Hydrogen as energy source to avoid environmental pollution

Suilma M. Fernández Valverde
Depto. de Química, Gerencia de Ciencias Básicas, ININ, México, D.F., México

Received: September 2, 2001; accepted: May 30, 2002.

RESUMEN
El hidrógeno como energético para el futuro fue propuesto hacia fines de los años setenta. La razón principal fue la crisis petrolera, la cual llevó a considerar la necesidad de la substitución de los hidrocarburos por fuentes alternas de energía. El hidrógeno como fuente de energía, no sólo es el elemento más abundante en el universo, también es muy común en la Tierra. Es la fuente de energía alterna más importante para la creciente demanda energética y la respuesta para la necesidad actual de una energía limpia, eficiente y tecnológicamente amigable con el ambiente. Al quemar hidrógeno se produce agua y óxidos nitrosos, los cuales pueden ser eliminados utilizando celdas de combustible. Una celda de combustible es un sistema electroquímico que genera electricidad en una forma silenciosa y eficiente. Si a partir de una fuente de energía primaria que no produzca CO₂, como la solar, eólica o nuclear, se obtiene el hidrógeno, durante la generación de la energía se puede evitar la contribución al efecto invernadero y la lluvia ácida. El hidrógeno puede también ser utilizado como un portador de energía. Se presenta el estado del arte en investigación y desarrollo del uso del hidrógeno en México y en el mundo.

PALABRAS CLAVE: Contaminación ambiental, energía, almacenamiento y transporte de hidrógeno, celdas de combustible, fisión.

ABSTRACT
Hydrogen was proposed in the seventies as an energy source for the future. The main reason for the proposal was the petroleum crisis, which called attention to alternative energy sources and the necessity of hydrocarbon substitution. As an energy source, hydrogen is the most abundant element in the universe and is also common on earth. Hydrogen is the most important alternative energy source for the growing energy demand and is the answer to the present need for clean, efficient and environmentally friendly energy technologies. Burning hydrogen produces water and a small amount of nitrogen oxides, which can be eliminated with fuel cells. A fuel cell is an electrochemical device that produces electricity without combustion in an efficient and silent manner. If the hydrogen is obtained from a primary CO₂ free energy source, such as solar, wind or nuclear, the greenhouse effect and the acid rain could be avoided during energy generation. Hydrogen can also be used as an energy carrier. The state of the art in research and development on hydrogen worldwide and in Mexico is presented.

KEY WORDS: Environmental contamination, hydrogen energy, storage and transportation, fuel cells, fusion.

INTRODUCTION
Hydrogen was discovered by H. Cavendish in 1766; he concluded that water was not an element but was formed by hydrogen and oxygen. The name “hydrogen”, which means “water former” in Greek, was proposed by A.L. Lavoisier in 1783. This highly reactive element, the first one in the periodic table, has two isotopes, deuterium and tritium. Hydrogen is the most abundant element in the universe and the third one in the earth’s surface where it occurs as a diatomic molecule or combined with other elements; 70% of the existent hydrogen is found in water and in organic matter. Since the beginning of the 19th century, scientists have recognized hydrogen as a potential source of energy; it is known that hydrogen could be used as a primary energy source if the nuclear star reactions of hydrogen isotopes could be reproduced in magnetic containers. In fact, the energy of nuclear fusion is currently under research and development and an ambitious program in this field has been launched: the International Thermonuclear Energy Reactor (ITER). This new energy source is characterized by advantageous safety characteristics, almost unlimited fuel resources and low environmental impact. In long term, fusion reactors offer the potential for replacing fossil energies (Aymar, 2001)

As a secondary energy source, hydrogen could be obtained using a primary energy source followed by electrolysis (Kreuter and Hoffman, 1998), thermochemical cycles (Funk, 2001) or biomass (Das and Veziroglu, 2001) to produce hydrogen. Its direct burning forms small amounts of nitrogen oxides, but when fuel hydrogen is converted to electricity through an electrochemical process in a fuel cell, it only produces water as a sub product preventing environmental pollution. One of the problems concerning the use of hydrogen as an energy source is its acceptance by the public, the main point being safety, particularly because of accidents.
which occurred during the last century, the most striking one being the Hindenburg, the German airship explosion in 1937 when 36 people were killed. An investigation published by NASA concluded that the paint used on the zeppelin cover was the cause of the accident rather than hydrogen (Bain and Van Vorst, 1999). Today hydrogen is as safe as other fuels. In 1997, a study by the Ford Motor Company concluded that, with the proper engineering, the safety of a hydrogen fuel cell vehicle would be potentially better than a gasoline or propane vehicle.

Environmental pollution from fossil fuels produces inorganic and organic contaminants, such as sulfuric and nitric acids which affect life, as well as CO₂, the main contributor to global warming (Ogden, 1999). Particulate matter pollution to the atmosphere is also a product of fossil fuel burning. The future availability of oil indicates that the best oil fields have already been discovered; moreover new oil fields will increase the production cost.

**METHODOLOGIES**

**Fuel cells**

Hydrogen has the advantage to generate electricity when combined with oxygen to produce water. Figure 1 shows the cycle for hydrogen energy. A fuel cell is an electrochemical device, where hydrogen or other fuels can be converted to electricity using an electrocatalyst; since this conversion is not limited by the Carnot cycle, the efficiency in the generation of electricity is higher than in conventional engines. Fuel cells operate at different working temperatures and could, therefore, be used in different applications at sites where stable and continuous electrical current is needed. Such is the case of hospitals, shopping malls, dwellings or transportation. Table 1 presents the main types of Fuel Cells together with the working temperature and their kind of fuel. If hydrocarbons instead of hydrogen are used as fuel, a small amount of CO₂ is formed.

In the past years several companies have been created to do research and development on fuel cell energy: Tokyo Electric Utility, Kansai Electric Power International Fuel Cells, Toshiba, Siemens/Westinghouse, Plug Power/GE, Fuel cell Energy Corp, EPRI, Ballard Power Systems and others. Furthermore Westinghouse Company has announced the marketing of a 1 MW solid oxide fuel cell power plant 70% efficient, which started to operate in 2001. A new member of the fuel cell family is the regenerative fuel cell, in which water is separated into hydrogen and oxygen by a solar-powered electrolyzer. The hydrogen and oxygen are fed into the fuel cell, which in turn produces electricity and water. The water

![Fig. 1. Water can be separated using a primary energy source, then stored and used as energy carrier. The utilization of hydrogen produces energy and water, after which the cycle can be repeated.](image-url)
is then recirculated back to the solar-powered electrolyzer where the process is repeated. The choice of an adequate fuel cell depends on its use.

**Hydrogen production**

Four hundred billion cubic meters of hydrogen are produced worldwide each year mainly at oil refineries or by electrolysis in chemical industries. At present, the most common and least expensive method to produce hydrogen is steam reforming. In this process methane (CH₄) or other hydrocarbon is heated over a catalyst and decomposed into hydrogen and carbon monoxide. If steam is added more hydrogen is produced and carbon dioxide is obtained as a subproduct (Astanovsky *et al.*, 1994).

Coal can be used for hydrogen production as well, but in this case the carbon dioxide produced needs to be sequestered. Sequestration is the deposition of the exhausted gases that have been produced in steam reforming or coal gasification, into depleted oil gas fields, deep coal beds or deep saline aquifers. Presently China, Italy and India have formal plans to cooperate in hydrogen production by gasification.

Hydrogen can also be extracted from oil, gasoline and methanol through reforming, but in these cases carbon sequestration technologies are required. In October 2000, BP and Ford donated $20 million to Princeton University to study the technical and economical viability of this approach.

Besides, hydrogen can be produced directly with sunlight and water by biological organisms (Das, 1998) or by using semiconductors-based systems. The use of non CO₂ hydrogen producing technologies such as wind, solar or nuclear can help to avoid global warming and environmental pollution.

**Hydrogen storage and transportation**

Hydrogen can be stored as compressed gas, as liquid hydrogen and as metal hydrides (Hanneken, 1999). Although some hydrides are commercial, studies on new alloys with better conditions of temperature and pressure storage are still needed. Research for hydrogen storage in carbon structures is currently under way worldwide. Table 2 shows the different methods of hydrogen storage together with their applications. In Kiev, Germany, the town gas which is composed of 60% hydrogen has been stored in a gas cavern since 1971. Gas de France has stored hydrogen-rich refinery products in an aquifer structure, and The Imperial Chemical Industries had stored hydrogen in salt mines caverns.

Hydrogen transportation depends on the needs. At present about 5% of the hydrogen produced is delivered as liquid or gas by truck or pipelines. In Table 3, the different

<table>
<thead>
<tr>
<th>Type</th>
<th>Operation temperature (°C)</th>
<th>Fuel</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphoric acid</td>
<td>170-210</td>
<td>Hydrogen</td>
<td>Most mature fuel cell technology.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Natural Gas</td>
<td>200 kW up to 1Mw units</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Methanol</td>
<td></td>
</tr>
<tr>
<td>Molten Carbonate</td>
<td>650</td>
<td>Hydrogen</td>
<td>60% efficiency and with cogeneration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Natural Gas</td>
<td>85% efficiency</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Carbon Monoxide</td>
<td>10 kW to 2 MW units</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Landfill Gas</td>
<td></td>
</tr>
<tr>
<td>Solid Oxide</td>
<td>800-1000</td>
<td>Hydrogen</td>
<td>Efficiency equivalent to molten carbonate.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Natural Gas</td>
<td>units up to 200 kW</td>
</tr>
<tr>
<td>Alkaline</td>
<td>60-90</td>
<td>Hydrogen</td>
<td>Efficiency up to 70%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Natural Gas</td>
<td>220 kW units</td>
</tr>
<tr>
<td>Proton Exchange Membrane</td>
<td>80-90</td>
<td>Hydrogen</td>
<td>Primary options for light-duty vehicles</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Methanol</td>
<td>50 to 250 kW</td>
</tr>
</tbody>
</table>
For hydrogen transportation, a 210-kilometer hydrogen pipeline has been operating in Germany since 1939. In the USA over 720 km of hydrogen pipelines are found along the Gulf Cost and around the Great Lakes. The longest hydrogen pipeline is found in Europe between France and Belgium.

### International Standards

In 1990 the International Standards Organization in Geneva, Switzerland, decided to start formulating the international standards for hydrogen energy technology. The ISO/TC 197, which is committed to preparing the international safety hydrogen standards, comprises 12 participating countries and 15 observers and maintains communication with 10 organizations including 8 technical committees.

### Research in the World and in Mexico

At present, hydrogen is mainly consumed on site for petroleum refining or for ammonium fertilizers, resins, plastics and solvent manufacture. Additionally hydrogen obtained through electrolysis is important in the alimentary industry. The amount of hydrogen used as an energy source, or as an energy carrier, to transport energy from the point of production to the point of utilization, is almost negligible. Nevertheless, several research and development projects on hydrogen energy are under way at the international level; a brief account of the major projects appears on Table 4 (Dunn, 2001). The financial support of USA for hydrogen projects is still 1/5 of the budget for the clean coal technologies, and only 1/10 of that for nuclear power.

The European Union is testing electrolyzers that operate with solar or wind energy for hydrogen production, making research in materials for fuel cells. Besides some fuel cell buses are already in use in Bavaria. In Japan, the WE-NET (World Energy Network) project has done research and development on fuel cells, hydrogen stations, metal hydride storage, thermo-chemical hydrogen production obtained from the helium gas cooling of the High Thermo-Chemical Nuclear Reactor (HTGR), and cars working with fuel cells. Iceland wants to become the world’s first hydrogen economy and a very ambitious multimillionaire project is under way. Germany has developed a project with Saudi-Arabia, Hy-Solar, to use solar energy for hydrogen production via electrolysis. Argentina wants to use the enormous potential of the Patagonia wind for the same purpose. Canada has very important projects on hydrogen production, storage and transportation, as well on fuel cells. Cuba has an incipient but interesting national hydrogen program. The International Energy Agency (IEA) has a hydrogen program with 13 participating countries: some of which are the following: Japan, USA, Canada, Italy, The Netherlands, Norway, Spain, Sweden and Switzerland. Researchers, industries, and users are working on regulations for the use of hydrogen.

In Mexico, the institutions doing research and development on hydrogen are the following: Instituto Nacional de Investigaciones Nucleares (ININ), Instituto de Investigaciones Eléctricas (IIE), and Instituto Mexicano del Petróleo (IMP), all of which are a part of the Secretaría de Energía (Energy Minister). Other research centers are: Centro...
de Investigación y de Estudios Avanzados (CINVESTAV), Instituto Politécnico Nacional (IPN) and Instituto Tecnológico de Monterrey (ITM) as well as Universidad Nacional Autónoma de México (UNAM), Universidad Autónoma Metropolitana (UAM), Universidad de las Américas (UA) and Universidad Autónoma de Zacatecas (UAZ). There are approximately 30 people working in all the fields related with hydrogen energy materials. The main studies under way deal with synthesis and characterization of: oxides to be used as anodes for electrocatalytic cells; semiconductors to be used as electrodes in solar electrolysers (López et al., 2002, Arriaga and Fernández, 2002); mixed metal alloys for hydrogen storage (Palacios et al., 2002); catalysts materials for fuel cells (Durón et al., 2000) and power electrical generation. Likewise determination of the life cycle analysis of hydrogen fuel is in progress.

The researchers working on hydrogen are very interested in developing the infrastructure required for the application of hydrogen as a fuel; as a result of their interest and efforts, the Mexican Hydrogen Society was founded three years ago. The benefits of a Mexican hydrogen program can be grouped in four main areas:

a) Alternative energy sources for a growing energy demand.

b) An answer to the present need for clean, efficient and environmentally friendly energy technologies.

c) A better use of our natural resources, both renewable and non renewable.

d) A better knowledge of energy alternatives for energy strategies and policies.

CONCLUSIONS

In first world countries, projects for research, development and demonstration are in progress; in developing countries, only Saudi Arabia, Argentina and Turkey have international projects. In Mexico, most of the studies under way are on research materials for hydrogen production and storage, and on materials for fuel cells. We feel that a major integration with the world hydrogen communities is needed.

Furthermore, if the projects succeed in lowering the cost of hydrogen production and storage, and of fuel cells, and if people accept hydrogen use, the future renewable energy will be hydrogen energy, which will result in preventing environmental pollution.

BIBLIOGRAPHY


PALACIOS, A. F., M. H. CALDERON BENAVIDES, J. G. CABAÑAS MORENO, J. BONIFACIO MARTÍNEZ and J. L. ITURBE GARCÍA, 2002. Hydriding and dehydriding properties of Mg$_2$Ni and Mg$_2$Ni$_{0.95}$Cu$_{0.05}$ prepared by mechanical alloying. *Int. J. of Hydrogen Energy*. (Accepted for publication)

Suilma M. Fernández Valverde
*Depto. de Química, Gerencia de Ciencias Básicas, ININ*
*A.P. 18-1027, 11870 México, D.F., México*
*Email: smfv@nuclear.inin.mx*