

1 Introduction

1.1 Fuel Cells - Relevance and Importance

‘What’s so great about fuel cells?’ should be a question synonymous with ‘What’s so great about pollution, changing the climate or running out of oil, natural gas and coal?’ As we head into the new millennium, it is time to put renewable energy and planet-friendly technology at the top of our priorities. Dawn of this new millennium witnesses a triumphal technological march centered on Fuel Cells! ‘Clean Energy’ is a technological edict that is echoing around the globe. Fuelled by concerns about environmental pollution, energy security, and climate change, the notion of a ‘clean technology’ is moving beyond the realm of scientists and engineers and into the lexicon of political and business leaders. Energy is the lifeblood of the global economy. Getting somewhere, sharing information, and producing things all require energy. Throughout the industrial age and into the information age, energy has served as the foundation for mankind’s progress. Technology is the prime propellant of growth, modernization, progress, prosperity, power and prestige. There is no escape for us from the accelerating effect and massive impact of technology on our outlook, our life styles—social and cultural— and economic structure. The greater the capacity of a nation to generate, transfer and utilize technology, the faster is the nation’s growth. The goal is development, the tool is technology and the path is science. Hence, science and technology are the chariot wheels of any development process today. Few technologies have the potential to change the world for the better as the fuel cell, which offers a potentially nonpolluting and renewable way to generate electricity. Fuel cells are efficient, clean, safe and reliable. They attract increasing commercial interest for both automotive and stationary power generation. The advent of fuel cells is powering an energy revolution.

Hydrogen represents an alternative source of energy carrier to the oil based economy. Fuel cells, harness hydrogen for energy production, and thus may lead to the transition. To fully exploit the capabilities and operational advantages, the research and development of fuel cells have to confront innumerable challenges and have to wait for a variety of technological breakthroughs. Fuel cells have the potential to satisfy future energy needs. Air and space power professionals presently review the ongoing conflicts over energy and fossil-fuel resources with the intention of making this transformation potential a reality as well as to understand the promise and limitations of fuel cell technologies, so as to take advantage of the transformation.

The attractive features of the fuel cells are:

- They are simple with the possibility of direct energy conversion
- They show efficiencies greater than the existing fuel burning engines and also work with a flat efficiency curve even at part loads
- They are silent without any rotating/moving components

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- Fuel cell power plants can be constructed in modular mode to match load and increase reliability,
- Fuel and size flexibility is possible,
- Fuel cells can be exploited for Combined Heat and Power (CHP) generation with more electricity (40%–45% and 35%–40% heat),
- They do not generate SO_x and NO_x emissions,

How fast might the energy system evolve towards hydrogen? Energy transitions were driven by growing energy demands, local scarcities, and the continual search for more abundant and accessible energy sources. The 19th century was considered to be the age of the **Steam Engine** while the 20th century is considered as the age of the **Internal Combustion Engine** and 21st century may well come to be recognized as the age of the **Fuel cells**.

1.2 Historical Highlights

In 1839, the first fuel cell was conceived by Sir William Robert Grove, a Welsh judge, inventor and physicist. He mixed hydrogen and oxygen in the presence of an electrolyte, and produced electricity and water. The invention, which later came to be known as a fuel cell, did not produce enough electricity to be useful. In 1889, the term ‘fuel cell’ was first coined by Ludwig Mond and Charles Langer, who attempted to build a working fuel cell using air and industrial coal gas. Another source states that it was William White Jaques who first coined the term ‘fuel cell.’ Jaques was also the first researcher to use phosphoric acid in the electrolyte bath. In the 1920s, fuel cell research in Germany paved the way to the development of the carbonate cycle and solid oxide fuel cells of today. In 1932, engineer Francis T Bacon began his vital research into fuels cells. Early cell designers used porous platinum electrodes and sulfuric acid as the electrolyte bath. Using platinum was expensive and using sulfuric acid was corrosive. Bacon improved on the expensive platinum catalysts with a hydrogen and oxygen cell using a less corrosive alkaline electrolyte and inexpensive nickel electrodes. It took Bacon until 1959 to perfect his design, when he demonstrated a five-kilowatt fuel cell that could power a welding machine. Francis T Bacon, a direct descendent of the other well known Francis Bacon, named his famous fuel cell design the ‘Bacon Cell’. In October of 1959, Harry Karl Ihrig, an engineer for the Allis-Chalmers Manufacturing Company, demonstrated a 20-horsepower tractor that was the first vehicle ever powered by a fuel cell.

During the early 1960s, General Electric company produced the fuel cell-based electrical power system for NASA’s Gemini and Apollo space capsules. General Electric used the principles found in the ‘Bacon Cell’ as the basis of its design. Today, the Space shuttle’s electricity is provided by fuel cells, and the same fuel cells provide drinking water for the crew. NASA decided that using nuclear reactors was too high a risk, and using batteries or solar power was too bulky to use in space vehicles. NASA has funded more than 200 research contracts exploring fuel cell technology, bringing the technology to a level now viable for the private sector. The first bus powered by a fuel cell was completed in 1993, and several fuel cell cars are now being built in Europe and in the United States. Daimler Benz and Toyota launched prototype fuel cell-powered cars in 1997.

Fuel cell development is in its fifth cycle since the past attempts often failed. Although the promise of cheap, abundant power sounds exciting, the true test comes in demonstrating practical

energy-production capability. It is not sure whether this time it will be successful and it is not clear whether we do have all the necessary advanced materials than we had in 1960 when the last cycle of development was pursued, so as to make it successful this time. However, the crucial issue now is not the technology or science (it is simply the reverse of water electrolysis) of fuel cell, but the economics. Unless this new power source can be made at a price levels wherein the applications can support, it will continue to remain as researcher's delight only. As stated earlier, there are only a few inventions that have taken so long from first demonstration to commercial use. Although William Grove first demonstrated in 1839, it was only in 1960, it was first used for US space applications. However, even today they are costly for use in other ordinary applications. A bird's eye view on historical development of fuel cell technology is given in Table 1.1.

Table 1.1 History of fuel cells—A chronology

1839	Grove-H ₂ —O ₂ fuel cell
1854	Proposal to use carbon and fats
1855	Becquerel-Carbon fuel/fused nitrate/Pt, O ₂
1877	Jablackoff-Carbon fuel/fused nitrate/cast iron, oxidant
1889	Mond and Lange-H ₂ /O ₂ cell similar to modern fuel cells, using perforated platinum electrodes; use of platinum foil covered with platinum black as catalyst; voltage developed 0.75 V.
1897	Jacques modified the fused salt cell, replacing nitrate with NaOH; cell developed IV and delivered 150 mA. Stone-Webster reported an efficiency of 85% for the above cell. Haber-Brunner demonstrated an indirect fuel cell in which H ₂ was produced by a chemical reaction.
1910	Taitebaum advocated the use of a porous diaphragm separator; addition of MnO ₂ to the positive electrode in the C/NaOH/Fe cell led to a voltage of 0.53 V, delivering a current of 0.02 A; addition of sawdust resulted in higher currents.
1911	Beutner used platinum tube electrodes containing H ₂ and O ₂ ; a lead diffuser electrode was also used; other electrolytes like HF and NaCl melts were suggested.
1912	Bantz and Ehrenbeg advocated a direct fuel cell with fused boride electrolyte, a carbon anode and a silver air cathode, the potential developed was 0.95 V but the current was negligible.
1913	Siegel improved upon the Mond-Lange cell. Since then several molten slat systems have been tried.
1911–1913	Biochemical fuel cells were strongly advocated and readvocated.
1960s	Germini and Apollo spacecraft
1980s	Space Shuttle
1990	California Air Resources Board announces zero emission vehicle mandate, requiring introduction of zero emission vehicles, and catalyzing interest in electric vehicles including fuel cell vehicles.
1993	George-town Bus demonstrated, with phosphoric acid fuel cell and onboard methanol reformer.
1993	Partnership for a New Generation of Vehicles (PNGV) announced, a government / industry partnership aimed at producing cars with three times the fuel economy of current vehicles. Big Three US automakers begin studies of options, including fuel cells.
1993	Ballard Power Systems demonstrates first hydrogen fuelled PEM fuel cell bus.
1995	Daimler-Benz demonstrates the NECAR 1, an experimental PEM fuel cell van with hydrogen storage.

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Table 1.1 (continued)

1995	Ballard Power Systems demonstrates improved hydrogen fuelled PEM fuel cell bus.
1995	Mazda demonstrates H ₂ fuelled PEM fuel cell golf cart.
1996	Toyota demonstrates experimental PEM fuel cell car with metal hydride storage.
1996	Daimler-Benz demonstrates the NECAR II, a prototype van with compressed hydrogen gas storage and Ballard fuel cell,
1997	Ballard begins demonstration of H ₂ PEM fuel cell buses in Vancouver, BC.
1997	Ballard and Daimler-Benz form US\$ 320 million joint venture to develop PEM fuel cell cars by 2005.
1997	Daimler-Benz demonstrates NECAR III , a prototype small car with PEMFC and onboard reformation of methanol.
1997	Toyota demonstrates PEM fuel cell car with onboard methanol reformer.
1997	Ford joins Daimler-Benz and Ballard in US\$ 420 million venture to commercialize PEM fuel cell car by 2004.
1998	GM announces intent to develop production ready prototype fuel cell car by 2004.
1998	Chrysler announces intent to develop production ready prototype fuel cell car by 2004 with onboard reforming of gasoline.
1998	Mobil and Ford form alliance to develop onboard fuel processors for fuel cell vehicles.
1998	Mazda joins Ballard, Daimler-Benz and Ford alliance to develop fuel cell automobiles.
1998	Ronda announces intent to develop methanol fuelled fuel cell vehicle.
1998	Nissan announces intent to develop fuel cell vehicle.
1999–2004	The developments and initiatives are too many to be listed. Only a few representative ones are given. (The selection is random and not on any priority basis.)
1999	Fuel cell Research and Innovation network Canada formed
2000	Matsuda joins Daimler Chrysler and Nisseki Mitsubishi for Fuel cell development
2000	Honda FCX-V3 and Nissan (FCV) vehicles GM H1 fuel cell vehicle
2000	EPRI's Fuel cell Program -MW PAFC Demo
2000–2002	EPRI's Fuel Program 200 kW SOFC-CT test
2001	Matsuda (FC-V3) Honda (FCX-V3/V4), Toyota (FCHV-3/4/5)
2001	Fuel cell bike by Aprilia
2001	Mazda and Daimler Chrysler first to test fuel cell vehicles on public roads in Japan, while Honda tests a new version of its fuel cell vehicle in California
2001	EPRI's Fuel cell program 250 kW MCFC application
2002	European Fuel cell group started
2002	Japan Hydrogen and Fuel Cell demonstration project
2002	Honda (FCX4) Toyota (FCHV-BUS2) Nissan (X-Trail FCV) launched
2002	S10 Gasoline Fuel cell vehicle
2002	EPRI's Fuel cell program - 5 kW PEM and SOFC tests
2003	Daihatsu (Move FCV-K-II)
2003	Avista Labs will deliver the first fuel cell to be installed
2003	National Fuel cell bus technology Initiative - accelerating the use of hydrogen in transportation
2004	Honda delivers hydrogen powered fuel cell vehicles to the Mayor of San Francisco

(EPRI - European Parliaments Research Initiative)

In more recent years, a number of manufacturers - including major auto makers and various federal agencies have supported ongoing research into the development of fuel cell technology for use in fuel cell vehicles (FCV) and other applications. Fuel cell energy is now expected to replace traditional power sources in coming years—from micro fuel cells to be used in cell phones to high-powered fuel cells for stock car racing.

However, in spite of several advantages, the fuel cells have not yet turned out to be a common source for power because of their high cost. Also endurance and reliability of high temperature units are not yet demonstrated. The technology is not yet familiar to the power sector and the necessary infrastructure is yet to be established for the fuel. However the possibility of zero emission regulation (already imposed in California and many other northern states of United States of America) can be met by the use of electric vehicles only, which means, adaptation of the fuel cells for transport applications appears to be necessary.

Automakers are on the leading edge of developing and exploiting fuel cell technology. Every major auto manufacturer has scheduled a fuel cell-based car for near-term production. Essentially, such vehicles are electric cars that do not 'plug in' each night to recharge their batteries. Rather, they generate electricity from some form of hydrogen-rich fuel. Currently, fuel cell cars and buses provide mileage ranges commensurate with those of conventional gas-powered vehicles. The principal challenges lie in making these vehicles cost-competitive with those powered by internal combustion engines and in developing a safe and efficient fuel-distribution infrastructure.

1.3 What are Fuel Cells?

Fuel cells are electrochemical devices consisting of an electrolyte, an ion containing solution, liquid or solid in contact with two electrodes (anode where the oxidation of the fuel takes place and a cathode where the reduction of oxygen occurs) capable of converting directly any consumable fuels to electrical energy through the performance of a chemical reaction. In the production of electricity through this mode the only by products are heat, carbon dioxide and water and thus can be considered to be avoiding any of the environmental side effects. The electrochemical process in the fuel cell can be efficient converting nearly 80% of the chemical energy of the fuel into electricity in contrast to the thermal power plants which give efficiency around 40%. In structure, *fuel cells* are similar to *batteries* except that in batteries the chemical energy is stored and need to be recharged or replenished as the case may be, while in the fuel cells the fuel is constantly fed to the cell so that consistent generation of electricity is ensured. Fuel cells can be constructed in modular form and hence fuel cell power plants can be erected to provide electricity for a number of applications ranging from electric vehicles to large grid connected utility power plants for stationary power for communities. A single cell normally produces a voltage around 1.0 V. To obtain higher voltages the cells have to be connected in series to form a stack. The heat rejected in the process can be used for different on-site thermal consumption which makes the fuel cells suitable for combined heat and power generation for buildings and industry. In Fig. 1.1 a single cell configuration of a fuel cell is shown.

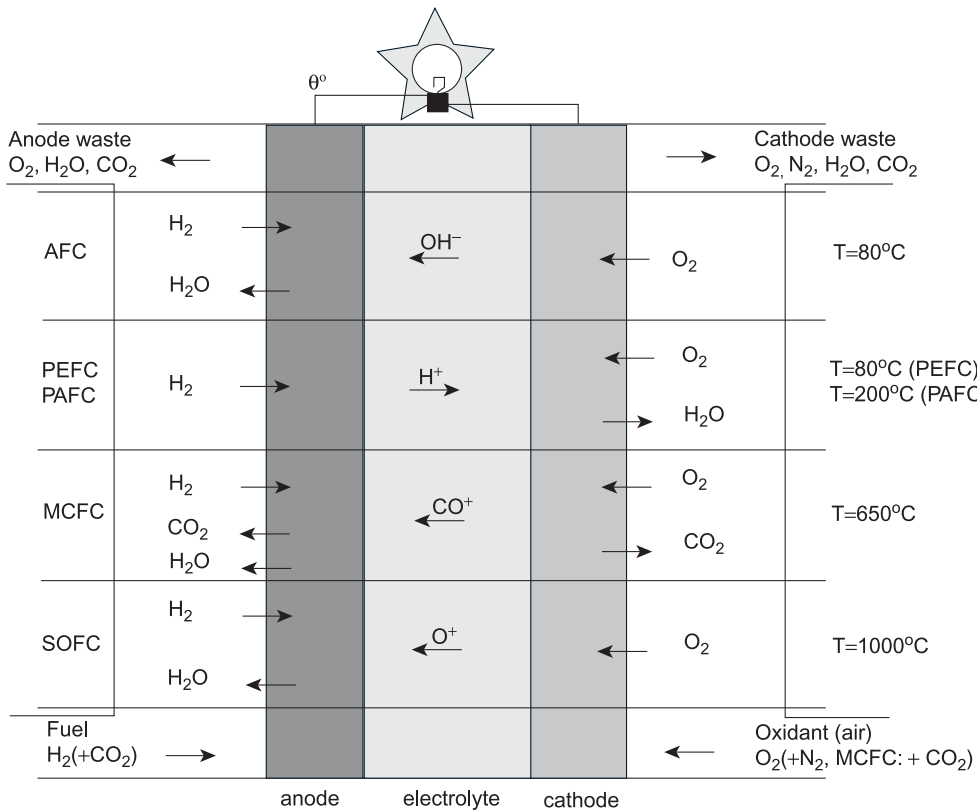


Figure 1.1 Schematic representation of a fuel cell

1.4 Fuel Cells: How do they differ from batteries?

Fuel cells have similar components and characteristics of a battery, but differ from them in several ways. A battery is an energy storage device and the extent of storage is determined by the amount of the chemical reactant stored within the battery itself. In the primary battery the maximum energy available is determined by the amount of the chemical reactant stored and will cease to produce electrical energy when the chemical reactants are consumed or discharged. However, in a secondary battery, recharging which involves transferring energy from an external source regenerates the reactants. A fuel cell however, as stated above is an energy conversion device that has theoretically the capability of producing electrical energy as long as the fuel and oxidant are supplied to the electrodes. General wear and tear, electrochemical corrosion, the material stability and malfunctioning of the components may limit the life of fuel cells.

Depending on the nature of the ionic species involved in the electrolytic cell, the direction of transport of these species can differ. Similarly the site of water (oxidized product) formation and removal can also be different. The fuel or oxidant flows over the surface of anode and cathode and

generate electrical energy by the electrochemical oxidation of the fuel (in this example hydrogen) and electrochemical reduction of the oxidant (usually oxygen). The electrolyte not only helps in the transport of the dissolved reactants to the electrodes but also conducts ionic charge between the electrodes and thus completes the electric circuit as shown in Fig. 1.1. The electrolyte can also act as a barrier to prevent fuel and oxidant gas streams to mix with each other, which will reduce the efficiency of the fuel cell. The functions of the electrodes in a fuel cell can be listed as follows:

- They provide the necessary sites where ionization and deionization reactions can take place.
- They facilitate the ion transport away from or into the three-phase interface once it is formed.
- They provide a physical barrier that separates the bulk gas phase and the electrolyte.

In order to carry out all these functions the electrode material should be both catalytically active and should be a conductive material, simultaneously porous and also should be in solid form. The porous nature should be such that it is permeable to both the electrolyte and the gases.

1.5 Fuel Choice

Appleby and Foulkes have reported that in theory any chemical substance capable of undergoing chemical oxidation and any oxidant that can be reduced can be continuously burnt or reduced galvanostatically at the anode and the cathode of a fuel cell respectively. Like combustion systems, fuel cells can use oil, natural gas, coal and methanol. These fuels, however, have to be pre-processed into a suitable hydrogen-rich form. Fuel cells can also use hydrogen obtained by electrolysis of water using stand-by electricity from photovoltaics or wind energy. Fuel cells operate at maximum efficiency, when operating on pure hydrogen and pure oxygen. Pure oxygen is very expensive, and thus air is used as the source of oxygen in most applications except where the extra cost can be justified, as in the space program. Pure hydrogen is expensive, and difficult to transport and store, therefore, like pure oxygen it is only used in special cases. Gaseous mixtures of hydrogen (H_2) and carbon dioxide (CO_2) which can be created by the 'processing' of fossil fuels or biomass are used instead of hydrogen in most commercial uses of fuel cells. The most economical sources of the necessary H_2/CO_2 fuel mixture have been found to be gaseous hydrocarbons such as natural gas and propane, light hydrocarbon liquids such as naphtha and methanol (from biomass), heavier hydrocarbon liquids such as fuel oil and coal.

Organic fuels may be used either directly or indirectly in fuel cells. In the direct method, the fuel is the anodic reactant. In the indirect method, the organic compound is reformed chemically in a separate reactor into hydrogen or a mixture of hydrogen and CO, which are then led into the anode chamber of the fuel cell. The advantage of the anode reaction is the oxidation of hydrogen, which is a well-known process in some cases. It is the reaction of a mixture of H_2 and CO at high temperatures, which is also fast. The competition at the present time between the direct and indirect methods of utilization of organic fuels lies with size, weight, cost and efficiency of the

chemical reformers for the indirect method on one hand and the electrochemical activity and cost of the electrode materials for direct oxidation on the other.

Table 1.2 lists the various fuels that can be employed as the reductant in fuel cells. It is seen from the table that hydrogen is the most promising fuel because of its maximum energy density and the maximum voltage that can be derived which is closer to the theoretical value. However, the use of hydrogen as fuel is always associated with the complexity in storing and handling, which drives one to reflect on an alternative fuel. Electrochemists are challenged to use a fuel, which is easily transportable and easily converted into energy from the liquid state. Next to hydrogen, methanol is the favoured fuel from the aspects of cost, efficiency, availability, existence in liquid state, stability, oxidizing ability, and electrical yield per gram of fuel. Though methanol has lower energy density than hydrogen, it is attractive over the other fuels, which pose other problems.

Table 1.2 Chemical and electrochemical data on various fuels

Fuel	ΔG^0 (kcal/mol)	E_{theor}^0 (V)	E_{max}^0 (V)	Energy density (kWh/kg)
Hydrogen	-56.69	1.23	1.15	32.67
Methanol	-166.80	1.21	0.98	6.13
Ammonia	-80.80	1.17	0.62	5.52
Hydrazine	-143.90	1.56	1.28	5.22
Formaldehyde	-124.70	1.35	1.15	4.82
Carbon monoxide	-61.60	1.33	1.22	2.04
Formic Acid	-68.20	1.48	1.14	1.72
Methane	-195.50	1.06	0.58	-
Propane	-503.20	1.08	0.65	-

Ammonia has limitation not only in its storage and handling but also the maximum voltage that can be derived is lesser than that of hydrogen and methanol. Hydrazine has higher theoretical cell voltage than all the other fuels, but it exhibit the problem of self decomposition leading to the mixed potential and therefore the experimental value obtained will not be truly accounted for by the complete electrochemical combustion of the fuel.

Since the other fuels such as formaldehyde, carbon monoxide and formic acid are already in their partially oxidized form, the power density derived from them will be practically lower than other fuels. The use of hydrocarbon such as methane, propane and their higher homologues required reformation to be effectively used as fuels. Carbon monoxide resulting from reforming hydrocarbons acts as a poison for anode electrocatalysts in low temperature fuel cells, and its removal from the fuel source is a challenging task. Other potential contaminants such as sulphur containing compounds may pose further and new requirements for catalysts and their development. Methanol can be electro-oxidized at a fuel cell anode either directly or indirectly. If used indirectly, methanol is initially reformed to give hydrogen in a high temperature step. The reactor required to accomplish this, however, both lowers practical power densities and rises the inherent thermal

signature of the overall power source system. As a consequence, there are strong incentives for developing fuel cells that directly oxidize methanol as a fuel in their anodic compartments.

Hydrogen has been advocated to be the fuel for fuel cell applications for the following reasons:

- It is highly reactive when suitable catalysts are used;
- It could be produced from hydrocarbons especially for terrestrial applications;
- It has the high energy density (refer to Table 1.2);
- It can be stored cryogenically for closed environment applications like space.

Similarly the choice of oxidant is gaseous oxygen since it is readily and economically available from air for terrestrial applications and can also be stored in closed environments. A three-phase interface is established among the reactants, electrolyte and the catalyst in the region of the electrode. This interface is particularly important if the electrolyte used is in liquid form. In such a fuel cell the reactant gases diffuse through a thin electrolyte film that wets portions of the electrode and react electrochemically on the electrode concerned. However, if the electrodes were to be flooded then this transport of reactant species may be restricted and hence lead to decreased electrochemical performance of the electrode.

The current debate concerns which form of hydrogen fuel are suitable and adoptable. The winner in the fuels race will determine the rate of fuel cell proliferation. Three of the main contenders at this time are pure hydrogen, methanol or other liquid hydrocarbons, and methane (natural gas), each of which presents unique challenges for fuel cell development and fuel distribution.

Not surprisingly, pure hydrogen is the most efficient fuel for these devices as shown above but presents myriad problems associated with making it viable. For example, it is not readily available in nature but most often encountered in compounds in which hydrogen atoms chemically bond to one or more other elements. Separating those bonds takes energy, thereby decreasing the relative efficiencies of fuel cells. Furthermore, the processing, storing, and distributing of pure hydrogen is difficult in the near term to become globally viable. Pure hydrogen is simply difficult to obtain, and even when one has it, a great deal of pressure and volume is necessary to store it in order to reap the energy-to-weight efficiencies. Nevertheless, when manufactured renewably (for example, solar power), pure hydrogen in a fuel cell creates a true zero-emission system, with only heat and water as by-products. In the light of the difficulties associated with producing the element in its pure form, however, most fuel cell developers turn to another alternative for their source of hydrogen.

Since the automotive industry is the primary developer of fuel cells, liquid hydrocarbons lead the way as fuel sources. In particular, considerable research involves using methanol, whose principal advantage is its similarity to gasoline and, hence, worldwide familiarity for its production, transportation, and distribution. Depending upon their source, liquid-hydrocarbon fuels can also become a renewable energy resource. Disadvantages include storage, corrosiveness, and fuel waste due to 'crossover' in the fuel cell membrane.

Regular gasoline and ethanol are just two of the available liquid-hydrocarbon alternatives, but the need for 'reformation' of the fuel prior to introduction into the fuel cell system remains to be the constant factor among all liquid sources. The reforming process extracts hydrogen from the more complex molecular structures; however, the fact that carbon monoxide and carbon dioxide can become additional by-products of the energy-production cycle makes these systems less attractive.

While the transportation industry focusses on liquid hydrocarbons, the stationary power-production industry is investigating natural gas as a source of hydrogen.

As a potential source of hydrogen for fuel cells, natural gas boasts an established delivery infrastructure and significantly reduced greenhouse-gas emissions. Outside that established infrastructure, however, the need to compress natural gas and to use special dispensing equipment reduce its appeal as a source of hydrogen. Lastly, because natural gas is nonrenewable, reliance on it as a fuel offers meager benefits for long-term energy security. But another development promises to make natural gas the fuel of the twenty-first century.

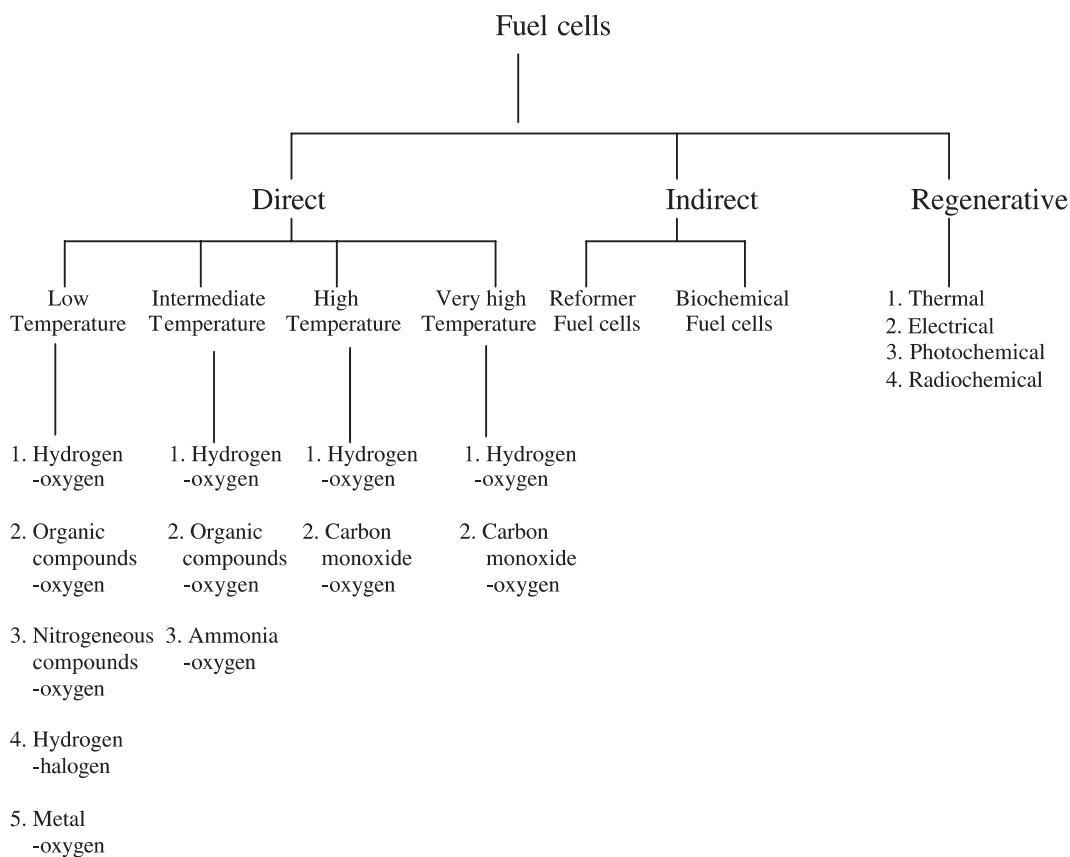
Especially worthy of mention are methane hydrates. Methane is the chief constituent of natural gas. Although no consensus exists regarding the total amount of natural gas discovered and/or producible, one may assume a reasonable figure of 5,000 trillion cubic feet. Despite tremendous obstacles, if only a small fraction of these hydrates could be recovered in the form of usable gas, the potential for natural gas as a source of energy takes on staggering dimensions. For fuel cell applications, this source presents tremendous opportunities. Whether pure hydrogen, liquid hydrocarbons, or natural gas emerges as the primary source for fuel cells, the development of each is assured.

There are three common methods of processing these hydrocarbon fuels to create the H_2/CO_2 mixtures required by fuel cells. 'Steam reforming' is a simple process involving the reaction of light hydrocarbon fuels with steam. 'Partial oxidation' is the incomplete burning of a fuel and is used to process heavier hydrocarbon liquids and coal is 'gasified', by reacting coal with oxygen and steam at high temperatures. Fuel processing can be performed at any stage before the fuel is added to the fuel cell, but it is most common to perform the processing at the 'point of use' as this eliminates the need for storage of the hydrogen rich fuel. Liquid hydrocarbons such as naphtha and methanol are preferable for transportation applications of fuel cells because they are easily transported and stored and can be steam reformed at the point of use. Large stationary fuel cell power plants are generally designed to use natural gas, fuel oil or coal as a source of fuel, depending upon local costs and availability.

1.6 Classification of Fuel Cells

Fuel cells can be classified on the basis of various parameters which include the nature and type of fuel used, whether the fuel is processed outside (external reforming) or inside (internal reforming) and the temperature of operation. A typical classification based on temperature of operation as well as in other ways is given in Scheme 1. However the most common classification of fuel cells is on the basis of electrolytes used in the fuel cell. This classification leads to

1. Proton Exchange Membrane (polymer electrolyte) Fuel cells (PEMFC)
2. Direct Methanol Fuel Cell (DMFC)
3. Alkaline Fuel Cells (AFC)
4. Phosphoric Acid Fuel Cells (PAFC)
5. Molten Carbonate Fuel Cells (MCFC)
6. Solid Oxide Fuel Cells (SOFC)



Scheme 1. Classification of fuel cells

With the exception of the direct methanol fuel cell (DMFC), characterization and nomenclature of these systems stems from the nature of electrolyte that is employed. DMFC stands alone in involving carbonaceous fuel (MeOH) fed directly to the anode; all other systems employ hydrogen as the anode fuel, either as a pure gas, or as a hydrogen-rich gaseous mixture. A catalytic steam reformer, or partial oxidation reactor, fed with fuel is used to generate the hydrogen-rich gas suitable for the fuel cell anode. The characteristics of each of these types of fuel cells are assembled in Table 1.3.

1.7 Outlook

Fuel cells are power-generating devices having a wide range of applications including stationary power generation (MW), portable power generation (kW) and transportation (kW). They appear to be a practical answer to the world's pressing need for clean and efficient power as they operate at high efficiencies and can run on a variety of fuels from solar hydrogen to methanol from biomass

Table 1.3 Typical Characteristics and other essential features of Fuel cell types

Fuel cell Type	PEMFC	AFC	PAFC	MCFC	SOFC
characteristics					
1. Operating temperature range (K)	303–353	053–373	373–493	923–1123	973–1273
2. Current density	high	high	moderate	moderate	High
3. Likely applications	Electrical utility, portable power, transportation	Military and space, residential plants	Electric utility and transportation	Electric utility	Electric utility
4. Advantages	Low temperature, quick start up, solid electrolyte reduced corrosion and management problems	High performance, simple design	High efficiency for cogeneration, can tolerate impure hydrogen fuel	High efficiency, flexibility of fuel types, internal reforming possible, CO/CO ₂ tolerant	High efficiency, flexibility of fuels, solid electrolyte reduces corrosion and management problems, internal reforming possible
5. Disadvantages	Sensitive to fuel impurities (minimal CO), water management	Expensive removal of CO ₂ from fuel/air supplies	Low current/power, large size/weight, leakage problem	High temperature enhances corrosion, breakdown of cell components, longer start-up, start-stop cycle creates problem of thermal fatigue and cracking of parts	High temperature enhances corrosion, breakdown of cell components, longer startup-start-stop cycle creates problem of thermal fatigue and cracking of parts
6. Electrodes	Pt	Ni/Ag metal oxides, noble metals	Pt	Ni anode, NiO cathode	Co-ZrO ₂ Ni-ZrO ₂ anode, Sr-LaMnO ₃ cathode, Y ₂ O ₃ -stabilized ZrO ₂ electrolyte
7. Charge carrier	H ⁺	OH ⁻	H ⁺	CO ₃ ²⁻	O ²⁻

Table 1.3 (continued)

Fuel cell Type	PEMFC	AFC	PAFC	MCFC	SOFC
8. Cell Reactions	$\begin{aligned} & \text{H}_2 \rightarrow 2\text{H}^+ + \\ & 2e^- \frac{1}{2}\text{O}_2 + \\ & 2e^- + \\ & 2\text{H}^+ \rightarrow \text{H}_2\text{O} \end{aligned}$	$\begin{aligned} & \text{H}_2 + 2\text{OH}^- \rightarrow \\ & 2\text{H}_2\text{O} \\ & + 2e^- \frac{1}{2}\text{O}_2 \\ & + \text{H}_2\text{O} + \\ & 2e^- \rightarrow \text{H}_2\text{O} \end{aligned}$	$\begin{aligned} & \text{H}_2 \rightarrow \\ & 2\text{H}^+ + 2e^- \\ & \frac{1}{2}\text{O}_2 + 2e^- + \\ & 2\text{H}^+ \rightarrow \text{H}_2\text{O} \end{aligned}$	$\begin{aligned} & \text{H}_2 + \text{CO}_3^{2-} \rightarrow \\ & \text{H}_2\text{O} + \text{CO}_2 + \\ & 2e^- \frac{1}{2}\text{O}_2 + \\ & \text{CO}_2 + 2e^- \rightarrow \\ & \text{CO}_3^{2-} \end{aligned}$	$\begin{aligned} & \text{H}_2 + \text{O}^{2-} \rightarrow \\ & \text{H}_2\text{O} + 2e^- \\ & \frac{1}{2}\text{O}_2 + 2e^- \rightarrow \\ & \text{O}^{2-} \end{aligned}$
9. Water management	evaporate		evaporate	gaseous products	Gaseous products

to gasified coal. Over the coming decades concerns over depleting stocks of natural resources and a growing awareness of the environmental damage caused by widespread burning of fossil fuels will help to drive the development of fuel cells for both transport and stationary power sources. The future developments in fuel cell technology requires the integration of several disciplines, including materials science, surface science, catalysis, processing, thermal engineering, electrochemistry, control engineering and sensors. Electro-catalysis plays a unique role in addressing various challenges associated with fuel cell technology. Aside from exhibiting electro-catalytic activity towards the electrode reactions the electro-catalysts must be stable within the working cell. Most of the electro-catalytic materials are stable in alkaline solutions but AFC is very sensitive to the presence of CO_2 (either in fuel stream or in the air stream) and this has limited its application to the situations only where pure hydrogen and pure oxygen can be supplied for fuel cells employing acidic electrolytes, stability of the electro-catalyst is difficult to realize. Therefore, nature of electro-catalysts is critically dependent on the nature of the fuel cell. High temperature molten carbonate and solid oxide fuel cells (MCFC and SOFC) present difficulties of thermal stability as well as compatibility with the electrolyte. In addition most electro-catalysts for fuel cells are made from noble metals, especially platinum. It is of practical importance, to minimize loadings of the electro-catalysts over the electrodes and to maximize their effective utilization in the electrode structure. Fuel cells are currently expensive to produce (for automobiles, they can be ten times the price of conventional engines), and the hydrogen they use can be difficult to store and distribute. Yet, fuel cells today are much less expensive and more powerful than the prototypes used in 1960s NASA space capsules to produce both power and water. We are now on the brink of mass-rollouts of the technology in several areas. A nineteenth century scientific curiosity may well transpire to be the power source for the twenty-first century and beyond.

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