

Alternative Sources of Energy— An Introduction to Fuel Cells

By E.A. Merewether

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Gale A. Norton, Secretary

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Abstract

Fuel cells are important future sources of electrical power and could contribute to a reduction in the amount of petroleum imported by the United States. They are electrochemical devices similar to a battery and consist of a container, an anode, a cathode, catalysts, an intervening electrolyte, and an attached electrical circuit. In most fuel cell systems, hydrogen is supplied to the anode and oxygen to the cathode which results in the production of electricity, water, and heat. Fuel cells are comparatively efficient and reliable, have no moving parts, operate without combustion, and are modular and scalable. Their size and shape are flexible and adaptable. In operation, they are nearly silent, are relatively safe, and generally do not pollute the environment.

During recent years, scientists and engineers have developed and refined technologies relevant to a variety of fuel cells. Types of fuel cells are commonly identified by the composition of their electrolyte, which could be either phosphoric acid, an alkaline solution, a molten carbonate, a solid metal oxide, or a solid polymer membrane. The electrolyte in stationary power plants could be phosphoric acid, molten carbonates, or solid metal oxides. For vehicles and smaller devices, the electrolyte could be an alkaline solution or a solid polymer membrane. For most fuel cell systems, the fuel is hydrogen, which can be extracted by several procedures from many hydrogen-bearing substances, including alcohols, natural gas (mainly methane), gasoline, and water.

There are important and perhaps unresolved technical problems associated with using fuel cells to power vehicles. The catalysts required in several systems are expensive metals of the platinum group. Moreover, fuel cells can freeze and not work in cold weather and can be damaged by impacts. Storage tanks for the fuels, particularly hydrogen, must be safe, inexpensive, of a reasonable size, and contain a supply sufficient for a trip of several hundred miles. Additional major problems will be the extensive and costly changes in the national infrastructure to obtain, store, and distribute large amounts of the fuels, and in related manufacturing.

Introduction

This report describes and compares fuel cells and is one of a series of reports from the Energy Program of the U.S. Geological Survey prepared in response to requests from the public for information regarding contemporary sources of power and unconventional sources of electricity. The Energy Program is concerned mainly with resources of natural, energy-rich materials, particularly with accumulations of coal, crude oil, natural gas, and uranium minerals. However, the Program also includes investigations of less developed sources of energy, including deposits of tar sand, oil shale, and biomass. Additionally, there are tentative plans to review the energy potential of hydropower and gas-to-liquids technology as well as areas that might supply geothermal, solar, or wind power.

A fuel cell is an electrochemical device, similar to a battery, that generally combines hydrogen from any of several sources and oxygen (which can come from air) to produce electricity, heat, and water (Baird and Hayhoe, 1993). Basically, a fuel cell is composed of an anode (a negative electrode) and a cathode (a positive electrode), which are separated by a liquid or solid electrolyte (fig. 1). Generally, the electrodes are permeable or contain channels that distribute hydrogen or other substances and oxygen. The electrodes are frequently accompanied by catalysts, commonly platinum or palladium (Geyer, 2000). In most fuel cells, hydrogen atoms enter the cell at the anode where their electrons are removed, producing direct current electricity and positively charged hydrogen ions (cations). Direct current can be converted to alternating current by an inverter. The electrons flow through an external circuit that extends from the anode to the cathode. The external circuit can include electric motors, lighting systems, or other electrical devices. The hydrogen ions travel through the electrolyte to the cathode where they recombine with the electrons and oxygen to produce water and heat (Smithsonian Institution, 2001).

Fuel cells are almost endlessly rechargeable and productive, operate without combustion, have no moving parts, are nearly silent, and have an excellent safety record. Those

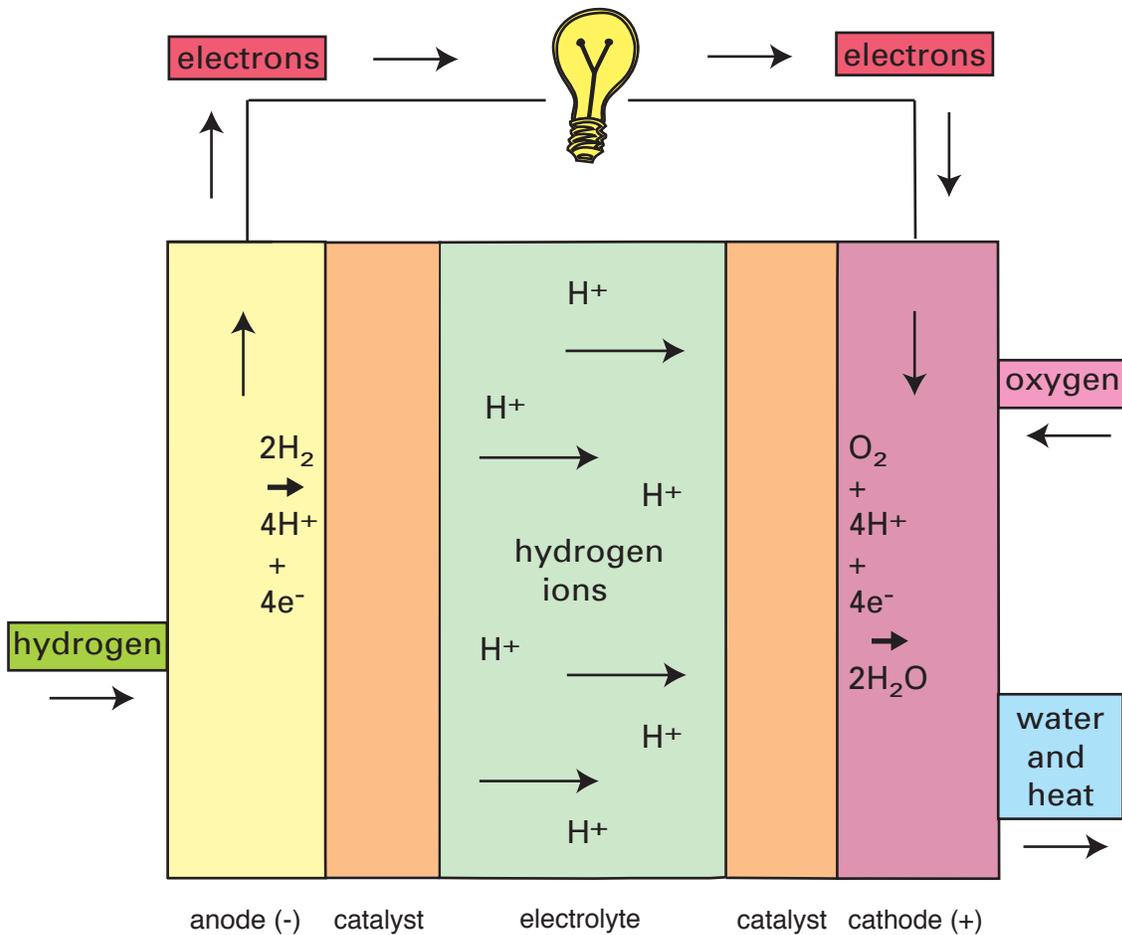


Figure 1. A schema for a typical fuel cell wherein the electrolyte is a proton exchange membrane (PEM) and the catalysts are platinum. Hydrogen molecules when added to the anode and a catalyst lose their electrons, which travel through an external circuit from the anode to the cathode, activating electrical devices enroute. Hydrogen ions formed at the anode and a catalyst move through the electrolyte to the cathode and another catalyst where they combine with the electrons and oxygen to produce water and heat.

recently developed for powering automobiles have an estimated life span of decades (Baum, 2002). Fuel cells can be modular and scaleable; many joined together are called a fuel-cell stack. These characteristics allow the gradual addition of electrical capacity in response to increases in demand, as well as flexibility in the selection of sizes and locations for new stationary power plants. If stationary power plants are built at sites of electrical need, less of the electricity generated is lost during transmission and distribution (Geyer, 2000). Presently, the main planned uses of fuel cells are for the production of electricity at stationary power plants and to supply electricity for motors that move buses, trucks, and cars. Other contemplated applications include power for dwellings, trains, motorcycles, snowmobiles, watercraft, aircraft, and assorted electronic equipment (Jacobson, 1999).

Hydrogen for fuel cells that power vehicles is derived from external sources and thereafter placed in onboard storage systems or is provided by an onboard “fuel reformer” that

extracts hydrogen from accompanying supplies of methanol, gasoline, or other substances (Geyer, 2000). Pure hydrogen for the storage systems can be obtained from alcohols, naphtha, benzene, methane, propane, gasoline, and diesel fuel. Hydrogen is released when hydrocarbon-bearing materials in the presence of catalysts are subjected to pressurized steam (gasification) (U.S. Department of Energy, 1999, 2002). It can also be obtained from water by electrolysis, where the electricity could be supplied by hydroelectric generators, wind turbines, solar cells, or other producers of power. Hydrogen can also be generated by photoelectrochemical and photobiological procedures (U.S. Department of Energy, 2002). In a few commercial fuel cells, gaseous mixtures of hydrogen and carbon dioxide are extracted from fossil fuels or biomass and used instead of pure hydrogen (Baird and Hayhoe, 1993).

When converting the chemical energy in hydrogen-rich materials into electricity, efficiencies are as much as 80 percent for fuel cells and a maximum of only 40 percent for

conventional thermal power plants (International Fuel Cells, 2000a, 2000b). Power plants based on fuel cells are more dependable than diesel-powered generators (Beardsley, 1996). They have lower maintenance costs and longer life expectancies than the alternatives (Baird and Hayhoe, 1993). The operation of fuel cells provides heat for space heating and is virtually pollution free, although when fueled by natural gas, fuel cells can produce a small amount of carbon dioxide. Compared with combustion-based processes for generating electricity, a one-megawatt fuel cell system would save more than 200,000 pounds of air pollutants and 11 million pounds of carbon dioxide from the atmosphere during each year of operation (International Fuel Cells, 2000a, 2000b). A typical, medium-sized car powered by fuel cells using hydrogen will have a system efficiency of more than 50 percent (Bellona Foundation, 2000). The same car with an internal combustion engine has an average fuel efficiency of 12 percent.

History

The possibility of generating electricity by reversing the electrolysis of water was discovered by Sir William Grove in about 1839 (Society of Automotive Engineers, 2001). Charles Langer and Ludwig Mond first used the term “fuel cell” in 1889 while attempting to create a practical fuel cell using coal gas (a mixture of hydrogen, methane, carbon monoxide, other hydrocarbons, carbon dioxide, nitrogen, and oxygen) and air. In the first few years of the 20th century, there were efforts to develop a fuel cell that would use carbon or coal to produce electricity. Francis Bacon developed a usable hydrogen-oxygen cell containing an alkaline electrolyte and nickel electrodes in 1932. However, a practical system was not demonstrated by Bacon and his associates until 1959. In the same year, Harry Karl Ihrig presented a tractor of 20 horsepower that was powered by fuel cells (Society of Automotive Engineers, 2001). NASA began developing a compact generator of electricity for use on space missions in the late 1950s and fuel cells have been providing electricity and water on spacecraft since the 1960s. More recently, many companies and governmental agencies have supported research concerning fuel cell technology for possible use in stationary power plants, homes, vehicles, water craft, and small electronic devices including cell phones. Mainly because of the dependence of the United States and other nations on imported crude oil, research to develop less conventional sources of energy has accelerated during the past decade.

Components

The electrolyte in a fuel cell can be phosphoric acid, alkaline solutions (generally potassium hydroxide in water), molten carbonate (sodium, potassium, lithium, or magnesium carbonate), a solid metal oxide (commonly calcium or

zirconium oxide), or a solid polymer membrane [the proton-exchange membrane (PEM), a thin permeable sheet] (table 1). Using phosphoric acid, a silicon carbide matrix holds the electrolyte, and the electrodes are composed of finely dispersed platinum on carbon paper (U.S. Department of Energy, 2002). This type of fuel cell requires relatively pure hydrogen for the anode, operates at temperatures of 150–200 degrees Celsius (C) [about 300–400 degrees Fahrenheit (F)] (U.S. Department of Energy, 2002), and has an electrical output of as much as 200 kilowatts. This fuel cell is comparatively heavy and inappropriate for use in vehicles but can be used in stationary installations such as power plants.

Fuel cells containing molten carbonate and solid metal oxide electrolytes can be used as highly efficient power-generating stations, although these fuel cells are not portable and operate at much higher temperatures than cells using phosphoric acid or PEM. The high temperatures enable hydrogen and carbon monoxide to be electrochemically oxidized at the anode (Steele and Heinzl, 2001). Potential fuels include natural gas and coal-derived gas. Existing units using molten carbonate electrolytes have electrical outputs of as much as two megawatts and their nickel electrode catalysts are inexpensive compared to the platinum or palladium used in other cells. A pilot plant for the city of Santa Clara, California, that uses a molten carbonate electrolyte, operates at a temperature of 650 degrees C (1202 degrees F). Molten carbonate salts are highly corrosive and require carefully designed and maintained facilities.

If the electrolyte is a solid metal oxide, commonly a thin ceramic layer of zirconium oxide, the cathode is usually composed of lanthanum manganate and the anode is composed of nickel-zirconia (U.S. Department of Energy, 2002). This fuel cell (a direct fuel cell) is a promising option for high-powered applications, such as industrial uses or central electricity generating stations. The cell operates at temperatures of nearly 1000 degrees C (1,832 degrees F) and has an electrical output of as much as 100 kilowatts. The high operating temperature allows the extraction of hydrogen from fuels without the use of a reformer. However, where the electrolyte consists of solid metal oxides, the fuel cells can suffer from leakage and sealing problems (Beardsley, 1996).

In lightweight fuel cells for use mainly in automobiles, buses, and trucks, the electrolyte can be an alkaline solution or a solid polymer membrane [the proton-exchange membrane (PEM)]. These cells require relatively pure hydrogen for the anode (Steele and Heinzl, 2001). In alkaline electrolytes, the operating temperature is 150–200 degrees C (about 300–400 degrees F) and the electrical output ranges from 300 watts to 5 kilowatts (Smithsonian Institution, 2001; Society of Automotive Engineers, 2001). Alkaline cells were used in Apollo spacecraft to provide both electricity and drinking water. However, one disadvantage is that containers filled with liquid can leak.

The PEM electrolyte is a solid, flexible, fluoride polymer film, a fluorocarbon ion exchange with a polymeric membrane (U.S. Department of Energy, 2002). This fuel cell will not leak

Table 1. Types of fuel cells—their components and characteristics.

Type of fuel cell	Electrode composition	Electrolyte composition	Operating temperature	Fuel	Electrical output	Portability of fuel cell	Potential problems	Potential uses
Phosphoric acid	Platinum on carbon paper	Phosphoric acid	150–200°C	Hydrogen	As much as 200 kilowatts	Not portable	Too heavy for many uses	Stationary installations
Alkaline solution	Insufficient information	Alkaline solution—potassium hydroxide in water	150–200°C	Hydrogen	300 watts to 5 kilowatts	Portable	Containers of liquids can leak	Vehicles
Molten carbonate	Anode: nickel-chromium. Cathode: nickel oxide (lithium doped)	Molten carbonate salt—sodium, potassium, lithium, or magnesium carbonate	About 650°C	Methane	As much as 2 megawatts	Not portable	Too heavy for many uses; salts are highly corrosive	Stationary installations—power stations and industrial uses
Solid metal oxide	Anode: nickel zirconia. Cathode: lanthanum manganate	Solid metal oxide—calcium or zirconium oxide	Nearly 1,000°C	Methane	As much as 100 kilowatts	Not portable	Too heavy for many uses; leakage and sealing problems	Stationary installations—power stations and industrial uses
PEM (proton-exchange membrane)	Unknown	Solid, fluorocarbon-polymer film (a thin, flexible, permeable sheet)	About 80°C	Hydrogen	Unknown	Portable	Unknown	Homes and vehicles
Direct methanol	Unknown	Polymer membrane	50–100°C	Methanol	Unknown	Portable	Unknown	Vehicles
Reversible—unitized regenerative	Unknown	PEM (proton-exchange membrane) in water	Unknown	Hydrogen	Unknown	Portable	Unknown	Vehicles

or crack and operates at a temperature of about 80 degrees C (176 degrees F) which is low enough for the cell to be suitable for vehicles and homes. Nevertheless, the platinum catalyst used on both sides of the membrane is costly and the hydrogen for fuel must be purified.

The direct methanol fuel cell is similar to the PEM cell because the electrolyte is a polymer membrane. However, the fuel is methanol instead of hydrogen. A catalyst on the anode draws hydrogen from liquid methanol, eliminating the need for a fuel reformer. This cell has an operating temperature of 50–100 degrees C (122–212 degrees F) (Society of Automotive Engineers, 2001) and has considerable potential value for use in vehicles.

The unitized regenerative or reversible fuel cell functions alternately as a fuel cell, producing electricity and water, and as an electrolyzer, generating hydrogen and oxygen. This cell has a PEM electrolyte and “oxidation and reduction electrodes that reverse roles when switching from charge to discharge” (Walter, 1997). Water is moved from the anode to the cathode. A major advantage of the regenerative fuel cell, when combined with a lightweight hydrogen storage unit, is the comparatively low total weight, which is appropriate for use in a variety of vehicles.

New Developments

The widely recognized potential of fuel cells as sources of electricity for stationary power plants, for motors in vehicles, and for other purposes has encouraged investigations by government agencies and by large and small companies in several nations. Prototypes of micro fuel cells, which can be smaller than a deck of cards, are being prepared by several companies (Hill, 2002). Studies during the past decade have developed and described a variety of components and systems. One company produces an assortment of small fuel cells, one of which has an alkaline electrolyte and will function when any of several liquid or solid hydrogen-rich materials are dissolved in the electrolyte. They also offer the unusual aluminum/air cell that contains an aluminum anode, which is fuel for the cell, and an electrolyte consisting of salt water. In the fuel cell system of a recent concept-vehicle from a major manufacturer, the required hydrogen is extracted from sodium borohydride, a compound related to borax (Brown, 2002).

For hydrogen storage, solid state materials include metal hydride alloys that reportedly absorb and desorb hydrogen rapidly at low pressures and at temperatures of 0–200 degrees C (0–392 degrees F) (Fuel cell investors portal, 2002). Carbon nanotubes, which are carbon molecules in the form of long thin tubes, are another potential hydrogen storage medium. They are also suitable for electrodes and can be used in sensors for hydrogen, especially for the smallest fuel cells (NEC Corporation press release, 2001). Another potential storage material is glass microspheres that will fill with hydrogen when their permeability is modified by changes in temperature (U.S. Department of Energy, 2002).

Several major manufacturers have developed fuel cell systems that will produce enough hydrogen and electricity to power vehicles. The two systems commonly proposed include either an onboard fuel processor (fuel reformer) or the direct hydrogen system. The feedstocks currently preferred for these systems are gasoline or methanol for the onboard processor and natural gas for the direct hydrogen system (U.S. Department of Energy, 1999). A system using an onboard processor and gasoline is favored by many because a new and widespread infrastructure would not be required. The option of an onboard processor and methanol would need additional infrastructure but would be more readily implemented than the direct hydrogen system. However, present fuel reformers, which can extract hydrogen from several hydrogen-rich materials, increase the cost of the system, reduce the overall efficiency, and produce carbon dioxide (Brown, 2002; Schrope, 2001). They also must be heated for several minutes before they can function. These characteristics contribute to a common opinion that fuel reformers would be part of an interim technology.

Using the direct hydrogen system for passenger vehicles will require the development of a new national infrastructure for generating and supplying this gas. Hydrogen generators, which can be steam reformers, partial oxidation units, or electrolyzers, will probably be widely distributed and can obtain hydrogen from natural gas, propane, alcohol, gasoline, or water (U.S. Department of Energy, 1999).

Evaluations

Several practical and fundamental issues concerning the applications of fuel cells have not been resolved. In cold weather, fuel cells can freeze and stop working (Baum, 2002). They are also fragile and could be damaged when powering vehicles on rough roads. Furthermore, the catalysts required in several fuel cell systems are expensive metals of the platinum group. For fuel cells that require pure hydrogen, the associated gas storage devices must be safe, efficient, and relatively inexpensive. Storing and supplying hydrogen for cells in vehicles and in smaller mechanisms is a current technical problem. For a trip of 373 miles (600 kilometers) in the family car, using hydrogen and without refueling, a conventional pressurized storage tank would need to be much too large for the vehicle (Schrope, 2001). However, promising, newly developed, smaller storage tanks contain either metal hydride alloys, carbon nanotubes, or glass microspheres. Nevertheless, replacing most of the present combustion-based, energy-producing mechanisms throughout the world with less conventional, power-producing devices will probably require extensive and costly changes in sources of fuels, in the related national infrastructure for storage and distribution of fuels, and in associated manufacturing.

Steele and Heinzel (2001) assumed “that fuel cells have to be designed for operation on hydrocarbon or alcohol fuels

to ensure that the technology” will penetrate the relevant markets. If hydrogen is essential for fuel cells, which of the potential materials will be used as sources and how will the gas be extracted? For the large-scale production of hydrogen, the currently cheapest method is “steam reforming of natural gas, which produces significant emissions of greenhouse gases” (Steele and Heinzl, 2001). Additionally, using present technology, more energy is required to extract hydrogen from natural gas and other fuels than can be obtained from the hydrogen (Baum, 2002).

Another technical challenge in obtaining electricity from fuel cells, according to Beardsley (1996), is the high cost of their manufacture. David Brown (2002) reported that “fuel cells are relatively expensive to manufacture and operate, in relation to their output.” In a column in a financial magazine, Jerry Flint (2002) stated that hydrogen fuel cell engines would function for vehicles but are not currently available by means of mass-production technology. Consequently, those engines will be too costly for powering cars during the next twenty or more years. However, in a description of an automobile powered by fuel cells that was recently developed by a major corporation, Baum (2002) indicated that the cost of manufacturing this new vehicle will be much less than the cost of building a new traditional car. Baum (2002) also proposed that this unconventional new automobile would be ready for mass production in about the year 2010.

Conclusion

Fuel cells could be a major and necessary source of energy within a decade. They have great potential as the basic elements of large and small stationary power plants and as the source of electricity for vehicles and smaller devices. Their size and shape are flexible and adaptable. They are modular, have no moving parts, operate without combustion, are comparatively efficient and reliable, are nearly silent, generally do not pollute the environment, and are quite safe. The byproducts of the operation of fuel cells using pure hydrogen are only water and heat. Hydrogen for most of the cell systems can be extracted from many hydrogen-bearing materials by gasification and other procedures and from water by electrolysis. A fuel cell installation in Groton, Conn., consumes methane from a nearby landfill to produce electricity and heat. Nevertheless, preparing the infrastructures required for extracting, storing, and distributing hydrogen for use in many of the vehicles in the U.S.A. will be a major achievement.

Stationary power plants based on fuel cells are now feasible and are economically and environmentally appealing. As a source of power for transportation, fuel cell systems have been improved recently by means of intensive development and probably will soon be used in the larger vehicles. The systems for vehicles might include fuel reformers for extracting hydrogen, first from gasoline and later perhaps from natural gas, propane, or alcohols. Eventually, when pure

hydrogen is widely available, fuel reformers will be unnecessary. The electrical requirements of many small mechanisms could be satisfied by micro fuel cells which presently are being developed. In recent years, scientists and engineers have been devising and refining technologies relevant to fuel cells and have suggested new applications. They have proposed a variety of materials for use as electrodes, catalysts, electrolytes, and fuel.

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Glossary

A

Alkali: A basic substance (the opposite of an acidic substance) such as a hydroxide or carbonate of an alkali metal (commonly sodium or potassium).

Anion: A negative ion. In anion-mobile fuel cells, anions move through the electrolyte toward the anode.

Anode: One of two terminals (electrodes) in a fuel cell or battery. In a fuel cell, it is where the fuel reacts and releases electrons.

C

Carbonate: An electro-negative part of a compound. Composed of carbon and oxygen.

Catalyst: A substance that initiates a chemical reaction and enables it to proceed but is not affected by the reaction.

Cathode: One of two terminals (electrodes) in a fuel cell or battery. In a fuel cell, it is where oxygen combines with hydrogen ions and electrons to produce water.

Cation: A positive ion. In cation-mobil fuel cells, cations move through the electrolyte toward the cathode.

Coal gas: A fuel gas produced from coal. Its average composition, by volume, is 50 percent hydrogen, 30 percent methane, 8 percent carbon monoxide, 4 percent other hydrocarbons, and 8 percent carbon dioxide, nitrogen, and oxygen (Nelson, 1965).

Combustion: An act or instance of burning or oxidation accompanied by the generation of light and heat.

D

Direct fuel cell: A type of fuel cell in which a hydrocarbon fuel is fed directly to the fuel cell stack; an external reformer to generate hydrogen is not required.

E

Electrochemistry: A science that deals with the relation of electricity to chemical changes and with the interconversion of chemical and electrical energy.

Electrode: An electrical terminal (anode or cathode) that conducts an electric current into or out of a battery or fuel cell.

Electrolysis: The producing of chemical changes by the passage of an electric current through an electrolyte.

Electrolyte: One or more chemical compounds that conduct ions from one electrode to the other inside a battery or fuel cell.

Electron: An elementary subatomic particle that carries a negative electrical charge.

F

Fuel cell: A device for generating electricity by chemically combining a fuel (commonly hydrogen) and oxygen.

H

Hydrogen: A nonmetallic chemical element, normally a gas, composed of one proton and one electron. It is the fuel for most fuel cells.

I

Inverter: A device for converting direct current electricity to alternating current electricity.

Ion: An atom or group of atoms that carries a positive or negative electric charge as a result of having gained or lost one or more electrons.

K

Kilowatt: 1,000 watts—a measure of electric power.

M

Matrix: A framework within which something else functions.

Molten carbonate: In one type of fuel cell, a molten electrolyte that consists of carbon, oxygen, and another element, such as sodium, potassium, lithium, or magnesium.

Megawatt: 1,000,000 watts—a measure of electric power.

N

Natural gas: Hydrocarbons that exist as a gas or vapor, usually consisting of methane and lesser amounts of propane and ethane.

Impurities in natural gas commonly include nitrogen, carbon dioxide, and hydrogen sulfide.

O

Oxygen: A nonmetallic chemical element, normally a gas, composed of eight protons, eight neutrons, and eight electrons.

P

Phosphoric acid: A solution of a combination of the elements phosphorus, hydrogen, and oxygen that can serve as the electrolyte in a fuel cell.

Polymer: A solid, natural or synthetic chemical compound or mixture of compounds composed essentially of repeating molecular units.

Potassium hydroxide: A compound composed of potassium, hydrogen, and oxygen that when dissolved in water forms a basic solution, which can serve as the electrolyte in a fuel cell.

Proton exchange membrane (PEM): A polymer sheet or membrane that can serve as the electrolyte in a fuel cell.

R

Reformer: A device that extracts hydrogen from hydrocarbons.

Regenerative fuel cells: Types of fuel cells in which the fuel and, in several types of cells, the oxidant are regenerated from the oxidation products.

S

Solid oxide: A combination of oxygen and another element (commonly calcium or zirconium) that forms a solid electrolyte for one type of fuel cell.

Stack: A series of individual fuel cells connected within an electricity generating system.

W

Watt: A unit of power equal to the work done at the rate of one absolute joule per second or to the rate of work represented by a current of one ampere under a pressure of one volt.