Emerging Partnerships for the Development of Fuel Cell Transport

By
Kanehira Maruo
Section of Science and Technology Studies
University of Gothenburg, Box 700, SE 405 30 Gothenburg, Sweden
Tel +46 31 773 4924, Fax +46 31 773 4933,
E-mail: kanehira.maruo@ctv.gu.se

and
Ben Lane
Energy and Environment Research Unit, Faculty of Technology
The Open University, Walton Hall, Milton Keynes, MK7 6AA, Great Britain
Tel +44 1908 653970, Fax +44 1908 654052, E-mail: bml5@tutor.open.ac.uk

Introduction - the coming era of fuel cell vehicle technology

In the field of automotive technology today, it seems like something significant is happening. During the recent years, from such innovative technologies have been presented as direct-injection gasoline engines, new direct-injection 'common-rail' diesel engines, the so-called zero level emission gasoline engines, electric vehicles with advanced batteries, hybrid vehicles, fuel-cell vehicles and so on, and several of them are already on the market. The first three engines may be regarded as results of incremental improvement of the existing internal-combustion engines, and the last three as radical alternatives which are based on advanced electric vehicle technologies. Among them, fuel-cell vehicles are emerging today as the most promising technology to substitute the internal combustion engine.

Almost all (or at least 14) of the world's large automobile manufactures are making significant investments in the development of fuel cells for road transport applications. Daimler-Benz, Ford, GM, Opel, Toyota, Honda, Nissan, Mazda and others have intensive research programs which aim to bring fuel cell vehicles to the marketplace. However, many technical, economical and political obstacles remain in the drive to produce a fuel cell vehicle. First, there is no general consensus about the precise fuel cell technology which is most suited to road transport. Second, there is no general consensus about which fuel should be used. Third, the problem of a non-existent fuel distribution infrastructure has yet to be addressed. And fourth, very few companies have the necessary expertise to fully develop a fuel cell vehicle in-house. As a result, some companies are choosing to co-operate with others to pool their research and development programs. Collaborating companies will provide complimentary knowledge, skills, and resources to the development process.

Most notably, Daimler-Benz (Germany) are in partnership with Ballard Power Systems (Canada) who are world leaders in fuel cell technology. This co-operation has already led to the Daimler-Benz Necar 3 fuel cell car and the Nebus fuel cell bus which are working prototype vehicles. The experience has been so positive for the companies involved that there is now a commitment to commercialize these vehicles by the year 2004. In the end of 1997, these two partners have been joined by a third member; the Ford Motor Company. These three players in partnership form a formidable alliance in the development of fuel cells for transport.

This paper will detail the precise nature of the co-operative strategies employed by the Daimler-Benz/Ballard/Ford partnership. It will highlight the complimentary skills and know-how offered by each company and identify the key strengths in the alliance. Also, the research will compare this collaborative approach with the experience of Toyota and General Motors/Opel which are conducting research and development mainly in-house and of ZEVCO which is a small UK company set up with the specific task of bringing a fuel cell taxi to market reality. The paper will try and predict which styles of fuel cell vehicle development will most likely lead to a successful outcome and which strategy will result in the dominance of the future market of fuel cell vehicles.

Fuel Cells - technical descriptions

Why fuel cells?

Why are so many auto manufacturers investing in fuel cell technologies? Daniel Sperling, director of the Institute of Transportation Research at University of California, Davis, wrote only four years ago:

> Fuel cell vehicles seem almost too good to be true.[1]

Many experts had at that time regarded fuel cells as bulky and expensive devices maybe feasible for buses but not for passenger cars. Today, the situation is totally changed. Within 6 or 7 years' time the first series-produced fuel cell cars may be rolling on the roads in Germany, Japan, and North America. There already is a strong feeling of a severe competition between some of the largest auto manufacturers in the world. In January 1998, GM unveiled an advanced model of a fuel cell drivetrain, and officials stated the company's intent to have a "production ready" fuel cell vehicle by 2004. In March 1998, Opel, GM's German subsidiary, presented a methanol fuel cell-powered Sintra van. Opel declared that GM/Opel would commercialize the fuel cell vehicles in 2004, which is the same year mentioned many times by several Daimler-Benz executives when the company would begin to market its fuel cell powered vehicles. Dr. Ferdinand Panik said in September 1997 in London that:

> Whoever becomes the first to cross the finishing line in this particular race, that is to say, whoever produces the first marketable vehicle, will be able to determine the rules of the game. For this reason Daimler-Benz has a strong commitment in this field ... Daimler-Benz would like to be the first to offer a fuel cell powered mass-produced vehicle in the marketplace.[2]

Even Toyota wants to be the first with fuel cell-powered electric cars. Toyota's President Hiroshi Okuda recently said:

> Our engineers have a strong feeling that we will be first to market.[3]

In fact, Okuda had wanted to say 2003, but Toyota's engineers stopped him. Instead, it was Honda's president who declared in July 1998 that Honda would become the first one in 2003.[4] Nissan unveiled a prototype fuel cell-powered, hybrid-electric vehicle in September 1998, and said it planned to start selling fuel-cell vehicles by 2003-2005.[5]

All these activities and declarations may of course be 'shadow boxing' before the environmentally oriented public. Still, those auto makers and fuel cell makers, together with governments, gas, oil and methanol industries, are investing billions of dollars in fuel cells. There is thus every reason to follow this environmental/technological competition for the implementation of fuel cell powered vehicles.

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[1] Sperling, Daniel, 1995, *Future Drive — Electric Vehicles and Sustainable Transportation,* Washington, D.C.• Covelo, California.

[2] Panik, Ferdinand, 'Fuel cells for vehicle applications in cars - bringing the future closer' in J*ournal of Power Sources* 71 (1998), p. 36-38.

[3] Kalhammer, Fritz R., Prokopius, Paul R., Roan & Vernon P., Voecks Gerald E., 1998, *STATUS AND PROSPECTS OF FUEL CELLS AS AUTOMOBILE ENGINES — A REPORT OF THE FUEL CELL TECHNICAL ADVISORY PANEL*, Prepared For State of California Air Resources Board
Sacramento, California; *Automotive News Europe* 2 February 1998.

[4] *Fuel Cells 2000,* www.fuelcells.org/fuel/fct/goingon.shtml. last updated August 5, 1998.

[5] *Calstart News Note* 09/02/98.

What is a fuel cell?

A fuel cell reverses the process of electrolysis in which an electric current breaks down water into oxygen and hydrogen gas. In 1839, William Robert Grove discovered that hydrogen and oxygen could be recombined to produce water and electric current. This 'Solution looking for a problem'[6] technology began to be used first in the American space program in the 1960s. Gradually, it has found more and more application areas - from moon expeditions and space shuttles to submarines, tanks, stationary power plants, and in the recent years to buses and cars. Since the beginning of the 1990s several automobile manufacturers began, often with the initiative of the U.S. Department of Energy (DOE), to launch intensive R & D activities in the fuel cell. Fuel cells are regarded as very attractive by those automobile manufacturers, because they believe that:

- They are much more efficient than internal combustion engines. They can greatly reduce green house gas emissions from road vehicles.
- They are extremely clean. By using hydrogen-powered fuel cells or Direct Methanol Fuel Cells one can make zero emission vehicles.
- They have no moving parts, no vibrations, and no noise.
- They have no drawbacks that battery-powered vehicles have (e.g. short range, heavy weight, short-lived batteries, emissions from electric power plants, and some difficulties of warming the vehicle coupe).
- They are virtually maintenance free.
- They are suitable for a mass-production, and no expensive metals but platinum are used. Because the use of platinum is going to be minimised (will soon become the same amount of platinum per vehicle as in the three-way catalyst in an internal combustion engine's exhaust system), fuel cell engines can be as cheep as today's gasoline engines. According to Daimler-Benz, fuel cell engines would reach this price level at the production rate of 250,000 per year.[7]

Eight types of fuel cells

Eight different kinds of fuel cells are currently developed in the world. These are Phosphoric Acid Fuel Cells (PAFC), Proton Exchange Membrane Fuel Cells (PEMFC) or Solid Polymer Fuel Cells (SPFC) or Polymer Electrolyte Fuel Cells (PEFC), Molten Carbonate Fuel Cell (MCFC), Solid Oxide Fuel Cell (SOFC), Alkaline Fuel Cells (AFC), Direct Methanol Fuel Cells (DMFC), and Regenerative Fuel Cells. Brief descriptions of them are given below.

Phosphoric Acid (PAFC)
This is the most commercially developed type of fuel cell. It is already being used in such diverse applications as hospitals, nursing homes, hotels, office buildings, schools, utility power plants, and airport. Phosphoric acid fuel cells generate electricity at more than 40% efficiency — and nearly 85% if steam this fuel cell produces is used for cogeneration — compared to 30% for the most efficient internal combustion engine. Operating temperatures are rather high (150-175°C). These fuel cells also can be used in larger vehicles, such as buses and locomotives.

Proton Exchange Membrane Fuel cells (PEMFC)
These cells operate at a relatively low temperature (about 80°C), have high power density, can vary their output quickly to meet shifts in power demand, and are suited for applications, — such as in automobiles — where quick start-up is required.

Direct Methanol Fuel Cells (DMFC)

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[6] *AUTOMOTIVE ENVIRONMENT ANALYST* February 1997.
[7] *Calstart News Note* 09/02/98.

DMFCs are similar to the PEM cells in that they both use a polymer membrane as the electrolyte. However, in the DMFC, the anode catalyst itself draws the hydrogen from the liquid methanol, eliminating the need for a fuel reformer. Efficiencies of about 40% are expected with this type of fuel cell, which would typically operate at relatively low temperatures. Higher efficiencies are achieved at higher temperatures. DMFCs are going to be developed by the Jet Propulsion Laboratory (JPL) and the University of Southern California.

Molten Carbonate Fuel Cells (MCFC)
Molten carbonate fuel cells promise high fuel-to-electricity efficiencies and the ability to consume coal-based fuels. This cell operates at a high temperature (1,000°C). The first full-scale molten carbonate stacks have been tested in California in 1996.

Solid Oxide Fuel Cells (SOFC)
The solid oxide fuel cell could be used in big, high-power applications including industrial and large-scale central electricity generating stations. Some developers also see solid oxide use in motor vehicles. A 100-kilowatt test is being readied in Europe. Two small, 25-kilowatt units are already on line in Japan. A solid oxide system usually uses a hard ceramic material instead of a liquid electrolyte, allowing operating at very high temperatures (over 1,000°C). Power generating efficiencies could reach 60%.

Alkaline Fuel Cells (AFC)
Long used by NASA on space missions, these cells can achieve power generating efficiencies of up to 70 percent. They use alkaline potassium hydroxide as the electrolyte. Until recently, they were too costly for commercial applications, but several companies are examining ways to reduce costs and improve operating flexibility.

Regenerative Fuel Cells
Regenerative fuel cell makes it possible to create an almost closed system of power generation. Water is electrolysed into hydrogen and oxygen by a solar power. The hydrogen and oxygen are fed into the fuel cell which generates electricity, heat and water. The water is then recirculated back to the solar-powered electrolyser and the process begins again. These types of fuel cells are currently being researched by NASA and others world-wide.

Among those eight types of fuel cells PEMFC has been chosen by most of the large automobile manufacturers who are developing fuel cell vehicles. Some small manufacturers (ZEVCO and EAC) are making alkaline fuel cells. Direct methanol fuel cells may reach commercial maturity as early as 2008.[8]

How does a PEM fuel cell work?

As most of the world's large automobile manufacturers are investing in the PEMFC, only the function of the PEM type fuel cells is described bellow. A PEM fuel cell consists of two electrodes sandwiched around a polymer electrolyte membrane. Oxygen passes over one electrode and hydrogen over the other, generating electricity, water and heat. Hydrogen fuel is fed into the "anode" of the fuel cell. Oxygen (or air) enters the fuel cell through the cathode. Encouraged by a catalyst, the hydrogen atom splits into a proton and an electron, which take different paths to the cathode. The proton passes through the membrane, but electron cannot pass it. These electrons create a separate current that can be utilized before they return to the cathode, to be reunited with the hydrogen and oxygen in a molecule of water. A single fuel cell has a cell voltage of about 0.7 volts and can deliver 350 watts. To give a full-size fuel cell electric vehicle adequate acceleration and top speed, about 50-70 kW of peak power is needed. It means 150-200 cells must be stacked together. For automotive applications, such cell stacks need to be very compact, with a volume of

[8] American Methanol Institute, 1998, *The Promise of Methanol Fuel Cell Vehicles.*

no more than about 50 litters. One can picture to oneself a single fuel cell as big and thin (500 square cm in area and 0.5-0.7 cm thick) as a computer mouse pad, and a fuel cell stack of 50 kW consisting of 150 such mouse pads piled up upon each other and being 100 cm high. Such a stack weighs 50 kg. The single fuel cell consists of a 'membrane-electrode assembly' (MEA) and a (actually two x 1/2) 'flow field plate' (sometimes even called separator plate). The MEA is an anode-PEM electrolyte-cathode composite structure in which each layer is made as thin as possible without losing the mechanical integrity of the composite structure or the electrochemical activity of the two electrodes. Anode and cathode consist of a conducting catalyst support material (most often a porous form of carbon) which is mixed or impregnated with a platinum or platinum/Ruthenium catalyst and bonded to opposite sides of the membrane. The flow field plate contains channels cut in carbon or graphite on both sides of a gas-impervious layer which distribute hydrogen-containing fuel gas and air to the anode and cathode sides of the membrane, respectively. Flow field plates must be conducting and in electric contact with the electrodes to collect the current and transmit it between adjacent cells. The air stream channels also remove the water created as a by-product of the electrochemical process. The cell stack assembly is held together with tie rods that apply a compressive force on the stacked cells by means of end plates. These plates also provide connections for air and fuel gas flow to and from the stack, coolant circulation, and the electric power output of the stack. A state-of-art fuel cell stack of 50 kW containing 150 fuel cells consists thus of 150 MEAs, 149 flow field plates, and two end plates.

A fuel cell system which includes a "fuel reformer" can utilize the hydrogen from any hydrocarbon fuel - natural gas, coal gas, ethanol, methanol, ammoniac, and even gasoline and diesel gas. Fuel cell systems with reformers have more complicated and somewhat are less efficient and clean than hydrogen-fuelled fuel cells, but since the fuel cell relies on chemistry and not combustion, emissions from this type of system would still be much smaller than emissions from the cleanest fuel combustion processes.

How can a fuel cell engine be manufactured?

There are several resemblances between the fuel cell engine manufacturing and the computer manufacturing. The heart of a fuel cell engine is the MEA, and it corresponds to the Central Processing Unit (CPU) in a computer. An important raw material to MEA is polymer resin, and its role corresponds to silicon wafer's in the computer world. Precisely as in the silicon wafer business in which a Japanese, an American and a German firm totally dominate the world market, only a few manufacturers in the world (DuPont, Asahi Chemicals, Asahi Glass, and Dow Chemicals) are producing polymer resins and serving all fuel cell manufacturers. Furthermore, in processes to make MEAs such micro engineering technologies as screen printing and photo etching are used, in almost exactly the same ways as in manufacturing processes of integrated circuits. Another similarity between the computer business and the fuel cell business is that those auto manufacturers who want to make fuel cell vehicles are dependent on a few numbers of fuel cell manufacturers, precisely as most of the world's computer manufacturers are dependent on delivery of CPUs (processors) from Intel and AMD. There is, however, a difference between the two businesses. Almost all the MEA manufacturers also make whole fuel cell stacks (except 3M), while Intel is not making own computers (AMD makes own computers).

A MEA is an empty and lifeless device. It works only when hydrogen and oxygen (or air) are pumped into it. To keep the MEA working an adequate level of humidity must be kept. Two air pumps and a humidifier are thus needed.[9] And, of course, a fuel feeding system including a tank and manifolds is needed, too. In the cases of using other fuel than pure hydrogen, e.g., methanol and gasoline, a fuel reformer which extracts hydrogen from these fuels is needed. At this reforming process (steam reforming) some amount of carbon monoxide (CO) is generated. CO damages catalyst coating on the MEA. A CO reducing device must be attached to the system.

The electric current generated in a fuel cell stack must be utilized by one or several electric motors to drive a car. An electric power controller (a computer/power electronic device such as inverter, converter and peak-power tracer) is needed. The electric controller technology has been brought to the level of commercial readiness during the last few years as part of developing battery-powered electric vehicle technology and it does not provide any technical difficulties for today's large auto manufacturers.

The fuel cell vehicle technology is thus a hybrid technology which combines the electric vehicle technology (electric controller and electric motor), the steam-powered vehicle technology (quick starting steam reformer), and the internal combustion technology (fuel tank, manifolds and air pumps).

[9] Mazda claims that it has developed a system which does not need an extern humidifier (*ELECTRIC VEHICLE PROGRESS* 1/3 98).

Three fuel cell vehicle configurations

For the automobile application a fuel cell engine must be quick in start, have quick responses to ever changing driving speeds, and a robustness to endure severe driving conditions ranging from Greenland to Sahara. The engine and its assisting systems must be packaged so compactly that passengers and baggage can conveniently be accommodated in the car. An especially difficult problem is that the fuel cell powered car must be able to be competitive in price with a gasoline car. On the other hand, the useful life of a fuel cell engine does not need to be more than 5,000 hours. For a stationary fuel cell power plant a much longer life span (100,000 hours or more) is necessary.

Steven Glaser & Frank Escombe of the Escovale Consultancy Services mean that there are three competing fuel cell configurations: a) full fuel cell approach, b) hybrid approach, and c) a small fuel cell used as a range extender for a battery EV commuter vehicle.[10]

Full fuel cell approach
Daimler-Benz has hitherto been pursuing the full fuel cell approach. Its Necar 3 was equipped with a 50 kW fuel cell stack, and its Necar 5 will be equipped with a 75 kW stack. Necar 3 needs a start up time of between two and three minutes.

Hybrid approach
The start up time of the full fuel cell type vehicles may become shorter in future (30 seconds to one minute), but a hybrid fuel cell vehicle can have a much quicker start because it is boosted by a battery or an ultracapacitor. A battery or an ultracapacitor also can absorb braking energy and thus enhance the energy efficiency of the car. A drawback of the hybrid solution is that the vehicle system becomes more complicated. Toyota, Honda, Nissan, Mazda, and GM/Opel are pursuing the hybrid fuel cell configuration. Toyota regards that a 25 kW fuel cell provides enough cruising power. When assisted by a 25 kW battery pack it can drive a 50 kW electric motor, which is in turn as powerful as a 75 kW (100 HP) gasoline engine.[11]

Small fuel cell range extender approach
There is only one manufacturer who is pursuing the third configuration strategy — a small fuel cell used as a range extender. ZEVCO's fuel cell-powered London taxi is equipped with a 5 kW alkaline fuel cell which charges the taxi cab's battery, and extends its driving range. ZEVCO has plans to upgrade the fuel cells to 10 kW making it comparable in power to diesel taxis.[12] Usually, alkaline fuel cells are regarded very expensive — $2,000-3,000/kW. ZEVCO's 5 kW fuel cell stack may cost between $10,000 and $15,000. These are well within acceptable price range. The ZEVCO London taxi has been bought for about $67,000.[13]

Fuels for fuel cells

The choice of fuel is one of the most important decisions to be made by any fuel cell vehicle developers, energy company, and government. Decisions are going to be based on technical, economical, environmental, and infrastructure considerations. Currently, hydrogen, methanol, and gasoline are considered by the involved players as feasible options.

Hydrogen

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[10] Steven Glaser & Frank Escombe of the Escovale Consultancy Services in the UK. Fuel Cells: From Curiosity to Commitment. presented at the Intertech Conference on Commercializiling Fuel Cell Vehicles 97, cited in *ELECTRIC VEHICLE PROGRESS* 15/4 98.

[11] Because of its favorable torque characteritics an electric motor has about 50% more power, in the most usual driving ranges, than a gasoline engine with the same horse power.

[12] *Oxy-Fuel News*, September 7, 1998.

[13] Hart, David & Bauen, Ausilio, 1998, *Fuel Cells — Clean power, clean transport, clean future*, Financial Times Energy, London.

Hydrogen has excellent electrochemical reactivity at PEM fuel cell anodes, and hydrogen-air fuel cell technology has attained levels of power density and efficiency adequate for automobile propulsion. If hydrogen were to become a practical, generally available and affordable fuel in the foreseeable future, this could reduce the complexity and cost and thus enhance the success prospects of automotive fuel cell.[14] Hydrogen powered fuel cell vehicles also are genuine zero emission vehicles.

Three major problems surrounding hydrogen must however be addressed before hydrogen will be chosen: a) difficulties to store hydrogen onboard, b) high cost of hydrogen, and c) lack of infrastructure for distribution of hydrogen. Storage of hydrogen as a gas compressed to 5000 psi requires a 10-fold larger volume than gasoline for the same amount of energy. 200 litres of compressed hydrogen would be necessary for a 600 km range. As studies by Ford have shown, tanks for storage of this amount of hydrogen cannot be accommodated in a car without seriously compromising the space allocated to passengers and cargo. The volume problem is much reduced if hydrogen is stored as a liquid or bound chemically to a metal alloy. Both approaches have been explored, but they introduce new issues. Because of the equipment and electricity required, liquefaction adds to the cost of gaseous hydrogen, and it reduces overall energy efficiency significantly. Storage of liquid hydrogen also is expensive because of the need for high-performance insulation, heat exchangers, and safety measures. Storing hydrogen as a metal alloy hydride has been under investigation for more than 25 years, but the specific storage capacity (e.g., in kg hydrogen per kg of alloy) is still inadequate, and the cost is too high for automotive applications. Toyota claims to have developed a new alloy with adequate storage capacity but its cost is considered too high, leading Toyota to shift most of their development effort to methanol. These facts make clear that breakthroughs in hydrogen containment or storage materials would be needed to meet technical requirements and cost criteria for hydrogen storage onboard automobiles.[15]

In the meantime, there are several promising technologies to store hydrogen onboard in the future. Researchers at the Northeastern University in Boston have developed a carbon material that a US DOE laboratory calculates may be able to store enough hydrogen for a travel 5,000 miles, in a 25 litre package weighing about 87 kg. The material. described as microscopic graphite fibres or 'carbon whiskers' is thought to store gaseous hydrogen by a combination of absorption and adsorption. The material is said to be capable of storing 75% hydrogen by weight, a significant advance on the previous best method employing carbon nanotubes which achieved 4% of their weight. If applied to vehicles, canisters containing hydrogen stored under 40-50 bar pressure would be swapped at fuelling points, and empty canisters would be recharged at high pressure in a process taking up to 24 hours.[16]

Natex Corporation has been granted patents for a system which generates hydrogen and stores it as a pelletised fuel. The corporation also announced that its joint venture partner Powerball Technologies shipped their first Powerball Tank on 3 March 1998 to Warsitz Enterprises, a California fuel cell company.[17]

Some oil companies seem, however, to attach a large potential for the future hydrogen market. Chris Fay, chief of the British Shell, hold a speech at the launch of the ZEVCO taxi, Westminster, 30 July 1998, saying:

> Hydrogen is a potentially important development in the search for 'sustainable transport' and 'sustainable energy.' That's why Shell has established a Hydrogen Economy team dedicated to investigate opportunities hydrogen manufacturing and new fuel cell technologies in collaboration with others. We believe that hydrogen fuel cell powered cars are likely to make a major entrance into the vehicle market throughout Europe and the US by 2005. In addition, we see potentially enormous opportunities opening up in the domestic fleet bus and taxi market as government encourages cleaner alternatives to conventionally powered vehicles. This trend poses a real challenge to a company like Shell to develop new products, new technologies and to prepare and to inform our customers for the changes that lie ahead. ...

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[14] Kalhammer, et. al., 1998.

[15] Kalhammer, et. al., 1998.

[16] *AUTOMOTIVE ENVIRONMENT ANALYST* March 97. p 4.

[17] *AUTOMOTIVE ENVIRONMENT ANALYST* April 98.

Clearly, Shell remains committed to supplying the fuels and products which the consumer needs and wants. But sometimes it's not enough to wait for consumer demand to dictate product development. Sometimes, we have to take the lead. ... But at Shell, we are convinced that hydrogen, like auto LP gas, represents one of the fuels of tomorrow. Hydrogen can form part of a serious national strategy for tackling the air quality problem and for providing consumers with cost-effective and efficient alternatives to conventional fuels.[18]

A new interesting player is the government of Iceland. German automaker Daimler-Benz AG, Canadian fuel cell-maker Ballard Power Systems and the government of Iceland have signed an agreement to begin pilot production of hydrogen. Daimler-Benz will supply several fuel cell-powered buses to Iceland's Industry and Fuel Ministry for testing; the buses will use hydrogen produced at a pilot plant near Reykjavik. Initially, a feasibility study on the production of hydrogen using hydro-electric power will be conducted by Iceland, Daimler-Benz and Ballard beginning in the fall; later phases will explore the feasibility of exporting hydrogen. Daimler-Benz intends to mass-produce hydrogen-powered buses beginning in 2004.[19] Iceland has been producing hydrogen since the 1970s. The Icelandic government is interested in fuel cell engines for fish boats.[20]

Three German-based automakers, the national electric utility and two oil companies, Shell and Aral, agreed to work together with the ministry for traffic. The joint program will examine three alternatives for cost and environmental impact: hydrogen or natural gas engines; electric motors with either battery or fuel cell; and hybrid engines. But the partners do not have a clear strategy yet. At this point they only agree that manufacturers, politicians and energy suppliers need to work together. "There is no guarantee for success," said Holst Teltschik, BMW board member. "But we have to begin. We have to find solutions to stay globally competitive, and we can only find these in cooperation with politicians and the industry." Teltschik said that he first proposed the idea to Germany's ecology minister Andrea Merkel in 1995. "I am happy that the government has taken up this suggestion again." BMW Chairman Bernd Pischetsrieder said in March that real progress in environmental areas can occur only "if the oil industry makes sufficient contributions." BMW has developed a new concept car 'LH200' that burns hydrogen in its internal-combustion engine and the firm says the car could be produced on standard assembly lines "within a few years," reports the Car Connection. The automaker has been experimenting with hydrogen-fuelled cars since 1978.[21]

BMW is almost the only major automobile manufacturer in the world who is not developing fuel cell vehicles.[22]

Methanol

Methanol has been considered for fuel cell power generation for a number of years because it can be processed into a hydrogen-rich fuel gas fairly easily and efficiently by steam or autothermal reforming. Processing of methanol onboard a vehicle presents a number of difficult challenges. Nevertheless, much of the automotive fuel cell and fuel processor development worldwide is focusing on methanol, mostly for technical but also for longer-term strategic reasons.

At present, however, world capacity for methanol production would be sufficient only for a fraction of just the U.S. fleet of personal automobiles, raising questions about the implementation and costs of the required methanol production and distribution infrastructures. According to information from Methanex and, also, the American Methanol Institute, world production of methanol has grown to 26 million tons per year, mostly in response to growing demands for methanol-based chemicals and motor fuel additives such as MTBE and MTAE. Even at this level, the energy equivalent of world methanol production is only about 6% of U.S. gasoline consumption. Methanex representatives stressed that their company is prepared to make the

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[18] HyWeb Gazette and Swedish Hydrogen Forum (www.h2forum.org).

[19] *Calstart News Note* 05/12/98.

[20] Jan Johansson, Swedish Hydrgen Forum.

[21] *Calstart News Note* 09/22/98.

[22] There are rumours about BMW's secret project using a liquid hydrogen fuelled 30 kW PEMFC stack from Siemens in a 3-series BMW car (Hart & Bauen, 1998).

necessary investments if and as the demand from methanol-powered fuel cell electric vehicles develops.

Gasoline
Gasoline, of course, meets the cost and logistic criteria as an automotive fuel cell fuel and is an efficient, liquid hydrogen carrier of high energy density. However, compared to methanol, gasoline requires a somewhat more complex and less efficient chemical processing system for its conversion into a hydrogen-rich fuel gas stream. This is primarily because of the substantially higher temperature needed to chemically activate gasoline in the primary processing reaction. To date, gasoline fuel processors have seen less development for automotive applications and are less advanced than methanol processors although this situation is changing in the United States.
In summary, methanol and gasoline are the current focus of worldwide efforts to develop automotive PEM fuel cell electric engines; hydrogen is unlikely to play a role in the foreseeable future except perhaps in limited volume produced from natural gas locally for bus or similar vehicle fleets. Better processability, somewhat higher fuel cell engine efficiency, reduced carbon dioxide emissions and longer-term energy strategic advantages are claimed for methanol. The existence of the required production and distribution infrastructures is the obvious advantage of gasoline although it is not clear at present to which extent petroleum distillates need to be modified to meet the purity and processability requirements of gasoline fuel processors. The technical, economic and policy bases for a rational choice between methanol and gasoline are not likely to be available until current development efforts have proceeded considerably further and cooperative efforts between fuel cell engine developers and fuel suppliers have identified preferred fuel strategies for fuel cell electric engines and vehicles. These strategies may well turn out to be different for different regions.[23]

Fuel production and distribution costs

Some of the fuel cell vehicle proponents regard gasoline cars (near zero-emission vehicles) and battery electric cars (if and when advanced batteries will become available at affordable costs) as greatest rivals to fuel cell vehicles in future automotive market. There also is a rivalty between pure hydrogen, methanol, and gasoline as the fuel to fuel cell engines. The cost issue may be decisive.

Hydrogen
A recent study by the Argonne National Laboratory developed detailed capital cost estimates for the production and distribution infrastructures for six fuels (RFG, diesel fuel, DME, methanol, ethanol, and hydrogen). Infrastructure costs were estimated for 2015 (limited penetration, requiring daily production and distribution of hydrogen with the energy equivalent of 70,000 barrels of gasoline) and 2030 (wide penetration; daily production of 1.6 million barrels of gasoline equivalent). For hydrogen, the estimated production facilities capital costs were $10 billion (2015) and $230-400 billion (2030); the costs of the required distribution facilities were $7.7 and $175 billion. Another recent study, performed by Directed Technologies, Inc., analyzed various hydrogen production schemes with capacities to serve between 5000 and 500,000 fuel cell vehicles and concluded that 5000 psi compressed hydrogen could be delivered to fuel cell vehicles at costs that would be competitive with gasoline per mile driven. The basis of this statement is a comparison of a gasoline vehicle operating at 24.5 mpg on taxed gasoline with a fuel cell vehicle operating achieving around 80 mpg (gasoline energy equivalent) on untaxed hydrogen. If the comparison were made between hydrogen and gasoline on the same basis (80 mpg, tax free), hydrogen would cost 2-3 times more per mile driven than gasoline even under most favorable assumptions. The lowest estimate of capital costs for a large-scale hydrogen production and distribution infrastructure is $100 billion for a system with one million barrels per day gasoline energy equivalent.[24]

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[23] Kalhammer, et. al., 1998.
[24] Kalhammer, et. al., 1998.

Developers of smaller-scale hydrogen production technology (e.g., IFC, ADL, Hydrogen Burner) and producers of industrial hydrogen (e.g. Air Products) claim that cost of this hydrogen could be low enough for automotive applications, for example, in the order of $2.50-3.00 per kg, or about $2.25-2.75 (tax-free) per energy equivalent of one gallon of gasoline. However, there is still considerable uncertainty regarding the capital cost of such units.[25]

Gasoline

In the gasoline car case, it is interesting to know how large is vested interest in oil distribution infrastructure. The American Methanol Institute recognizes that the massive distribution network at the retail level is one of the great historical achievements of the oil industry. In the United States, nearly $100 billion is invested in the infrastructure to produce, refine, distribute, and retail market motor fuels, and each year over $10 billion is spent to maintain and upgrade this network. This extensive network includes 200,000 retail gasoline stations and 30,000 diesel stations.[26] Francois Castaing, Chrysler's head of vehicle engineering, said.

> There's $200 bn invested in the way gasoline is distributed today ... this is not going to change overnight just because the car companies have fuel cell prototypes.[27]

It may be so that $200 bn were invested in the gasoline distribution infrastructure in the world and $100 bn only in the USA. The most interesting figure is $10 bn that is annually spent in the USA to maintain and upgrade this network.

As mentioned above, it is sulfur contents in gasoline that comtaminate fuel cells. There also is a consensus between the involved players that it is cheaper to reduce sulfur at refineries than at individual vehicles. The de-sulfurizing of gasoline may not be so expensive as some oil companies want to tell us. One of the U.S.'s smallest refinaries will be among the first to produce virtually sulfur free gasoline and diesel. Denver-based Inland Resources plans to invest $130 million in refinery upgrades and pipeline expansion to tie its ultra-low-sulfer crude output at Monument Butte, Uta, to a former Pennzoil refinery at Roosevelt, Uta. Central to the plan is the construction of a hydrocracker to the 15,000 bbl/day refinery.[28]

Methanol

Daimler-Benz believe that adding methanol pumps at gas stations would be no greater obstacle than adding pumps for unleaded gasoline was. The experience with today's alternative fuel internal combustion vehicles argues for the Daimler-Benz's side in that dedicated methanol and ethanol pumps are showing up at gas stations already. If fuel cell vehicles come along that are both cleaner and more efficient than today's cars, stations would have even greater incentive to install methanol pumps.[29]

Daimler-Benz is negotiating with the oil industry and methanol industry. Ballard has already established an alliance with Methanex, the world's greatest methanol producer. A memorandum of understanding has been entered into by Methanex Corporation, a methanol supplier, and Ballard Power Systems under which Methanex will cooperate to promote the commercialization of methanol-based fuel cells for electric vehicles and other applications. "Methanex is adopting a leadership position to ensure methanol infrastructure is not a barrier to this leading edge technology," said Pierre Choquette and added, "The potential magnitude of fuel cell growth over the next ten years is very exciting." Methanex is located in Vancouver, BC Canada, as is Ballard.

A modern methanol plant with a typical capacity of 1 million tons per year can be constructed and put on stream in less than 3 years at a cost of about $350 million or less than $700 per vehicle since the output of just one such plant would be sufficient to meet the needs of more

[25] Kalhammer, et. al., 1998.
[26] American Methanol Institute, 1998.
[27] *AUTOMOTIVE ENVIRONMENT ANALYST* Feb. 97.
[28] *Oxy-Fuel News - Monthly Markets Update*, September 14, 1998.
[29] *AutoWeek*, March 3–9, 1997, cited in American Methanol Institute, 1998.

than 500,000 methanol fuel cell vehicles. Methanol produced by such plants can compete in today's marketplace, and larger plants are expected to result in yet lower methanol production cost. The establishment of a methanol distribution infrastructure is a more complex issue. With the exception of a limited distribution capability for M85 (a blend of 85% methanol and 15% gasoline) in parts of California, there is no infrastructure for methanol automotive fuel distribution at present, and the methanol industry is not in the business of owning and operating fuelling stations. It is reasonable to assume, however, that alliances between the methanol industry and distributors and/or retailers of gasoline would develop apace with the emergence of an automotive fuel cell market for methanol. The investments required to establish limited and complete methanol distribution infrastructures has been estimated by Stork et al., as $360 million and $9 billion, respectively, which corresponds to costs of between $70 and $100 per vehicle. This study also generated estimates for methanol production, as follows: limited infrastructure (70,000 bbl/day capacity) investments for methanol production about $3.2 billion ($640 per car), full infrastructure (1.6 billion bbl/day) $84 billion ($720 per car). These numbers are somewhat but not materially higher than the production plant investments mentioned by Methanex.[30]

Metanol de Oriente (Metor), a joint venture between Mithsubushi Corp., Mitsubishi Gas Chemical Co., Venezuela state company, Pequiven, and Invesiones Polar, plans to build a second 770,000 metric-ton-per-year methanol plant. The plant has a reported price of $267 million. Together with an existing 750,000 metric-ton-per-year plant, this new plant gives Metor over 1.5 million metric ton per year of capacity. The existing plant is exporting its products to Europe and the U.S., and the new plant to all markets including Asia. Mitsubishi wanted to expand its capabilities in Venezuela because of the area's competitive natural gas costs.[31]

Electric

Compared with all these, installation costs of building electric vehicle charging site appears very cheap. According to Diane Wittenberg, President of Edison EV in EV California, an EV charging site installation costs is between $7,000 and $15,000. In the U.S. there were 325 chargers at 125 sites. In Southern California alone there are 270 chargers at 110 sites.[32] Pure battery electric vehicles with quick recharging capacity may be able to become formidable rivals both to fuel cell vehicles and gasoline cars.

Fuel Cells — important players

Fuel Cell stack manufacturers

Ballard

Ballard is today's world leader in automotive PEM fuel cell technology. More than 200 people there are working on fuel cells. Its current stack power density of more than 1 kW/litre is far better than any competitors. It has delivered more than 500 developmental stacks to a wide variety of customers. The joint ventures with Daimler-Benz and with Ford provide Ballard with the resources and capabilities to pursue extensive programs of technology improvement and cost reduction. Ballard has established leading-edge technologies for all main functional components of PEM cells and stacks. In collaboration with Johnson Matthey, it has developed electrocatalysts that give Ballard's fuel cells high performance at low loadings, good tolerance to CO in the anode input gas, and acceptable endurance. Ballard's series '700' stacks with power density of 1 kW/liter were co-developed with Daimler-Benz before their joint venture, are now being used in the NeCar 3 experimental fuel cell vehicle of Daimler-Benz. The Ballard series '800' 50 kW stack is used in General Motors'program. Ongoing efforts at Ballard are focusing on the series '900' 75 kW automotive fuel cell stack which is intended for volume production and application in the fuel cell

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[30] Kalhammer, et. al., 1998 .

[31] *Oxy-Fuel News,* September 21, 1998.

[32] Diane Wittenberg's speech at EVS-14 in Orlando, Florida, December 1997.

vehicle Daimler-Benz plans to commercialize in 2004/5. Some of the stack design goals are: Stack Output power 75kW, stack voltage 215 V, Power density 1.4 kW/liter, Life 4000 hours.

All parts of Ballard's cell and stack technology are being designed for high-volume, low-cost manufacturability. Once mature production at rates broadly comparable to those of modern internal combustion engine plants are attained, stack production cost is projected to decline to $20-35/kW.[33]

In January 1997, Ballard Power Systems, Inc. has announced it has received another $766,500 in orders from Daimler-Benz AG to supply fuel cells. The contract is in addition to the $2.3 million contract received in August 1996 and the existing $15 million joint-development program between the two that began in 1993.[34]

In February 1997, Ballard Power Systems has received a $3 million (U.S.) order from Delphi Energy and Engine Management Systems to supply fuel cells for integration into Chrysler 's fuel cell vehicle project. Ballard and Delphi have had a long-term relationship working on a methanol fuel-cell program sponsored by the Department of Energy, which is still in progress.[35]

In March 1997, Nissan Motor Co. has placed another order to Ballard for its fuel cells, this time for (U.S.) $1.6 million. The relationship that began in 1991 when Ballard first delivered a fuel cell to the Japanese automaker for evaluation in its fuel cell-powered electric vehicle projects.[36]

In February 1998, Honda placed $1.7 million Fuel Cell Order with Ballard. A subsidiary of Honda Motor Co. has placed a (U.S.) $1.7 million order with Ballard Power System Inc. for small fuel cells for use in portable-power and speciality applications. Run on hydrogen. Honda has purchased Ballard Fuel Cells for automotive applications also in 1996.[37]

In March 1998, Ballard Secured $2.5 million Fuel-Cell Order From GM. This is the second order from GM.[38]

Energy Partners

Energy Partners' stacks feature a potentially low cost, molded separator plate. EP has built a number of multi-kW PEM hydrogen-air/oxygen stacks and sold them to research organizations worldwide. Other stacks were tried for powering several small, experimental fuel cell vehicles.[39] In October 1997, the vehicles began a demonstration at the Palm Springs Regional Airport.[40] EP participated in the DOE/Ford automotive fuel cell stack development and evaluation program (1995-96) and delivered a 10 kW hydrogen-air PEM stack to Ford under that program. EP's stack used Gore's MEA but was not chosen in Ford's downselect. Subsequently, EP was awarded one of DOE's PRDAs to improve stack design. This stack technology is now being developed further under the current round of DOE contracts for 50kW stacks. In the first phase, EP will try to complete the development of a separator plate molded from a high-conductivity composite containing graphite, and it will fabricate a 10 kW proof-of-concept stack. In the second phase, EP is to construct a 50 kW stack as part of a PEM fuel cell power plant capable of operating on processed gasoline and/or methanol.[41]

H-Power

H-Power is a small company that has been active in phosphoric acid and PEM fuel cell development for 15 years. From an earlier emphasis on military applications, H-Power in the early 1990s expanded activities into PEM fuel cell technology for small stationary and portable power applications.

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33 Kalhammer, et. al., 1998 .
34 *Calstart News Note* 01/08/97.
35 *Calstart News Note* 02/28/97.
36 *Calstart News Note* 03/20/97.
37 *Calstart News Note* 02/10/98.
38 *Calstart News Note* 03/17/98.
39 Kalhammer, et. al., 1998 .
40 *Fuel Cells 2000,* www.fuelcells.org/fuel/fct/goingon.shtml. last updated August 5, 1998.
41 Kalhammer, et. al., 1998.

H-Power has a unique metallic separator plate technology. Plates are made by diffusion bonding thin metal sheets cut in the appropriate patterns from sheet stock by a photo-etching technique. With this approach, H-Power can produce very thin separators with precisely defined flow fields and cooling passages, an important advantage for the fabrication of compact, high performance automotive PEM fuel cell stacks. Because it lends itself to automation, H-Power's technique should permit mass production of separators at relatively low cost, thereby meeting a key requirement for automotive applications. At this time, however, H-Power does not seem to have plans for transfer of their separator plate technology to other organizations.[42] H-Power was the system integrator in the original DOE/Georgetown program and now makes PEM fuel cells for a variety of specialty mobile applications.[43]

International Fuel Cells (IFC)
International Fuel Cells' involvement with PEM technology began in 1985 with acquisition of General Electrics' solid polymer electrolyte technology and business. Beginning in the late 1980s, IFC developed high reliability PEM fuel cells for military applications. One product of these developments was a 20 kW fuel cell power system for an underwater vehicle. This stack utilized a carbon/graphite separator plate adopted from IFC's phosphoric acid technology. Work on automotive PEM fuel cell technology began about 3 years ago with IFC's successful response to a Ford procurement of a hydrogen-air PEM stacks for testing and evaluation purposes under DOE's automotive fuel cell R&D program. Under the Phase II contract, IFC delivered a 50kW/250 Volt two-stack PEM fuel cell power plant with a power density of 0.55 kW/liter and an efficiency of 50% at rated power; at 10kW output (cruise power), efficiency is 60%. Under a new $11 million DOE contract IFC will develop a fuel-flexible 50 kW power plant that can operate on gasoline, methanol or natural gas; system power density will be 0.25 kW/liter.[44] On August 1, 1998, IFC's parent, United Technologies Corporation (UTC) teamed up with Toshiba to set up a joint venture in the U.S. which aims to start commercial production of fuel cells for cars in 2003. The restructuring allows UTC to put more focus on fuel cell development for vehicles, and brings significant new financial resources to the job.[45]

Plug Power (PP)
Plug Power is an organization established in 1997 by Mechanical Technologies Inc. (MTI) and Detroit Edison Development Co. as a partnership to commercialize the PEM fuel cell technology developed at MTI since the early 1990s. Plug Power has grown rapidly and now has more than 100 staff engaged in PEM fuel cell technology development. The primary business goal is to develop PEM fuel cell stack and system technology for stationary power generation. Along with Arthur D. Little, Inc., and Los Alamos National Laboratory, Plug Power successfully demonstrated a fuel cell operating on reformate from gasoline. The group is now focusing on integrating the system into a vehicle. The system is expected to be twice as efficient as gasoline powered internal combustion engines, with over 90% less emissions.[46] Arthur D. Littele and Plug Power will start the commercial production of gasoline PEM fuel cell by 2005.[47] PP also has become engaged in DOE's PEM fuel cell program, first as a supplier of a 10 kW stack under the Ford procurement, presently as one of the organizations selected to develop and deliver by the year 2000 a 50 kW PEM fuel cell power system capable of operating on processed gasoline. The fuel processor for that system is to be provided by ADL. Currently, Plug Power is seeking strategic partners willing to invest in further development of Plug Power's technology and to provide some of the resources that will be required to manufacture and commercialize the technology.[48]

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[42] Kalhammer, et. al., 1998.
[43] *Fuel Cells 2000,* www.fuelcells.org/fuel/fct/goingon.shtml. last updated August 5, 1998.
[44] Kalhammer, et. al., 1998.
[45] *Fuel Cells 2000,* www.fuelcells.org/fuel/fct/goingon.shtml. last updated August 5, 1998.
[46] *Fuel Cells 2000,,* www.fuelcells.org/fuel/fct/goingon.shtml. last updated August 5, 1998.
[47] *ELECTRIC VEHICLE PROGRESS* 15/11 97.
[48] Kalhammer, et. al., 1998.

Allied Signal
Allied Signal began to work on PEM fuel cell technology when it got a DOE contract for development of a 50 kW hydrogen-air stack intended for automotive applications. Allied's stack design has several unique features. Foremost is the hexagonal shape of the cells and, therefore, of the stack footprint. This design results in a considerable simplification of stack manifolding and sealing. Another Allied stack feature is a metallic separator plate which allows dense stacking of cells. The design is now being implemented in a DOE-funded program in which Allied will develop a 50 kW PEM fuel cell system capable of operating on processed methanol or gasoline. The performance goals for that system include 40% efficiency and a power density of 0.35 kW/liter.[49]

DeNora
Italian fuel cell researcher DeNora S.P.A. is working with PEM fuel cells for buses and marine applications. The company is completing an advanced design PEM fuel cell for a European Union bus program.[50] DeNora has delivered a hydrogen fuelled 30 kW PEM stack to FEVER. A primary business interest of DeNora in PEM fuel cells is in the supply of complete hydrogen-air fuel cell systems for power generation using industrial waste hydrogen available on site as a byproduct of the chlor-alkali and other industrial processes. DeNora also is positioning itself to supply their PEM fuel cell stacks for other high value stationary power generation markets, partnering with fuel cell system and/or power plant suppliers. In the transportation field, DeNora is interested in supplying their technology to higher-value niche markets for specialized work vehicles. The company sees itself primarily as a licensor rather than as a manufacturer of PEM fuel cell stack technology for the automobile mass market with its very severe cost and weight constraints for fuel cell engines.[51]

ZEVCO/EAC
The Belgium-based ZEVCO Co. got started in 1991 with the goal of developing useful alkaline fuel cell technolgy for EVs. Alkaline fuel cell that consumes supercooled hydrogen and air. Tested in Elcat (Finnish Subaru).[52] Recently, ZEVCO delivered the borough of Westminster, London, a fuel cell-powered taxi which is equipped with a 5 kW alkaline fuel cell.[53]

Electric Auto Corp. (EAC) is planning to manufacture alkaline fuel cells in a converted textile plant in Alabama. To shorten the time to begin production, EAC is seeking to license a fuel-cell manufacturing system developed by ZEVCO. EAC expects to be able to sell both the fuel cells and batteries at a cost of $50 per kilowatt, roughly the same as today's internal-combustion engines. Professor Karl Kordesch of the Technical University in Graz, Austria, who built the world's first practical fuel-cell car in 1970 while working for Union Carbide, is supervising testing of EAC's fuel cell in Austria.[54]

Siemens
Siemens has currently about 100 technical staff in fuel cells. About two-thirds of this staff is working on PEM fuel cell technology, with emphasis on the submarine power source application. Siemens recently developed a simplified cell technology that appears amenable to low-cost mass production. The key cell performance characteristics and stack technology goals of this technology are: Stack Output power ~ 6 kW, Stack power density: 0.4 kW/kg. Siemens projects a cost of 200 DM/kW (approximately $110/kW) for a complete hydrogen-air system when manufactured in volume, e.g., 100,000 units per year. Because this cost is still too high for automotive applications, further development of the cell and stack technology and of appropriate manufacturing processes will be necessary. Siemens expects to make a decision in 1999 whether to pursue automotive stack technology development and manufacturing beyond that year. Siemens is seeking an automobile manufacturer as an alliance partner to develop PEM fuel cell engines. As a partner in a joint FCEV

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49 Kalhammer, et. al., 1998.
50 *Fuel Cells 2000,* www.fuelcells.org/fuel/fct/goingon.shtml. last updated August 5, 1998.
51 Kalhammer, et. al., 1998.
52 *ELECTRIC VEHICLE PROGRESS* 1/6 97
53 *Fuel Cells 2000,* www.fuelcells.org/fuel/fct/goingon.shtml. last updated August 5, 1998.
54 *Calstart News Note* 02/21/98.

venture, Siemens could offer not only one of the largest fuel cell technology capabilities anywhere but, in addition, leading-edge electric drivetrain technology as well as the very large technical and financial resources of a world leader in a wide range of electric and electronic technologies.[55]

General Motors
GM has own R&D on PEM fuel cells. GM has completed the design of a 50 kW stack. This stack will incorporate the advances in electrocatalyst, MEA, and separator technologies currently being pursued within GM and in collaboration with several outside organizations. The need to reduce costs is the major driver in these efforts. The GM program has initiated some manufacturing development work, but they have left open the options whether and which PEM fuel cell components and subsystems will be manufactured or purchased. GM's corporate philosophy entails full understanding of all aspects of PEM fuel cell technology to permit informed future decisions on technology selection and partnering. With their fuel cell technology and skill base, engineering capabilities, and financial resources, GM will be able to move rapidly into engineering and manufacturing development of a competitive PEM stack technology.[56]

Honda
The low-level fuel cell program initiated by Honda in 1989 was expanded significantly about 3 years ago, and further expansion is likely. PEM cell component and stack development comprise a major part of Honda's current program, with core technology R&D and feasibility assessment planned for another 2-3 years. The status of Honda's stack technology are: Output power 6.0 kW, Power density approximately 0.2 kW/liter. Honda develpoed own MEAs which used Nafion membranes and modest loadings of commercial catalysts. Manufacturing considerations are entering Honda's development efforts even at the core technology stage, but it has not yet been decided which components Honda will manufacture.[57]

Nissan
At present, Nissan's PEM fuel cell program appears to be quite modest. Nissan's activities have concentrated on estimating efficiencies and emissions of FCEVs and comparing them with gasoline-powered ICE vehicles, and evaluating two PEM stacks purchased from Ballard. A systematic program to develop PEM fuel cell components and subsystems does not exist at present but appears to be planned. Nissan's PEM fuel cell laboratory research started in 1996, with a focus on the direct methanol fuel cell because of its potential for reduced complexity. Nissan technical staff mentioned methanol crossover and the relatively low operating temperature limit of Nafion-type membranes as the most serious barriers to the development of practical direct methanol technology. Nissan is now engaged in an internally funded effort to develop a new membrane with higher resistance to methanol crossover and tolerance for operating temperatures above 150°C.[58]

Toyota
Toyota's fuel cell program began around 1990, with emphasis on development of hydrogen storage alloys and PEM stacks. The Toyota experimental fuel cell-battery hybrid EV, shown first in 1996, had a 15 kW hydrogen-air fuel cell, with hydrogen stored in form of a metal hydride. The characteristics of Toyota's stack technology are: Output Power 15 kW, Stack weight 120 kg, Stack volume 100 liters (stack power density 0.15 kW/liter). MEAs were developed and fabricated in-house using Nafion membranes and low catalyst loadings; separator plates were machined from sintered carbon. Ten 25 kW stacks have now been built, but Toyota engineers means that their stack technology is still developmental and that systematic manufacturing engineering and process development efforts must await breakthroughs in the prospective costs of key components including membranes/MEAs and the separator plate.[59]

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[55] Kalhammer, et. al., 1998.
[56] Kalhammer, et. al., 1998.
[57] Kalhammer, et. al., 1998.
[58] Kalhammer, et. al., 1998.
[59] Kalhammer, et. al., 1998.

Aishin Seiki
The Japanese all-round auto components maker, Ainshin Seiki, showed its own fuel cell stack at the 14th Electric Vehicle Symposium (EVS-14) in the end of 1997.

Mitsubishi Electric
Mitsubishi is carrying out a PEM fuel cell R&D program aimed primarily at stationary power generation applications, but several elements of the program have relevance for the automotive power source applications, including in particular Mitsubishi's development of a compact reformer. It was pointed out to the Panel that Mitsubishi Heavy Industries also is developing PEM technology, but no decision has been made as to which Mitsubishi organization will eventually work with Mitsubishi Motors to develop automotive PEM fuel cells.[60]

Fuel Cell Component Developers/Suppliers

Asahi Chemical Co.
Asahi Chemical produces the basic resin for manufacture of fully fluorinated polymer PEMs. While the current price of these membranes is high, Asahi Chemical believes that it should be possible to reduce membrane costs by the order of magnitude required to make such membranes acceptable for automotive fuel cells. The key will be the development of a sufficiently large market (for example, 1 million m^2/year) to provide the needed economies of scale. Asahi Chemical also is working on fluoropolymer membranes suitable for automotive applications. A relatively thin, reinforced experimental membrane is showing conductivity, strength and shape retention characteristics comparable to Nafion-type PEMs. These membranes are made from standard fluoropolymer resin and can be produced with existing machinery.[61]

DuPont
DuPont's NAFION membrane has become widely adopted in PEM fuel cells. Nafion offers very good ionic conductivity, outstanding chemical stability and high quality, uniformity and freedom from pinholes and other defects, critically important characteristics for the fuel cell application. The main drawback of Nafion is its high price. At least nine fluorochemical reaction processes are involved in synthesizing the perfluorinated, chemically functionalized ionomer resin from which membranes are made; some of these processes involve hazardous intermediates and thus require stringent controls to ensure safety. Because of the modest markets for Nafion-type membranes (currently about 100,000 m^2/year worldwide), resins and membranes are made in relatively small volume by chemical industry standards. Thus, the high cost of resin production plants and membrane manufacturing equipment must be recovered in the sale of a limited amount of product, resulting in rather high prices. DuPont recently announced their future pricing schedule to serve a membrane market created by annual production of 150,000 PEM fuel cell engines and vehicles. At this volume (between 1 and 2 million m^2 per year, more than 10 times the current world market), membrane prices will drop to less than \$50/m^2, or less than \$10/kW for a high performance PEM stack. Two other factors could result in yet lower membrane costs per kW: the integration of ionomer resins or solutions (rather than the finished membrane) into MEA production, and/or (in the longer term) recycling and reuse of membranes in resin or membrane manufacture.[62]

Ballard Power Systems
Ballard has evaluated the products from several of the major manufacturers of Nafion-type, fully fluorinated PE membranes. Concern about the high cost of commercially available membranes (about \$600 per m^2, equivalent to nearly \$100/kW) led Ballard to develop a proprietary, partially fluorinated PE material. At present, polymer resin is produced by Ballard in-house and then

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60 Kalhammer, et. al., 1998.
61 Kalhammer, et. al., 1998.
62 Kalhammer, et. al., 1998; *AUTOMOTIVE ENVIRONMENT ANALYST* April 98; *Calstart News Note* 03/03/98.

fabricated into BAM (Ballard Advanced Material) membranes by vendors. Ballard's capacity for batch production of resin is sufficient to meet anticipated needs for several years. A continuous process is being developed for automated production of low-cost resin that should permit membrane costs to drop below $\$50/m^2$ in mass production. Using Nafion-type commercial or their own BAM membranes and platinum-based electrocatalysts, Ballard is producing high performance membrane-electrode assemblies in house, in the assumption that they will eventually manufacture MEAs on a large scale. However, Ballard still is open to the possibility of purchasing MEA components if specifications and price meet Ballard's criteria.[63]

W. L. Gore Associates
Based on Gore's core competencies in fluoropolymer materials technology and membrane processing and backed by a strong management commitment, Gore established a team in 1994 to develop technology and a business in ionomer (ionically conducting polymer) membranes. This team rapidly developed GORE-SELECT, a membrane micro-reinforced with teflon fibers and made from the same ionomer resin that is used to produce DuPont Nafion membranes. MEAs made with these membranes have demonstrated impressive advances in PEM cell performance.[64]

3M
3M has successfully developed a new MEA with high performance and excellent CO tolerance at low catalyst loadings. 3M also has developed a process for continuous fabrication of complete 5-layer MEA structures as a roll good. On the basis of MEA composition and performance, and with the expected low cost of the roll good manufacturing process, 3M projects MEA costs in the order of $5-10/kW. 3M believes that this MEA cost should permit stack costs of $ 20/kW, or $1000 for a 50 kW automotive PEM stack. A key assumption underlying 3M's MEA cost projection is a membrane cost of around $\$20/m^2$, about 1/30 of current prices for Nafion-type membranes. 3M believes that this cost should be achievable in mass production, e.g. one million m^2 per year. 3M estimates that it will take 2 years to develop their MEA technology to the point where an early commercial production line could be set up in an existing roll good production facility. As a materials company, 3M wants to commercially produce MEAs but not stacks or entire fuel cell systems. 3M intends to establish alliances with stack manufacturers to ensure that stack manufacturing processes take full advantage of future availability of 3M's MEA as a continuous roll.

Hoechst
Hoechst is one of the world's largest producers of chemicals and polymer products. Hoechstís Corporate Research & Technology (CR&T) has become engaged in PE membrane development believing that such membranes could turn into a major business opportunity if automotive PEM fuel cells can capture major markets. Assuming that fluorinated PE membranes will be too expensive for automotive fuel cells and that their stability exceeds automotive requirements, Hoechst CR&T has developed a hydrocarbon-based PE membrane with a projected cost less than 10% of a Nafion-type membrane. MEAs based on this membrane have been fabricated at Hoechst and independently tested in laboratory cells, demonstrating sufficient stability up to at least 5000 hours. Hoechst can produce this membrane to order in pilot quantities and has supplied samples to major European PEM fuel cell developers for evaluation purposes.[65]

Johnson Matthey
Johnson Matthey is one of the world's leading developers and suppliers of noble metals and noble metal catalysts. The company has made a significant commitment to PEM fuel cell development, and it has adopted a long term plan to develop and supply fuel cell components containing noble metals, from the catalysts themselves to electrodes and complete MEAs. In pursuit of that plan, Johnson Matthey established collaboration and business relationships with many leading fuel cell

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63 Kalhammer, et. al., 1998.
64 Kalhammer, et. al., 1998.
65 Kalhammer, et. al., 1998.

developers worldwide. A number of them now use Johnson Matthey's catalysts in their MEAs. In their own laboratories, Johnson Matthey is developing platinum and platinum alloy catalysts of higher electrochemical activity and improved electrode structures.

Fuel reformer manufacturers

Arthur D. Little, Inc. (ADL)/Epyx Corp.
Arthur D. Little's compact, lightweight multifuel reformer was made with funding from DOE's Office of Transportation Technologies and the state of Illinois plus internal funding. The ADL process begins by vaporizing the fuel and partially oxidizing it with air to produce hydrogen and carbon monoxide. Using steam and a catalyst, a shift reactor then converts most of the carbon monoxide into carbon dioxide and produces more hydrogen. Finally, air is injected over a catalyst and reacts with the remaining carbon monoxide to convert it to carbon dioxide, leaving hydrogen-rich gases.[66] ADL has formally announced the formation of a spin-off company to commercialize a component that allows fuel cells to operate on gasoline, ethanol or other fuels. The new company, Epyx Corp., intends its fuel processors to be used in the automotive, energy and utility-industry markets. It plans to begin initial sales of small-scale portable power units in the year 2000; systems for stationary power and transportation applications are planned for years 2002 and 2005, respectively. Fuel cells convert hydrogen into electricity without using combustion, but hydrogen refueling infrastructure is currently lacking. For this reason, Epyx's "Multi-Fuel Processor" is designed to convert today's existing fuels - gasoline, ethanol, methanol, propane and natural gas - into hydrogen. Epyx says it will be working with several strategic partners, including the U.S. Department of Energy.[67]

Delphi
Delphi, the former GM subsidiary and now independent has worked together with Chrysler and GM in developping the hydrogen-extraction process from gasoline and fuel cell system.

Catalytica Advanced Technologies and Alliance, and McDermott Technology, Inc.
The California Energy Commission (CEC) has reportedly selected two firms that will partner to develop a key component for gasoline reformers for fuel-cell vehicles. The gasoline "desulfurizer" will be developed by Mountain View, Calif.-based Catalytica Advanced Technologies and Alliance, Ohio-based McDermott Technology, Inc. The aim of the project, which is part of the CEC's Transportation Energy Technologies Advancement Program (TETAP), is to enable the conversion of commercially available gasoline into hydrogen for use in fuel cells for transportation applications. Fuel cells convert hydrogen into electricity in a process that does not use combustion. Sulfur, which is present in gasoline, "pollutes" fuel cells and shortens their life. The two companies are also cooperating on natural-gas reformers for stationary fuel cells.

Johnson Matthey
Johnson Matthey is developing fuel processor technology.

BASF
Daimler-Benz will be receiving assistance withreformer catalysts for fuel-cell vehicles from BASF AG, according to a BASF press release. The reformer will produce hydrogen from methanol, a liquid fuel that can be handled much like gasoline or diesel. The reformer catalyst, a mixture of copper, zinc and aluminum, results in the production of hydrogen, carbon dioxide and carbon monoxide from methanol. Reformer catalysts present special challenges because of the flexible demands of automotive driving cycles. Daimler-Benz's first-stage vehicle that uses a methanol reformer, the "NeCar 3," has already been built. The current focus is on improving the reformer technology and reducing its size for a pre-production prototype due in 1999. Daimler-Benz has also

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[66] *The Epri Journal* (May-June 1997).
[67] *Calstart News Note* 02/26/98; *ELECTRIC VEHICLE PROGRESS* 15/3 98.

teamed with Ford Motor Co. and Ballard Power Systems in a joint venture to commercialize fuel-cell systems for automobiles.[68]

Royal Dutch/Shell
See the section of Oil industry's changing attitude against fuel cells.

Ford/Mobile alliance
See the section of Oil industry's changing attitude against fuel cells.

Fuel cell vehicle manufacturers

Daimler-Benz
Diamler-Benz has been road testing a fuel cell van since 1993, declaring that the fundamental barriers to commercialization have been overcome. Daimler unveiled its second-generation fuel cell vehicle, a van called NECAR 2, in May 1996. The fuel cell engine ran on hydrogen stored in tanks on-board the vehicle. In October 1997, Daimler unveiled NECAR 3, a methanol-fueled fuel cell vehicle. Daimler-Benz and Ballard announced their partnership in April 1997. Daimler-Benz unveiled a fuel cell bus in May 1997 that runs on stored hydrogen and has a range of 250 km. The bus is being road-tested in Stuttgart, Germany.[69] In 1996, when DB began to consider fuel cells as a future engine for mass-produced automobiles, methanol was selected as fuel because of the greater ease and higher efficiency of processing methanol into a hydrogen-rich gas. At present there is little or no infrastructure for supplying large quantities of pure methanol. DB has, therefore, initiated discussions with the methanol and oil industries to stimulate discussion and possible development of suitable methanol production and distribution infrastructures. A special organization (Fuel Cell House = FCH) was formed in 1996 to lead the DB fuel cell vehicle program. Headed by a Senior Vice President who reports directly to the DB Executive Vice President for Passenger Car Development, FCH has about 30 staff members of its own, and it can call on the entire capabilities of DB including the corporate research groups and vehicle testing facilities as well as the engineering expertise and facilities of Mercedes Benz. The Daimler-Benz FCH also is empowered to enter into special arrangements. Management and key technical activities of the Daimler-Benz Fuel Cell House and DBB are being consolidated in one facility in Nabern near Stuttgart, Germany. About 75 technical staff are engaged primarily in methanol fuel processor development and in the integration of the required subsystems into complete fuel cell power plants. Component and subsystem development is focusing on configurations amenable to mass manufacturing and on advanced manufacturing techniques, taking advantage of the modern automotive engineering and manufacturing development expertise and techniques (such as computer-aided design and rapid prototyping) available at the various Mercedes Benz R, D&E facilities in the Stuttgart area. Daimler-Benz engineering staff believe that fuel cell technology is fundamentally better suited for very rapid, low-cost manufacturing than conventional engine production. Over the next 2 years, every part of the fuel cell engine will be developed to the point where processes for mass production are established and engine performance and cost can be estimated with confidence. Subsequent generations of NeCar vehicles will represent increasingly packaged versions of the engine technology. NeCar 5, scheduled for late 1999, will approach a production prototype configuration, with room for 4 persons and luggage in the rather small A-Class vehicle. At the end of 1999, a decision will be made whether to invest in manufacturing facilities for fuel cell engines. A go-ahead decision presupposes management confidence that fuel cell engines and vehicles will be able to compete with conventional engines and vehicles on all points while being cleaner and more efficient. Daimler-Benz top management recognizes that a positive decision is not assured but is confident that DBB with its allies have the ability to engineer all aspects of fuel cell engine technology to the point of commercial viability when mass-produced at least 100,000 engines and vehicles per year once full production is first established, and growing to perhaps 500,000 or more

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[68] *Calstart News Note* 05/01/98.
[69] *Fuel Cells 2000,* www.fuelcells.org/fuel/fct/goingon.shtml. last updated August 5, 1998.

units per year eventually. Several years and investments of more than $ 1 billion will be needed from this decision point until the various manufacturing facilities are in place and operating reliably. Additional time will be required until FCEVs can be offered to the general public; even with a completely successful program, this cannot occur before 2004/5. The Daimler-Benz Management Board is prepared to support the necessary investments in the belief that the fuel cell is the potentially best alternative to the internal combustion engine given the requirements for ever cleaner engines and the emerging pressures to reduce carbon dioxide emissions from automobiles.[70]

Peugeot/Citroen
Peugeot/Citroen is involved in a European joint PEM fuel cell program researching reductions in fuel cell system weight and costs.[71]

Renault
A joint Franch-Italian-Swedish venture has resulted in a fuel cell concept vehicle based on a Renault station wagon, the FEVER.[72]

[70] Kalhammer, et. al., 1998.
[71] *Fuel Cells 2000,* www.fuelcells.org/fuel/fct/goingon.shtml. last updated August 5, 1998.
[72] *Fuel Cells 2000,* www.fuelcells.org/fuel/fct/goingon.shtml. last updated August 5, 1998.

Volkswagen/Volvo

In a joint project, Volvo and Volkswagen have announced plans for a methanol-fueled PEM fuel cell hybrid "Golf"-type car to be on the road by 1999.[73] Volvo report FC has big problems with weight, accessories, cost, and the need to advance the technology in every way.[74] Volvo participates in the EU supported FEVER project.

Ford Motor Corporation

Ford has established its P2000 program to produce a light weight, highly advanced family sedan. The P2000 concept vehicle will act as a platform for a variety of advanced drivetrains, including fuel cells. In December 1997, Ford announced that it will bring its electric vehicle technology and US$420 million to a new international fuel cell vehicle alliance with Ballard and Daimler-Benz.[75] Ford previously has used fuel cells from Energy Partners, Plug Power and International Fuel Cells, but Ford's partnership with Damler-Benz and Ballard means that it will use Ballard's stacks in its vehicles.

Mazda

The Mazda FCV program began in 1990 with a golf cart built for testing. This proof-of-concept car equipped with Ballard PEM cells with maximum power output of 8.1 kW was shown in 1992. In December 1997, Mazda showed its Demio subcompact FCEV with hydrogen-based fuel cell supplemented for power surge by an ultracapacitor. Hydrogen is stored as a metal hydride. A small air compressor feeds in air. The stack is more compact than usual. Much volume was saved by eliminating the external air humidifier normally installed on PEM fuel cells. The fuel cell is rated at 20 kW while the ultracapacitor can deliver bursts additional power of upp to 40 kW. Ford is the major shareholder in Mazda, but this fuel cell program is independent of the Ford development agreement with Daimler-Benz and Ballard Power Systems, known as The Alliance.[76] The Alliance uses methanol fuelled full fuel cell vehicle with 75 kW fuel cell stack from Ballard, while Mazda's Demio is a hydrogen fuelled hybrid car using a 20 kW fuel cell produced in house. Mazda has no clear commercializing plan for its fuel cell car.

General Motors

GM is working with Delphi and Ballard to develop fuel cell engines. In January 1998, GM unveiled an advanced model of a fuel cell drivetrain, and officials stated the company's intent to have a "production ready" fuel cell vehicle by 2004. GM is currently testing the feasibility of integrating a fuel processor — which would extract hydrogen from methanol — with the fuel cell engine, and hopes to finish testing of a proof-of-concept vehicle by 1999.[77] According to GM's own estimation several hundred million dollars will be required over the relatively near term to establish a technology leadership position, and the growth and corporate consolidation of GM's fuel cell activities in a dedicated organization make clear that GM intends to be among the leaders. The corporation appears fully committed to the development and commercialization of fuel cell electric vehicles if it can be done.[78]

Opel

General Motor's German subsidiary, Opel, has shown a fuel cell version of its Sintra sport utility vehicle at the Geneva Auto Show in March 1998.[79]

Opel's goal is to commercialize FCV by 2004. GM is focusing much of its fuel cell R & D at Opel's Global Alternative Propulsion Center in Germay.[80]

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73 *Fuel Cells 2000,* www.fuelcells.org/fuel/fct/goingon.shtml. last updated August 5, 1998.

74 *ELECTRIC VEHICLE PROGRESS* 15/8 98.

75 *Fuel Cells 2000,* www.fuelcells.org/fuel/fct/goingon.shtml. last updated August 5, 1998

76 *ELECTRIC VEHICLE PROGRESS* 1/3 98.

77 *Fuel Cells 2000,* www.fuelcells.org/fuel/fct/goingon.shtml. last updated August 5, 1998.

78 Kalhammer, et. al., 1998.

79 *Fuel Cells 2000,* www.fuelcells.org/fuel/fct/goingon.shtml. last updated August 5, 1998.

Chrysler
Chrysler Corporation had said the most likely source of hydrogen for the first fuel cells in electric vehicles would be gasoline because it was so widely available. Chrysler had worked with Delphi Automotive Systems to develop a fuel cell engine system for the car. In early 1997, Chrysler unveiled a full-size model of a fuel cell vehicle that would run on gasoline. The fuel cell system utilizes a fuel reformer, developed by Arthur D. Little, Inc., which converts gasoline and other liquid fuels to hydrogen on-board the automobile. Chrysler had also worked with Allied Signals and the oil industry. Chrysler had expressed the hope that it could have a working vehicle by 1999, with commercialization possible by 2015 in mid-size cars. In 1998, Chrysler and Daimler-Benz merged to form DaimlerChrysler.[81] Recently, Chrysler announced that it would suspend its fuel cell program.[82]

Toyota
In October 1996, Toyota unveiled a pre-production fuel cell vehicle based on its RAV4L V sport utility vehicle. The vehicle ran on hydrogen stored on-board in solid form in a hydrogen-absorbing metal alloy developed by Toyota. Toyota uses a hybrid configuration relying on batteries for acceleration. One year later, Toyota unveiled a new, methanol-fueled version of its FCEV. The car, operating on a PEM fuel cell with a fuel reformer, has a range of 500km (310mi) on a full tank. A Toyota executive said the company's focus would be on hydrogen or methanol as fuels for its vehicles, with methanol being the preferred option since the existing infrastructure for gasoline could easily be converted to methanol distribution.[83] An important aspect of Toyota's approach is that their fuel cell will be part of a hybrid vehicle power system which will use a nickel-metal hydride battery and an electric drive train much like the RAV4 EV. The hybrid battery will reduce the demand for rapid response (including cold start) and peak power of the fuel cell engine. Consistent with this, the fuel cell engine will be rated at 25kW compared to the more typical 50-60kW of other developers. The battery will be capable of about 25kW as well, for a total peak power output of 50kW. The drawbacks of hybrid drive systems (greater system complexity and the cost of the battery apparently) are judged acceptable by Toyota, perhaps on the basis of the experience with, and expectations for the Prius hybrid vehicle.[84]

Honda
Honda's PEM fuel cell program, started in 1989, to date has not sought much publicity. In Honda's corporate view, fuel cell electric vehicles offer the best prospects for minimizing or, in the longer term, perhaps eliminating both, air pollutant and greenhouse gas emissions. In Honda's view, the fuel cell will eventually replace the internal combustion engine although no time frame was mentioned. Consistent with the potential importance of the fuel cell and Honda's strong engineering orientation, Honda staff believe that they must master all aspects of this new power source technology. Similar to Toyota's, Honda's fuel cell development program is therefore carried out in-house at this time; make-or-buy decisions will come once Honda's competitiveness can be assessed against the capabilities and costs of outside suppliers of fuel cell components and subsystems. Honda staff emphasized that their work still is R&D to establish the core technologies for a future fuel cell engine. The currently committed resources (about 30 staff plus modern lab-level component fabrication and stack testing facilities) are consistent with this but likely to increase in the near future. Assuming continued R&D success, Honda anticipates entering an approximately 5-year phase of subsystem integration and power plant field tests. The implication from this is that, given complete success, FCEV commercialization could begin around 2005/06 , but in Honda's view the timing of market penetration is likely to be different in the U.S., Japan, the European Community and Asia, reflecting significant socio-economic differences. Despite the

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[80] *Jidousha kougaku*, September 98.
[81] *Fuel Cells 2000,* www.fuelcells.org/fuel/fct/goingon.shtml. last updated August 5, 1998.
[82] *Automotive New Europe*, September 14, 1998.
[83] *Fuel Cells 2000,* www.fuelcells.org/fuel/fct/goingon.shtml. last updated August 5, 1998.
[84] Kalhammer, et. al., 1998.

anticipated challenges, Honda is committed to make the necessary investments in technology development, engineering, manufacturing development and production facilities because of the ultimate potential of FCEVs.[85] In July 1998, Honda's president announced the company plans to develop a fuel cell vehicle by 2003.[86]

Nissan

Nissan Motor Corp. has unveiled a prototype fuel cell-powered, hybrid-electric vehicle and says it plans to start selling fuel-cell vehicles by 2003-2005, reports Nihon Keizai Shimbun. The vehicles will use fuel cells developed by Ballard Power Systems and incorporate on-board reformers that convert methanol to hydrogen. The fuel-cell vehicle also uses a lithium-ion battery pack, as does the Nissan Altra EV that the automaker is currently testing in the United States.[87]

ZEVCO

ZEVCO received an order from the borough of Westminster, London, for the first of several battery-augmented hybrid vans powered by alkaline fuel cells. The first van, delivered in April 1998, cost approximately US$67,000. The borough plans to set up two hydrogen refuelling stations, and may order 20-50 more of the vans, at an expected cost of about half of the original.[88]

ZEVCO's fuel cell-powered London taxi is equipped with a 5 kW alkaline fuel cell which charges the cab's battery. ZEVCO has plans to upgrade the fuel cells to 10 kW making it comparable in power to diesel taxis. There are many advantages to the new taxi, accordingb to Nick Abson, CEO of ZEVCO. The total lifetime running cost of the vehicle is estimated to be $85,000 versus $134,000 for the standard diesel version. Hydrogen fuel cells cut fuel-operating costs by half, making them cheaper than independent battery and fuel cell systems. Other advantages to ZEVCO's hydrogen fuel cell include: lower maintenance costs; lower driver health costs; and reduced environmental damage compared to traditional vehicles. ZEVCO believes it has found the first viable alternative to diesel power, and predicts by the year 2005 that hydrogen fuel powered cars will make a major entrance into the vehicle market throughout Europe and the U.S.[89]

Georgetown University

Georgetown University is working with Ballard, International Fuel Cells, the bus manufacturer NOVABUS, and others under a U.S. Department of Transportation contract to develop full size transit buses powered by PEM and phosphoric acid fuel cells. Georgetown managed the first modern U.S. fuel cell vehicle demonstration. It delivered three buses beginning in 1991, powered by phosphoric acid fuel cells, under a contract with the Department of Energy. In 1998, Georgetown University unveiled a second-generation fuel cell bus which runs on liquid methanol.[90]

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[85] Kalhammer, et. al., 1998.
[86] *Fuel Cells 2000,* www.fuelcells.org/fuel/fct/goingon.shtml. last updated August 5, 1998.
[87] *Calstart News Note* 09/02/98.
[88] *Fuel Cells 2000,* www.fuelcells.org/fuel/fct/goingon.shtml. last updated August 5, 1998.
[89] *Oxy-Fuel News*, September 7, 1998.
[90] *Fuel Cells 2000,* www.fuelcells.org/fuel/fct/goingon.shtml. last updated August 5, 1998.

Strategic alliances for Fuel Cell Vehicles

Why are alliances needed?

Ballard Power Systems says about its alliance strategy:

> Ballard's objective is to be first to market. To achieve this, we form strategic partnerships with global market leaders. This strategy combines Ballard's leadership in fuel cells and fuel cell systems with our partners' financial commitment and product engineering, manufacturing, marketing, distribution, and service capabilities, enabling us to advance deliberately, with reduced risk. By being first to market, the Ballard Fuel Cell will set the standard for those that follow.[91]

Ballard has core technologies. Its object is to be first to market with reduced risk. What it wants is to ally with some global market leaders who have financial, product engineering, manufacturing, marketing, distribution, and service capabilities. Chris Fay, chief of the British Shell, said at the launch of the ZEVCO taxi, Westminster, 30 July 1998:

> The launch of Zevco's hydrogen powered Millennium taxi, a zero emissions vehicle, gives us an exciting glimpse of the future. Not so very long ago, this type of event would have been unthinkable. But working together, energy companies, car manufacturers and niche market specialists such as Zevco, are pushing back the technological barriers of what can be achieved. Further developments in fuel technology and vehicle manufacturing will need creativity, initiative and risk taking - precisely the qualities demonstrated by Zevco, with support from the City of Westminster, ... And that applies to all of us - central and local government, energy companies, manufacturers, and crucially, consumers. One thing is certain. Long-term improvements in air quality can only come about through positive partnership between government, regulators, manufacturers, the energy industry and consumers. Partnership is the key.

This oil company executive wants to establish a partnership between government, regulators, manufacturers, the energy industry and consumers.
American Methanol Institute, the trade association for the methanol industry in the USA established in 1989, and its member companies produce roughly one-half of the world's supply of methanol, says:

> A number of strategic alliances have already been formed to support the introduction of fuel cell and alternative fuel vehicles. Broad-based strategic partnerships that involve the automotive, methanol, natural gas, and oil industries, along with government, should be encouraged.[92]

The maximal alliance seems to consist of a fuel cell manufacturer like Ballard, a catalyst manufacturer like Johnson Matthey, a polymer resin manufacturer like DuPont, an automobile manufacturer like Mercedes-Benz, an oil company like Shell, a methanol manufacturer like Methanex, some governments, some academic organizations, and customers. All but polymer resin manufacturers and most of customers (who don't know yet what is going on) have expressed their wish to participate in some kind of alliances.
The only significant player who may feel that not invited to the party is the electric utility industry who is afraid that the progress reports of fuel cell vehicles can be used to kill pure electric by reducing motivations for the building up of infrastructure for battery-powered EVs. Rick Tempchin, director of electric transportation for the Edison Electric Institute (EEI, the industry association of the investor-owned electric utility companies) pointed out that electric vehicles would just be starting to built, and said, "Rather than wait another decade for reasonable priced fuel cell vehicles, the U.S. can benefit in short order from amazing clean air technology available now. Electric cars and trucks are available from the world's top manufacturers this year."[93]

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91 Ballard Power Systems Inc. *1997 Annual Report.*

92 *The Promise of Methanol Fuel Cell Vehicles 1998.*

93 *ELECTRIC VEHICLE PROGRESS* 1/12 97.

Further, in a statement on Electric Vehicles in 1998 and Beyond, EEI concluded that fuel cell/gasoline systems have distinct disadvantages. The EEI is particularly against gasoline-powered fuel cell vehicles. The EEI means that they are likely to be more costly than battery drive systems, they are likely to be far more complex to maintain than pure electric-drive autos, and they continue our reliance on imported oil. In addition, by relying on gasoline, the public is left with the problems of evaporative emissions in refuelling and storage, fuel spills at service stations, refineries and transport points, oil and fuel leaks and emissions at refineries, and oil spills from pipe lines and oil tankers, like the Exxon Valdez.[94]

Seven types of alliances

Generally speaking, there may exist following seven types of alliances.
• Merger. A typical example of a merger is that of between Daimler-Benz and Chrysler.
• Acquisition. VW has acquired Skoda and Rolls/Roys. Toyota is going to acquit its subsidiary Daihatsu. International Fuel Cells' involvement with PEM technology began in 1985 with acquisition of General Electrics' solid polymer electrolyte technology and business. Daimler-Benz's engagement in the fuel cell technology began with its (internal) acquisition of Dornier, which had been working with fuel cells for the European space project.
• Strategic Shareholding. – Daimler-Benz and Ford have become strategic shareholders in Ballard Power Systems. Toshiba has become a strategic shareholder of International Fuel Cells.
• Joint venture. Matsushita Battery Co. and Toyota have a joint venture, Panasonic EV Energy, for development and sales of NiMH batteries. GM/Ovonic has established in the U.S. for the same purpose.
• National R & D partnerships - The U.S. DOE's fuel cell programs, the battery consortium, USABC, and president Clinton's PNGV are such partnerships.
• Limited Strategic partnerships. An example of this is the GM/Toyota EV 'inductive' charging infrastructure partnership that has been announced in June 1998. Ford and Honda also have announced their 'conductive' charging partnership in the same month.
• Inter-governmental co-operation for evaluations of new technologies. Canada and the states of New Jersey and California have agreed to jointly run environmental evaluations of the performance of a range of technologies. Job 1 will be to evaluate fuel cells built by Ballard Generation Systems in Canada.[95]

Important alliances for fuel cell vehicles

The Ballard/Daimler-Benz/Ford Alliance
The most widely known alliance is that of between Ballard, Daimler-Benz, and Ford (often called simply 'the Alliance'). The Alliance has been built up by two steps.

In 1997, Daimler-Benz became a strategic shareholder in Ballard, and two joint venture companies were established. This strategic alliance included the purchase by Daimler-Benz of a 25% minority equity interest in Ballard and establishment of DBB Fuel Cell Engines, with a mission to develop and manufacture transportation fuel cell systems, and Ballard Automotive, with a mandate to market automotive fuel cells and fuel cell systems to car, bus, and truck manufacturers globally. Ballard Power System will develop, manufacture, and supply fuel cells for the alliance as well as for integration by automakers who choose to develop their own fuel cell engines.

In December 1997, Ford Motor Company announced that it would join the Ballard/Daimler-Benz alliance. Under the term of transaction, Ford will acquire a 15 % interest in Ballard, reducing Daimler-Benz's interest to 20%. Ford will acquire 22% interest in DBB Fuel Cell Engines and establish a new joint venture with Daimler-Benz and Ballard to commercialize electric drive-trains primarily for vehicles. Ford will also become a partner in Ballard Automotive.[96]

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[94] *ELECTRIC VEHICLE PROGRESS* 1/4 98
[95] *ELECTRIC VEHICLE PROGRESS* 15/7 1998.
[96] *Ballard Annual Report 1997.*

In August 1998, a new company to develop electric drivetrains for fuel cell-powered vehicles - Ecostar Electric Drive Systems Co. - has formally been named and launched by Ford Motor Co. and its fuel-cell partners Daimler-Benz and Ballard Power Systems. Ford is the majority owner in Ecostar; Ballard and Daimler-Benz own 21 and 17 percent, respectively. The company intends to have its fuel-cell powertrains in commercially available vehicles by 2004.[97]

The Ballard Power Systems can best be described as Strategic Shareholding, and DBB Fuel Cell Engines, Ecostar Electric Drive Systems, and Ballard Automotive as Joint Ventures. The Ballard-Daimler/Benz-Ford Alliance Structures is described bellow:[98]

Table 1 — The Ballard-Daimler/Benz-Ford Alliance Structures
(B=Ballard Power Systems, DB = Daimler-Benz AG, F = Ford Motor Co.)

	The 1997 B-DB alliance	The 1998 B-DB-F alliance
Ballard Power Systems	B 75%; DB 25% (Total Can$800 m = US$560 m)	B 65%; DB 20%; F 15% (Total Can$1,973 m =US$1,381 m)
DBB Fuel Cell Engines	B 1/3; DB 2/3	B 27%; DB 51%; F 22% (Total Can$530 m =US$371 m)
Ballard Automotive	B 50%; DB 50%	probably B 1/3; DB 1/3; F 1/3
Ecostar Electric Drive Systems		B 21%; DB 17%; F; 62% (Total Can$326 m = US$228 m)

The table above shows that the value of Ballard Power Systems has increased from 1997 to 1998 by 147%. Ballard's share in this alliance is Can$1,494 m, Daimler-Benz's share Can$720.5 m, and Ford's share Can$614.5 m. The total of Can$2,829 m is equal to US$1,980 m. (Ballard Automobile is not included in these figures.)

Ballard's contribution to the Alliance is its fuel cell technology. What can Daimler-Benz contribute to the Alliance? In CARB Fuel Cell Panel's view, these are:

> With assistance of Daimler-Benz manufacturing experts, manufacturing processes are being standardized, documented, and computerized, and engineers at the Ballard plant site work closely with manufacturing groups at DB to convert these techniques into manufacturing methods.[99]

It is, in another word, the modern mass-production method.

What is Ford's contribution to the Alliance? Ford's role is defined as the commercializing of electric drive-trains primarily for vehicles. Daimler-Benz can do this as well as Ford can. There is a kind of redundancy here. A thinkable explanation is that Ford desperately needs Ballard's fuel cell technology, and Ballard and Daimler-Benz need Ford's money. In the meantime, there are two more redundancies — Chrysler and Mazda. Chrysler has been developing gasoline-powered fuel cell vehicles. The merger between it and Daimler-Benz has automatically made Chrysler a member of the Alliance. In September 1998, Chrysler announced that it suspends work on fuel cell.[100] It implies that a strong proponent of the gasoline-powered fuel cell has stepped out. Mazda is controlled by Ford, but it has own fuel cell vehicle program. In December 1997, Mazda showed its Demio subcompact FCEV equipped with a 20 kW hydrogen-based fuel cell supplemented for power surge by an ultracapacitor. Mazda's fuel cell program is independent of the Ford

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97 *Calstart News Note* 08/06/98.

98 The presented figures are taken from *Ballard Annual Report 1997*, several issues of *Calstart News Note*, Kalhammer, et. al., 1998 , and Hart & Bauen.

99 Kalhammer, et. al., 1998.

100 *Automotive News Europe*, 14 September 1998.

development agreement with Daimler-Benz and Ballard Power Systems.[101] As Mazda has no clear commercializing plan for its fuel cell vehicle it seems more likely that it joins the Alliance and contributes to it with its packaging technology (Demio FCV is the most compact fuel cell powered passenger car ever made) and its internal humidier technology than it proceeds further with its own program.

The GM/Toyota (non-existing) fuel cell alliance
There have been many speculations about another big fuel cell alliance between General Motors and Toyota. In June 1998, GM and Toyota announced plans to jointly develop a new inductive charging system for electric vehicles.[102] Several newspapers reported that a joint fuel cell development program agreement was included in this GM/Toyota deal.
Later on, this was denied by Toyota. Toyota points out that only EV charging deal with GM has been discussed and nothing else. Toyota also cooperates with VW in the vehicle recycling issue, but not in the fuel cell issue.

FEVER
FEVER (Fuel cell Electric Vehicle of Extended Range) started 1994 under the European Program for Joule. A 30 kW PEM fuel cell engine developed by De Nora is installed in a Renault station wagon. Stored liquid hydrogen is used. FEVER uses a hybrid configuration using a NiMH battery pack. Renault (France), DeNora (Italy), Ecole des Mines de Paris (France), Ansaldo (Italy), Air Liquide (France), and Volvo (Sweden) participate in this EU supported R & D partnership.[103] It is not quite sure that this R & D partnership is going to be developed to the level of a commercializing alliance like the Ballard/Daimler-Benz/Ford Alliance. Today, FEVER is far behind the Alliance.

Staying outside of the Alliance?

Which options do those auto manufacturers who are not joining in the Alliance have? These are:

A. Develop own fuel cell engine in house or in partnerships with others.

B. Those who want to develop own fuel cell engines can buy fuel cells from Ballard Power Systems.

C. Those who want to purchase DBB fuel cell engines can do so from Ballard Automotive.

D. Find another fuel cell manufacturer and work together with it.

E. Do not invest in the fuel cell technology.

The option A is the most expensive and most risky option. But, if a company's primary goal is, as Ballard, Daimler-Benz, Honda and Toyota have declared, to be first to market and set the standard for those that follow, this option is the one that must be chosen. Those who choose the option B need to invest heavier in the technology than those who choose the option C, but they will be able to sell their products with greater added value. The option D is the least expensive option, but the potential risk to become a loser in the next century may be large. Toyota seems to have chosen the option A, but it may consider the option D, too. Honda, Nissan and GM/Opel are combining the options A and the option B. Chrysler had been pursuing the options A and B, but it has now chosen the option E, but without risking to become a loser because it has merged with Daimler-Benz. Ford had been pursuing options B and D. Ford had worked with the fuel cell makers, Ballard, International Fuel Cells and Mechanical Technology Incorporated. Today, Ford is a partner in the Alliance, but it seems to play a more aggressive role than Chrysler. Recently, Ford announced that

[101] *ELECTRIC VEHICLE PROGRESS* 1/3 98.
[102] *Calstart News Note* 06/01/98.
[103] *ELECTRIC VEHICLE PROGRESS* 1/1 98 and 15/7 98.

it intends to become the environmental leader in the auto industry. As part of its multi-pronged initiatives, it would be conducting real-world tests of a fuel cell-powered, mid-size car early next year, is developing a hybrid-electric vehicle, and is expected to announce plans for a light-weight aluminium car that is more fuel-efficient. Ford says it will also introduce clean vehicle technology before it is required. New Ford Chairman William Clay Ford, Jr. - great-grandson of the company's founder and considered by many to carry a strong environmental ethic - made the announcements.[104]

Oil industry's changing attitude against fuel cells

Texaco's Chairman and CEO Peter Bijur said at the World Energy Council's 17th Congress in Houston, in September 1998, that the days of the traditional oil company are numbered, in part because of emerging technologies such as fuel cells for transportation. His comments came to attendees of "I believe we are living through the last days of the traditional oil company," Bijur said. Among the things he sees forcing a change upon the oil industry are new transportation technologies - such as vehicles powered by fuel cells rather than gasoline - and countries with emerging economies that Bijur expects to "exert more control over their natural resources." Rather than take an ownership interest in oil efforts in new areas, he predicts the oil firms of the future will increasingly offer technical expertise. "An oil company's value will shift from the value of its reserves to the value of its knowledge," Bijur said.[105]

Oil refining-industry executives have also been told to expect a 30 percent decline in the demand for lubricants by the year 2015 as a result of fuel-cell cars, according to oil-industry consulting-firm Kline & Co. The announcement to a National Petroleum Refiners Association conference in March 1998 caused the biggest stir of the conference, where refiners were also told that fuel-cell vehicles require no engine oil, which accounts for nearly 85 percent of the lubricants currently used in passenger-car applications. Citing rapid advances in fuel-cell technology, Thomas F. Glenn, the consulting firm's marketing manager, said, "It would be easy to interpret the current industry dynamics as 'doom and gloom,' and for those unable or unwilling to adapt to change, this may be true. For others, however, the changes and challenges offer an opportunity to capture market share by offering products and services that provide measurable performance advantages."[106] A crisis awareness may be spreading among the oil companies. Besides, the oil industry in Europe is under a strong pressure to reduce sulfur content in gasoline. It is the European automobile industry who is pressuring.[107] The auto industry means that without cleaner gasoline no cleaner air, and also that the oil industry hitherto has done too little for the environment. Low sulfer content gasoline is needed for direct injection gasoline engines to work, and ultra-low or zero sulfer gasoline is needed for fuel cell engines to work.

In September 1998, Shell and Texaco has decided to work together in Europe. Royal Dutch/Shell and Texaco announced an alliance that will combine the two companies' refining and marketing businesses in Europe, reports the New York Times. Aside from gasoline, the agreement could have future implications for the distribution of alternative fuels such as hydrogen in Europe. Together, Shell and Texaco will operate 15,938 gas stations throughout the region. Both companies hope the alliance will save them $200 million a year.[108]

In the recent years, several alliances between Automobile manufacturers and oil companies for fuel cell technologies and fuels for fuel cells are announced.

In May 1997, two oil companies, Arco and Exxon, announced that they are teaming with General Motors to develop a fuel cell for hybrid electric vehicles that will convert gasoline to hydrogen on-board the vehicle, reports the Los Angeles Times. This is reportedly the first time the automaker has been involved in a joint-venture fuel cell project with an oil company. Atlantic

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[104] *Calstart News Note* 09/24/98.
[105] *Calstart News Note* 09/15/98.
[106] *Calstart News Note* 03/24/98.
[107] *AUTOMOTIVE ENVIRONMENT ANALYST* Feb. 98 p. 5; *AUTOMOTIVE ENVIRONMENT ANALYST* April 98 p. 15.
[108] *Calstart News Note* 09/04/98.

Richfield (Arco) subsidiary Arco Products Corp. and Exxon Research & Engineering Co. will lend their fuel-processing experience to the two-year effort. If feasibility is indicated, the project is likely to be extended.[109]

Ford Motor Co. and Mobil Corp. announced in March 1998 a "broad-based" strategic alliance to speed the development and market integration of advanced fuel and vehicle technologies. The two will collaborate on development of fuel-processor technology to allow fuel cells to run on existing fuels such as gasoline and on cleaner-burning, direct-injection diesel engines and fuel. The two are exploring both fuel reformers located on-board vehicles and those that could be located at existing gasoline stations. Also, in the near term, Ford and Mobil will jointly develop marketing strategies for natural gas and other alternative fuel-powered vehicles (AFVs) Ford already builds.[110]

In August 1998, Shell also annouced that it teams with DBB Fuel Cell Engines on fuel cell Cars. Two weeks after Shell announced it will explore the use of hydrogen as a transportation fuel, the Royal Dutch/Shell Group has struck a deal with a Daimler-Benz unit to jointly research fuel-cell technology, reports Reuters. DBB Fuel Cell Engines GmbH, is a joint venture between Ballard Power Systems, Daimler-Benz, and Ford Motor Co.. Shell has reportedly developed a technique to convert liquid fuels into a hydrogen-rich gas. According to a statement jointly issued by Shell and DBB, "The result could be a car which has the environmental advantages of fuel-cell power plus the convenience of filling up at an existing petrol (gasoline) station."[111]

Shell is not a beginner in the fuel cell business. In the 1960s, Keith Williams at the Shell Research and Technology Centre at Thornton led the design team of the first UK fuel-cell car.[112] And, the development of a direct methanol fuel cell for automotive use was the objective of a project at Shell, UK during the late 1970s and early 1980s.[113]

Discussions

CARB Fuel Cell Panel summerizes the current fuel cell vehicle development situation as follows:

In summary, major efforts are underway in the North America, Europe and Japan to develop PEM fuel cell technology and systems for automobile propulsion. They are being undertaken by the organizations whose participation and leadership is essential if a commercially viable automotive fuel cell electric engine and vehicle is to emerge: leading automobile manufactures with track records in advanced automotive technology, including the development of electric and hybrid vehicles. Equally important, the world's leaders in PEM fuel cell technology are, or will be, participating in key alliances with these manufacturers. The integrated efforts are supported by well-focused government R&D programs of significant size (especially in the United States), and they draw on the advanced technology leadership of a growing number of organizations who look to PEM automotive fuel cells as a potentially large business opportunity for their specialized products and skills. In the Panel's estimate, the R&D investments made to date and the commitments for next few years by major fuel cell developers and automobile manufacturers already are between $1.5 and 2 billion, and additional resources (both, financial resources and technical capabilities) are likely to be committed as programs move increasingly from R&D into the larger and more expensive phases of engine systems integration and evaluation/testing, engineering of component, subsystem and system technologies for low cost mass production, and development of the required manufacturing processes. The efforts to date already have resulted in major technical advances, especially in PEM fuel cell stack technology but also in other critical subsystem areas.

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109 *Calstart News Note* 05/21/97.

110 *Calstart News Note* 03/05/98; *ELECTRIC VEHICLE PROGRESS* 1/4 98.

111 *Calstart News Note* 08/17/98.

112 Chris Fay's speech at the launch of the Zevco taxi, Westminster, 30 July 1998.

113 Transport research COST 302 Prospects for electric vehicles in Europe, European seminar, Brussels, 15 and 16 October 1987, Introductory statements of the rapporteurs and summaries of the sessions, edited by F. Fabre, A. Klose, Commission of the European Communities. D-G for Transport & D-G for Science, Research and Development, 1988 p. 6.

Probably more important than any comparisons of program status is that major steps are still ahead even for the most advanced programs before confident predictions are possible on the commercial prospects of fuel cell electric engines and vehicles, and still more time will be required until FCEVs can be launched. At this time, the most compelling arguments for the Panel's cautious optimism about these prospects are that remarkable technical advances have been achieved in a relatively short time, and that the promise of the fuel cell as a new, fundamentally cleaner and more efficient automobile engine is being pursued with an unprecedented combination of resources by powerful organizations acting in their own interest and with strong public support. The Panel, therefore, considers the statements of several major automobile manufacturers that they expect to have production-ready fuel cell electric vehicles by the year 2004 as bona fide expressions of the automakers' plans and confidence. Given the current status, the steps still ahead, and the limited time available for their completion, success at every turn and manufacturing investment decisions at the earliest possible times will be required to commercialize fuel cell electric engines and vehicles in a short 6 years from now.[114]

The Fuel Cell Panel's 'cautious optimism' seems to be based on Ballard's and Daimler-Benz's openness and dynamic engagement. We cannot but agree with the Panel. It does seem very likely that Ballard will be successful in launching the series production of the 75 kW, 1.4 kW/litre fuel cell stack by 2004. It will be mounted on Daimler-Benz's class A body and on Ford's super lightweight P2000 body. Daimler-Benz apply the full fuel cell configuration. Ford may apply the full or eventually hybrid configuration. Ford's P2000 fuel cell car will probably have a better performance than Daimler-Benz's A class fuel cell car, but more expensive. General Motors/Opel will apply the hybrid configuration, using a 50 kW fuel cell stack from Ballard or another fuel cell manufacturer and a NiMH battery pack from GM/Ovonic. GM may mount this hybrid drivetrain on its EV-1 body. EV-1's 'T-bone' space for batteries may excellently suites to a fuel cell stack, a fuel reformer, and some batteries. The fuel cell stack will be much lighter than those batteries that GM currently uses. It will be a very fast car, but it is a two-seater car with a limited market. GM needs a four-seater model. Opel may use its Sintra van body. It is much larger than the fuel cell powred EV-1.

The strength of the Japanese auto manufacturers is their quickness to launch a series production once they have locked-in a final design. Apparently, Toyota's and Honda's own fuel cells are not as advanced as Ballard's. Their stacks have not reached the power density level of 0.5 kW/litre, while Ballard is soon going reach the 1.4 kW/litre level. Besides, by the Summer 1998, Toyota has manufactured only 10 fuel cell stacks, while Ballard has delivered more than 500. Traditionally, the Japanese auto manufacturers develop all new technologies in-house in order to test all possible aspects out, and to reach a high system integration level. When they are ready for series production they usually put them out to some component suppliers, who have eventually been developing the same kind of technologies. (Aishin Seiki is developing own fuel cell system.) As the auto manufacturers keep technological competence in-house, they can negotiate with the component suppliers from a strong position. Toyota may use its RAV4 body, but it is not likely that the body design will be attractive enough in 2004. Honda's president declared that the company will be the first to market — already in 2003. Honda may then be forced to use Ballard's fuel cell stack.

The Ballard/Daimler-Benz/Ford Alliance, GM/Opel, Toyota, and Honda doubtlessly have capacities to commercialize fuel cell vehicles by 2004/5.
Their investment cost will be moderate $2 billion to $3 billion each under the coming 3 to 4 years. Such a small manufacturer as Volvo has recently invested more than $4 billion in the development and marketing of a traditional gasoline car, C70.

The greatest barrier for the successful introduction of fuel cell vehicles seems to be the fuel supply problem. Fuel suppliers must decide on new investment of tens and hundreds of $ billions. The current situation is:

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[114] CARB Fuel Cell Panel Report.

• The automobile manufacturers want to use methanol, especially now when Chrysler, the foremost proponent of the gasoline-fuelled fuel cell engine, has left the game board.
• The methanol industry is very interested in this global fuel cell game. It says that it can produce enough methanol, and that there are prenty of natural resources to produce methanol many years ahead. A methanol production plant costs only several hundred million dollars and takes 3 years to build. Unfortunately, the methanol industry has not infrastructure for distribution of methanol to customers.
• The oil industry has the world-wide infrastructure for fuel distribution, and it also has natural gas, from which most methanol is made today. But, it does not seem to be interested in methanol. The oil industry is more interested in hydrogen, which is much more expensive to produce and distribute than methanol.

During the recent two years, three promising oil company/automobile company partnerships are annouced:

• The Arco/Exxon/GM agreement, announced in May 1997, to develop a fuel cell for hybrid electric vehicles that will convert gasoline to hydrogen on-board.[115]
• The Mobil/Ford agreement, announced in March 1998, to build up a "broad-based" strategic alliance to speed the development and market integration of advanced fuel and vehicle technologies, including development of fuel-processor technology to allow fuel cells to run on existing fuels such as gasoline.[116]
• The Shell/DBB Fuel Cell Engines agreement to jointly research fuel-cell technology. Shell has reportedly developed a technique to convert liquid fuels into a hydrogen-rich gas. According to a statement jointly issued by Shell and DBB, "The result could be a car which has the environmental advantages of fuel-cell power plus the convenience of filling up at an existing petrol (gasoline) station."[117]

All three deal about the development of technology to use gasoline in fuel cells. It is rather clear for anyone what these oil companies want. Daimler-Benz is talking both to the oil industry and the methanol industry, and Ballard has an agreement with the world's largest methanol producer, Methanex, but they are not enough. We may have some reasons to recall what happened in the 1970s and 1980s. As the response to the Clean Air Act Amendment of 1970 (the Muskie-Bill), the automobile industry, together with some catalyst makers and electric companies, developed the three-way catalyst technology. The three-way catalyst could work only with un-leaded gasoline. In Japan and California the oil industry, rather quickly, began to distribute the un-leaded gasoline, but the oil industry resisted very hard to do so in the whole USA. General Motors became then forced to drive an aggressive lobby activities to bring the U.S. government to persuade the oil industry to introduce the un-leaded gasoline. It delayed until 1986, when the Muskie Bill was implemented in the whole USA. In California and Japan it could be implemented already in 1977 and 1978, respectively.[118]

(1998.09.30)

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[115] *Calstart News Note* 05/21/97.

[116] *Calstart News Note* 03/05/98; *ELECTRIC VEHICLE PROGRESS* 1/4 98.

[117] *Calstart News Note* 08/17/98.

[118] Maruo, Kanehira, 1992, "A Social-Scientific Perspective on Emission Control Issues" in *Proceedings, 25th ISATA Silver Jubilee International Symposium on Automative Technology and Automation. Dedicated Conference on the Motor Vehicle and The Environment - Demands of the Nineties and Beyond.* London, pp 49-55; Maruo, Kanehira, 1992, "The Three-Way "Catalysis" - How the General Motors Three-Way Catalyst Became the Ruling Technical Solution to the Automobile Emission Problem." In *Automobile Engineering in a Dead End: Mainstream and Alternative Developments in the 20th Century.* Publications in Human Technology No 5. University of Göteborg, pp 45-61.