STATIONARY & TRANSPORTATION FUEL CELL APPLICATIONS

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ABSTRACT

Fuel cell technology is being used in stationary power generation and as prime movers for transportation applications. Fuel cell types include Alkaline (AFC), Proton Exchange Membrane (PEMFC), Phosphoric Acid (PAFC), Molten Carbonate (MCFC) and Solid Oxide (SOFC).

Stationary PAFC technology has been commercially available for the last decade, but has made only minor inroads to power generation markets. Low temperature simple cycle PEM fuel cell technology, under development, appears to be best suited for small residential and commercial building applications. High temperature MCFC and SOFC technologies appear to be better suited for larger cogeneration plants or in hybrid configurations that marry gas turbines with fuel cells. Hybrid systems are more fuel efficient and provide higher electric output per unit weight of fuel cell power plant equipment; a key factor in making fuel cells technology economic and viable for international markets.

Fuel cell technology has been successfully demonstrated within bus fleets and development for lightweight personal automobile systems continues. The price/performance goals for transportation fuel cell systems are more aggressive than stationary applications. However, the large size of the automobile market and motivation to develop zero or near zero emission vehicles are significant drivers for development of fuel cell transportation systems. As a secondary effect, fuel cell transportation research will improve low temperature stationary fuel cell viability for commercialization.

OVERVIEW OF FUEL CELL TECHNOLOGY

Fuel cells produce direct current (DC) electricity from the electrochemical potential created by a fuel (e.g., hydrogen) and an oxidizer (e.g., oxygen). Fuel cells are similar in construction and operation as batteries, but are designed to minimize electrode sacrificing and are fed reactants continuously. Fuel cell power plants have ultra-low air emissions and can perform at high efficiency even in relatively small capacity sizes because they are not constrained by Carnot efficiencies as are heat engines such as gas turbines.

Sir William Grove constructed the first fuel cell in 1839. However, it was Francis T. Bacon that was able to build and operate the first technically practical fuel cell in 1959. In 1964 Allis-Chalmers produced a 750 W fuel cell to power a one-person underwater research vessel. In the early 1960's, the National Aeronautics and Space Administration (NASA) began incorporating fuel cells into human-operated space vehicles. The first major success of this large research effort was the use of proton exchange membrane (PEM) fuel cells in the Gemini space capsule. Electrical power for NASA's Space Shuttle Orbiter is provided by alkaline fuel cell power plants designed, developed, and built by UTC Fuel Cells (IFC), a subsidiary of United Technologies Corporation.

Fuel cell power plants contain three primary subsystems. The *fuel processor* converts raw fuel, such as natural gas, to "stack fuel"[1] such as hydrogen.[2] The *fuel cell stack*,[3] which is the heart of the plant, converts stack fuel and oxygen to DC electricity. The *power conditioner* converts DC electricity from the stack into load- or grid-compatible AC electricity. It usually consists of an inverter, transformer, and electrical protection devices. Figure 1 illustrates the fuel cell power plant subsystems.

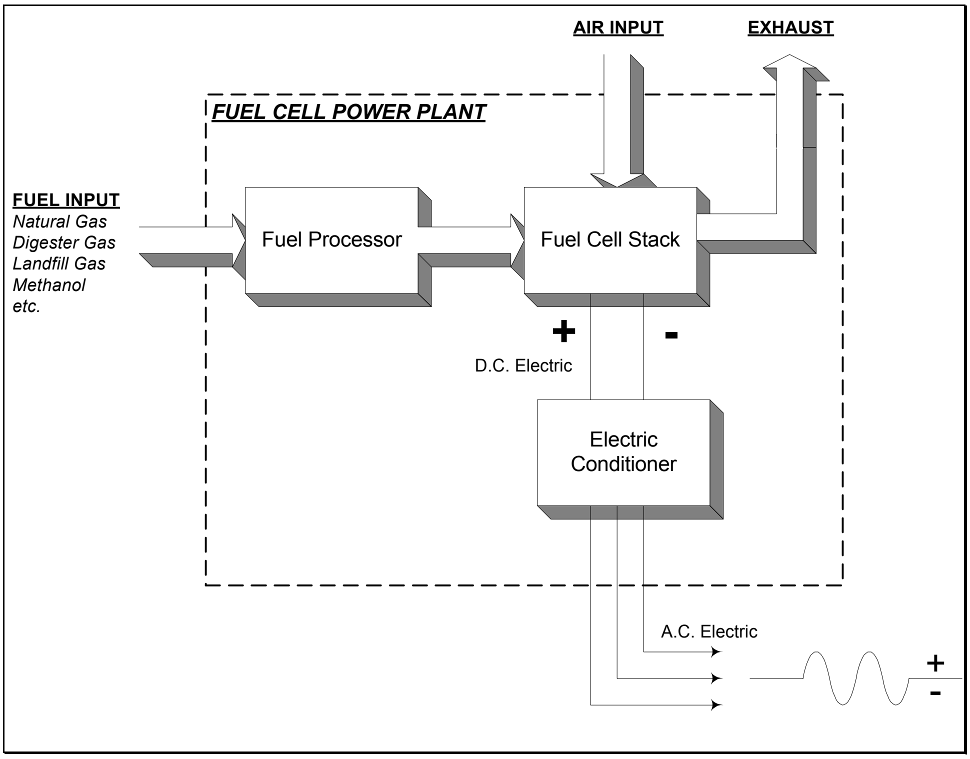

Figure 1 - Fuel Cell Power Plant System

Fuel cells are identified by the type of electrolyte they use. The main types of fuel cells are; proton exchange membrane (PEMFC), phosphoric acid (PAFC), molten carbonate (MCFC) and solid oxide (SOFC). PEMFC and SOFC have solid electrolytes in them while PAFC and MCFC have liquid electrolytes in them. Each fuel cell uses specific electrochemical reactions to produce electricity, operates at different temperatures, and use different types of catalysts to assist in the electrochemical reaction. The characteristics of each fuel cell type are summarized in Table 1.

Table 1 - Summary of Major Differences of Fuel Cell Types

Source: Fuel Cell Handbook, 5^h ed., U.S. Department of Energy

	AFC *Alkaline*	**PEMFC** *Proton Exchange Membrane*	**PAFC** *Phosphoric Acid*	**MCFC** *Molten Carbonate*	**SOFC** *Solid Oxide*
Electrolyte	Mobilized or Immobilized Potassium Hydroxide	Ion Exchange Membrane	Immobilized Liquic Phosphoric Acid	Immobilized Liquic Molten Carbonate	Ceramic
Operating Temperature	65 C - 220 C	80 C	205 C	650 C	800-1000 C now, 600-1000 C in 10 tc 15 years
Charge Carrier	OH-	H^+	H^+	$CO3^=$	$O^=$

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[1] "Stack fuel" is the fuel that is delivered to the fuel cell stack. This is typically hydrogen, but for MCFC and SOFC can also include carbon monoxide.

[2] High temperature fuel cells such as, MCFC and SOFC, can reform fuels internally using the exothermic energy given off by the stack electrochemical reaction.

[3] The "fuel cell stack" is an assembly of several single anode-electrolyte-cathode single cell units.

	AFC *Alkaline*	**PEMFC** *Proton Exchange Membrane*	**PAFC** *Phosphoric Acid*	**MCFC** *Molten Carbonate*	**SOFC** *Solid Oxide*
External Reformer Required for CH_4	Yes	Yes	Yes	No	No
Prime Cell Components	Carbon-based	Carbon-based	Graphite-based	Stainless Steel	Ceramic
Catalyst	Platinum	Platinum	Platinum	Nickel	Perovskites
Product Water Management	Evaporative	Evaporative	Evaporative	Gaseous Product	Gaseous Product
Product Heat	Process Gas + Electrolyte Calculation	Process Gas + Independent Cooling Medium	Process Gas + Independent Cooling Medium	Internal Reforming + Process Gas	Internal Reforming + Process Gas
Primary Applications	Aerospace, Marine, Transportation, Stationary, Portable	Aerospace, Transportation, Stationary, Portable	Stationary, Transportation	Stationary, Marine	Stationary, Transportation, Portable
Stack Fuel[4]	H_2	H_2	H_2	H_2, CO	H_2, CO, CH_4
Reactant Diluents	-	CH_4, CO_2, H_2O	CH_4, CO_2, H_2O	CH_4, CO_2, H_2O	CO_2, H_2O
Catalyst Poisons	CH_4, CO_2, H_2O, CO, S (H_2S & COS)	CO (>10 ppm) S (H_2S & COS) (No Studies to Date)	CO (>5,000 ppm) S (H_2S & COS) (>50 ppm)	S (H_2S & COS) (>0.5 ppm)	S (H_2S & COS) (>1.0 ppm)

Proton Exchange Membrane Fuel Cell

The PEMFC (also called the polymer electrolyte membrane fuel cell, the polymer electrolyte fuel cell (PEFC) or the solid polymer fuel cell (SPFC)) is a low temperature (80 C) fuel cell that requires relatively high purity hydrogen to generate electricity. PEMFCs have a long history in the aerospace industry where they have demonstrated operational stability, reliability, and performance. They are favored as the fuel cell power plant of choice for transportation applications because of their simple stack design, high power density, rapid start time, and ability to operate at open circuit conditions[5]. However, PEMFC low operating temperatures require expensive platinum catalysts to aid the electrochemical reaction kinetics.

The PEMFC features a hydrated solid polymer electrolyte. Because its electrolyte is solid, unlike phosphoric acid and molten carbonate fuel cells, hydrogen and oxygen gases can be sealed in better, reducing reactant crossover, a major concern in fuel cells. It also makes the stack structurally more stable and able to tolerate vibration and system acceleration well.

The PEMFC generates electricity from electrochemical reactions at the anode and cathode, which promote ionic current through the electrolyte and electron current through an external load. The by-product of these reactions is water, in liquid phase, produced on the cathode side of the fuel cell. Specifically, the chemical reactions are -

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

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

This reaction is illustrated in Figure 2.

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[4] "Stack fuel" is the fuel that is directly introduced into the anode side of the cell. This fuel is the result of processing of the raw fuel which may be natural gas, LPG, town gas, digester gas or some other raw fuel.

[5] Open circuit operation refers to the mode of fuel cell operation where the load has been disconnected from the fuel cell power plant by opening the electric delivery circuit. This stops the electron current flow from the stack creating a maximum potential condition. Most fuel cell types will experience severe and accelerated corrosion within the stack internal components in an open circuit.

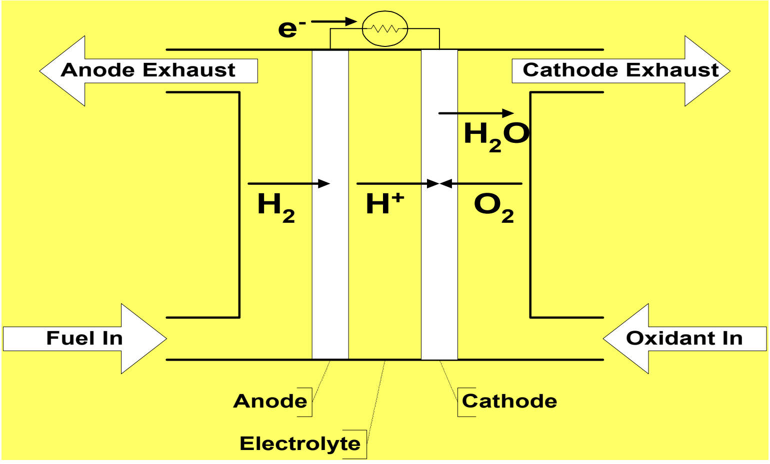

Figure 2 - PEM Fuel Cell Electrochemical Reaction

PEMFCs are sensitive to sulfur[6], carbon monoxide (CO), and carbon dioxide (CO_2). Sulfur and CO poison the catalysts on the anode side, causing degraded performance and shortened stack life. CO can be liberated from the catalyst at elevated temperatures, but this is limited by electrolyte membrane temperature tolerances. CO_2 also decreases stack performance, but to a lesser extent, and can be easily liberated from the catalyst by anode flushing with low concentration CO_2 gas or the use of low carbon fuels (e.g., natural gas). Sulfur must be removed either from the raw fuel feed stock or from the processed hydrogen-rich fuel stream before contacting the anode. Typically, for fuels like natural gas, it is easier to scrub the sulfur from the raw fuel stream using conventional absorption or adsorption beds.

Phosphoric Acid Fuel Cell

PAFCs were the first fuel cell type targeted for widespread stationary deployment. The PAFC is distinguished by the use of an acidic electrolyte and dispersed platinum catalyst supported on carbon black. PAFC electrochemistry is virtually the same as a PEMFC; a hydrogen ion is the charge carrier through the electrolyte. The PAFC stack (see Figure 3) is typically constructed of graphite resin and Teflon, which offer superior conductivity, resistance to corrosion and thermal stability. PAFC stacks operate at 200°C and are slightly more tolerant of carbon monoxide than PEMFC.

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[6] Sensitivity of the PEM stack to sulfur is assumed, although no studies have been identified that have determine tolerance limits.

Figure 3 - 200 kW PAFC Stack Assembly
(Source: Ansaldo CLC)

Molten Carbonate Fuel Cell

MCFC stacks operate at much higher temperatures (650°C) than PEMFC or PAFC stacks. This high temperature allows MCFC to avoid the use of noble metals as catalyst. Higher operating temperatures increase the electrochemical reaction rates minimizing the need for catalysts, thus theoretically lowering catalyst costs and increasing fuel cell tolerance for fuel impurities. Just the same, sulfur and chlorine compounds still pose potential sources of fuel processor and stack poisoning and must be limited in the reactant streams.

MCFCs utilize a molten carbonate electrolyte; typically calcium or potassium carbonate. The cell electrodes are made of porous nickel. The anode is sintered nickel and the cathode is nickel oxide. A nickel-cladded stainless steel separator plate is place between cells. The separator plate also contains channels for the fuel and oxidizer gases to flow. Sealing between cells is accomplished by extending the molten electrolyte near the edge of the separator plate, thus forming what is called a “wet seal”. A MCFC stack during assembly is shown in Figure 4.

Figure 4 - Assembly of Molten Carbonate Stack
(Source: Fuel Cell Energy Corp.)

MCFC electrochemistry is based on carbonate ion transport. Because of the specific electrochemistry, carbon monoxide as well as hydrogen may be utilized to produce electric power. MCFCs are also very comfortable with CO_2 in the fuel stream. In addition, their high operating temperatures permit the following.

- High temperature steam production
- Internal fuel processing
- Hybrid operation with a gas turbine

Solid Oxide Fuel Cell

Current SOFCs utilize a ceramic electrolyte made of yttria-stabilized Zirconium Oxide (ZrO_2). It operates at very high temperatures (~1,000°C), but research is underway to produce SOFC stacks that operate at lower temperatures (<800°C). There are two major stack configurations for SOFC; planar and tubular. Figure 5 illustrates both configurations.

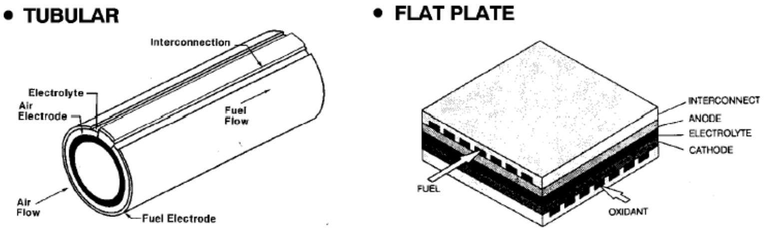

Figure 5 - SOFC Stack Configurations
(Source: US DOE)

Siemens Westinghouse is considered the leader in SOFC development. They pioneered the tubular stack configuration, shown in Figure 6, because of its advantages for high temperature dimensional stability and effective surface area. In Siemens' design, air is introduced into the center of the tube and the fuel flows on the outside of the tube.

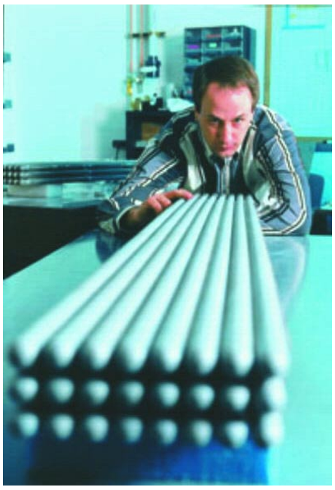

Figure 6 - Siemens Westinghouse SOFC Stack Tubes
(Source: Siemens Westinghouse)

Because of the extremely high temperature of the stack, fuel processing is conducted within the stack itself (internal reforming), like MCFC power plants.

SOFC electrochemistry is comprised of the transport of an oxygen ion through the electrolyte. This forms water vapor on the cathode side which is carried away by the fuel exhaust. This reaction is illustrated in Figure 7.

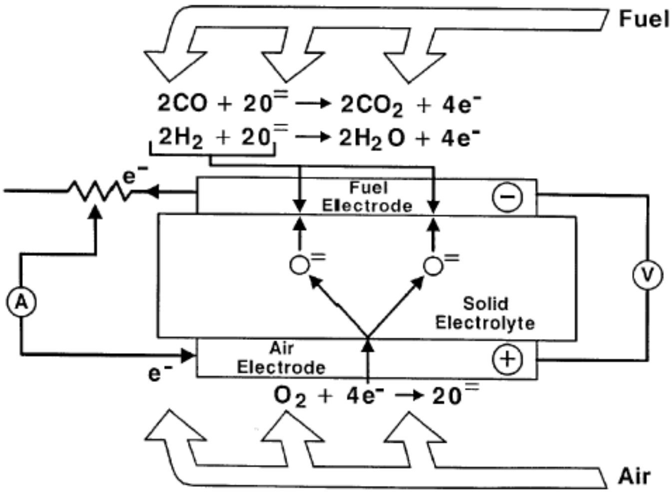

Figure 7 - SOFC Electrochemical Reaction Illustration

SOFC power plants can use CO and CH4 directly as fuels. However, they have sensitivity to sulfur, chlorine compounds and particulate matter in the reactant streams.

STATIONARY FUEL CELL APPLICATIONS

Stationary fuel cell applications can be separated into two broad categories; simple cycle and hybrid systems. Simple cycle systems have been developed for all fuel cell types. They consist of the typical fuel processing, stack, electric conditioning systems that produce compatible alternating current electricity. Hybrid fuel cells combine a Brayton cycle gas turbine with a fuel cell system; usually to increase fuel cell performance through stack pressurization while recovering energy from the exothermic stack reaction.

The stationary PEMFC power plant consists of the same primary subsystems as other fuel cell plants: stack, fuel processor, and power conditioner. However, the stack low operating temperature, water management, and intolerance of CO requires additional heat exchangers and fuel processing modules.

PEMFCs exhibit high power density, low operating temperature, mechanical stability, simple construction, and electrical compatibility with vehicle operation. In the search for a zero emission vehicle, major automobile manufacturers have move away from electric vehicles and have focused on PEMFC as a long-term technical solution.[7] However, most industry experts believe that *stationary* PEMFC applications will be commercialized before fuel cell powered vehicles.[8] Stationary PEMFC power plants will being developed for residential and commercial applications. The apparent dominant players in the stationary PEMFC market are:

- Honeywell (Formerly AlliedSignal Aerospace), for aerospace and stationary applications.
- Plug Power, LLC, a Joint Venture of Mechanical Technology, Inc., DTE Energy, and General Electric. Figure 8 illustrates a Plug Power residential fuel cell unit.

Figure 8 - Drawing of Commercial Plug Power PEMFC Fuel Cell (Source: GE MicroGen)

- IDATECH (Formerly Northwest Power Systems).
- H-Power, for rural residential applications.
- Energy Partners, which claims a low cost, high performance bipolar plate9.
- Mosaic, LLC, an Institute of Gas Technology, Endesco, and NiSource joint venture.
- UTC Fuel Cells, working with Toshiba and others on transportation and stationary applications.
- Avista Labs. Its work is primarily focused on industrial and commercial backup markets.
- Ballard Generating Systems, which is focusing on a commercial 250 kW unit and a 1-3 kW unit, in partnership with Tokyo Gas & EBARA Corporation. Figure 9 shows a Ballard 250 kW unit.

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[7] Major automobile manufacturers involved in fuel cell powered vehicle development are Daimler-Chrysler, Ford, Toyota, Mitsubishi and GM.

[8] This was confirmed by recent interviews with Gerry Merten, Sr. Project Manager, XCELLSIS (June 2, 2000) and Dr. Jack Brouwer, Assistant Director, National Fuel Cell Research Center (June 5, 2000)

[9] The “bipolar plate” separates anode-electrolyte-cathode cell units from one another within the stack. They separate the oxidant, for one cell, from the fuel in an adjacent cell and conduct electrons from one cell to another.

Figure 9 - Ballard Generating System's 250 kW PEMFC Unit

- Nuvera, a company formed after EPYX acquisition by De Nora.
- Toshiba, which is developing a 0.5 - 50 kW Stationary PEMFC.

The leader in development and commercialization of stationary PAFC power plants is UTC Fuel Cells Corporation (IFC) (a division of United Technologies Corporation). UTC Fuel Cells has been developing PAFC technology since the 1960s and is partnered with Toshiba and Ansaldo. Additional developers include Fuji Electric Corporation and Mitsubishi Corporation.

The IFC 200 kW PC25 is the only commercially available PAFC power plant. According to IFC, there are more than 200 PC25 units located in 15 countries including the U.S., Europe and Asia. Specifications for the PC25 are summarized below in Table 2.

Table 2 - IFC PC25 PAFC Specifications

Feature	Characteristics
Rated Electrical Capacity	200 kW/235kVA
Voltage and Frequency	480/277 V, 60 Hz, 3 phase 400/230 V, 50 Hz, 3 phase
Fuel Consumption	Natural gas: 2100 ft^3/h @ 4-14" water pressure Anaerobic digester gas: 3200 ft^3/hr at 60% CH_4
Efficiency (LHV Basis)	87% Total: 37% Electrical, 50% Thermal
Emissions	Negligible (< 1 ppm CO, SOx; 1 ppm NOx)
Thermal Energy Available Standard: High heat options:	 900,000 Btu/hr @ 140F 450,000 Btu/hr @ 140F & 450,000 Btu/hr @ 250F
Sound Profile	Conversational level (60dBA @ 30 ft.), acceptable for indoor installation.

Feature	Characteristics
Modular Power	Flexibility to meet redundancy requirements as well as future growth in power requirements.
Flexible Siting Options	Indoor or Outdoor installation Small footprint
Power Module: Dimensions and Weight	10' x 10' x 18' 40,000 lbs.
Cooling Module: Dimensions and Weight	4' x 14' x 4' 1700 lbs.

UTC Fuel Cell's PAFC has exhibited good fuel flexibility and has been demonstrated with a variety of fuels including natural gas, propane, digester gas, landfill gas and gasified MSW.

Toshiba has integrated PAFC plants with a number of alternative fuel applications such as -

BIOGAS

Fuel cell power plant can operate on biogas, which is generated from food industry waste water or garbage. Figure 10 shows a biogas-fueled PAFC application in Japan.

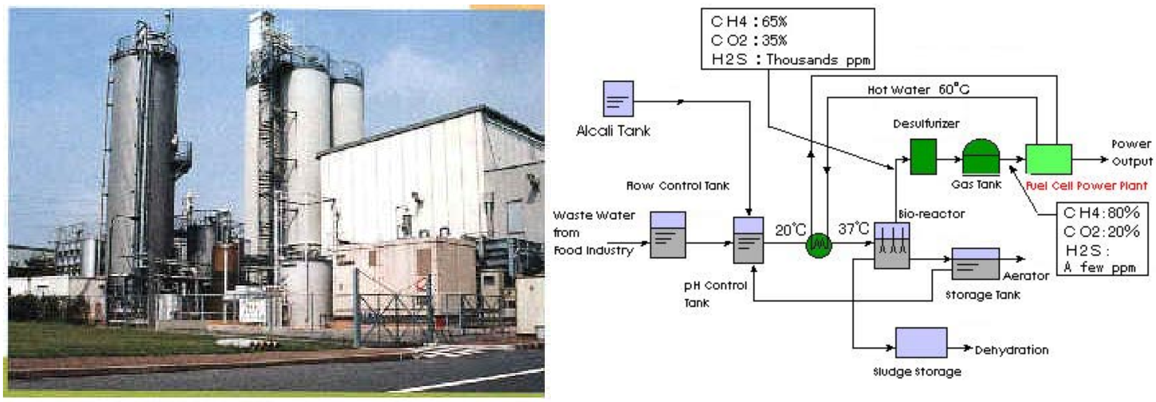

Figure 10 - Biogas Fueled PAFC at Sapporo Breweries, LTD: Chiba Brewery (Source: Toshiba)

ANAEROBIC DIGESTER GAS

Digester gas can be used by the PAFC power plant to produce electricity and to cogenerate useful thermal energy. ADG fueled PAFC plants have been installed in the U.S., Japan and Europe. See Figure 11 for process diagram.

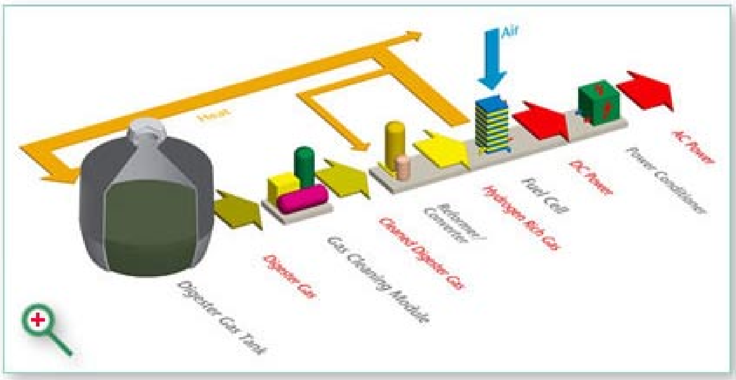

Figure 11 - PAFC Integrated Wastewater Treatment Plant in Cologne Rodenkirchen (Source: GEW Köln AG)

GASIFIED MSW

PAFC can utilize fuel gas generated from high temperature gasification of municipal waste as shown in Figure 12.

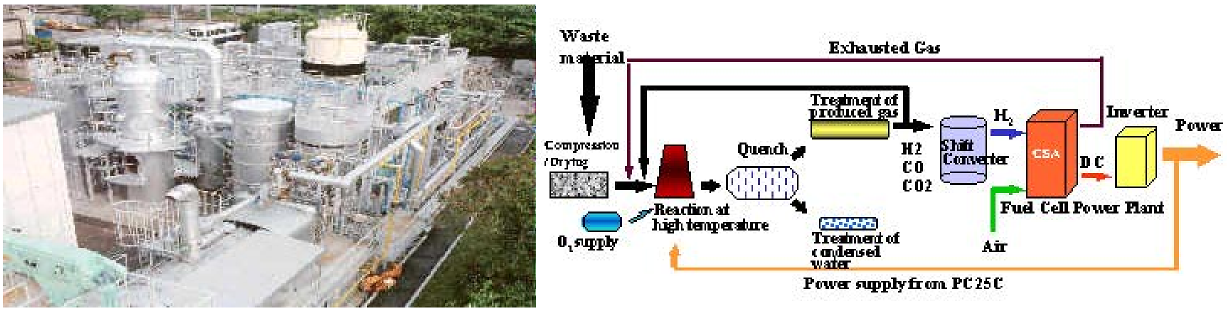

Figure 12 - Gasified MSW Fueled PAFC Power Plant

The U.S Department of Defense has installed PAFC power plants in a significant number of base facilities. Table 3 lists the DoD installation locations and operational dates.

Table 3 - DoD PAFC Fleet Location & Operation

SITE NAME	SERVICE	START DATE	OPER. HOURS	MWHRS OUTPUT	AVG KW	ELEC. EFF.	AVAIL.
MODEL B UNITS							
Naval Station Newport	Navy	01/23/1995	35,884	5,485.00	152.9	30.20%	82.00%
U.S. Army Soldier Systems Center	Army	01/27/1995	32,475	5,411.32	166.6	30.90%	74.30%
US Military Academy	Army	11/17/1995	28,534	4,777.55	167.4	31.60%	78.30%
934th Airlift Wing	Air Force	02/01/1995	26,174	4,210.26	160.9	29.00%	60.90%
Picatinny Arsenal	Army	10/11/1995	25,194	4,368.72	173.4	31.40%	67.50%
Naval Hospital MCB Camp Pendleton	Marines	10/06/1995	25,161	4,131.28	164.2	32.60%	67.60%
Naval Hospital MCAGCC Twentynine Palms	Marines	06/20/1995	20,905	3,392.95	162.3	31.50%	52.20%
Nellis AFB	Air Force	09/23/1995	16,687	2,845.94	170.5	29.60%	44.00%
Watervliet Arsenal	Army	10/29/1997	16,236	2,527.31	155.7	32.50%	85.10%
Fort Eustis	Army	09/12/1995	14,292	2,626.72	183.8	32.30%	37.40%
Kirtland AFB	Air Force	07/20/1995	14,136	2,084.22	147.4	31.20%	35.80%

SITE NAME	**SERVICE**	**START DATE**	**OPER. HOURS**	**MWHRS OUTPUT**	**AVG KW**	**ELEC. EFF.**	**AVAIL.**
Naval Oceanographic Office	Navy	10/07/1997	12,427	2,154.17	173.3	35.90%	62.90%
Pine Bluff Arsenal	Army	10/21/1997	9,099	1,689.12	185.6	34.00%	47.20%
CBC Port Hueneme	Navy	09/18/1997	6,828	1,340.97	196.4	36.40%	33.90%
B's TOTAL/AVG:			284,039	47,045.53	165.6	31.50%	59.20%
MODEL C UNITS*							
911th Airlift Wing	Air Force	12/18/1996	22,410	3,979.62	177.6		85.30%
Naval Hospital NAS Jacksonville	Navy	03/18/1997	19,726	3,662.95	185.7		80.90%
NAS Fallon	Navy	03/30/1997	19,485	3,348.44	171.8		78.20%
Subase New London	Navy	09/30/1997	18,164	3,355.27	184.7		92.10%
Fort Richardson	Army	12/17/1996	17,680	3,176.83	179.7		65.50%
Little Rock AFB	Air Force	08/17/1997	17,515	3,264.20	186.4		88.80%
Westover AFB	Air Force	09/19/1997	17,396	3,438.91	197.7		87.10%
Barksdale AFB	Air Force	07/24/1997	17,138	3,311.45	193.2		80.10%
Fort Huachuca	Army	07/28/1997	16,288	3,112.41	191.1		77.30%
Laughlin AFB	Air Force	09/16/1997	14,910	2,901.04	194.6		74.70%
US Naval Academy	Navy	09/22/1997	14,886	2,183.55	146.7		75.40%
Edwards AFB	Air Force	07/05/1997	14,483	2,796.85	193.1		63.70%
Fort Bliss	Army	10/10/1997	13,839	2,397.98	173.3		71.00%
Davis-Monthan AFB	Air Force	10/14/1997	13,780	2,599.94	188.7		69.70%
NDCEE	Other	08/14/1997	9,337	1,145.80	122.7		43.80%
C's TOTAL/AVG:			247,044	44,675.24	180.8		75.60%
B+C TOTAL/AVG:			531,084	91,720.76	172.7	N/A	67.70%

Currently the major U.S. developer of stationary MCFC is Fuel Cell Energy (FCE). Europe and Japan also have at least three developers each: Brandstofel Nederland Industries, MTU Friedrichshafen, Ansaldo, Hitachi, Ishikawajima-Harima Heavy Industries, Mitsubishi Electric Corporation and Toshiba Corporation.

A 2.9 MW MCFC power plant, shown in Figure 13, was constructed and operated in Santa Clara, CA. Its construction began in April 1994. The construction period included extensive balance-of-plant pretesting at the site while fuel cell stack manufacturing progressed simultaneously at FCMC. Start-up activities commenced in March 1996, and electricity was first generated on 25 April 1996. The demonstration lasted nearly a year and was completed March 1997.

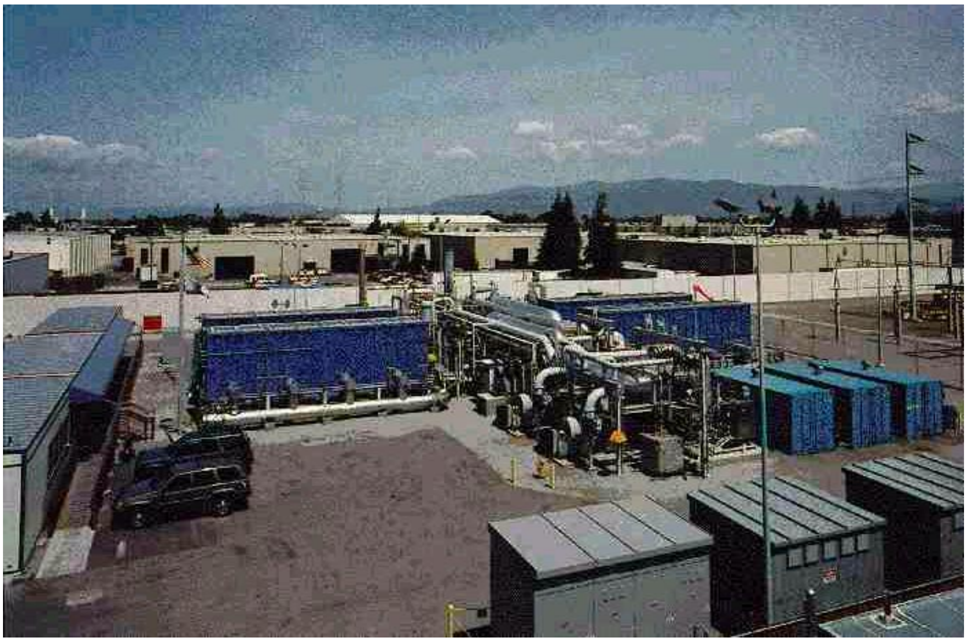

Figure 13 - Santa Clara MCFC Power Plant

FCE has MCFC plant designs in the 250 kW, 1,000 kW and 2,000 kW capacity size range. These power plants range from 47% to 50% LHV efficiency and can provide up to 400°C exhaust at 5,120 SCFM suitable for heat recovery. An illustration of FCE's one MW unit is shown in Figure 14.

Figure 14 - FCE 1 MW MCFC Power Plant
(Source: Fuel Cell Energy, Corp.)

Currently FCE has, or is in process of supplying MCFC power plants for demonstration at the following locations.

- Bielefeld, Germany - Natural gas 250 kW unit installed at University of Bielefeld
- Rhoen Klinikum, Germany - Natural gas 250 kW unit for cogeneration application in hospital.
- Mercedes-Benz, AL, USA- Auto production plant.
- Kentucky, USA - 2 MW gasified coal fueled MCFC power plant.
- Danbury, CT, USA—Initial testing of 250 kW MCFC with turbine in hybrid configuration.
- Los Angeles Dept. of Water and Power, CA - three units have been ordered.
- King County, WA, USA - 1 MW digester gas fueled MCFC.
- Marubeni Corporation - Five units to be sited for demonstration. Sites yet to be determined.

- United States Coast Guard Air Station Cape Cod in Bourne, MA – Has order one 250 kW unit installed in 2002.

MCFC are highly compatible with carbon rich fuels such as digester gas, landfill gas and gasified coal, as well as natural gas and propane. MCFC plants have been tested and operated on liquid fuels such as kerosene and distillate under US DoD funding. In these tests, a pre-reformer is added to gasify the liquid fuels before reforming[10] takes place in the stack.

Developers of planar SOFC technology include SOFCo (partnered with Ceramatec and McDermott Technology), Pacific Northwest Laboratories, AlliedSignal Aerospace and Ceramic Fuel Cells Limited. Current SOFC planar development is primarily focused on systems smaller than 100 kW.

Siemens Westinghouse is currently field testing a 300 kW SOFC hybrid units which are recording 60% LHV efficiency. The unit was installed at the University of California Irvine's National Fuel Cell Research Center in California in 2000. Siemens Westinghouse has commitments to demonstrate six units ranging from 250 kW to 1 MW in both simple and hybrid configuration. Table 4 lists SOFC historical and future demonstrations.

Table 4 - SOFC Technology Demonstrations Past, Present & Future

Time Year	Customer	Stack Rating (kWe)	Cell Length (mm)	No. of Cells/Stack	Oper.(Hrs)	Fuel
1986	TVA	0.4	300	24	1760	H_2+CO
1987	Osaka Gas	3	360	144	3012	H_2+CO
1987	Osaka Gas	3	360	144	3683	H_2+CO
1987	Tokyo Gas	3	360	144	4882	H_2+CO
1992	JGU-1	20	500	576	817	PNG
1992	Utilities-A	20	500	576	2601	PNG
1992	Utilities-B1	20	500	576	1579	PNG
1993	Utilities-B2	20	500	576	7064	PNG
1994	SCE-1	20	500	576	6015	PNG
1995	SCE-2	27	500	576	5582	PNG
1995	JGU-2	25	500	576	13194	PNG
1998	SCE-2/NFCRC	27	500	576	3394+	PNG
1997	EDB/ELSAM-1	125	1500	1152	4035	PNG
1999	EDB/ELSAM-2	125	1500	1152	10,000+	PNG
2000	SCE PSOFC/MTG	180	1500	1152	250+	PNG
2001	OPT	250	1500	2304	NA	PNG
2002	RWE 300 kW hybrid	230	1500	1728	NA	PNG
2002	Edison Spa 300 kW hybrid	230	1500	1728	NA	PNG
2003	Ft. Meade 1MW hybrid	800	1500	5760	NA	PNG
2003	EnBW 1 MW hybrid	800	1500	5760	NA	PNG
2003	Shell – CO_2 Separation	250	1500	2304	NA	PNG

Hybrid fuel cells result from the combination of fuel cell simple cycle technology with conventional

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[10] "Reforming" is a process where a fossil fuel such as natural gas is converted into a hydrogen rich gas. The process typically is used to convert natural gas using high temperature steam.

gas turbine technology. Hybrid fuel cells can be configured in a number of schemes. The most common hybrid fuel cell configuration is the replacement of the gas turbine combustor with the fuel cell stack (see Figure 15). In this configuration, the stack operates at elevated pressures and exhausts hot gases for expansion through the turbine. Hybrid fuel cells simultaneously generate electricity from the gas turbine generator and the fuel cell stack. Hybrid fuel cell gas turbine power plants have been demonstrated at efficiency levels of 60%[11] (~300 kW). There are studies to produce larger more complicated hybrid plants that can operate at +70% LHV efficiency. DOE studies indicate that a mature hybrid power plant will cost 25% less than comparably-sized fuel cells and produce electricity at 10 to 20% less cost than today's conventional power plants.[12, 13]

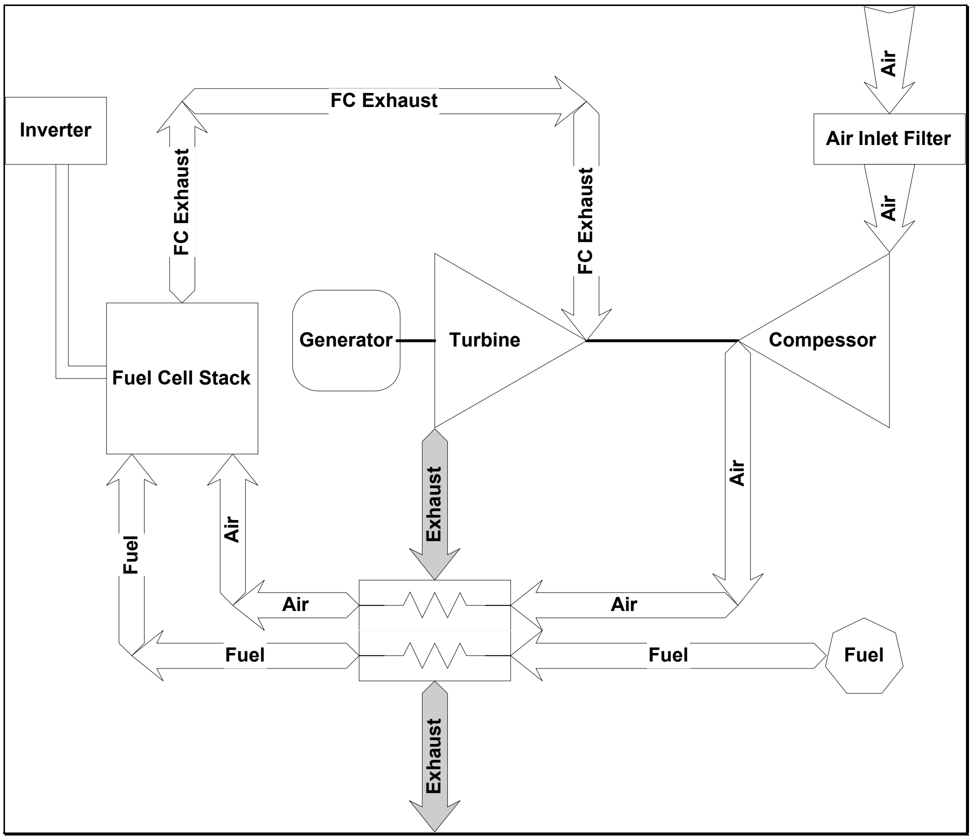

Figure 15 - Hybrid Fuel Cell Process Diagram

Siemens Westinghouse is leading the development of hybrid fuel cell technology. They have a 300 kW unit in testing at the U.C. Irvine National Fuel Cell Research Center (shown in Figure 16).

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[11] Lower heating value (LHV) efficiency. Where LHV is the energy content of the fuel when water vapor, produced during combustion, is not condensed.

[12] R. Gemmen, et al, "Technical Development Issues and Dynamic Modeling of Gas Turbine and Fuel Cell Hybrid Systems", Proceedings of the 1999 Review Conference on Fuel Cell Technology, August 1999.

[13] "Developing Power Systems for the 21st Century – Fuel Cell/ATS Hybrid Systems", U.S. Dept. of Energy, National Energy Technology Center & Office of Industrial Technologies, Project Facts for Advanced Clean/Efficient Power Systems, PS031.1999.

Figure 16 – Hybrid SOFC 300 kW Power Plant
(Source: Siemens Westinghouse)

In addition to the work with hybrid SOFC technology, Fuel Cell Energy Corporation is also pursuing a hybrid molten carbonate configuration under DOE funding. In their design, fuel cell exhaust heats compressed air. The air is then expanded and used as the fuel cell oxidant (see Figure 17) to produce expected efficiencies as high as 75% in plants up to 20 MW.

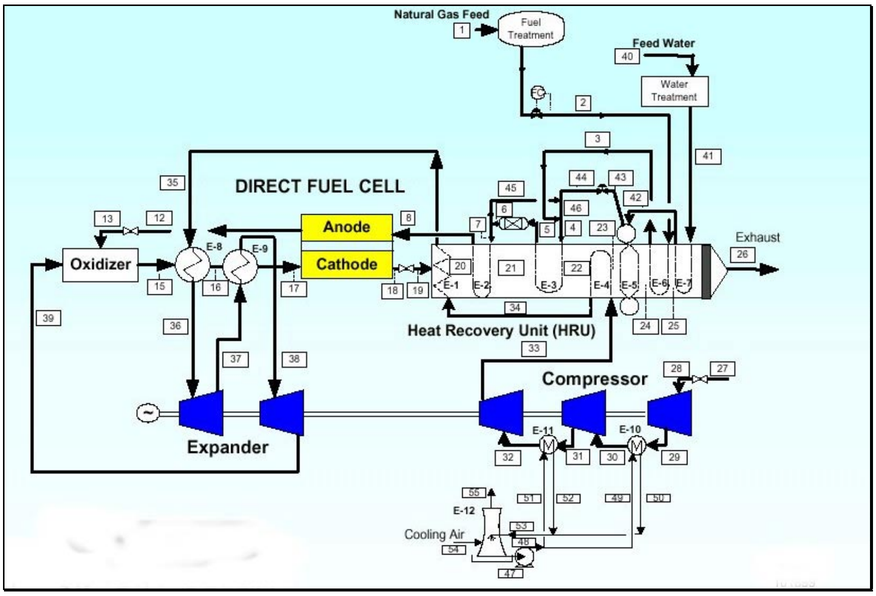

Figure 17 – MCFC Hybrid Configuration
(Source: FuelCell Energy, Corp.)

The US DOE Vision 21 program seeks to advance fuel cell technology by developing hybrid configurations that produce power plants with efficiencies exceeding 70%. This long-term vision is expected to take years to realize, but the high temperature fuel cell (SOFC and MCFC) and advanced gas turbine technologies have been developed and are improving. Work continues in hybrid cycle optimization and development of lower temperature SOFC technologies that would make them more compatible with advanced hybrid designs.

TRANSPORTATION FUEL CELL APPLICATIONS

Many areas of types transportation can benefit from the improved efficiency and reduced environmental impact of fuel cell technology. Fuel cells have been researched in a number of applications including –

- Personal Vehicles
- Buses
- Trains[14]
- Surface Ships & Submarines[15,16]
- Aircraft[17]

However, the bulk of the research and public, as well as commercial investment, have been in fuel cell personal and bus vehicle system development. Since the 1970's, there has been increased development of fuel cells for both light-duty and heavy-duty vehicles.

In the early 1970s, K. Kordesch modified a 1961 Austin A-40 two-door, four-passenger sedan to a fuel cell/battery hybrid car. This vehicle used a 6-kW alkaline fuel cell in conjunction with lead acid batteries, and operated on hydrogen carried in compressed gas cylinders mounted on the roof. The car was operated on public roads for three years and about 21,000 km.

Development work in the 1980's focused on the Proton Exchange Membrane fuel cell (PEMFC) for use in light-duty and heavy-duty vehicle propulsion. A major drive for this development was the need for clean, efficient cars, trucks, and buses that can operate on conventional fuels (gasoline, diesel), as well as renewable and alternative fuels (hydrogen, methanol, ethanol, natural gas, and other hydrocarbons).

There are several variations of how the fuel cell vehicle can be configured. The dominant configurations are enabled by the development of computer controlled power electronics, commercial introduction of the hybrid electric vehicle technology and the maturity level of essential components such as –

- Hydrogen storage
- Fuel processing
- Electric energy storage

Various vehicle configurations that have been introduced by leading automobile developers–

- direct-hydrogen fuel cell power plant and electric motor drive train
- direct-hydrogen fuel cell power plant, energy storage and electric motor drive train
- onboard fuel processor, energy storage and electric motor drive train

The typical fuel cell vehicle configuration includes the following sub-systems:

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[14] D. Duncan, et. al., "Feasibility of Fuel Cell Railway Locomotives: A Study of Energy Alternatives", Environment Canada Transportation Systems Branch, April 2001.

[15] Marine Fuel Cell Propulsion http://www.dot.gov/onedot/library/tech-share/marinefuelcell.cfm

[16] "World's Largest PEM Fuel Cell Planned for German Submarine", http://w4.siemens.de/newsline.d/pressfor/e_9834_d.htm#Meldung1

[17] News Release, "Boeing to Explore Electric Airplane", Seattle, Nov. 27, 2001.

- System Controller – controls fuel, air and power delivery.
- Fuel Cell Power Plant – Fuel Cell Stack and fuel processor.
- Power Conditioning – Inverter and DC-DC converter.
- Electric Drive – Motor controller and motor(s) (which also act as generator(s) during braking)
- Energy Storage – battery system or ultracapacitors.
- Fuel Storage – fuel tank and delivery system.

Fuel cell vehicles can utilize DC as well as AC drive systems, although the latter is more efficient, reliable and typically is less complicated. Figure 18 illustrates the detailed system configuration of a fuel cell vehicle.

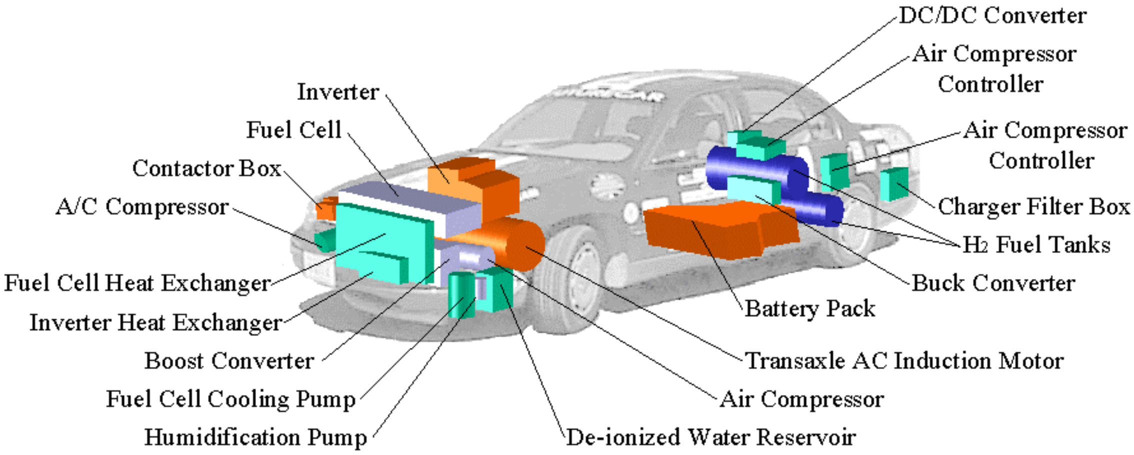

Figure 18 Integration of Fuel Cell Technology into the Hybrid Electric FutureCar (Source: Virginia Polytechnic Institute and State University Mechanical Engineering Department Blacksburg, Virginia)

Working with the U.S. Department of Transportation and Georgetown University, UTC Fuel Cells in 1998 integrated a 100-kilowatt phosphoric acid fuel cell system into a full-sized bus. The bus, capable of running on a number of fuels including methanol and compressed natural gas, is currently operating as a student shuttle service on the Georgetown campus. Figure 19 shows the system layout of the 100 kW Fuel Cell Georgetown bus.

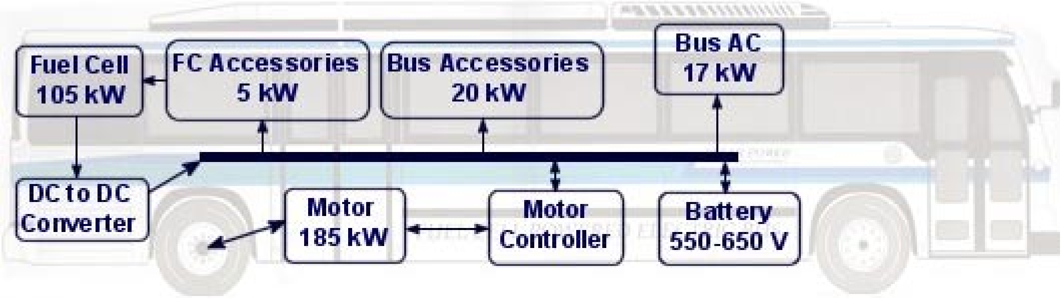

Figure 19 - IFC's 100 kW IFC Bus System Layout (Source: Georgetown University)

On the outside, many prototype fuel cell vehicles look similar to electric hybrid and conventional internal combustion automobiles. However, there are major technological differences between electric hybrid and fuel cell vehicles in the power plant and fuel systems.

Both electric hybrid and fuel cell vehicles utilize electric drive systems for propulsion and energy storage systems (i.e., batteries or ultracapacitors) to meet surge power requirements and to store electricity from regenerative braking. For the fuel cell vehicle, a fuel cell system is the prime power generator.

Illustrated in Figure 20 is a simple process diagram of the 100 kW PAFC system used in IFC's bus, currently being demonstrated at Georgetown University, Washington D.C. This system is a derivative of IFC's successful PC25 stationary fuel cell power plant. This illustration includes other important system components within the fuel cell power plant such as the stack cooling, fuel processor heat input, water management, air system and fuel supply system.

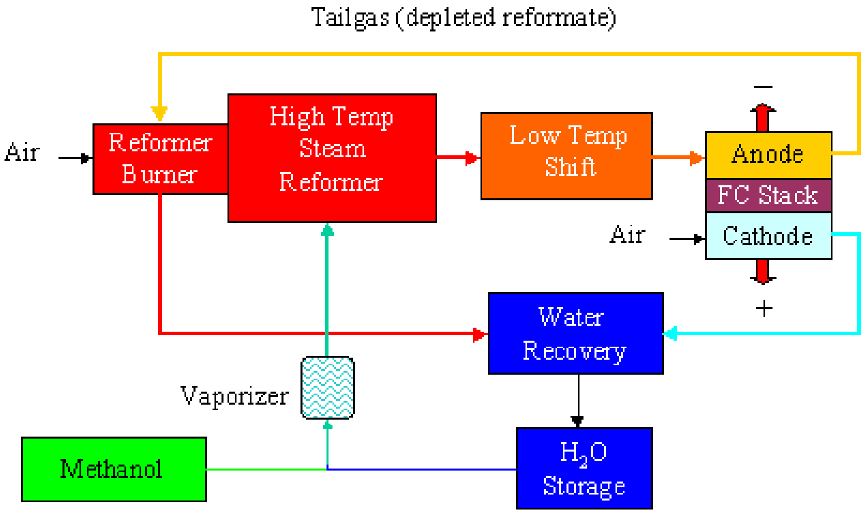

Figure 20 - IFC Bus 100 kW PAFC System
(Source: Georgetown University)

As illustrated methanol fuel is mixed with water, vaporized and then converted into hydrogen using a steam reformer and low temperature shift reactors. The hydrogen is introduced into the fuel cell stack anode and air is delivered to the cathode side of the fuel cell. The electrochemical reaction results in DC electricity being generated by the stack. In addition, cathode gas exhaust, which is heavy with water vapor, is cooled in a water recovery system. The anode exhaust, which contains some remaining free hydrogen, is used as fuel for the reformer burner.

The direct methanol fuel cell is similar to a PEMFC in that it uses a polymer membrane as an electrolyte. However, a catalyst on the DMFC anode draws hydrogen from liquid methanol, eliminating the need for a fuel reformer. It operates at relatively low temperatures (~200°F) and could potentially achieve a 34% conversion efficiency. In addition, the technology is simple and relatively inexpensive to produce.

Inside the direct methanol fuel cell (DMFC), a catalyst-coated membrane separates a negatively charged chamber filled with a methanol/water solution, and a positive charged chamber filled with air. The membrane allows hydrogen ions from the methanol to pass through from the negative to the positive side, creating an electric current.

The DMFC stack maintains two important performance characteristics that are heavily desired in automobile propulsion systems:

1. Stack has the ability to rapidly respond to stepwise changes in load.
2. Stack has the ability to start operating at temperatures slightly above freezing.

While DMFC technology offers many advantages, it is approximately 3 to 4 years behind the direct hydrogen fuel cell (DHFC) technology[18]. The major limitations for direct methanol fuel cells include[19]-

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[18] Source: Methanex

[19] Source: UTC Fuel Cells- 50-kilowatt Ambient Pressure Automotive PEM Fuel Cell and Direct Methanol Fuel Cell Development, October 27, 1997.

- Methanol crossover from the anode to the cathode across the membrane separator.
- High polarization of the anode for oxidation of methanol.

The half reactions and the overall reaction or the DMFC are presented below:

Oxidation Half Reaction: $CH_4O + H_2O \rightarrow CO_2 + 6\ H + + 6\ e-$
Reduction Half Reaction: $3\ /2\ O_2 + 6\ H + + 6\ e- \rightarrow 3\ H_2O$
Overall Reaction: $CH_4O + 3\ /2\ O_2 \rightarrow CO_2 + 2\ H_2O$

The leading developers of the DMFC technology include-

- Energy Visions Inc., Ottawa, Canada
- Forschungszentrum Jülich
- Jet Propulsion Laboratory, Pasadena, CA
- Manhattan Scientifics, Inc.
- Los Alamos National Laboratory, U.S. Department of Energy

Drive Systems

Electric motor drive systems used in prototype fuel cell vehicles are very similar to the systems employed in commercial hybrid electric vehicles. In a fuel cell vehicle, the traction motor converts electrical energy from the fuel cell generator or energy storage system into mechanical energy to propel the wheels of the vehicle. System and motor controllers and power conditioning equipment are used for power management throughout the power train system. Figure 21 illustrates the energy and control pathways between major components in an electric power train system.

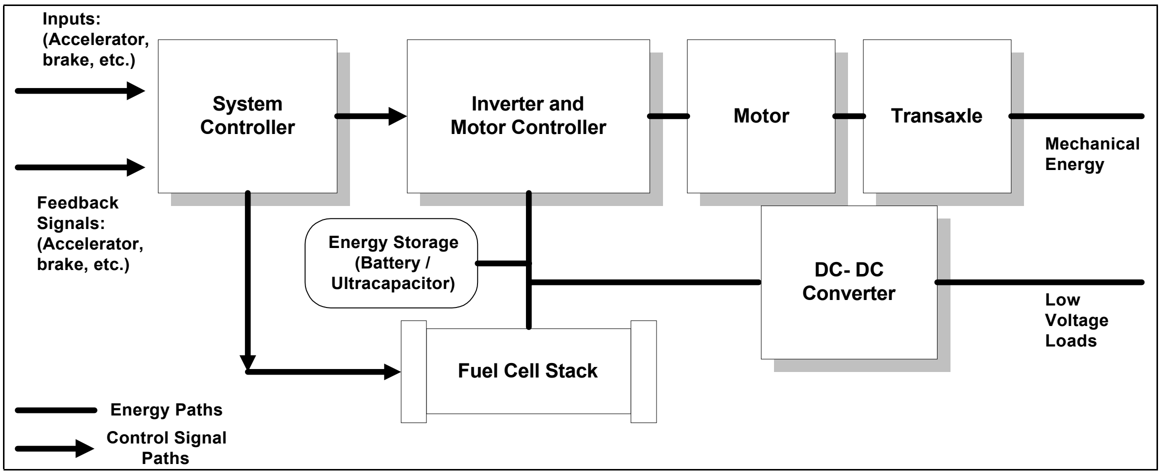

Figure 21 - Major Components in an Electric Power Train System

Motors currently being evaluated for use in fuel vehicles include AC induction, permanent magnet, and switched reluctance. For transportation applications, AC motors are difficult to optimize for power and efficiency. Permanent magnet and switched reluctance motors are more efficient, have a greater power density, weigh less and are more cost-effective[20].

The motor controller is a solid state power conditioning device that moderates the power flow to the motor and in and out of the other sub-systems. The controller uses power electronics to convert the direct current (DC) electricity generated by the fuel cell and battery system to alternating current (AC)

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[20] Source: US DOE Office of Transportation Technologies – Hybrid Electric Vehicles Electric Drive System Components and Vehicle Accessories.

and manage motor power output under varying system loads.

An important advantage of fuel cell and hybrid electric vehicles over traditional vehicles is the ability to recover a portion of the energy otherwise lost to braking (known as regenerative braking). In fuel cell vehicles, when the driver brakes, the motor becomes a generator, using the kinetic energy of the vehicle to generate electricity, which can be stored in the battery for later use.

Major developers of electric motor drive systems include –

- Ballard Electric Drives and Power Conversion Division (formerly Ecostar) - electric drive systems for the XCELLSIS Fuel Cell Bus. Figure 22 is a picture of Ballard's electric drive system used in the Xcellsis fuel cell bus.

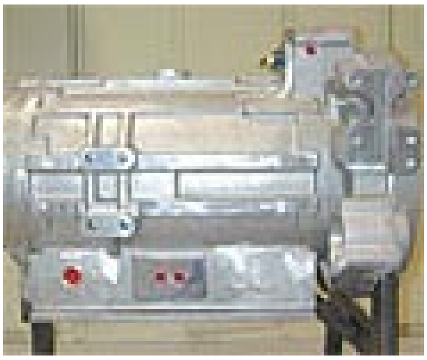

Figure 22 - Electric Drive System for Fuel Cell Bus
(Source: Ballard Electric Drives and Power Conversion Division)

- Siemens Automotive - supplies electric motor drive systems for compact and midsize vehicles and trucks weighing up to 4 tons, in the 30 to 35 kW power range. Figure 23 is a picture of Siemens' prototype electric motor drive.

Figure 23 - Siemens Electric Motor Drive Under Testing
(Source: US DOE Argonne National Laboratory)

- Enova Systems – product line includes drive systems ranging from 10 kW to 120 kW. Enova has a business affiliation with Hyundai Motor Company and Ford Motor Company.

- Allison Transmission (division of General Motors) – a leading developer of drive systems for heavy-duty vehicles. Patented the Allison Electric Drives™ technology.

- ISE Research – developed the ThunderVolt™ TB30-H drive (partnered with Thor Industries and IFC to build the ThunderPower™ fuel cell bus).

- Solectria – develops and markets vehicle motor controllers, DC-DC converters and motors up to

240 kW.

Onboard Fuel Storage

Hydrogen is the simplest and most common element in the universe. It has the highest energy content per unit of weight (52,000 British Thermal Units (Btu) per pound) of any known fuel. Under atmospheric conditions, hydrogen is a colorless, odorless, and tasteless gas. For direct-hydrogen fuel cell vehicles, onboard hydrogen can be stored as a compressed gas (~3,000 to 5,000 psi), cryogenic liquid (about –259 deg C), or binding hydrogen to solids in metal hydrides or carbon compounds. Although each storage method has desirable characteristics, no method currently satisfies all the efficiency, size, weight, cost, and safety requirements for transportation or utility use.

The Hydrogen on Demand™ system can deliver hydrogen at a rate of 800 -1000 liters per minute, at a pressure of up to 150 psi at 100% humidity. The preliminary performance levels[21] of the Natrium are as follows

- Fuel economy - 30 mpg gasoline equivalent
- 0-60 mph - 16 seconds
- Top speed - 80 mph
- Range - 300 miles
- Emissions - Zero emissions Millennium Cell and Chrysler's Liberty and

Fueling Options & Infrastructure Requirements

Although fuel cell vehicles promise fuel flexibility (depending on fuel processing technology), the choice in fuel is critical because of the potential impacts to the established vehicle fuel infrastructure. For example, onboard conversion of gasoline into hydrogen is technically challenging, but has the least impact on fuel infrastructure for many developed countries. On the other hand, the use of compressed hydrogen greatly simplifies the configuration of fuel cell vehicles, because no fuel processor is needed, but is the most difficult fuel to store and distribute.

General fuel chemical specifications are summarized in Table 5.

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[21] Source: DaimlerChrysler.

Table 5 - Candidate Fuels for Fuel Cells

Fuel	**Formula**	**Low Heat Value Btu/lb (kcal/kg)**	**Specific Weight lb/ft^3 (kg/l)**	**Specific Energy Btu/gal (kcal/l)**	**Heat of Vaporization Btu/lb (kcal/kg)**	**Vapor Pressure lb/in^2 (mm Hg)**	**Boiling Point °F (°C)**	**Approx. Flammability Range % by vol.**
Ethanol	C_2H_5OH	11,596 (6,442)	49.08 (0.789)	76,422 (5,089)	376 (210)	~1.5 (~75)	172 (78.3)	4-14
Gasoline[a]	C_8H_{18}	~19,000 (10,556)	44.78 (0.720)	114,130 (7,600)	128 (71)	~9.7 (~500)	258 (125.7)	1-6
Hydrogen (5,000 lb/in^2)	H_2	51,530 (28,628)	1.43 (0.023)	9,881 (658)	—	—	-423 (-252)	4-74
Natural gas[b] (Methane) (5,000 lb/in^2)	CH_4	21,485 (11,936)	14.31 (0.230)	41,222 (2,745)	—	—	-260 (-162)	5-13.5
Methanol	CH_3OH	8,636 (4,798)	49.26 (0.792)	57,065 (3,800)	473 (263)	~2.4 (~125)	148 (64.5)	3-36

[a] Gasoline is a blend of hydrocarbons and varies with producer, application and season. N-Octane is reasonably representative of properties except vapor pressure, which is intentionally raised through the addition of lighter specie. The vapor pressure value shown is typical of gasoline, not N-Octane.

[b] Natural gas is a mixture of gases which varies considerably depending on the source. However, methane is the primary constituent of all natural gas and its properties are reasonably representative.

Fuel Cell Vehicle Technology Status

Key developers are expected to introduce into the transportation market the first commercial light-duty fuel cell vehicle sometime in 2003, continuing through 2010. The early commercial fuel cell vehicles are expected to be direct-hydrogen fueled. Significant technological advancements have occurred in liquid fuel processing (i.e., gasoline, methanol, ethanol, etc.), but the demanding requirements (i.e., size and weight, start-up time, tolerance of impurities, etc.) associated with on-board reformers make direct-hydrogen vehicle the best candidate for early commercialization.

Key demonstrations of light-weight fuel cell vehicles are listed in Table 6.

Table 6 - Major Developers of Light-duty Fuel Cell Vehicles[22]

Manufacturer	Model	Vehicle Type	No. Passengers	Curb Wt.	GVW	Fuel Cell Type	Development Stage	Target market Introduction
BMW	750hl	sedan				PEM	demonstration	
Daihatsu	MOVE FCV	microvan	4			PEM		
DaimlerChrysler	NECAR 4	sedan	5			PEM	prototype	2004
DaimlerChrysler	NECAR 4A	sedan	5			PEM	demonstration in CA	2004
DaimlerChrysler	NECAR 5	sedan	5			PEM	concept	2004
Ford	FC5	sedan	5			PEM	concept	2004
Ford/Th!nk	Focus	sedan	5			PEM	demonstration	2004
Ford/Th!nk	P2000	sedan	5	3340		PEM	prototype	
GM	EV1	coupe	4	3030			prototype	
GM	Precept	sedan	5	1243 kg		PEM	0	
GM/Opel	Zafira	minivan					concept	2004
GM/Opel	HydroGen1 (Zafira 2nd gen)	minivan	5	~3400			concept	
Honda	FCX-V1	sedan	4			PEM	concept	2003
Honda	FCX-V2	sedan	4			PEM	prototype	2003
Honda	FCX-V3	sedan	4	1750 kg		PEM	prototype	2003
Hyundai	Santa Fe	SUV	5	3571		PEM		
Jeep	Commander	SUV	5				concept	2010?
Jeep	Commander 2	SUV	5	5715			concept	
Mazda	Demio FCEV	sedan/wagon	4				prototype	
Mazda	Premacy FC-EV	sedan/wagon	5	1850 kg			prototype testing in Japan 2/15	2005
Mitsubishi	FCV	sedan					concept	2003-2005
Mitsubishi/Mitsubishi Heavy Industries							concept	2005
Nissan	Xterra	SUV					demonstration	2003-05
Nissan	Altra based	wagon	5				concept	2003-2005
Nissan	R'nessa	SUV					concept	2003/4
Toyota	FCEV RAV4	SUV					concept	2003
Toyota	FCEV RAV4	SUV					concept	2003
VW	Bora HyMotion	sedan						
VW/Volvo		mini						
Zevco	Taxi/van						production	

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[22] Source: US DOE Office of Transportation (last updated March 2001)

Manufacturer	**Model**	Engine/motor			Batteries/Storage Device			
		Fuel	Type	Power	Make	Type	Number	Capacity
BMW	750hl	LH2/gasoline	IC engine, 5.4L, V6	204 hp				
Daihatsu	MOVE FCV	methanol	FC			NiMH		
DaimlerChrysler	NECAR 4	liquid hydrogen						
DaimlerChrysler	NECAR 4A	hydrogen						
DaimlerChrysler	NECAR 5	methanol						
Ford	FC5	methanol						
Ford/Th!nk	Focus	methanol	PEM FC by Xcellsis					
Ford/Th!nk	P2000	H2/LH2	Zetec, 2L, V4		none			
GM	EV1	methanol	AC induction motor	137hp	Ovonic	NiMH	44	
GM	Precept	hydrogen	3 phase AC induction	85 kw			28	12v
GM/Opel	Zafira	methanol						
GM/Opel	HydroGen1 (Zafira 2nd gen)	LH2	3 phase AC Sync.	56kW				
Honda	FCX-V1	hydrogen	Honda/Ballard	49kW				
Honda	FCX-V2	methanol	Honda/Ballard	49kW				
Honda	FCX-V3	hydrogen	permanent magnet AC Sychronous motor	60kw	Honda	Ultracaps		
Hyundai	Santa Fe	H2	Panther AC 3-phase induction motor (Enova)	65kW				
Jeep	Commander	gasoline/other	DC					
Jeep	Commander 2	methanol	AC induction motors (2-one front and 1 back)	82		NiMH		90kW
Mazda	Demio FCEV	hydrogen	AC syncronized motor	40kw		Ultracapacitor		
Mazda	Premacy FC-EV	methanol	AC induction	65				
Mitsubishi	FCV	methanol	Pm motor	40kW		Li ion		
Mitsubishi/Mitsubishi Heavy Industries								
Nissan	Xterra	methanol	neodymium magnet synchronous traction motor			Li ion		
Nissan	Altra based	methanol			Sony	Li ion		
Nissan	R'nessa							
Toyota	FCEV RAV4	hydrogen						
Toyota	FCEV RAV4	methanol	permanent magnet motor					
VW	Bora HyMotion	LH2	asyncronous electric motor	75kW				
VW/Volvo		methanol						
Zevco	Taxi/van	hydrogen						

		Fuel Cell			Fuel		Emissions	Regen.
Manufacturer	**Model**	Type	Number	kw	Economy	range	Level	Braking
BMW	750hl	IFC PEM (in place of regular battery)	1	5		350 km	ZEV	
Daihatsu	MOVE FCV	PEM		16				
DaimlerChrysler	NECAR 4	Ballard Mark 700	2	70		280		
DaimlerChrysler	NECAR 4A	Ballard Mark 900				120		
DaimlerChrysler	NECAR 5	Ballard Mark 900		75				
Ford	FC5	Ballard						
Ford/Th!nk	Focus	Ballard Mark 900		80		100 mi		
Ford/Th!nk	P2000	Ballard Mark 700 PEM	3	25 ea	58/81	100 mi	ZEV	n
GM	EV1				80	>300	ULEV	y
GM	Precept	PEM	400 cells	75	108	500	ZEV	
GM/Opel	Zafira							
GM/Opel	HydroGen1 (Zafira 2nd gen)	GM	195 cells	60		00 km/250		
Honda	FCX-V1	Ballard		60		112		
Honda	FCX-V2	Honda Polymer Electrolyte FC stack		60				
Honda	FCX-V3	Ballard PEM		62		112 mile	ZEV	
Hyundai	Santa Fe	IFC Series 300	single stack	75				
Jeep	Commander				50% more		90% less	
Jeep	Commander 2	Ballard Mark 700, with on-board methanol reformer	2		24	120	SULEV	y
Mazda	Demio FCEV	Polymer electrolyte (Mazda)	4	20		170	ZEV	
Mazda	Premacy FC-EV	Ballard	PEM w/reformer					
Mitsubishi	FCV	Mitsubishi group		40				
Mitsubishi/Mitsubishi Heavy Industries								
Nissan	Xterra	Ballard Mark 900						y
Nissan	Altra based	Ballard		10				y
Nissan	R'nessa							
Toyota	FCEV RAV4			25				
Toyota	FCEV RAV4			70			1/10th	y
VW	Bora HyMotion			75		220 mi	ZEV	
VW/Volvo								
Zevco	Taxi/van	Alkaline						

Manufacturer	Model	Other Charac.	Information source	Date of Introduction
BMW	750hl	dual fuel, RWD		
Daihatsu	MOVE FCV	CVT		
DaimlerChrysler	NECAR 4		Detroit free press, www.freep.com/business/qfuture18.htm	1999
DaimlerChrysler	NECAR 4A		AEI March 2001 p 67.	2000 for the Ca FCP demo
DaimlerChrysler	NECAR 5			2000
Ford	FC5		Ford news web site	Francfort 9/99
Ford/Th!nk	Focus	H2 @ 5,000 psi, 1 elec. Motor by Ecostar	EV News Dec (Energy-Futures)	
Ford/Th!nk	P2000	H2 storage in nanotubes	brochure from EVS17	
GM	EV1	batteries charge in ~2 hr	GM web site, www.gm.com/vehicles/us/innovations	
GM	Precept	chemical hydride storage		01/01/2000
GM/Opel	Zafira	demonstrator has batteries, but prod. model would not		Geneva 1997
GM/Opel	HydroGen1 (Zafira 2nd gen)		AEI March 2001, pp 68-69	Paris 1998
Honda	FCX-V1	long wheelbase, metal hydride tank for H2 storage	Automotive News	Tokyo show 11/99
Honda	FCX-V2		Automotive News	Tokyo show 11/99
Honda	FCX-V3	H2 tanks in trunk, FC starts in 10 s	H & FC Letter Nov, Honda press rel. on web	09/01/2000
Hyundai	Santa Fe		H2 & FC Letter June 2000, SAE paper 2001-01-0540	
Jeep	Commander	2 EPIC motors to provide 4WD	DaimlerChrysler web site, www.daimlerchrysler.com/specials/concept	LA 1999
Jeep	Commander 2	2 motors, on-board reformer, regen, injection molded thermoplastic body parts	DCX press release on web, Automotive News Jan 15, 01, AEI 3/01 p.66-67	10/01/2000
Mazda	Demio FCEV	ultracapacitor for extra 20 kw energy, metal hydride storage		Eco Japan 97 in Kyoto 12/97
Mazda	Premacy FC-EV		Mazda PR: www.e.mazda.co.jp	Feb-01
Mitsubishi	FCV			
Mitsubishi/Mitsubishi Heavy Industries				
Nissan	Xterra		AEI March 2001, p78	Nov-00
Nissan	Altra based		Nissan web, www.nissan=na.com/news/news_usa_051699.html	
Nissan	R'nessa			
Toyota	FCEV RAV4			
Toyota	FCEV RAV4			
VW	Bora HyMotion		AEI March 2001, p72	Nov-00
VW/Volvo				
Zevco	Taxi/van			1st demonstrated 12/99

Heavy-duty fuel cell vehicle (i.e., fuel cell transit bus) has achieved technological advancements beyond that of the light-duty automobile. This is due to the fact that mass transit buses and its associative fueling infrastructure have the necessary attributes for extensive testing and demonstration of fuel cells. These elements include[23]-

- Compatible weight/volume constraints are agreeable to existing fuel cell technology.
- Reduced emission transit buses have immediate environmental benefits to inner cities.
- Buses are centrally fueled.

---

[23] Source: Georgetown University Advanced Vehicle Program

- Structured routes and maintenance allow quantification of operational and cost issues.
- Serves as full size operational laboratory to resolve technical issues hindering automotive use.

DaimlerChrysler plans to offer the world's first commercial fuel cell buses in Europe sometime in 2002. The company plans to deliver 20 to 30 buses, based on the Citaro 12-meter city bus design. The Citaro is capable of transporting a maximum of 70 passengers. The price for each bus is expected to be $1.2 million[24]. This does not include the hydrogen fueling infrastructure which the bus operators have to pay for themselves at costs that could range anywhere from around $100,000 to $1 million.

Eight compressed hydrogen gas tanks are carried on the roof over the front axle. The 250 kW fuel cell system is located on the roof in the center, and the main electric motor is in the back. The driving range is about 186 miles, and top speed is 50 mph.

The price for a direct-hydrogen fuel cell bus is expected to decrease considerably in the future. As shown in Figure 24, the price for a cell bus in 2007 is estimated to be $367,000[25], which is approximately $100,000 more than a comparable diesel bus.

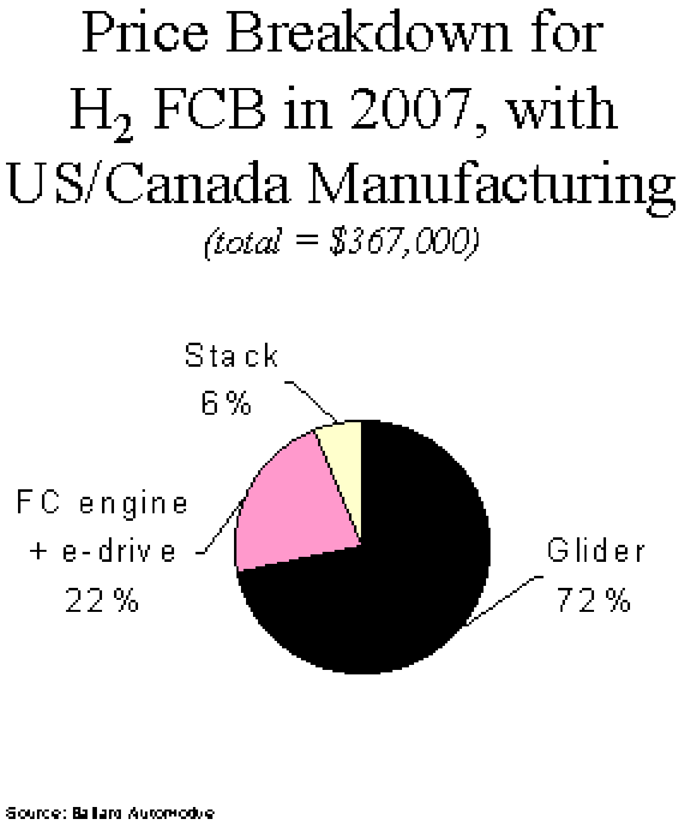

Figure 24 - Price Breakdown for Direct-Hydrogen FCB in 2007
(Source: Center for Energy and Environmental Studies, Princeton University)

However, at mass production levels the price could fall below $300,000[26]. Figure 25 compares the price of a 40-foot low-floor fuel cell and diesel bus.

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[24] Hydrogen & Fuel Cell Letter - DaimlerChrysler Offers First Commercial Fuel Cell Buses to Transit Agencies, Deliveries in 2002

[25] Center for Energy and Environmental Studies, Princeton University - Commercialization Prospects for Fuel Cell Buses - Center for Energy and Environmental Studies, Princeton University.

[26] Direct Technologies, Inc. - Presentation to UNPD/GEF – Commercialization of Fuel Cell Buses, 4/27/2000.

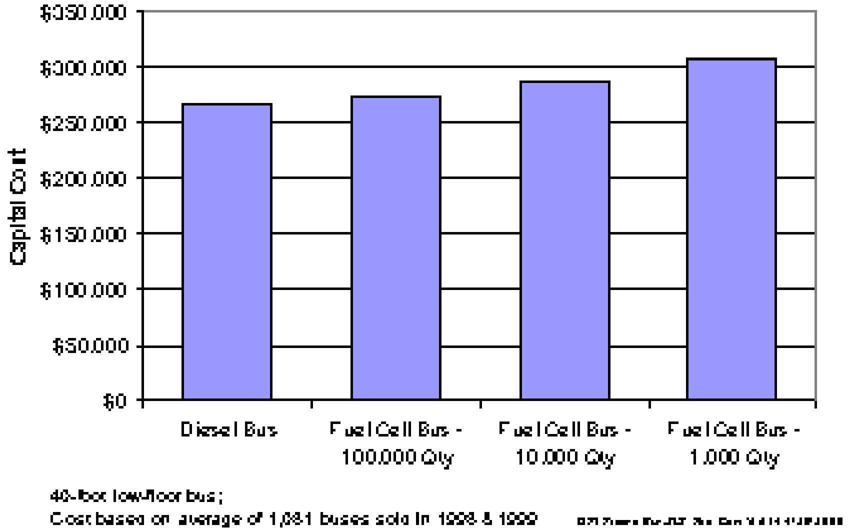

Figure 25 – Comparison of Fuel Cell Bus Cost

CONCLUSIONS

Stationary PAFC technology has been commercially available for the last decade, but has made only minor inroads to power generation markets. Low temperature simple cycle PEM fuel cell technology, under development, appears to be best suited for small residential and commercial building applications. High temperature MCFC and SOFC technologies appear to be better suited for larger cogeneration plants or in hybrid configurations that marry gas turbines with fuel cells. Hybrid systems are more fuel efficient and provide higher electric output per unit weight of fuel cell power plant equipment; a key factor in making fuel cells technology economic and viable for international markets.

Transportation fuel cell technology has been successfully demonstrated within bus fleets and developments for lightweight personal automobile systems continue. The price/performance goals for transportation fuel cell systems is more aggressive than stationary applications. However, the large size of the automobile market and motivation to develop zero or near zero emission vehicles are significant drivers for development of fuel cell transportation systems. As a secondary effect, fuel cell transportation research will improve low temperature stationary fuel cell viability for commercialization.