Chapter 2 - Status quo in fuel cells

2.1 - Overview

Fuel Cells (FC) are electrochemical devices that allow the direct convertion of an oxidisable fuel into electricity, with an electric efficiency - usually calculated from the Lower Heating Value[1] (LHV) of the fuel - ranging from 40 to 60%. The first FC was realised in England (1839) by Sir William Grove, aiming at demonstrating the feasibility of reversing water electrolysis. Grove realised his " gas battery " introducing hydrogen and oxygen into a sulfuric acid solution with platinum electrodes. At that time progress in mechanics had already led to the development of steam engines, at first employed in deep coal mines, then in transport. Electricity generation was not yet an industry, the fuel cell stayed at the lab.

In a quick glance at industrialisation we can realize how, historically, after Watt's steam engine, huge efforts by industries and research have influenced 20th century, and our lives, by thermal engine mass production. Motors and turbines are today the main prime movers for transportation and electricity generation. We just mention that :

In 1894 Ostwald, co-founder of the new science of Physical Chemistry along with Van't Hoff and Arrhenius, delivered a lecture to the Bunsengesellschaft, the German national society dedicated to the new subject (Electrochemistry). In it he looked forward to a future in the next century where machines would operate on the principles of the new science, rather than on laws governing the volume changes of gases under the influences of heating and cooling, which were established in the early days of physics. The new machines would operate without steam boilers, flames, soot and smoke and other forms of pollution. They would convert the chemical energy of fuels directly into work, rather than first converting it into heat via an inefficient thermal cycle. Ostwald clearly hoped that the steam engine, with its 10% efficiency, would be replaced by an efficient and non-polluting machine to directly generate electricity from chemical energy sources, which would open up a new civilisation in the coming century[...]His dream, unfortunately, did not come about. The steam engine was improved until its efficiency ultimately reached 40% and the internal combustion engine became the source of choice for smaller uses. However, the advantages of the fuel cell which he observed are still there to be exploited, and one century later, it now promises to become a clean, efficient source of energy, for use beyond the year 2000.*[2]

*When operated with natural gas and with a bottoming steam cycle, large (MW) gas turbines reach 58% efficiency, with prospects of 60% in the future. In the 200kW power range diesel engines reach 40-44% efficiency and gas engine are between 35-39% (Source LENI).

The different FC technologies, operation temperatures, technology status and respective bottlenecks are synthetically presented in the Table 2.1 below.

Fuel Cell Electrolyte	Temp (°C)	Status	Disadvantages
Polymer membrane (NafionTM, Dow, Asahi, Gore, PSI, Dais)	70	Mobile and stationary applications (0.1 - 300 kW) system assessment	CO< 20 ppm
Alkaline(85 wt% KOH in water)	80-150	Mature technology for air independent applications (1-40 kW)	Pure H2 and O2,
Phosporic Acid	200	Commercial200kW CHP units (300$(kW), portable 200W	η_{el} max 43% (nat. gas), price

[1] The heating value of an oxidisable substance is equal to the recoverable thermal energy resulting from the complete combustion ; when the the water produced from the hydrogen oxidation is condensed we talk of higher heating value (HHV), otherwise it is the lower one. Efficiencies are often calculated from the LHV, although the PEMFC produces liquid water and the HHV is applicable.

[2] J. Appleby, : " Fuel Cell technology : status and future prospects ". Energy. The International Journal 21, 1996, pag 1.

Molten Carbonate ($Li_2CO_3 + K_2CO_3$)	700	Field testing (1MW)	Corrosion, limited modularity, low η_{el} Need CO recycling
Solid Oxide ($ZrO_2 + YO_3$)	800-1000	Pre-commercial (3-10kW) 200kW tests	Max 0.25 A/cm^2 at 0.7 Volts Hardware stability
Direct Methanol (Nafion^{TM})	90-130	Laboratory (few W)	High Pt loading, lifetime
Heteroply Acid PWA ($H_3PW_{12}O_{40}\bullet 29H_2O$)	20-50	Laboratory (few W)	Dissolution of the electrolyte

Table 2.1 - Types of fuel cells and their status.

Although FC research's peculiarity is its extremely evolutionary, discontinuous pattern, we will try in this chapter to " picture " its status quo at present by a survey of programs, companies reports and more informal information taken from sector's experts. We focus on the Proton Exchange Membrane Fuel Cell technology.

2.2 - Fuel Cells programs

FC are regarded with interest by many energy agencies[3], because of their high efficiency and extremely low emissions, if operated with conventional fuels - i.e. other than hydrogen. There are several programs and many companies involved in the development of different fuel cell technologies. We will only mention the most important.

2.2.1 - European Community

Europe represents an important market for FC. The European Parliament's Commitee on Transport has adopted a draft report for a 10 year program to increase the use of alternative fuels and electric vehicles[4]. The European Union has established a fuel cell commercialisation program, where EU takes in charge funding for all marginal costs (e.g. services, capital equipment) associated with the production of the FC, if at least two European countries provide 50% of the direct financing required for industrial development. The Joule, Brite-Euram and Thermie programmes deal, within the EU Framework Program, with the issues of research and development, manufacturing processes and demonstration projects of FC respectively. In total, funding from 1992-1995 amounted to 32 million ECU. The EU strategy document puts emphasis on the PEMFC technology - low temperature and low cost - to achieve commercialisation of a CHP system before 2000.

2.2.2 - Switzerland (OFEN)

The Swiss Fuel Cell program is led by the Federal Office of Energy (OFEN) in co-operation with research institutes (EPFL, ETHZ, Paul Scherrer Institute) and private companies (Sulzer). Former Swiss FC research focussed on the development of Solid Oxide Fuel Cells (SOFC) with Asea Brown Boveri (ABB), but the Swiss-Swedish company abandoned FC development in 1991 as part of a business decision not to manufacture small generation equipment. Sulzer has recently founded Sulzer Hexis Ltd. a company devoted to the commercialisation of the HEXIS™ planar SOFC stack. The Paul Scherrer Institute (PSI) leads research in PEMFC on membrane developments and, more

[3] Armies, with the space industry, are an inportant sector involved because of the specific features of FC, e.g. part load performance, low noise/vibration levels and low off-gas temperature (for infra-red signature), which well comply with the recent shift to a higher electric/propulsion equipment ratio. See : D. Schmal, and B. Barendrecht " FC on-board of naval ships, activities in the Netherland ". European Fuel Cell News, August 1996.
[4] See: European Commission " Joule Program " and " Ten years of Fuel Cell Research " 1995.

recently, on Membrane Electrode Assemblies (MEA) and stacks[5]. Work is under way, in co-operation with EPFL for the development of a FC reformer to process liquid fuels to hydrogen in a drivetrain[6].

2.2.3 - U.S.A[7].

The United States have adopted several legislative measures in the 1990's to support the development and commercialisation of low emission technologies. The federal government passed the National Energy Strategy and the Clean Air Act in 1990. President Clinton has sponsored in 1993 an agreement between the government and the Big Three - " Partnership for a new generation of vehicles " - to develop technlogies for a new, super-clean car for the next century. The federal government also introduced in 1993 the Environment Technology Act to develop demand for environmental technologies. The California Air Resource Board adopted in 1990, the world's most stringent Low Emission Vehicle program, establishing a set of vehicle emission standards and classes. Car manufacturers have to meet the average fleet emission standards by combining four types of vehicles. For exemple as soon as 1998 2% of all new vehicles were to have been Zero Emission Vehicles, 10% in 2003. This target has been recently postponed for five years because of the strong opposition of the California Manufacturer's Association (CMA), representing around 800 companies. A report of the U.S. General Accounting Office warns : " Batteries are far from being perfected, the production cost are excessively high and the market potential is highly uncertain. Ultra-Low-Emission Vehicle, cleaner gasoline and programs to substitute the most polluting vehicles on the roads are more promising at far less cost "[8]

Ballard[9], world leader in PEMFC, suggests that it gives the time for PEMFC vehicle infrastructure to be implemented, thus recognising FCV as the only alternative to the ICEV.

2.2.4 - International Energy Agency[10]

The International Energy Agency (IEA) is been actively engaged in improving the state of fuel cell technologies with a co-ordinated programme of research, technology development and system analysis on Molten Carbonate, Solid Oxide and Polymer Electrolyte fuel cells systems. An Implementing Agreement for a programme of research, development and demonstration on advanced fuel cells was signed by seven countries in April 1990. A strong emphasis is given to information exchange between participants. Programs are subdivided in Annexes, each including its specific research Tasks. In 1995 the Implementing Agreement has been extended for three years and a new programme for 1996-1998 was developed, including:

Annex VI	Molten Carbonate Fuel Cells under Real Operating Conditions
Annex VII	Solid Oxide Fuel Cells under Real Operating Conditions
Annex VIII	Polymer Electrolyte Fuel Cells
Annex IX	Fuel Cells Systems for Stationary Applications
Annex X	Fuel Cells Systems for Transport Applications.

[5] At the PSI a 60W Electrochem stack has been adapted to work with their membrane, replacing the Nafion 117 of the original design with a remarkable increase in current density (from 0.3 to 0.7 A/cm2).
[6] Autothermal reformers are treated in Ch.5.
[7] Web page http:\\www.eren.doe.gov/hydrogen/hydrprod.htm. Padro, C.E.G.: "The hydrogen program of U.S."
[8] Note fom K. Kordesch:"Fuel Cells and their applications". VCH Ed. 1996, page 356.
[9] Ballard Annual Report 1996.
[10] See: IEA Advanced Fuel Cells Annual Reports, 1995 and 1996.

2.2.5 - Japan

The Japanese government, aware of country's energy dependance, has been actively working to reduce hydrocarbon consumption by long-term initiatives. Through the Moonlight Project, started in 1981, government support was provided for the development of energy efficient conversion systems, including Alkaline and Phosphoric Acid FC. Since 1992, under the Sunshine Project, Japan is providing support for the development and commercialisation of renewable energy sources, e.g. solar, wind and geothermal. Co-ordinated by the New Energy and Industrial Technology Development Organisation (NEDO), research for high-efficiency technology switched to Molten Carbonate, Solid Oxide and Proton Exchange Membrane FC. Under these initiatives the government has made a sound effort to create synergies with the gas industry and electric power utilities. The World Energy Network program (WE-NET) of Japan[11] considers energy security and sustainability with an all-round perspective, by implementation of a worldwide energy network for effective supply, transportation and utilisation of renewable energy, using hydrogen as clean, secondary energy vector. WE-NET extends over 28 years from 1993 to 2020.

2.3 - Some active companies in PEM fuel cell technology

2.3.1 - Arthur D. Little

Arthur D. Little is an American consulting company adressing future energy markets, providing reports for the World Bank and the US Departement of Energy in early 90's. A.D. Little is now technically contributing to PEMFC technology, with projects on ethanol[12] and hydrocarbon reformers for mobile applications, through development of a fuel-flexible processing system for on-board hydrogen generation, to fuel a PEMFC. The possibility of converting gasoline into hydrogen would allow a " no-infrastructure-change " market penetration strategy to fit the FC vehicle to the existing refilling network. Estimates of costs of A.D. Little technology are 16-26 $/kWel for the 50 kWel autothermal reformer in high production volume (10,000 units/yr.). Besides the reformer, the system will include a fuel purification reactor to selectively oxidize the CO contained in the reformate gas from the reformer (PROX) whose catalyst is likely to cost < 100 $ for a 50 kWel unit[13].

2.3.2 - Ballard Power Systems

Ballard, the world leader in development and production of PEM fuel cell technology, was founded in 1979 by Dr. G.E.H. Ballard in Vancouver, British Columbia, Canada, to conduct research on lithium batteries. In 1983, Ballard began developing PEMFC through contracts with the Canadian government, to improve for military applications, the performance of the General Electric PEMFC - air instead of oxygen as oxidant and graphite to replace the expensive niobium plates. In 1989, it changed its name to Ballard Power Systems, which is the parent company of the Ballard Group

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[11] M. Chiba, H. Arai, K. Fukuda, : " Hydrogen Energy Technology Development in Japan : New Sunshine Program ". Proc. XI HEC 1996.

[12] G. Block and W. Mitchell : " Evaluation of Hydrated Ethanol in an Advanced Fuel Processor for Fuel Cell Vehicles ", SAE Technical paper 971646.

[13] For more information on AD Little concept see European Fuel Cell News volume 4, March 1997. Cost estimates are taken from W.L. Mitchell et al. : " Development of fuel processors for transportation and stationary fuel cell systems ", November 20 1996 Fuel Cell Seminar and W.L. Mitchell et al. : " Development of multi-fuel hybrid partial oxidation fuel processors for fuel cell vehicles and hydrogen re-fueling stations ", 30th Annual ISATA Conference, Florence, Italy, June 16-19 1997.

including Ballard Advanced Materials Corporation and Ballard Battery Systems Corporation. The first developed a propietary, low-cost electrolyte membrane, the second was sold in 1995.[14]

Both the federal and the provincial Canadian government have played a main role in financing the development of Ballard FC technology, together with venture capital financing. Ballard has a defined strategy for market penetration, in three phases, which include heavy vehicle, stationary power and Zero Emission cars.[15] The company is preparing for mass production of PEFC systems for heavy-duty vehicles at the turn of the century.

In 1995 Ballard Power Systems has ended co-operation for the membranes with Dow Chemicals and are now employing their own. The company has an exclusive agreement with Johnson Matthey (UK) for the production of platinum-coated graphite electrodes, but industrial sources indicate that JM might start soon selling the electrodes to other purchasers.[16]

Ballard Power Systems has created Ballard Generation Systems in December 1996 for stationary systems. This company has licencees in America (GPU International) and Europe (AEG and GEC-Alsthom) for the commercialisation of their products. The transportation market is also very active: besides the major car manufaturers, it will deliver three buses to the Chicago Transit Authority and British Columbia Transit of Vancouver. A special mention needs to be made about cars : Daimler-Benz has provided 300 million US$ funding for a joint company which will design, produce and commercialise FC powertrains for buses, trucks and automobiles, with methanol as fuel. This might be the final, long-awaited step to commercialisation. The 250kWel power plant prototype fuelled by natural gas started operation in August 1997.

2.3.3 - De Nora

The Oronzio De Nora group is an electrochemical industrial company based in Milan. The core activity has been the development of industrial electrolysers : mercury technology and more recently membrane-electrolysers for the chlorine-alkali industry. In 1990 De Nora constructed a 1 kW PEFC stack, which is still working on discontinuous tests, with proprietary technology, based on metallic hardware and carbon gas diffusion electrodes.

In 1995 De Nora bought E-Tek, an American company producing ELAT™, a carbon-based electrode for PEMFC, in order to integrate the stack components. De Nora FC have often Du Pont membranes.

De Nora has major commitments in the frame of Euro-Quebec Hydro Hydrogen Project for the realisation of the stack for the fuel cell bus. This project was led with the participation of Ansaldo Ricerche for the fuel cell system. Other De Nora customers are TNO (NL), Ecole des Mines (F), DLR (D), ENEA (I) and Renault for the FEVER car project of the European Union Task Force " Car of Tomorrow ". In most of their projects DeNora is a supplier and not a partner for reasons of confidentiality.

[14] The Ballard membrane is based upon a trifluorostyrene polymer, less fluorinated than commercial electrolytes. Ref in K. Prater : " SPFC for transport and stationary applications ", Journal of Power Sources 61, 1996.
[15] Http ://www.env.gov.bc.ca.dpa/ar/eeiampaw.html#1.5 " Estimated Economic Impacts and Market Potentials Associated with the Development and Production od Fuel Cells in British Columbia ". By KPGM March 1996.
[16] R. Evans, Johnson Matthey, Precious Metals, Catalysts and Materials, personal communication.

The Italian company has developed a low-cost metallic bipolar plate derived from membrane electrolysis experience[17] which matches the cost targets of the European FC project and it appears suited for mass production.

2.3.4 - International Fuel Cells

IFC has produced over 70 phosphoric acid power plants, employing the proprietary ONSI PC25™ 200 kW unit - 40% electric efficiency - and is the only company actively commercialising a fuel cell system[18]. IFC has developed an advanced production process able to produce nearly 100 units per year. In PEM technology IFC holds a patent, since 1980, covering bipolar plates made of moulded graphite-fluoropolymer composite, which simplify the stack functioning by a wicking action[19]. IFC delivered a 50 kW PEM hydrogen-fed power plant operating at ambient air pressure and it is working on a 50 kW multi-fuel PEM for FCV.

2.3.5 - Mitsubishi

Mitsubishi Heavy Industries announced in 1994 the development of a 5 kW PEM fuel cell system incorporating a natural gas reformer. This project was jointly pursued with Tokyo Gas. MHI has also developed a 15 kW stack. Eventhough in the past MHI reported that fuel cell technologies and activities are not a high priority, probably based upon their mandate to develop pressuried, fluidized-bed coal burners, for the Asian market, the company has developpped a novel compact methanol reformer for a 10 kW stack.

2.3.6 - Sanyo[20]

Sanyo, involved with FC since 1960 with methanol-air and hydrazine-air prototypes, actually develops SOFC, PAFC, PEMFC and MCFC technologies. The company has developed and commercialized a 250 W portable PAFC unit of 25 kg, which uses pure hydrogen stored in a metal hydride as fuel with one hour autonomy.

In PEMFC development the effect of platinum catalyst loading and liquid electrolyte content was studied. During 4000 hours test a 1%/1000 h voltage degradation rate was considered satisfactory ; two stacks of 500 W and 1 kW worked at 0.5 A/cm2 and 0.6 V(3 atm).

Sanyo has built a 1 kW planar SOFC under contract with NEDO in the New Sunshine project. This module has 160x30 cell with a power density of 0.22 W/cm2 ; the endurance was tested for more than 1800 h and decay rate was 4.4%/1000 h. Concerning MCFC, Sanyo was testing a 30 kW internal reforming system for petroleum-fueled co-generation applications including a Ru-ZrO2 catalyst for LPG.

2.3.7 - Siemens

Around 1984, Siemens licenced PEM fuel cell technology from General Electric. Since that time, Siemens has been actively involved in this area by developing air independent (*i.e.* with pure oxygen) PEMFC systems. Siemens developed PEMFC systems for electric submarines - 212 class - for the German Navy. A 300 kW PEM system was recently delivered to Howaldtstwerke-Deutsche Werf shipyards in Kiel, Germany. This system, once re-engineered, could then be useful for buses.

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[17] See U.S. Patent No. 4,340,452

[18] See CLC-Ansaldo: "Papers presented at congress and seminars in 1995".

[19] A.J. Lawrence, U.S. Patent No. 4 214 969 (July 29, 1980)

[20] Y. Mikaye et al. : " Status of fuel cells R&D activities at Sanyo ", Journal of Power Sources 61 (1996).

Most of Siemens patents and applications relate to high temperature fuel cells systems and subsystems[21], although recently an internally-humidified H2/air 10kW PEM fuel cell system for a fork lift truck has been introduced for Solar-Wasserstoff-Bayern. One important partner is the Hoechst group. In the frame of European project BRITE, Siemens has developed a technique for compact low-cost membrane-electrode-assemblies[22] (MEA) with corrugated metallic bipolar plates; moreover, the group has presented a commercialisation strategy for FC to begin in 1998-2000. The FC stacks work at 1.5 bar (abs. pressure) and have a power density of 350 mW/cm2 at 0.75 V ; cost target are 200 DM/kW for the whole system assuming 100.000 pieces per year[23].

2.4 - Stationary applications

The electricity generation industry is mainly interested in overall system efficiency and lifetime although in the last years emissions abatement became a major concern as well. FC systems generating hydrogen from fossil fuels - as the ONSI 200kW PAFC - are noiseless and have practically no air polluting emissions (particulate, NO_X , SO_2). The greenhouse gases (CH4, CO2) emitted, determined by the overall system efficiency (40%), place the FC system above small gas turbines (< MW units). On the other hand, the comparison with engines is less favourable, since diesel and gas unit have electrical efficiencies of 44% and 39% respectively. Saying this, FC systems do have comparative advantages : they are noise and air pollution-free without clean-up devices, which reduces operation & maintenance costs, while the absence of moving parts increases the lifetime to about 40.000 hrs. These features allow FC to be user-sited even in densely-populated areas, thus avoiding T&D lines cost and (increasingly important!) visual impact.

This section offers a brief review of recent mobile and stationary applications for FC systems by the type of FC technology[24].

2.4.1 - PAFC

The phosphoric acid fuel cell technology was developed in the 70's by ONSI, a company of International Fuel Cells (IFC), division of United Technology, and Fuji. Industrial production started in 1990. In most commercial PAFC systems natural gas is used as fuel.

In the commercial PC25TM, the methane stream undergoes a steam reforming process to get a hydrogen-rich gas - previously having cleaned up the sulfur content by a zinc sacrificial reagent[25]. Fuji completed, in 1989 a 11 MW PAFC power plant in Goi, Japan. After this experimental unit the company did not intend to start commercial production, maybe because of the performance degradation of the stack. IFC has become world leader of this technology with the PC25TM model (200kWel), commercial since 1992. In Europe the licensee is Celle a Combustibile (CLC), a jointly-held company of Ansaldo-Finmeccanica and ONSI (see section 2.3.4).

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[21] Siemens is also actively involved in SOFC development (tubular technology from Westinghouse) and in the Direct Methanol FC (DMFC), which are catalyst-adapted PEMFC, but DMFC will not be fully discussed in this paper since research is still at a basic stage and current density, as far as we know has not gone further than 200 mA/cm3.

[22] MEA's are detailed in chapter 3.

[23] E. Grecksch et al. : " PEM Fuel Cells : Development and Commercialisation ", paper presented at Intertech Conference : " Commercialising FC vehicles ", Sep.17-19, 1996, Chicago.

[24] See also S. Penner and al. : " Fuel Cell commercialisation ", Pergamon University Press 1995.

[25] This unit is the hydrodesulphurator, the reaction is ZnO2 + H2S (ZnS + H2O. Reformer reaction is CH4 + H2O (3H2 + CO.

Investment costs are around 3000 \$/kW, but the American Department of Energy (DOE) has set a grant - 1000 US\$/kW for the first 25 units sold - in 1996. The stack costs 750 \$/kW. Industry reports affirm that major niche market exist for PAFC to be competitive with conventional power plants in oil refining and clorine-alkali industry, where high quality by-product hydrogen can be used almost for free[26]. In the first half of 1995 a 1.3 MW PAFC plant was completed for AEM, the electric utility of Milan, by Ansaldo, using European components for gas reforming and electric inverter. The PAFC technology has reached a maturity of more than 500.000 cumulated hours, in real-environment grid-connected units, which confirmed high reliability and efficiency, although a small, constant degradation of the stack performance (0.5%/y), due to catalyst poisoning, is observed. In Switzerland it is estimated that 10% of the electricity could be produced by FC for premium power or with by-product hydrogen from the chemical industry. A PC 25 is on field testing at Services Industriels de Genève, with a cost of electricity between 10/15 Sct./kWh (0.06/0.09 \$/kWh)[27].

2.4.1.1 - An Italian Paradox : The Assemini Project.

In the industrial area of Assemini, Sardinia, Enichem, of the ENI Group - major world petrochemical company - has a chlorine-alkali industry, producing, with De Nora membrane electrolysers, soda and chlorine, with pure hydrogen, as a by-product. Estimations made by CLC-Ansaldo have found that with the flow of hydrogen it is possible to generate 9/10 MWel by employing 10x900 kW d.c. hydrogen modules at 50% electrical efficiency - since no reformer would be required. This is a perfect example of " niche " for FC : hydrogen in Assemini is burnt at present and fuel cells could be sold at marginal cost. However, payback time (6 years) due to "political " electricity costs (\$0.03/kWh) for the 50 MW of the electrolysis, plus the subventions for coal mines in the close Sulcis region - where an all-purpose IGCC plant will be constructed - have won out so far. Moreover, industrial sources indicate that hydrogen might be sold to the close Sarroch refinery for petroleum cracking. Enichem is a major chemical group and Ansaldo a power plants supplier and a FC developer and licencee, through CLC : it is sometimes sad not to see some evident synergies at national level coming about faster.

2.4.2 - Molten Carbonate Fuel Cell

In high temperature systems the shortcomings of gas purity can be avoided since elevated temperatures accelerate the chemical processes, avoiding the need of a noble metal catalyst as platinum. There are two types of MCFC: the external reforming and the internal reforming. In the first, more conventional MCFC, the fuel is desulphurised and undergoes a reforming process before being fed to the anode. The internal reforming, also called direct fuel cell (DFC) simplifies the procedure thanks to a reforming catalyst in the anode chamber of the cell. The electrochemical reactions occuring in MCFC are[28] :

$$H_2 + CO_3^{--} \Rightarrow H_2O + CO_2 + 2e^- \quad \text{(anode)}$$

$$1/2\, O_2 + CO_2 + 2e^- \Rightarrow CO_3^{--} \quad \text{(cathode)}$$

[26] See C.R. Bentley (ERC): "Vendor development for commercialisation of fuel cells" EFC News, december 1996, special issue and B.R. Gilbert, M.Nawaz and T.P.Chen (Bechtel): "Fuel cells make their chemical process industry moves". Chemical Engineering, August 1995.
[27] See : D. Lan Nguyen : " GAZEL - SIG, Pile à Combustible au Gaz Naturel ", OFEN Annual Report 1996.
[28] From : " Fuel Cells - A Handbook ", (Revision 3) by J.H. Hirshenofer, D.B. Stauffer and R.R. Engleman. U.S. Department of Energy, Office of Fossil Energy, Mogantown Energy Technology Center, January 1994, p.4-1.

The overall reaction is:

$$H2 + 1/2\ O2 + CO2 \Rightarrow H2O + CO2$$

In some way, the MCFC technology goes beyond PAFC limitations and it involves similar commercial interests : fuel distributors and electricity producers. In addressing the competitive environment of energy production the research has been oriented towards a fuel cell which can directly convert conventional fuels, as methanol, gasoline, natural gas and ethanol. The MC technology simplifies the gas purification process, reduces electrode degradation and raises temperature for a topping cycle with a turbine. In the MCFC systems the high temperature (650°C) allows the direct processing of the fossil fuel into hydrogen for conversion into electricity. Nevertheless, CO_2 is required by the electrolyte in the process, which requires the fuel processor to be closely matched with the FC stack, thus necessitating dedicated reformer engineering for each size of the system. Applications are expected to get economies of scale and standardisation advantages in the range of few MW. One of the MCFC problems is that the power density of the cell is almost saturated, offering little perspectives of volume inprovements in the future. MCFC are direct concurrent to PAFC technology, which has low tolerance for CO and still suffers of quite high investment costs (also due to the precious metal catalyst).

2.4.2.1 - The MCFC proof : The Santa Clara Demonstration Project (SCDP)[29]

The 2.1 MW power plant construction started in April 1994 with the participation of the Fuel Cell Commercialisation Group (FCCG), a consortium of municipal, rural and investor-owned utilities in U.S. and Canada. The SCDP start-up activities began in March 1996, electricity generation began in April, but the plant had to be stopped in September because of insulation problems which affected 2 stacks. This was due to the high temperature of the fuel cell.

The MCFC is at the edge of commercialisation, since all the stack and BOP components are commercial, although series production has not started. The current weaknesses (which may increase operation & maintenance [O&M] costs in early commercialisation) are :

- Hardware corrosion by the electrolyte at high temperature (lifetime is expected to be 25.000 hours, eventually improved to 40.000).

- Dissolution of the nickel oxide cathode in the electrolyte creates a precipitate which causes short circuits in the system.

2.4.3 - Solid Oxide Fuel Cell

The solid oxide fuel cell (SOFC) technology is the one at the earliest stage of development, although its origins go back at the beginning of electrochemistry history. At the earlier days of electrochemistry research on conductivity was directed to try to replace the carbon filament, then used in the light bulb. Nernst realised a high performance Zirconia light source around 1893[30]. Because of its high operating temperature (1000°C), recent studies have considered lower temperatures for SOFC (600°C) and mobile applications feasibility, although the slow start-up is a major problem. The main advantage consists in the ability to oxidise the CO produced in the natural gas reforming.

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[29] See: European Fuel Cell Group 1996 Autumn Workshop: "MCFC needs" by Peterhans, S. and Santa Clara Demonstration Project web page: http://www.ttcorp.com/fccg/scdpnew1.htm.

[30] An interesting, detailed brochure is published by H. Möbius, : " On the History of Solid Oxide Fuel Cells.", J. of Solid State Electrochemistry 1 (1997).

There are three main configuration for a SOFC stack :

- The Tubular developped by Westinghouse, now licenced to Siemens (pre-commercial stage)
- The Planar conception of Sulzer Hexis^{TM} (pre-commercial)
- The Monolithic " Honeycomb " structure of Argonne National Laboratories (laboratory stage)

Overall expected efficiency of a MW-size SOFC power plant is up to 70%, though smaller systems without cogeneration would seldom exceed 40% efficiency. SOFC have problems of power stability when the FC is under load, but the multi-fuel possibilities, combined with the high grade heat for CHP make SOFC the ideal candidate for small scale units to shape a distributed power generation system in the future, if materials reliability is satisfactory.

2.4.4 - PEMFC

Ballard Power Systems is testing natural gas and methanol PEMFC stationary sytems and it has planned to start pre-commercial production of its 250 kW unit in 1998. The prototype started operation, grid-connected in August[31]. At present, European agents of Ballard products, AEG and GEC-Alsthom hope to install 250 kW units for electric utilities in Europe. These FC systems are designed to run on natural gas, but the fuel can be methanol or - of course - hydrogen. The system features a steam reformer, a water/gas shift and a more innovative selective oxidation unit, which is believed to include a precious metal catalyst[32]. Unfortunately, no operating data are available and cost is not fully disclosed yet, but it could be around 3 million US$ for pre-commercial units. The aimed strategy is to start full commercialisation after one year of tests in real condtions.

De Nora is at an earlier stage of development in stationary systems, its " new design " 30 kW-stack, is planned for 1998 ; such unit can be scaled to 50kW. The Italian company intends to start joint projects with utilities and it has active research on a CO purifier and on a CO-tolerant catalyst[33].

2.5 - Mobile Applications

As it is clearly explained by a car manufacturer expert, different domains and sciences are taken into consideration for mobile FC systems:

" When a FC is used to propel a vehicle it shares several attributes with battery-powered vehicles (low or even zero-tailpipe emissions, low noise, modularity and reasonable shape flexibility, perhaps similar manufacturing processes, need for electric drivetrain, etc.) while its fuel/air intake and exaust pipes, the available waste heat for cabin warming, and the relatively high energy density/low cost/rapid refuelling of fuel storage system evoke comparison with conventional [ICE] vehicles and may help to overcome the main obstacles of batteries ".[34]

A special attention in the field of mobile FC systems has to be given to the all-round storage/stack optimisation[35]. If efficiency and lifetime are parameters to be relaxed - for a mobile FC system

[31] Ballard Press release, September 1997.
[32] Selective oxidation, synonimous of Preferential oxidation, is treated in Ch. 5 - Hydrogen purification.
[33] See : C. Mantegazza, A. Maggiore : " PEMFC Activities at De Nora ", Proc. XI HEC, Stuttgart, October 1996.
[34] C.E. Borroni-Bird, Chrysler Corporation : " Fuel Cell commercialisation issues for light-duty applications ". J. of Power Sources 61 (1996) p 34.
[35] D. Schmal, and P.J. Van Duin, : " A method for the calculation of the minimum Fuel Cell system volume ". Proc XI Electric Vehicle Symposium Florence Italy. Vol. 2 pp. 1-9.

lifetimes of 5000 hours are acceptable - the cost of the FC powertrain has to compete with car engines.

2.5.1 - PEMFC

The economic and technical targets of mobile systems can only be fulfilled by the PEM technology; these are an investment cost of approx. 30$/kW (stack) and power density of 0.4kW/kg[36].

Recently, research has shifted from the stack power density to the fuel system definition and integration. The present goal of PEMFC industry is to create the conditions - e.g. system assessment, infrastructure, public acceptance - and set mass-manufacturing equipment to compete with conventional vehicles.

Besides the aspects of volume, weight and vehicle range, weight distribution, transient response and security in accident or fault situations are of major relevance for customer acceptance.

2.5.1.1 - Exemples of Fuel Cell Vehicles (FCV)

- Arthur D. Little is developing a gasoline reformer for a FC vehicle, the system featuring on-board partial oxidiser (POX), water-gas shift, and a preferential oxidizer (PROX) for fine-cleaning of hydrogen[37]. The gasoline reformer is jointly developed by A.D. Little with Chrysler ; the concept had an official presentation at the Detroit Motor Show in January 1997[38].

- Ballard has realised a pre-commercial 300 kW Bus and has developped the 60 kW Necar II with Daimler-Benz which is the state-of-the-art in FC vehicles for system weight, dimension and performances of speed and autonomy. The costs have been huge and only hydrogen is used, although the foreseen extra investment cost (compared to a diesel bus) for a FC bus - to come in 1998 - is expected to be 30 %.

- Daimler Benz is the first car manufacturer involved in FCV. The German company has unveiled the Necar III at the 57th International Motor Show, September 11-12, 1997 in Frankfurt. This FCV is " a long-awaited fuel cell version of Mercedes brand-new subcompact A-class model "[39] powered by a 50kW Ballard FC system featuring an on-board methanol reformer.

- De Nora is very active in the Joule and Brite European Programs by close co-operation with Ansaldo. The Italian company has supplied *standard* design FC stacks for the Euro Quebec Hydro-Hydrogen Pilot Project (EQHHPP) bus and it is co-operating with Renault, Volvo, Ansaldo Ricerche, Ecole des Mines and Air Liquide in the Fuel Cell Electric Vehicle for Efficiency and Range (FEVER) project. FEVER features 3x10kW improved design PEMFC to power in-wheel motors in a Laguna station wagon with 120 lt. (8 kg) liquid hydrogen tank and nickel-hydride for energy buffer and start up. The Hydro-Gen boat project, led by Ansaldo Ricerche (FC system, DC/AC converter), includes a 30 kW De Nora advanced design stack for the power generation[40] and liquid hydrogen system by Messer Griesheim.

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[36] These are the targets of the U.S. program Partnership for a New Generation of Vehicle (PNGV) in ref 35 above page 36.
[37] The CO clean-up - the most strategic research issue for FC system introduction - is discussed in Ch. 5.
[38] See web page : http ://www.arthurdlittle.com/tpd/fuel.htlm
[39] The Hydrogen & FC Letter, October 1997. Edited by Peter Hoffmann. Http ://www.mhw.net/~ hfcletter/.
[40] M. Tettamanti, A. Maggiore, : " De Nora informative brochure ", Milan, 1996.

- Siemens[41] has contracts with Solar-Wasserstoff-Bayern GmbH for a 10 kW fork-lift truck in the frame of the Bavarian government project for solar hydrogen technology development, in association with Bayernwerk AG, Linde and BMW. Hydrogen in the truck is stored in Metal Hydrides (MH).

- Toyota presented a hybrid RAV 4L FCV Jeep at the Tokyo Motor Show in October 1996, marking a record in metal hydride hydrogen storage[42]. The vehicle is powered by a 25 kW proprietary PEMFC stack with a nickel-hydride battery buffer for peak load and start up. Toyota has also unveiled a new version of the RAV 4L at the 1997 Frankfurt motor show : on-board methanol steam reformer, 500 km range and regenerative braking.[43]

It has to be noted that hydrogen is not a commercial fuel and suffers low energy density in its gaseous form (besides safety concerns). Liquid hydrogen sponsors include BMW which has proposed the concept of a " 1000 km FC car "[44], but the fuel cycle efficiency is heavily affected by the energy requirements for cryogenic storage (30 % of initial energy), and engineering costs are still prohibitive. It is so unlikely that in early commercialisation FC systems will use pure hydrogen as fuel except in the case of metal hydride storage, intensively pursued in Japan.

At present the crucial issue for viable mobile FC systems is the development of a compact unit generating CO-free hydrogen from a more friendly, *i.e.* liquid, fuel.

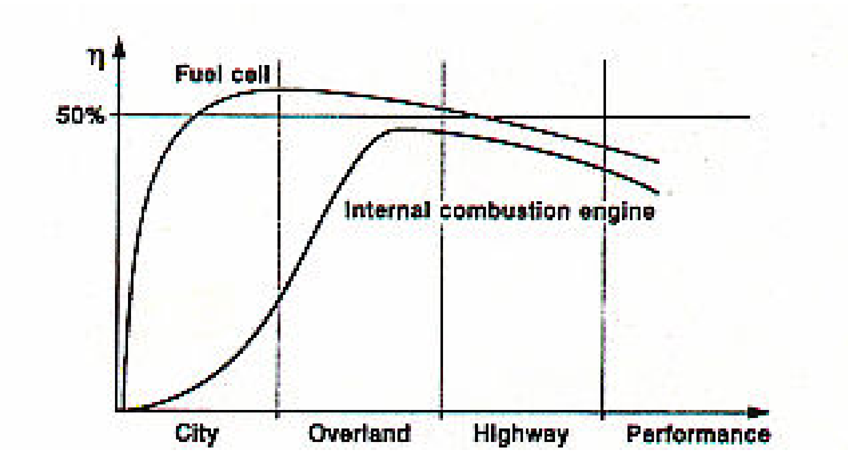
2.5.2 - Automaker interest in PEMFC

The Polymer Electrolyte technology has the best chances to reach both major performance targets and cost reductions (100/200 $/kW), some of the reasons being :

High Power density	up to 1 kW/lt.
Low temperature operation	70-90° C
Low cost materials	polymers, aluminium
Fast start up for intermittent operation	seconds.

Drive cycles studies[45] have shown that in light-load conditions and/or in an urban environment - the most common - FC have a net efficiency advantage compared to spark-ignition engines : 50% and 10% respectively. The FCV performances on the highway cycle are slighly above an ICE .

[41] W. Strobl : " Hydrogen as a road fuel for the future ; conditions and prerequisites " Proc. XI HEC, Stuttgart, 1996.
[42] See 4.3.1 for details on storage.
[43] More can be found in Hydrogen & Fuel Cell Letter, October 1997.
[44] J. Tachtler, C. Bourne : " Fuel Cell Systems for Passenger Cars - Opportunities and Requirements ". Fuel Cell Seminar, 1996, Orlando.
[45] Ref 35, page 34.



Graph. 2.1 - Efficiency of FC vs. ICE (Ref.35)

In the Graph 2.1 it should be noted that the comparison is between two different types of systems :

- An on-board FC system, where a FC produces electricity for a later conversion, via electric motors, to drive the wheels. If hydrogen it is stored into hydrides or produced in a reformer, then this system might include batteries for load variation.

- A non hybrid conventional systems with an internal combustion engine driving directly the wheels, the efficiency of the engine being particularly high.

A more rational comparison should be carried out between FC vehicular systems and hybrid internal combustion engine systems, which start to appear on the market. However this analysis goes beyond the scope of this report.

NOTE : Concepts for SOFC are being developped, by Dr U. Bossel and K. Yamada, because of the simpler fuel processor in a SOFC system (pre-reformer only). Nevertheless, the announced 2 minutes start up of a low temperature SOFC has yet to be demonstrated in real conditions[46].

2.6 - Conclusions

The FC technlogy is characterised by strong competition and interdisciplinarity, both where the power generation market and the vehicle industry are concerned. The FC system depends on the type of stack used, because balance of plant (BOP), or more precisely, engineering of the fuel processing, is very different.

It owns notice that higher temperatures allow a progressive " internalisation " of fuel reforming : in the low temperature FC all fuel processing is external. In PAFC there is some tolerance for CO up to some hundreds (2) ppm, avoiding the need for a fine purification step. In the case of MCFC the water/gas shift is eliminated, whilst in the case of SOFC the only gas processing is the pre-reforming of raw fuel.

Current trends in research find mobile applications of PEMFC as the most interesting, because PEMFC shock resistance, low temperature and impressive power density make them a credible solution to conciliate environment and mobility.

[46] See Ulf G. Bossel : " SOFC in Transportation " EFC news December 1996.

Storage safety is considered as a major barrier for commercialisation of hydrogen-fuelled FC. Nevertheless, the promising improvements of hydrides storage, like the carbon nanotubes, offer chances of greater safety - and favorable cost projections, to compete with gasoline, provided customers do not need a vehicle range of more than 250 km.

The technical competition is therefore between hydrogen fuel with its storage and infrastructure problems, and the validation of concepts of preparing hydrogen on-board the vehicle, using logistic fuels.