E-tutorial

ENS301CR: Natural Resources

Credit IV: Energy Resources

1.5. Hydrogen as a source of energy

By,

Dr. Moieza

INTRODUCTION:

An alternative fuel must be technically feasible, economically viable, easily convert to another energy form when combusted, be safe to use, and be potentially harmless to the environment. Hydrogen is the most abundant element on earth.

POSITION OF HYYDROGE IN PERIODIC TABLE:

Hydrogen is the first element in the periodic table .it contains only one electronic configuration is similar to the outer electronic configuration of alkali metals (ns^1) ,which belongs to the first group of the periodic table like halogens ($ns^2 np^5$) ,it is short by one electron to the corresponding noble gas configuration ($1s^2$) ,which belongs to the seventh group of the periodic table .

Hydrogen therefore, has resembles to alkali metals, which lose one electron to form unipositive, as well as with halogens, which gain one electron to form uninegative ion .

Like alkali metals ,hydrogen forms oxides ,halides and sulfides .however ,unlike alkali metals it has very high ionization enthalpy and does not posses metallic characteristics under normal conditions .in terms of ionization enthalpy ,hydrogen resembles more with halogens .

Occurrence:

Hydrogen is the most abundant (92%) element in the universe and is principle element in the universe and is the principle element in the solar atmosphere .the giant planets Jupiter and Saturn consists mostly of hydrogen . it occurs 15.4% in the earth crust in the combined form .quantitatively it is the ninth element in order of abundance in the earth crust in the combined form besides water ,it occur in plant and animal tissues ,coal ,petroleum ,clay ,carbohydrates ,proteins etc.

ISOTOPES OF HYDROGEN:

Atoms of the same element having same atomic number but different mass number s are called isotopes .isotopes having same number of protons and electrons but different number of neutrons .

Hydrogen has three isotopes

I. Protium or normal hydrogen($_1H^1$)
II. Deuterium or heavy hydrogen ($_1H^2$ or $_1D^2$)
III. Tritium($_1H^3$ or $_1D^3$)

Protium ($_1H^1$): it is the most commonly occurring isotope of hydrogen .it does not contain a neutron its atomic mass is 1.08 amu .a sample of natural hydrogen contains 99.984% of the isotope

Deuterium ($_1H^2$ or $_1D^2$): it contains one neutron .it atomic mass is 2.014 amu .a sample of natural hydrogen contains 0.0156% of this isotope

Tritium($_1H^3$):it contains two neutrons .its atomic mass is 3.016 amu .tritium occurs to the extent of 1 part of tritium in10000000 parts of ordinarily available hydrogen. Tritium is radio active isotope of hydrogen .it emits β particle

$_1H^3 \rightarrow {}_2He^3 + {}_{-1}e^0$

The isotopes of the element have the same electronic configuration and hence possess the same chemical properties .the only difference is in their rates of reaction ,mainly due to their different enthalpy of bond dissociation .however , in physical properties this isotopes differ considerably due to their large mass difference

Table 1: Some important physical properties of protium , deuterium and tritium

Property	Protium	Deuterium	Tritium
Relative abundance(%)	99.984	0.0156	10^{-15}
Relative atomic mass(amu)	1.008	2.014	3.016
Melting Point(K)	13.96	18.73	20.62
Boiling Point(K)	20.39	23.67	25.0
Density(gm/lit)	0.09	0.18	0.27
Enthalpy of fusion(kJ/mole)	0.117	0.197	0.250
Enthalpy of vaporization(kJ/mole)	0.904	1.226	1.393
Enthalpy of bond dissociation (kJ/mole)	435.88	443.4	446.9
Inter nuclear distance(pm)	74.14	74.14	74.14

Properties of pure Hydrogen :

Properties of Hydrogen

Property	Value
Molecular weight	2.01594
Density of gas at 0°C and 1 atm.	0.08987 kg/m^3
Density of solid at −259°C	858 kg/m^3
Density of liquid at −253°C	708 kg/m^3
Melting temperature	−259°C
Boiling temperature at 1 atm.	−253°C
Critical temperature	−240°C
Critical pressure	12.8 atm.
Critical density	31.2 kg/m^3
Heat of fusion at −259°C	58 kJ/kg
Heat of vaporization at −253°C	447 kJ/kg
Thermal conductivity at 25°C	0.019 kJ/(ms°C)
Viscosity at 25°C	0.00892 centipoise
Heat capacity (Cp) of gas at 25°C	14.3 kJ/(kg°C)
Heat capacity (Cp) of liquid at −256°C	8.1 kJ/(kg°C)
Heat capacity (Cp) of solid at −259.8°C	2.63 kJ/(kg°C)

Source: Adapted from *Kirk-Othmer Encyclopedia of Chemical Technology. Fundamentals and Use of Hydrogen as a Fuel*. 3rd ed., Vol. 4, Wiley, New York, 1992, 631p.

Table 2. Properties of Hydrogen

Molar mass	Acentric factor	Critical temperature T_c /k	Critical pressure P_c/bar	Critical compressibility factor Z_c	Critical molar volume V_c (cm^3/mol)	N.B.P. T_n/k
2.016	-0.216	33.19	13.13	0.305	64.1	20.4

tabe:3 critical properties

HYDROGEN AS A FUEL:

The key criteria for an **IDEAL FUEL** are inexhaustibility, cleanliness, convenience, and independence from foreign control.

Hydrogen as a fuel satisfies all the above requirements. It offers the highest potential benefits in terms of diversified supply and reduced emissions of pollutants and greenhouse gases. For the past 40 years, environmentalists and several industrial organizations have promoted hydrogen fuel as the solution to the problems of air pollution and global warming.

Similar to electricity, **hydrogen is a high-quality energy carrier,** which can be used with a high efficiency and zero or near-zero emissions at the point of use.

The Hydrogen production is increasing by about 10% every year. As of 2005, the economic value of all hydrogen produced worldwide was about $135 billion per year. The current global hydrogen production is 48% from natural gas, 30% from petroleum, 18% from coal, and **4% from electrolysis.**

Hydrogen is primarily consumed in two nonfuel uses:

(1) About 60% to produce NH_3 by the Haber process for subsequent use in fertilizer manufacturing.

(2) About 40%in refinery, chemicals, and petrochemical sectors

Physical Properties:

Hydrogen atom is the lightest element (Ordinary hydrogen has a density of 0.09 kg/m3.), consisting of only one proton and one electron.

Hydrogen atoms readily form H_2 molecules, which are smaller in size when compared to most other molecules.

Hydrogen is colorless, odorless, and tasteless and is about **14 times lighter than air,** and diffuses faster than any other gas. On cooling, hydrogen condenses to liquid at −253°C and to solid at −259°C.

Also, the gaseous hydrogen has one of the highest **heat capacity (14.4 kJ/kg K).**

Chemical Properties:

At ordinary temperatures, H_2 is comparatively nonreactive unless it has been activated in some manner. On the contrary, **hydrogen atom** is chemically very reactive, and that is why it is not found chemically free in nature. In fact, very high temperatures are needed to dissociate molecular hydrogen into atomic hydrogen.

For example, even at 5000 K, about 5% of the hydrogen remains undissociated. In nature, mostly the hydrogen is bound to either oxygen or carbon atoms. Therefore, hydrogen must be considered as an energy carrier—a means to store and transmit energy derived from a primary energy source.

From the safety point of view, the following are the most important properties of hydrogen when compared to other conventional fuels:

Diffusion: *Hydrogen diffuses through air much more rapidly than other gaseous* fuels. With a diffusion coefficient in air of .61 cm2/s, the rapid dispersion rate of hydrogen is its greatest safety asset.

Flammability: *Flammability of hydrogen is a function of concentration level and* is much greater than that of methane or other fuels. The limit of flammability of hydrogen in air at ambient condition is 4–75%, methane in air is 4.3–15 vol%, and gasoline in air is 1.4–7.6 vol%.

Fuel Properties:

Hydrogen is highly flammable over a wide range of temperature and concentration. Although its combustion efficiency is truly outstanding and welcomed as a fuel of the choice for the future, it inevitably renders several nontrivial technological challenges, such as safety in production, storage, and transportation

Energy Content:

Hydrogen has the highest energy content per unit mass of any fuel. For example, on a **weight basis**, hydrogen has nearly three times the energy content of gasoline (140.4 MJ/kg versus 48.6 MJ/kg).

However, on a **volume basis** the situation is reversed: 8,491 MJ/m3 for liquid hydrogen versus 31,150 MJ/m3 for gasoline.

The low volumetric density of hydrogen results in storage problem, especially for automotive applications. A large container is needed to store enough hydrogen for an adequate driving range.

One of the important and attractive features of hydrogen is its electrochemical property, which can be utilized in a fuel cell. At present, H_2/O_2 fuel cells are available operating at an efficiency of 50–60% with a lifetime of up to 3000 h

Table 4: Comparison of hydrogen with other fuels

Fuel	LHV (MJ/kg)	HHV (MJ/kg)	Stoichiometric Air/Fuel Ratio (kg)	Combustible Range (%)	Flame Temperature (°C)	Min. Ignition Energy (MJ)	AutoIgnition Temperature (°C)
Methane	50.0	55.5	17.2	5–15	1914	0.30	540–630
Propane	45.6	50.3	15.6	2.1–9.5	1925	0.30	450
Octane	47.9	15.1	0.31	0.95–6.0	1980	0.26	415
Methanol	18.0	22.7	6.5	6.7–36.0	1870	0.14	460
Hydrogen	119.9	141.6	34.3	4.0–75.0	2207	0.017	585
Gasoline	44.5	47.3	14.6	1.3–7.1	2307	0.29	260–460
Diesel	42.5	44.8	14.5	0.6–5.5	2327		180–320

Source: Adapted from *Hydrogen Fuel Cell Engines and Related Technologies*, College of the Desert, Palm Desert, CA, 2001.

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Environmental Aspects

The combustion of fossil fuels accounts for a majority of anthropogenic greenhouse gas emissions. Currently, fossil fuel combustion produces 7 Gtn/year carbon emissions. CO_2 emissions in 2050 can be expected to reach 14 Gtn/year of carbon. Hydrogen, when produced from reforming of natural gas, petroleum or coal, generates CO_2 as a by-product. For each ton of hydrogen produced from hydrocarbons, approximately 2.5 t of carbon is vented to the atmosphere. However, for each ton of hydrogen produced from current coal technology, approximately 5 t of carbon is emitted to the atmosphere.

PRODUCTION METHODS:

Because pure hydrogen does not occur naturally on Earth in large quantities, it takes a substantial amount of energy in its industrial production. There are different ways to produce it, such as electrolysis and steam-methane reforming process. In electrolysis, electricity is run through water to separate the hydrogen and oxygen atoms. This method can use wind, solar, geothermal, hydro, fossil fuels, biomass, and many other resources. Obtaining hydrogen from this process is being studied as a viable way to produce it domestically at a low cost. Steam-methane reforming, the current leading technology for producing hydrogen in large quantities, extracts the hydrogen from methane. However, this reaction causes a side production of carbon dioxide and carbon monoxide, which are greenhouse gases and contribute to global warming.

Hydrogen Production Methods:

1. Production of hydrogen from hydrocarbons
   a) Steam Methane Reforming
   b) Partial Oxidation of Hydrocarbons
2. Production of hydrogen by Coal Gasification
3. Hydrogen Production from Electrolysis of Water
4. Hydrogen Production from Nuclear Energy
5. Hydrogen Production from Wind Energy
6. Hydrogen Production from Biomass
7. Use of Solar Energy to Produce Hydrogen.

There are several methods for producing hydrogen. We can have a broad classification based on whether it is from a renewable source like wind energy, solar energy or from a non renewable source like coal, natural gas. Currently Conventional methods of producing hydrogen are the most widely employed process for hydrogen production accounting for nearly 90% global hydrogen production. But the problem with these methods is they liberate large quantities of CO2. Electrolysis of water accounts for 4% of global production, the advantages of this process is it is having well established technology & C02 free but Expensive compared to conventional process. The remaining processes are gaining importance because of their non polluting nature but technology is still at pilot plant scale level only and cost of production is also high as evident from the below table.

Table: 5 Estimated cost of Hydrogen Production, Transportation and Distribution (based on year 2003)

Primary Energy Source	Total cost $/kg H2
Natural gas reforming	1.99
Natural gas reforming+CO2 capture	2.17
Coal Gasification	1.91
Coal Gasification+CO2 capture	1.99
Wind Electrolysis	7.60
Biomass gasification	7.04
Biomass pyrolysis	6.22
Nuclear thermal splitting of water	2.33
Gasoline (for reference)	**1.12**

HYDROGEN STORAGE:

One of the most critical factors in inducting hydrogen economy is transportation and on-vehicle storage of hydrogen. The major contribution to the problem is from low gas density of hydrogen. For example, to store energy equivalent to one gasoline tank, an ambient pressure hydrogen gas tank would be more than 3000-fold the volume of the gasoline tank. Hydrogen can be stored as a gas, liquid and metal hydrides.

1. **Compressed gas storage:** Hydrogen is conveniently stored for many applications in high pressure cylinders. This method of storage is expensive and bulky because very large sized vessels are needed for storage of small quantities of hydrogen.
2. **Liquid storage:** on a small scale or moderate scale, hydrogen is frequently stored under high pressure in strong steel cylinders. But this kind of process is too costly for large storage applications. A more practical approach is to store the hydrogen as a liquid at a low temperature (cryogenic storage in vacuum insulated storage tank). **Ex:** The liquid hydrogen fuel used a rocket propellant.
   One problem with storing hydrogen as a liquid is its boiling temperature (20K) is very low, so it has to be stored under temperatures less than 20K. The storage tank has to be insulated, to preserve temperature, and needs to be reinforced to store the liquid hydrogen under some pressure.
3. **Storage as metal hydride:** Considerable interest has been shown recently towards storing hydrogen in the form of a metal hydride. A number of metals and alloys form solid compounds called metal hydrides, by direct reaction with hydrogen gas. When the hydride is heated the hydrogen will release. Ex: $FeTiH_{1.7}$, $LaNi_5H_6$, Mg_2NiH_4. The percentage of gas absorbed to volume of the metal is still relatively low, but hydrides offer a valuable solution to hydrogen storage. The volume of this storage device is only two fold greater than the equivalent gasoline tank, but unfortunately it is 20-fold heavier. The life of a metal hydride storage tank is directly related to the purity of the hydrogen it is storing. The alloys act as a sponge, which absorbs hydrogen, but it also absorbs any impurities introduced into the tank by the hydrogen. Thus, the hydrogen released from the tank is highly pure, but the tank’s lifetime and ability to store hydrogen is reduced as the impurities are deposited in the metal pores.

TABLE 1.8

Comparison of On-Board Hydrogen Storage

Fuel	Total Energy (MJ)	Fuel Weight (kg)	Tank Weight (kg)	Total Fuel System Weight (kg)	Volume (gal.)
5 gal. gasoline	662	14	6.4	20.4	5
Liquid hydrogen (20 K)	662	4.7	18.6	23.3	47
1.2 wt% H_2 stored in FeTi metal hydride	662	4.7	549.3	554	50
Compressed hydrogen (207–690 bar)	662	4.7	63.6–86.3	68.3–91	108–60

Source: Adapted from Kukkone, C.A. and Shelef, M., *Alternate Fuels*, National Research Council and National Academy of Engineering, National Academies Press, Washington, DC, 1992.

Table:6 BY USING HYDROGN AS A FUEL WE DEVELOP AN FUEL CELL:

FUEL CELLS

- A fuel cell is a device that converts the chemical energy from a fuel into electricity through a chemical reaction with oxygen or another oxidizing agent. / A Fuel Cell is an electrochemical device that combines hydrogen and oxygen to produce electricity, with water and heat as its by-product.
- It is a clean, quiet and highly efficient process, as the conversion of the fuel to energy takes place via an electrochemical process, not combustion.
- It is two to three times more efficient than fuel burning

The Invention of the Fuel Cell

Sir William Grove invented the first fuel cell in 1839. Grove knew that water could be split into hydrogen and oxygen by sending an electric current through it (a process called **electrolysis**). He hypothesized that by reversing the procedure you could produce electricity and water. He created a primitive fuel cell and called it a **gas voltaic battery**. Fifty years later, scientists Ludwig Mond and Charles Langer coined the term **fuel cell.**

Working of a Fuel Cell:

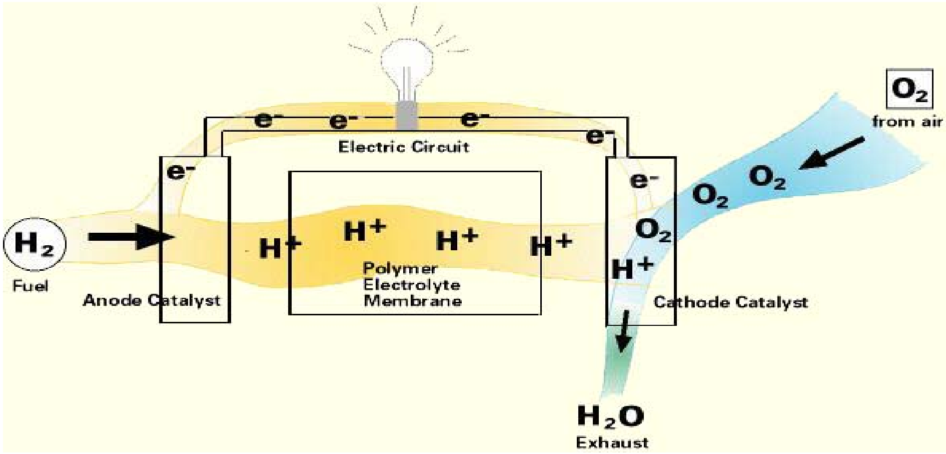

Figure 1

- Fuel cell works on the principle of reverse electrolysis
- It operates similarly to a battery, but it does not run down nor does it require recharging
- As long as fuel is supplied, a Fuel Cell will produce energy.
- A Fuel Cell consists of two catalyst coated electrodes surrounding an electrolyte. One electrode is an anode and the other is a cathode. The process begins when Hydrogen molecules enter the anode. At the anode, catalytic oxidation of hydrogen occurs.

This oxidation half reaction is written as $2H_2 \rightarrow 4H^+ + 4e^-$ -----1

The catalyst coating separates hydrogen's negatively charged electrons from the positively charged protons. The electrolyte allows the protons to pass through to the cathode, but not the electrons. Instead the electrons are directed through an external circuit which creates electrical current. While the electrons pass through the external circuit, oxygen molecules pass through the cathode. There the oxygen and the protons combine with the electrons after they have passed through the external circuit. When the oxygen and the protons combine with the electrons it produces water and heat.

The reduction half reaction can be written as $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ ----2

Reaction 1 is slightly endothermic, Reaction 2 is heavily exothermic and so heat is liberated along with water.

The two equations combined give the cell reaction as **$2H_2+O_2 \rightarrow 2H_2O$**

The power produced by a fuel cell depends on several factors, including the fuel cell type, size, temperature at which it operates, and pressure at which gases are supplied. A single fuel cell produces approximately 1 volt or less — barely enough electricity for even the smallest applications.

- To increase the amount of electricity generated, individual fuel cells are combined in series to form a stack. (The term “fuel cell” is often used to refer to the entire stack, as well as to the individual cell.) Depending on the application, a fuel cell stack may contain only a few or as many as hundreds of individual cells layered together.

Major Types of Fuel Cells:

In general all fuel cells have the same basic configuration - an electrolyte and two electrodes. Different types of fuel cells are classified by the kind of electrolyte used. The type of electrolyte used determines the kind of chemical reactions that take place and the temperature range of operation.

- Proton Exchange Membrane (PEM) Fuel Cells
- Direct Methanol (a subset of PEM) Fuel Cells
- Phosphoric Acid Fuel Cells
- Molten Carbonate Fuel Cells
- Solid Oxide Fuel Cells
- Alkaline Fuel Cells
- Regenerative Fuel Cells

1. Proton Exchange Membrane (PEM) Fuel Cells:

- This is the leading cell type for passenger car application
- Uses a polymer membrane as the electrolyte.
- Operates at a relatively low temperature, about 60- 80^{o}C
- The low operating temperature means that it doesn't take very long for the fuel cell to warm up and begin generating electricity
- Has a high power density, can vary its output quickly and is suited for applications where **quick startup** is required making it popular for automobiles

Limitations:

- Sensitive to fuel impurities
- Performance of the PEM fuel cell is limited by the slow rate of the oxygen reduction half reaction which is more than 100 times slower than the hydrogen oxidation half reaction.
- **Platinum** is expensive but is the only catalyst known so far that is capable of generating high rates of oxygen reduction at relatively low temperatures (about 80 degrees C) at which PEM fuel cells operate

Working of a PEMFC:

The PEM fuel cell consists of a current collector (including gas channels), gas diffusion layer, and catalyst layer on the anode and cathode sides as well as an ion conducting polymer membrane. Reactants enter the cell through gas channels, which are embedded in the current collectors (bipolar plate). The gas diffusion layers (GDL) are used to uniformly distribute the reactants across the surface of the catalyst layers (CL). Protons, produced by the oxidation of hydrogen on the anode, are transported through ion conducting polymer within the catalyst layers and the membrane. Electrons produced at the anode are transported through the electrically conductive portion of the catalyst layers to the gas diffusion layers, then to the collector plates and through the load, and finally to the cathode. Liquid water is transported through the pores in the catalyst and gas diffusion layers through a mechanism that may be similar to capillary flow. Upon reaching the gas channels, liquid water is transported out of the cell along with the bulk gas flow. Water may also be transported, in dissolved form, through the polymer portion of the catalyst layers and through the membrane. Heat produced in the cell is removed principally by conduction through the cell and convection by a coolant in contact with the collector plates.

Polymer Electrolyte Membrane:

- In the Proton-Exchange Membrane Fuel Cell (or Polymer-Electrolyte Membrane Fuel Cell) the electrolyte consists of an acidic polymeric membrane that conducts protons but repels electrons, which have to travel through the outer circuit providing the electric work.
- The desired characteristics of PEMs are high proton conductivity, good electronic insulation, high chemical and thermal stability, and low production cost [18].
- One type of PEMs that meets most of these requirements is **Nafion**.
- Nafion is the most commonly used and investigated PEM in fuel cells
- Nafion® from DuPont™, which consists of a fluoro-carbon backbone, similar to Teflon, with attached sulfonic acid SO_3^- groups.
- The membrane is characterized by the fixed-charge concentration (the acidic groups): The higher the concentration of fixed-charges, the higher is the protonic conductivity of the membrane.
- For optimum fuel cell performance it is crucial to keep the membrane fully humidified at all times, since the conductivity depends directly on water content.
- The thickness of the membrane is also important, since a thinner membrane reduces the ohmic losses in a cell.
- However, if the membrane is too thin, hydrogen, which is much more diffusive than oxygen, will be allowed to cross-over to the cathode side and recombine with the oxygen without providing electrons for the external circuit.
- Typically, the thickness of a membrane is in the range of 5-300 μ*m*

Catalyst Layer:

- The best catalyst material for both anode and cathode PEM fuel cell is platinum.
- Since the catalytic activity occurs on the surface of the platinum particles, it is desirable to maximize the surface area of the platinum particles.
- A common procedure for surface maximization is to deposit the platinum particles on **larger carbon black** particles
- The electrochemical half-cell reactions can only occur, where all the necessary reactants have access to the catalyst surface. This means that the carbon particles have to be mixed with some electrolyte material in order to ensure that the hydrogen protons can migrate towards the catalyst surface. This "coating" of electrolyte must be sufficiently thin to allow the reactant gases to dissolve and diffuse towards the catalyst surface

2. <u>Direct Methanol (a subset of PEM) Fuel Cells:</u>

- Methanol fuel cells are comparable to a PEMFC in regards to operating temperature, but are not as efficient as PEMFC.
- Also, the DMFC requires a relatively large amount of platinum to act as a catalyst, which makes these fuel cells expensive
- It also uses a polymer membrane as the electrolyte
- Different from PEM because the anode catalyst is able to draw hydrogen from methanol without a reformer
- Used more for small portable power applications, possibly cell phones and laptops.

3. <u>Phosphoric Acid Fuel Cells:</u>

- This is the most commercially developed fuel cell
- It generates electricity at more than 40% efficiency
- Nearly 85% of the steam produced can be used for cogeneration
- Uses liquid phosphoric acid as the electrolyte and operates at about 450 degrees F
- One main advantage is that it can use impure hydrogen as fuel
- It operates at a higher temperature than polymer exchange membrane fuel cells, so it has a longer warm-up time. This makes it unsuitable for use in cars.
- The phosphoric-acid fuel cell has potential for use in small stationary power-generation systems.

4. <u>Molten Carbonate Fuel Cells:</u>

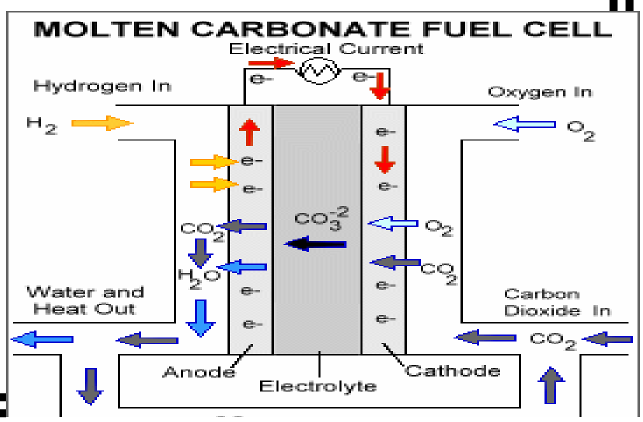

Figure 2

- Promises high fuel-to-electricity efficiency and the ability to utilize coal based fuels
- Uses an electrolyte composed of a **molten carbonate salt mixtures (Li, Na, K)**
- Require carbon dioxide and oxygen to be delivered to the cathode.
- Operates at extremely high temperatures 1200^{0}F
- They can generate steam that can be used to generate more power
- Primarily targeted for use as electric utility applications.
- Have been operated on hydrogen, CO, natural gas, propane, landfill gas, marine diesel and simulated coal gasification products
- Because of the extreme high temperatures, non- precious metals can be used as catalysts at the anode and cathode which helps reduces cost.
- **Disadvantage** is durability.

Reactions at fuel electrode: $H_2+CO_3^- = H_2O+CO_2+2e^-$

$CO+CO_3^- = 2CO_2+2e^-$

Reactions at oxygen electrode: $O_2+2CO_2+4e^- = 2CO_3^-$

5. Solid Oxide Fuel Cells:

- Uses a hard, non-porous ceramic compound as the electrolyte
- Can reach 60% power-generating efficiency
- Operates at extremely high temperatures 1800 ^{0}F
- Used mainly for large, high powered applications such as industrial generating stations, mainly because it requires such high temperatures.

Table7: Summary Sheet of All Types of Fuel Cells

	AFC	PEMFC	DMFC	PAFC	MCFC	SOFC
Electrolyte	NaOH / KOH	Polymer membrane		H_3PO_4	$LiCO_3$–K_2CO_3	ZrO_2 with Y_2O_3
Electrode Material	Metal or carbon	Pt-on-carbon			Ni +Cr	Ni/Y_2O_3–ZrO_2
Operating Temp. (C^0)	60-100	50-100	50-200	160-210	650-800	800-1000
Power Density (kW/m^2)	0.7 – 8.1	3.8 – 6.5	> 1.5	0.8 – 1.9	0.1 – 1.5	1.5 – 2.6
Practical Efficiency (%)	60	60	60	55	55-65	60-65
Applications	Transportation, Space, Military, Energy storage systems			Combine heat and power for decentralized stationary power systems	Combine heat and power for stationary decentralized systems and for transportation (trains, boats, …)	
Start-Up Time	min	sec	sec-min	hrs	hrs	hrs

6. <u>Alkaline Fuel Cells:</u>

- Used mainly by military and space programs
- Can reach 70% power generating efficiency, but considered too costly for transportation applications
- Used on the Apollo spacecraft to provide electricity and drinking water
- Uses a solution of **KOH** in water as the electrolyte and operates at 75-160 ^{0}F
- Can use a variety of non-precious metals as catalyst at the anode and cathode
- Requires pure hydrogen and oxygen because it is very susceptible to carbon contamination
- Purification process of the hydrogen and oxygen is costly
- Low cell lifetime which also affects the cost

7. <u>Regenerative Fuel Cells</u>

- Currently researched by NASA

- This type of fuel cell involves a closed loop form of power generation
- Uses solar energy to separate water into hydrogen and oxygen
- Hydrogen and oxygen are fed into the fuel cell generating electricity, heat and water
- The water byproduct is then recirculated back to the solar-powered electrolyser beginning the process again.

Table:8. Comparison of Fuel Cell Technologies

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Efficiency	Applications	Advantages	Disadvantages
Polymer Electrolyte Membrane (PEM)	Perfluoro sulfonic acid	50-100°C 122-212° typically 80°C	<1kW–100kW	60% transpor-tation 35% stationary	• Backup power • Portable power • Distributed generation • Transporation • Specialty vehicles	• Solid electrolyte re-duces corrosion & electrolyte management problems • Low temperature • Quick start-up	• Expensive catalysts • Sensitive to fuel impurities • Low temperature waste heat
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90-100°C 194-212°F	10–100 kW	60%	• Military • Space	• Cathode reaction faster in alkaline electrolyte, leads to high performance • Low cost components	• Sensitive to CO_2 in fuel and air • Electrolyte management
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a matrix	150-200°C 302-392°F	400 kW 100 kW module	40%	• Distributed generation	• Higher temperature enables CHP • Increased tolerance to fuel impurities	• Pt catalyst • Long start up time • Low current and power
Molten Carbonate (MCFC)	Solution of lithium, sodium, and/ or potassium carbonates, soaked in a matrix	600-700°C 1112-1292°F	300 kW-3 MW 300 kW module	45-50%	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP	• High temperature cor-rosion and breakdown of cell components • Long start up time • Low power density
Solid Oxide (SOFC)	Yttria stabi-lized zirconia	700-1000°C 1202-1832°F	1 kW–2 MW	60%	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte • Suitable for CHP & CHHP • Hybrid/GT cycle	• High temperature cor-rosion and breakdown of cell components • High temperature opera-tion requires long start up time and limits

Conversion Efficiency of a Fuel Cell:

The Electrical energy generated by a fuel cell depends on the free energy of the overall cell reaction. The free energy of formation of 1 mole (18g.) of liquid water from hydrogen and oxygen at atmospheric pressure is 56.67 kcal at 25^0C.The heat energy (enthalpy) of the reaction under same conditions is 68.26 kcal. The Theoretical efficiency of the conversion of heat energy in to electrical energy in a hydrogen-oxygen fuel cell is (56.67/68.26)*100 = 83%.

Efficiencies as high as 70% have been observed, but the practical cells using pure hydrogen and oxygen generally having 50-60% efficiency. The efficiency decreases when air is the source for oxygen. The overall thermal to electrical energy conversion also decreases when hydrogen is derived from hydrocarbons.

The theoretical e.m.f (voltage) of a fuel cell can be calculated from the reaction free energy. For a hydrogen-oxygen fuel cell at 25^0C with the gasses at atmospheric pressure, the ideal e.m.f is 1.23 volts. For the moderate currents at which the fuel cells operate the e.m.f is 0.7-0.8 volts.

Note: Even in an Ideal hydrogen-oxygen fuel cell, 17 % (100-83) of the chemical reaction energy (enthalpy) would be liberated as heat.

Importance of Hydrogen

- ✓ Fuel Cells require highly purified hydrogen as a fuel
- ✓ Researchers are developing a wide range of technologies to produce hydrogen economically from a variety of resources in environmentally friendly ways
- ✓ The biggest challenge regarding hydrogen production is the cost
- ✓ Reducing the cost of hydrogen production so as to compete in the transportation sector with conventional fuels on a per-mile basis is a significant hurdle to Fuel Cell’s success in the commercial marketplace
- ✓ Developing safe, reliable, compact and cost-effective hydrogen storage is one of the biggest challenges to widespread use of fuel cell technology
- ✓ Hydrogen has physical characteristics that make it difficult to store large quantities without taking up a great deal of space.

Applications of Fuel Cell Technology:

1. Transportation
2. Stationary Power Stations
3. Telecommunications
4. Micro Power

Transportation

a. All major automakers are working to commercialize a fuel cell car

b. Automakers and experts speculate that a fuel cell vehicle will be commercialized by 2010

c. 50 fuel cell buses are currently in use in North and South America, Europe, Asia and Australia

d. Trains, planes, boats, scooters, forklifts and even bicycles are utilizing fuel cell technology as well

Stationary Power Stations

a. Over 2,500 fuel cell systems have been installed all over the world in hospitals, nursing homes, hotels, office buildings, schools and utility power plants
b. Most of these systems are either connected to the electric grid to provide supplemental power and backup assurance or as a grid-independent generator for locations that are inaccessible by power lines

Telecommunications

a. Due to computers, the Internet and sophisticated communication networks there is a need for an incredibly reliable power source

b. Fuel Cells have been proven to be 99.999% reliable

Micro Power

- Consumer electronics could gain drastically longer battery power with Fuel Cell technology
- Cell phones can be powered for 30 days without recharging

- Laptops can be powered for 20 hours without recharging

Benefits of Fuel Cell Technology:

1. Reliability:

a) More reliable power from fuel cells would prevent loss of Business

b) Properly configured fuel cells would result in less than one minute of down time in a six year period

2. Efficiency:

a) Because no fuel is burned to make energy, fuel cells are fundamentally more efficient than combustion systems
b) Additionally when the heat comes off of the fuel cell system it can be captured for beneficial purposes. This is called Cogeneration
c) The gasoline engine in a conventional car is less than 20% efficient in converting the chemical energy in gasoline into power
d) Fuel Cell motors are much more efficient and use 40-60% of the hydrogen's energy
e) Fuel Cell cars would lead to a 50% reduction in fuel consumption
f) Fuel Cell vehicles can be up to 3 times more efficient than internal combustion engines
g) Fuel Cell power generation systems in operation today achieve 40% to 50% fuel-to-electricity efficiency
h) In combination with a turbine, electrical efficiencies can exceed 60%
i) When Cogeneration is used, fuel utilization can exceed 85%

3. Environmental Benefits:

a) Fuels cells can reduce air pollution today and offer the possibility of eliminating pollution in the future

b) A fuel cell power plant may create less than one ounce of pollution per 1,000 kilowatt-hours of electricity produced

c) Conventional combustion generating systems produce 25 pounds of pollutants for the same electricity

d) Fuel Cell Vehicles with hydrogen stored on-board produce ZERO POLLUTION in the conventional sense

e) The only byproducts of these Fuel Cell vehicles are water and heat

f) Fuel Cell Vehicles with a reformer on board to convert a liquid fuel to hydrogen would produce a small amount of pollutants, but it would be 90% less than the pollutants produced from combustion engines

g) Fuel Cell replacements would have an environmental advantage over batteries, since certain kinds of batteries require special disposal treatment

Challenges to Fuel Cell Technology:

1. Cost:

The cost of fuel cells must be reduced to compete with conventional technologies

Conventional internal combustion engines cost $25-$35/kW; a fuel cell system would need to cost $30/kW to be competitive

2. Durability and Reliability:

a. Researchers must develop PEMFC membranes that are durable and can operate at temperatures greater than 100 degrees Celsius and still function at sub-zero ambient temperatures.

b. A 100 degrees Celsius temperature target is required in order for a fuel cell to have a higher tolerance to impurities in fuel. Because you start and stop a car relatively frequently, it is important for the membrane to remain stable under cycling conditions. Currently membranes tend to degrade while fuel cells cycle on and off, particularly as operating temperatures rise.

c. For stationary systems 40,000 hours of reliable operation in a temperature range of -35 degree Celsius to 40 degrees Celsius will be required for market acceptance

d. Solid oxide systems have issues with material corrosion.

e. SOFC durability suffers after the cell repeatedly heats up to operating temperature and then cools down to room temperature System Size

f. The size and weight of current fuel cell systems must be reduced to attain market acceptance, especially with automobiles.

Storage and Other Considerations

Three hundred miles is a conventional driving range (the distance you can drive in a car with a full tank of gas). In order to create a comparable result with a fuel cell vehicle, researchers must overcome hydrogen storage considerations, vehicle weight and volume, cost, and safety.

Conclusion

- Most Promising technology
- Most viable for niche market use in the near future
- Widespread marketplace acceptance and use is still many years away.

HYDROGEN VEHICLE: A hydrogen vehicle is a vehicle that uses hydrogen as its on board fuel for motive power. Hydrogen vehicles include hydrogen fueled space rockets, as well as auto mobiles and other transportation vehicles. The power plants of such vehicles convert the chemical energy of hydrogen to mechanical energy it her by burning hydrogen in an internal combustion engine, or by reacting hydrogen with oxygen in a fuel cell to run electric motors. Wide spread use of hydrogen for fueling transportation is a key element to proposed hydrogen economy. Hydrogen fuel does not occur naturally on Earth and thus is not an energy source; rather it is an energy carrier. It is most frequently made from methane or other fossil fuels, but it can be produced using sources (such as wind, solar, or nuclear) that are intermittent, however the conversion loss to chemical energy makes the approach un eco nomicalonal large-scale. Integrated wind-to-hydrogen (power to gas) plants, using electrolysis of water, are exploring technologies to deliver costs low enough, and quantities great enough, to compete with traditional energy sources. There are various ways to produce hydro gen fuel such as: natural gas, coal, nuclear power, and renewable resources. By use of thermo chemical processes one can produce hydrogen from biomass, coal, natural gas and petroleum. Production of hydrogen electrolytic ally can also be demonstrated experimentally for power generated by use of sunlight, wind and nuclear sources.

Figure 3

In addition to this, sunlight alone can drive photolytic production of hydrogen from water by use of advanced photo catalytic water splitting and photo biological processes however none of these approaches can compete with the low cost and abundance of natural gas produced by the hydraulic fracturing of shale's . Many companies are working to develop technologies that might anciently exploit the potential of hydrogen energy for use in motor vehicles. AsofNovember2013 there are demonstration fleets of hydrogen fuel cell vehicles undergoing field testing including the Chevrolet Equinox Fuel Cell, Honda FCX Clarity, Hyundai ix35 Fuel Cell and Mercedes-Benz B-Class F-Cell. The hope that was widely promoted for hydrogen as an energy currency was that, hydrogen pre pared without using fossil fuel in puts, vehicle propulsion would not contribute to carbon dioxide emissions, and however this has preventable UN economical in light of the developments of fracking. The drawbacks of hydrogen use are high carbon emissions intensity when produced from natural gas of over 14 kg CO2 per kg of hydrogen, capital cost burden, low energy content per unit volume, low performance of fuel cell vehicles compared with gasoline vehicles, production and compression of hydrogen, and the large investment in infrastructure that would be required to fuel vehicles.

The Hydrogen Economy: *The Hydrogen Economy* is a hypothetical large-scale system in which elemental hydrogen (H_2) is the primary form of energy storage

Fuel cells would be the primary method of conversion of hydrogen to electrical energy .Efficient and clean; scalable , In particular, hydrogen (usually) plays a central role in transportation

Components of the Hydrogen Economy:

Figure 4

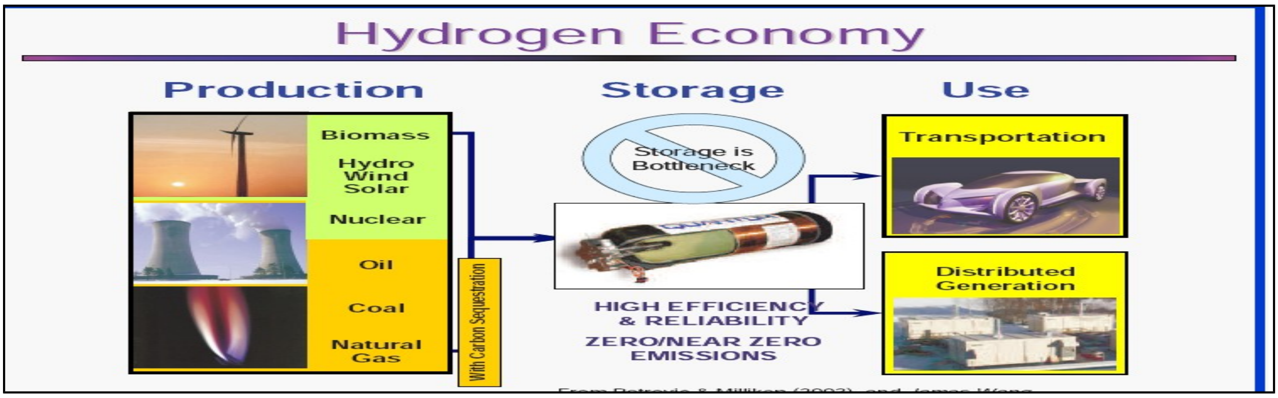

Figure 5

Various Applications :

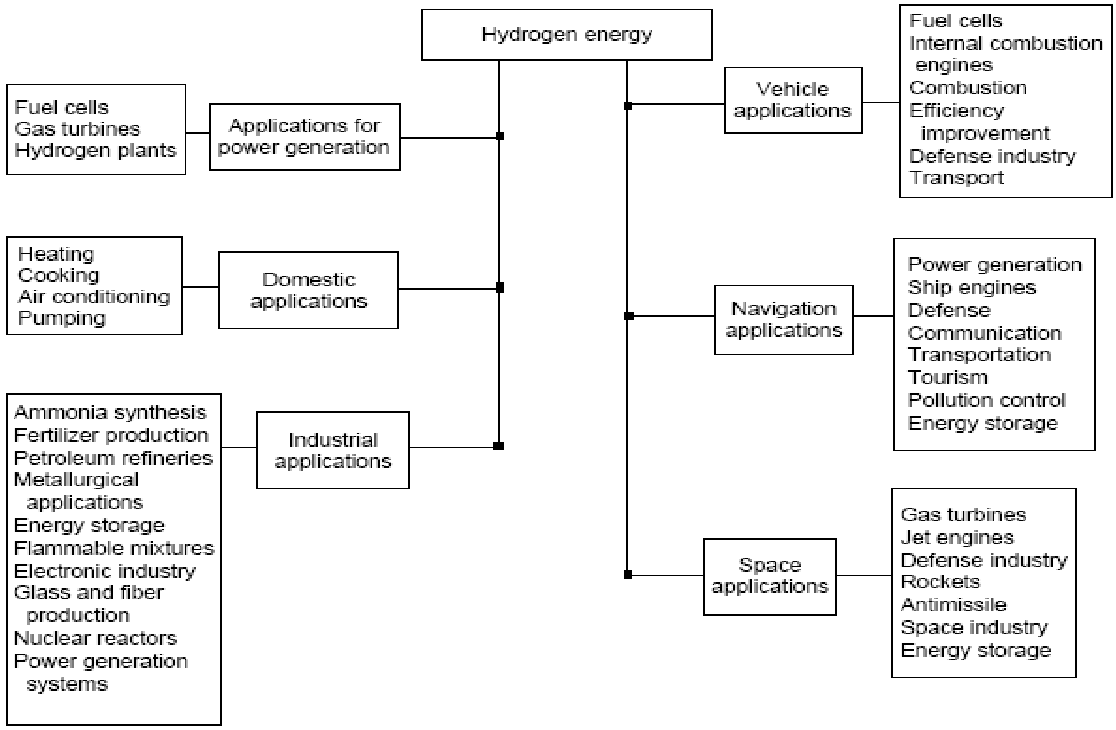

FIGURE 1.1
Application areas for hydrogen energy. (Reproduced with permission from Elsevier; Midilli, A., Dincer, I., and Rosen, M.A., *Renewable Sustainable Energy Rev.*, 9(3), 255–271, 2005.)

Figure 6