date. However, it could become so if national and international institutions are not aware of the extent to which market barriers may be created or reinforced.

- Publicly supported R&D and testing facilities (and/or University centres) that provide space (leased) and support services, such as hydrogen and other fuel supply, computer simulation, non-destructive testing, etc. (on a lease or fee for services basis) and are open to small and large firms alike, have been a vital feature in Canada. There are no similar facilities in the UK.

- SOFC technology is in a pre-commercialisation phase and may have reasonable and achievable commercialisation time-frames, i.e. within the next five years.

- A number of market segments are approaching the point at which PEM systems can be commercially competitive. These include remote power supply for non-grid connected users, standby power and Uninterruptible Power Supplies (UPS). The price differential for military and aerospace applications also makes these early adopter markets.

- In developing fuel cell systems that meet end-use needs, considerable cost reduction is needed throughout the value chain – base chemicals/materials to integrated systems. This is THE major focus of the industry; companies are focusing on realistic and achievable goals, with coverage of the entire value chain, including standardisation, certification, manufacturing and refuelling.

- Extension of product lifetimes and product reliability are other key issues that companies are directing R&D resources to overcome. It is clearly of paramount importance to deliver some significant "early wins" (and avoid over-selling) in order to maintain confidence in (and hence private sector finance for) fuel cell and hydrogen technologies.

- There is an increasingly urgent requirement for field data (i.e. there are insufficient units operating and not enough data to evaluate performance).

- In terms of investment, it is important to find ways of overcoming the high "burn rates" (i.e. capital expenditure rates). This is polarising some parts of the industry to look for early sales and hence revenue. There is also a recognition of the need for soft cash for commercialisation (repayable). All these factors tend to make R&D focussed on short term horizons.

- Private sector firms have been willing to fund fuel cell development, and access to venture capital and private funding has not been a significant issue. This may not be the case at present, and for the near to medium term additional market entry support and programmes to move fuel cell products into wider use may be critical. Use of Government purchase of fuel cell systems to emphasise acceptance of the technology could be an important stimulus as part of support initiatives.

Financing and Venture Capital

- The venture capital investment community in Canada consists of one specialist fund and half a dozen general energy funds. Whilst there appears to be room for more funds to enter the sector, there is a need for breadth to allow co-investment and the sharing of risk amongst investors. In addition, and crucially, there is a quoted fuel cell sector that provides an alternative exit route, something that is currently a barrier to the pace of growth of the venture capital sector in the UK.

- The availability of funding, whether from private or public sources, is important. However, it is not the only factor determining both the future development of the industry and those countries that will be at the forefront of its development. The geographical evolution of the industry will be determined by participants and investors selecting to operate in countries where there is the most favourable combination of regulatory policy, fiscal policy and funding. Financial markets will take account of the framework within which these policies are executed and allocate capital accordingly. Other countries (US and Japan) currently appear to be taking the lead on these issues. On present trends, this will attract greater quantities of capital from countries with less favourable frameworks.

Government Support for Fuel Cells and Hydrogen

- Canada has achieved its leadership position in fuel cell and hydrogen technologies and commercialisation due to a decade of considerable investment by the public sector: More than C$150 million (~£64 million) of public support has been provided, which has enabled finance to be raised in the markets approaching C$1 billion (~£400 million) – a leveraging effect of about 6:1. Current expenditure from public funds is approximately C$34m/year (~£14.4 million/year).

- This historically high (although currently declining) level of public sector investment over the last decade, initially directed at conceptual (R&D) and prototyping activity, has stimulated a near-exponential growth in R&D expenditure and effort since the mid-1990s to the level of approximately C$360 million in 2002/03 – mostly funded by the industry itself. Product development and commercialisation has followed, with domestic and export revenues being generated from 2000/01.

- A significant number of Federal Government Departments and agencies (seven) are actively supporting fuel cell and hydrogen related activities in Canada: This support is very well co-ordinated, both in terms of the different agencies focusing on different stages of the “concept-prototype-pre-production-production chain”, and in terms of overall administration/co-ordination through an inter-Government Co-ordination Committee.

- At the “concepts/prototyping” stages (ie basic science and applied R&D), NSERC (more-or-less equivalent to EPSRC in the UK) maintains a balance of activity between investigative-driven (non-project) science, basic science R&D projects and more strategic collaborative projects with industry partners in the fuel cells and hydrogen area. In addition, the establishment of five fuel cell “Chairs” in key universities/research institutes will help raise the profile and increase co-ordination. As a result of these initiatives, a large number of universities are active in this area (18+).

- NRC plays a vital role as a link between the more scientific investigation activity of NSERC and the more industrial RD&D activities involving NRCan, DND and IC. As such, it is highly involved in public-private (and other) partnerships, co-ordinating or undertaking itself strategic R&D. Of equal importance is the incubator role NRC has adopted, to foster early uptake of fuel cell and hydrogen technologies. One key way that NRC has addressed barriers facing start-up companies is to establish a suite of "hydrogen safe" laboratories and provide the hydrogen supply, storage, H&S services, etc., on a contract basis. NRC also takes a strong lead in technology transfer and international partnership initiatives (usually with Fuel Cells Canada as a partner).

- As well as administering a programme of fuel cell and hydrogen R&D through its Program of Energy R&D (PERD), NRCan leads a dedicated new initiative – the Canadian Transportation Fuel Cell Alliance (CTFCA) – focusing on developing hydrogen fuelling infrastructure for fuel cell vehicles. The CTFCA, which was launched mid-2001, is expected to have a total budget of C$69 million (~£29 million) (including industrysupport).

- In the defence area – a likely early-adopter market for fuel cell and hydrogen technologies – activity is highly collaborative, with DND working in conjunction with NRC, industry partners and internationally (USA, France, Australia). While expenditure is currently modest, this is likely to change significantly as DND moves from concept/prototyping activities to pre-production partnership activity.

- Industry Canada, through it's Technology Partnerships Canada (TPC) funding programme, has historically been the largest funding source for fuel cell and hydrogen related work in Canada. Expenditure in 2002/03 is expected to be about C$7 million (~£3 million).

- A Fuel Cell Commercialisation "Roadmap" is currently being prepared. This is an industry-led activity and is co-facilitated by IC and Fuel Cells Canada. It aims to identify and analyse the barriers to getting fuel cell products to market and provide recommendations on the actions that industry, Government and academia should take to best overcome these barriers. A Draft Roadmap Report will be produced by the end of 2002, leading to a strategy for implementation: This strategy will be strongly linked to the Innovation and Climate Change agendas.

- In Fuel Cells Canada, Canada has a very strong national industry association with a membership of more than 50 companies/organisations in the fuel cells and hydrogen area (including two UK organisations). FCC, which has only existed for about two years, receives considerable operating support from Federal and Provincial (BC) Governments. FCC recently commissioned a study by PricewaterhouseCoopers examining the status of, threats to, and opportunities for the Canadian fuel cell and hydrogen industry. The results are being actively used by FCC to lobby the Canadian Governments to increase funding for this area.

- Other market mechanisms to support, or act as "drivers" for, the development, demonstration and deployment of fuel cell and hydrogen technologies (to complement direct Government funding) are being established. When Canada ratifies the Kyoto Protocol – expected by the end of 2002 – Greenhouse Gas reduction targets will need to be established and attained; this will, no doubt, prompt further legislation/incentive mechanisms, with fuel cell and hydrogen technologies clearly a focus for activity.

8.3 Recommendations

- It is clear that Canada benefits from an integrated approach. Companies offering state-of-the-art fuel cell technology, fuel production, fuel storage solutions and systems integration, collaborate to develop the products that the market needs, with public funds and facilities channelled accordingly. It is recommended that consideration be given to emulating this approach, which does not currently exist in UK. This would require a positive approach by the DTI in order to foster development of the necessary critical mass.

- Compared to Canada, the UK fuel cell and hydrogen industry has had a very low level of public sector investment, and, as a result, has not developed sufficient concepts or prototype (and ultimately product) technologies that would enable it to compete effectively in the emerging world market for these technologies. UK companies have had difficulty raising capital and, as a consequence, have limited scope to invest their own resources in R&D. In order for the UK to be a "player" in this emerging market (which is not too late), it is recommended that significant and sustained public investment should be made in the industry.

- Public sector support for early demonstrations of fuel cell technologies has been of critical importance in enabling Canadian companies (including SMEs) to build their current leadership position. It is recommended that consideration be given in the UK as to the barriers that exist to obtaining finance for projects. These are concerned with perceived risk by the financial community and its unwillingness to lend to SMEs without a track record. Innovative finance mechanisms could be developed to enable demonstrations to take place with SME participation.

- Although, when compared to Canada, a smaller number of Government Departments and agencies are supporting fuel cell and hydrogen activities in the UK, there is only very limited liaison and co-ordination between them. It is recommended that this situation should be remedied as a priority, and is a pre-requisite of any substantial public sector investment in the sector. Within this framework, priority should be given to the establishment of a co-ordinating body providing a focus for communication, and the development of joined-up and consistent policy and innovation-friendly regulation.

- There is a strong interest in Canada to form or strengthen connections with the UK, including technical, industrial or academic exchanges. This presents potentially valuable opportunities for the UK to benefit from working closely with a comparatively mature industry and hence building capabilities in the UK in terms of sector skills and applied research activity. It is recommended that these opportunities be investigated with the DTI's ITS Secondment Programme and EPSRC.

- In the UK, a significant number of respected universities (more than eight) are active in the fuel cells and hydrogen area. Many of these universities have an excellent reputation overseas, including in Canada. This competence should be nurtured and developed as it is potentially a "way in" to more industrially driven activity in Canada and elsewhere. It is recommended that a UK capabilities report/directory be produced for the universities and research institutes; such a report/directory does not appear to exist for Canadian universities.

- In Canada, NRC performs a vital linking role between fundamental science activity and industrially-led applied R&D and demonstration, as well as having an incubator remit. While in the UK some of these roles are undertaken by EPSRC and DTI, many "fall between the stools" or are not co-ordinated. It is recommended that consideration be given to establishing a DTI-EPSRC LINK Programme for fuel cells and hydrogen.

- Publicly supported R&D and testing facilities that provide incubator support services for small and start-up companies have proved vital in developing the Canadian industry. It is recommended that the benefits of such facilities in the UK be evaluated.

- Although the UK undertook a (Government-led) "route mapping" activity for fuel cells and (separately) hydrogen in 2000/01, it is recommended that a more integrated, industry-led route mapping be conducted and that this be used to develop implementation strategies and guide public funding so as to successfully help UK companies commercialise fuel cell and hydrogen technologies and hence position the UK in the vanguard of countries in these areas.

- The UK does not currently have an industry association for fuel cells or hydrogen technologies, relying instead on two "virtual" networks (the Fuel Cells Network and H2NET). It is recommended that the establishment of an industry association (along the lines of Fuel Cells Canada) be a priority.

- The UK, having already ratified the Kyoto Protocol, may need to look further than the move to lower/zero carbon fuels and demand side measures to meet current and future Greenhouse Gas reduction targets. This may well include transport and stationary power generation technologies offering "step-change" emission reductions and a move towards a "hydrogen society". It is recommended that greater consideration be given to the importance of hydrogen infrastructure, fuel cells as an enabling technology, and associated opportunities. Demand for these technologies can be "shaped" through a range of mechanisms including sustainable procurement by Government, fiscal support, etc.

APPENDIX A

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APPENDIX B

MISSION ORGANISER - SYNNOGY

Synnogy is dedicated to helping all types of organisations respond effectively to the opportunities and challenges around new technology. Synnogy's current technology interests lie in the areas of energy generation, transmission and distribution, storage and end-use.

The Synnogy Team has been active in the area of fuel cells for several years, during which it has supported a wide variety of both public and private sector bodies in identifying new business opportunities and optimising their commercial strategies. In 2000 and 2001, Synnogy organised two highly successful Missions on aspects of fuel cell technology to the US. These Missions, which were organised have provided valuable insights into developments around commercialisation in the US, and have lead to collaboration between the UK and US.

Synnogy has extensive contacts with a range of organisations with an interest in fuel cell commercialisation. Over the past five years, it has worked with organisations as diverse as:

Advantica	Johnson Matthey	Sulzer Hexis
Air Products	Katalyst Ventures	UBS Warburg
AMEC	Landi Renzo	UK Dept. of Trade & Industry
Babcock Borsig	Morgan Materials	UK Environment Agency
Birmingham City Council	National Grid	UK Health and Safety Executive
Black & Decker	Porvair	UK Ministry of Defence
BNFL	Regentech	W.S. Atkins (Viridian Power)
BP	Rolls-Royce	Welsh Development Agency
DERA / DSTL	RWE	
Innogy	Scottish Power	
Intelligent Energy	Shell Hydrogen	
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APPENDIX C

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APPENDIX D

MISSION DISCUSSION TOPICS

The key questions to be addressed by the Mission fell into three groups:

Markets

- What are the timescales for commercialisation?
- Where will the early niche markets be?
- Where will the medium / long term markets be?
- Are there opportunities for technology transfer to accelerate commercialisation?
- What are the key barriers to commercialisation?
- Are there barriers which are specific to Canada?
- What are the opportunities and challenges around the evolution from an R&D situation to a mass production environment?
- How can these be overcome?
- What is the role for Government?
- How has funding for fuel cell related technology been managed and is there now sufficient funding available in the Canadian market for all levels of organisation? If not how might this be resolved?
- Do you see specific areas in which international co-operation is required or would greatly benefit all parties?
- How will fuel cells differentiate themselves from competition?

Technology

- What alternative materials might help to improve performance / reduce costs?
- Is materials research a large focus of Canada's funding? Are there opportunities for collaboration?
- What is the status of reformer technology and how is this likely to evolve in the short term?
- Can skills needs to be met? If not, what action is required?
- How can the following be optimised?:
- Power density
- manufacturability
- integration
- standardisation
- catalytic poisoning
- power quality
- system configuration (e.g. size reduction)

Economics

- What economic instruments might be appropriate to stimulate commercialisation?
- What might be their impact?
- Will they be significantly different across technologies? Or countries?
- Where will fuel cells fit into the Hydrogen Economy? How can they be optimised for use in hybrid and combined situations?
- How much impact will economies of scale have on cost?

- How can the costs of the following be minimised:
- plate manufacture
- platinum loading
- balance of plant
- Is there still an opportunity for innovation in fuel cell design and structure or is the Canadian system becoming dominated by existing players?

APPENDIX E

FUEL CELL TECHNOLOGIES

Technology	Electrolyte	Power Range	Description	Status
First Generation Fuel Cells - Mature				
Alkaline Fuel Cell (AFC)	Liquid Alkaline usually KOH	A few watts to 10s of kW	Characterised by a liquid potassium hydroxide KOH electrolyte. Main issues with these are the need to circulate the KOH and contamination of the membranes by CO_2.	Mature technology. Expensive but used in niche applications. Few manufacturers currently active. Technology may still find applications if later generation technologies fail.
Second Generation Fuel Cells – Currently Under Development (i.e. concept – prototype – pre-production – early adoption – production)				
Micro Direct Methanol (μDMFC)	Solid Polymer	< 50W	Low power PEM devices that will compete directly with traditional batteries. Methanol is the fuel delivered to the PEM device as a liquid. Typically to be used for mobile electronic equipment from phones to computers.	Advanced product trials, early commercialisation expected.
Direct Methanol (DMFC)	Solid Polymer	50-150W	PEM devices for higher power applications.	Early product proof of concept.
DMFC		500-2kW	PEM devices for much higher power ranges. These have very significant utility and opportunities due to availability of the methanol fuel.	Early R&D effort seems to confirm viability.
PEM	Solid Polymer	W-many hundred kW	Traditional PEM direct hydrogen solid polymer fuel cell. Whilst Siemens and Babcock have delivered a 200kW system generally they operate at around the few watts to 25kW.	Commercial product now available although power output limited to 1-2kW. A large number of companies are close to bringing stacks to market but few are bringing product.
Solid Oxide Tubular	Solid Oxide Material	100W-10mW	Tubular and planar SOFCs employ similar materials, but differ in terms of fabrication techniques. Applications include CHP, power generation, ship propulsion and trains. Natural gas is generally the fuel of choice.	
Solid Oxide Planar	Solid Oxide Material	100W-10mW		
Phosphoric Acid	Phosphoric Acid	200kW-11MW	The moderate operating temperature (200ºC) precludes internal reforming of hydrocarbon fuels, and so a separate reformer is required. Applications include power generation and CHP.	200kW systems now offered but not commercially competitive.
Molten Carbonate	Molten Carbonate material	5kW-2MW	Hydrocarbon fuels, including coal-derived fuel-gas, may be reformed directly at the anode and an external reformer is not necessarily required,.	Development programmes in Japan, the USA and Europe have

			However, sulphur tolerance remains a problem. Application areas include power generation, CHP, ship propulsion and trains.	produced many small prototype units in the 5-20kW range, and a 2MW plant has been demonstrated in the USA. 250kW systems are also being demonstrated but further R&D required.
Third generation technologies – R&D Concepts Only				
Direct H_2S Solid Oxide	Solid Oxide Material	100s kW and above	Taking H_2S as the fuel, the heat of the anode dissociates the hydrogen and sulphur. The application and fuel source makes it 3rd generation.	Conceptually proven, embarking on fund raising to commercialise (2-5 years to market).
DMFC	Liquid Acid	1kW – 5kW	A fuel cell from the Dr Karl Kordesh family of technologies. Claims better technical performance over PEM DMFC devices but has draw back of a liquid electrolyte. Given it is a Kordesh technology its currency is coincident with AFC (1st generation) but has not enjoyed widespread exposure and deals with inherent problems with DMFC.	Early R&D work, theoretical characterisation leading to prototyping during 2003, 2-3 years away from pre-production stage.
Micro Solid Oxide (μSOFC)		<10W	– New Micro Power Company: Lilliputian Systems • Integrated micro Solid Oxide Fuel Cell (SOFC) and micro-reformer on a silicon chip using MicroElectroMechanicalSystems (MEMS) technology from the integrated circuit industry • Extremely high energy densities • Targeting battery replacement market for next generation of portable electronics.	Early R&D work, theoretical characterisation leading to prototyping during 2003, 2-3 years away from pre-production stage.

APPENDIX F

FUEL CELL SYSTEM COMPONENTS AND INTEGRATION

Introduction

In order to make sense of the Balance of Plant (BOP) requirements and opportunities, the fuel cell product is considered at each stage of the value chain and the BOP needs considered for each stage. The section identifies the key areas of Balance of Plant opportunities surrounding the actual product system, as sold.

For each technology to be of value to any end-user, it must be manifested in an actual end-user product. Whilst the end-user product is a function of the product manufacturer's chosen position in the supply chain, it is what the final customer will purchase and use that defines what will be sold throughout the supply chain.

Generally, the end-user product contains the sub materials/components described below. For illustrative purposes, a PEM system is used. A similar pattern exists for other fuel cell technologies but the components will differ as they will for differing technologies power ranges.

The Base Chemicals/Materials

The lowest level of component are the raw materials used in the chemical composition of the membrane electrode assemblies (MEAs) as membrane materials and catalysts, current carriers and frames, metals/plastics for flow plate manufacture. Suppliers include Dupont, Johnson Matthey and Morgan Crucible Group.

Sub-assemblies comprise a vast array of chemicals used in differing compositions and differing parts of the MEA.

The Membrane Electrode Assembly

The base materials above are fabricated into the MEA product. MEAs are the individual cells which will produce electrical voltage and current, typically 0.5 to 1V at current densities of 100mA to 2A/cm^2. They may be fabricated by the suppliers of the chemicals or by separate companies who purchase the materials.

Sub-assemblies comprise:
- Raw materials formed into membranes
- Catalysts.

The Fuel Cell Stack

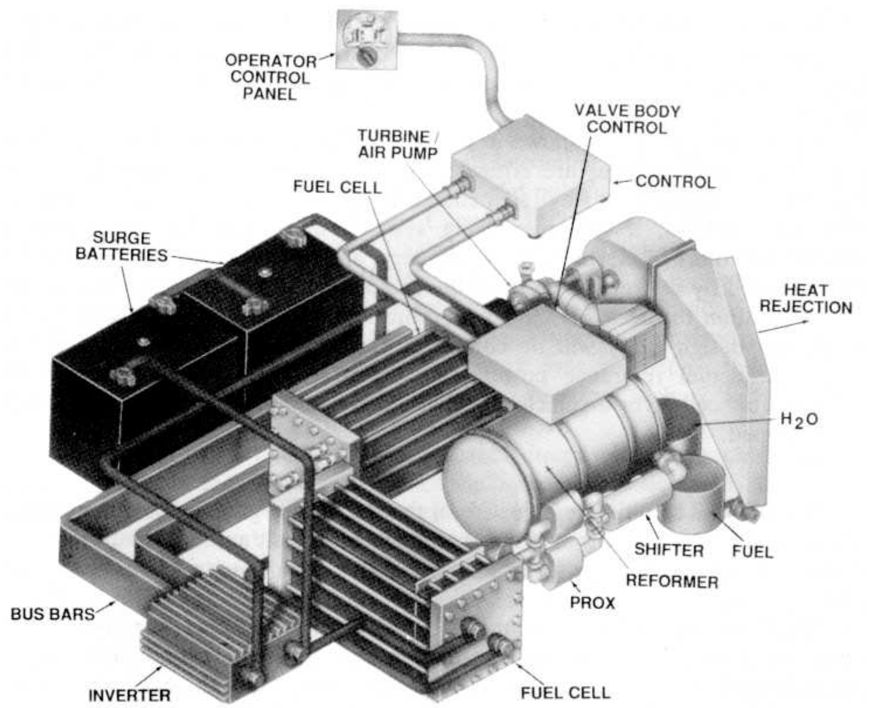
MEAs are assembled into an array comprising a stack. Connected in a parallel series combination depending on the technology, the configuration of the stack defines the voltage and current capabilities of the stack. Stacks are configured to produced mW to mega Watts depending on technology and application needs.

Sub-assemblies comprise:
- MEAs, Seals and end plates

- Connectors and manifolds
- Assembly metal work

The Fuel Cell Generator

At the generator level the stack is the central component. The balance of plant is required to control the flow of gasses to the stack, manage the environment inside and surrounding the stack and manage the water production. This typically will take gasses to defined specification, H_2 and usually air. H_2 and air to the fuel cell stack are required to have specific quality and humidity characteristics and presented to the stack ports at defined pressures. H_2 is normally delivered at pressure requiring an electronically controlled pressure regulator and the air needs to be pressurised requiring a compressor and filter. The stack temperature needs to be maintained within defined limits requiring combinations of heat exchangers, fans, humidifiers. To control these conditions and manage start up, shut down, fault detection and correction requires a range of sensors, data acquisition and process control hardware to measure the system and actuator devices to execute control and actions. Power to run the control system, sensors and actuators will be DC requiring DC/DC converter and some form of start up battery with trickle charger. A fuel cell generator concept is illustrated below (GM-DOE 10kW conceptual power source):



For an Uninterruptible Power Supply (UPS) the first second's response is still by battery and, for an engine, spike and peak loads are spread by batteries. Although batteries still figure in most systems, the market for battery replacement is one of reducing battery dependency. The Mission saw some small batteries in the power conditioning modules that allowed for spikes of a factor of five on the usual maximum. (The Mission didn't see flywheels or super capacitors used, but they are possibilities for the same reason). Good quality rechargeable batteries will be needed. New Ni-Zn rechargeable batteries are competitors to Pb-acid batteries.

Replacement times for batteries will become an issue when PEM membrane life is longer.

For PEM fuel cells, gas supply pumps were sometimes noted as an area for improvement, and some of the organisations visited during the Mission mentioned that they wanted better humidity control (this is to prevent membrane damage).

Sub-assemblies comprise:

- Gas and water pumps
- Valves and regulators
- Sensors (flow, temperature, pressure, H_2)
- Electronics and control (data acquisition and output controls, processors, software)
- Mechanical Assembly (chassis, mechanical components)
- Electrical Assembly (connectors, wiring, fusing etc.).

Systems

The system is the unit that will deliver power to the end-user and is the minimum required for any useful work. The final end-user product employs the fuel cell generator at its heart with further Balance of Plant. A system is configured for an end-user application.

A system will comprise:

- Fuel source, (including storage)
- Fuel cell generator
- Power conditioning (DC / AC or DC / DC)
- Interface between fuel cell and power conditioner (likely to include a battery depending upon overall system duty.

It may also include heat recovery systems in CHP systems.

The fuel source may be direct $H_{2,}$ in which case the application requires H_2 storage tanks, manifolding and pressure regulators taking pressure down to the defined input pressure for the generator. It will also likely require and isolating valve. For the installation in needs to be mounted and contained or if in a mobile application shock and vibration mounted. Alternatively the system may require a hydrocarbon being Natural Gas, LPG, methanol or others. These have to be contained delivering the fuel at defined conditions to the fuel cell input port and are contained as required. All must have some form of refuelling capacity.

The fuel cell system can be considered as a defined purchased item as described above. This system delivers unregulated DC, which will require power conditioning. All loads have defined characteristics and tolerance requirements. This will impose limits on voltage regulation, frequency regulation, transient response, fault tolerance etc. This will either a DC/DC unit or DC/AC unit. However there is also likely to be a start up buffer power requirement, possible a ride through power need or a power surge requirement that must be met by an auxiliary power buffer either battery, capacitors or other devices. For both PEM and Solid Oxide fuel cells in the 0.5kw to 50kW range there was consistent concern about power conditioning. It is taken as read that there is a good solid state approach to the issue of DC to AC conversion, but the problem seems to be that specialist inverter suppliers have not seriously addressed the particular cost, size and performance range needed by fuel cells. This is an area of potential market focus.

All of this must be monitored and controlled, packaged, supplied with a control panel and supplied with control systems, batteries, electrical bus, isolators and fault protection devices to protect the load, customers and internal sub system. Interface to the outside world will be through standard industry electrical connectors. Depending upon the installation additional safety devices may be required including gas sensors which may also need to be either intrinsically safe on in an explosion proof container.

At this stage in the industry there is a lot of bespoke control coding, and a large amount of monitoring equipment. Remote monitoring and control of units in the field is common. Rationalisation may happen, but it was not clear that any norms had been established to help bring down costs for component suppliers. Any study of the direction in which codes and standards are going may benefit from inclusion in the scope of a summary of data interfaces inside fuel cells, and seek to define what are the minimum long term external data inputs and outputs for O&M support and customer needs in Japan, North America and Europe.

Specialist applications of fuel cells may or may not have common Balance of Plant issues. For example, the reversible fuel cells planned for the sunlight powered weather/phone relay planes focus on very low weight, whilst the fuel cell approach to using H_2S from gas wells has some unique plant needs.

Sub-assemblies comprise:

- Fuel storage system and controls
- Fuel cell sub-system
- Power electronics and fuel cell interface
- Overall control systems and user interface
- System packaging.

The Need for System Characterisation

There is considerable opportunity in the area of demand characteristics for three reasons:-

- Assurance and certification
- Customers in specifying their needs
- Fuel cell suppliers in optimising their product range and commercial offer.

Reasons for this include the wide range of characteristics that a fuel cells will have to match as they address the numerous niche markets that will be the first users of fuel cells. Fuel cells are also still very expensive, and minimising their size, and maximising the efficiency of the system they are serving, are important ways of reducing costs. If you know a lot about the load variances (and ambient temperatures) designs can be better. An example of standard loads are used in “well to wheel” tests.