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Report

HYDROGEN ENERGY TECHNOLOGY
FOR
DEVELOPING COUNTRIES

prepared for

UNIDO
United Nations Industrial Development Organisation

by

37/5

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July 1989

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1. INTRODUCTION

Today, three quarters of the world's population, those living in developing countries, consume only about one-quarter of the world energy production, while those living in the industrial countries consume about three-quarters of the energy production. In other words, the peoples of the industrial countries have higher living standards than those of the rest of the world (i.e., the developing countries), since the gross national product per capita--which is a measure of the standard of living--is directly related to the energy consumption per capita. The peoples of the developing countries are aspiring and trying to improve their living standards, and hence increase their energy consumption.

Presently, the earth's population is about 5.1 billion and is growing at the rate of 1.8% per year. On the other hand, the demand for energy is growing at a much higher rate (at about 4-6% per year), since the developing countries are trying to increase their energy consumption faster than the industrialized countries. Today, most of this energy demand is met by fossil fuels (i.e., coal, petroleum and natural gas). On the other hand, it is estimated that the world fossil fuel production, beginning with petroleum and natural gas, will soon start declining.

Nonconventional energy sources such as solar, ocean thermal, wind, waves, currents, tides, thermonuclear, geothermal etc., are being considered as possible sources of energy to meet the growing demand. However, none of these new energy sources have all the desirable qualities of petroleum and natural gas. For example, some are only intermittently available, others are only available away from the consumption centers, and none can be used as a fuel for transportation. Therefore, it becomes necessary to find an intermediary or synthetic form of energy which can be produced using the nonconventional primary energy sources being considered.

In addition to being nonrenewable, the fossil fuels cause some other problems. Their combustion products pollute the environment and produce acid rains. The main combustion product of fossil fuels, CO_2, is causing the so-called "greenhouse effect." This is resulting in higher temperatures, droughts, melting of the ice caps, floods and climate changes.

Many scientists and engineers believe that a hydrogen energy system could form the link between the new energy sources and the user, and at the same time solve the environmental problems created by fossil fuels. It is the most economical fuel to produce, the cleanest and recyclable. In the hydrogen energy system, it is envisaged that hydrogen will be produced from the new nonfossil energy sources, and will be used in every application where fossil fuels are used today. In this system hydrogen is not a primary source of energy. It is an intermediary form of energy, a secondary form of energy, or an energy carrier.

Hydrogen has the most desirable properties for a fuel. It is the lightest and the cleanest fuel. It can be converted to other forms of energy more efficiently than other fuels. It is also the most abundant element in the universe. Many stars and planets are either entirely made up of hydrogen or contain large percentages of it. For example, the most abundant element in the sun is hydrogen. The sun's energy is produced by the fusion of hydrogen atoms or nuclei into helium. The planet Jupiter is made up of liquid and solid hydrogen. Even the interstellar space contains about 1 hydrogen molecule cm^{-3}.

On the other hand, on earth hydrogen is not abundant as a free element. It is found in natural gas in small percentages. It forms 0.2% of the atmosphere. These are very small quantities compared to the fuel needs of the world. Therefore, hydrogen must be manufactured using some primary energy source if it is to meet our fuel needs.

Industrial countries are the biggest users of fossil fuels, and therefore are the greatest sufferers from their environmental misdeeds. It is costing them large funds to try and remedy the damages, and the damages are growing with the increasing use of the fossil fuels.

On the other hand, the developing countries are trying to establish the infrastructure of their energy systems. As such, they have a great opportunity. They could opt for the clean and permanent Hydrogen Energy System, rather than to have to change to it later. This would be a more economical approach, and at the same time would save their environment from the ills of the fossil fuels. It would speed up their development, since the renewable primary energy sources needed are available to them, as well as improving their quality of life.

Since the aim of the developing countries should be to develop fully and reach the same status as the industrial countries, and to be able to contribute to the progress of the human civilization, this report will not only cover the present needs of the developing countries, but the future needs as well.

2. LIABILITIES OF FOSSIL FUELS

Presently, most (about 80%) of the world energy demand is met by fossil fuels. However, according to reliable estimates [1-3], the production of the fossil fuels will soon start decreasing. Figure 1 shows the projected production rates of world fossil fuels. The lower line estimates coal production if it is used as solid fuel. The middle curve is the expected rate of production of fluid fuels--petroleum and natural gas. World fluid fuel production will reach its peak around the year 2010, and then will start decreasing. The higher curve gives the total fossil fuel production estimates, if synthetic gas and gasoline produced from coal become available. In this case, production will rise until the year 2030, and then start decreasing.

The combustion products of fossil fuels are damaging the Earth's climate and environment. An important type of pollution, air pollution, is caused mainly by fossil fuels used to obtain energy for transportation, electricity production, heat generation, etc. This year alone fossil fuels will be spewing some 30 billion tons of CO_2, CO, SO_2, NO_x, soot and ash into the atmosphere.

In major cities around the world, air pollution is getting so bad that at times schools are closed, children sent home, and people are asked to refrain from physical activities so that they will not have to breathe excessively. Respiratory diseases are increasing and the life span is decreasing. The traffic police in Tokyo are regularly administered oxygen so that they can continue to perform their duties in the poisoned atmosphere of the city.

Acid rains produced by fossil fuels are literally killing our lakes. Already hundreds of lakes in Canada, Finland, Norway, Sweden and the United States of America have high enough acidity ratios produced by acid rains--that they are no longer a suitable habitat for fish and aquatic plants. They are literally dead! Every year, hundreds of more lakes are dying. This is causing some international tension between the industrial countries in the temperate belt and the countries to the north, since the former produce most of the ingredients for the acid rains, and the latter are on the receiving end, due to the prevailing winds.

Acid rains have also started contaminating sources of some drinking water, as a result of which babies are becoming sick and water pipes are corroding.

It is estimated that by the year 2035, the oceans will have such high acidity that they will no longer be a hospitable environment for fish.

Acid rains are also affecting crops. Studies show that the quality and quantity of farm products, forests and vegetation in general, are suffering. They are also causing irreversible damage to historical buildings and structures.

In addition to pollution and the acid rains, there is a new culprit--CO_2, the main combustion product of fossil fuels. For a long time, CO_2 was believed to be harmless. Now, there is evidence that because of the "greenhouse effect" caused by CO_2, the polar ice caps have started to melt and the oceans have started to rise. At the present time, the rate of rise is estimated to be about 1 to 1.5 cms per year, and this rate is growing with the increase of CO_2 in the atmosphere. It is projected that at this rate, when the melting process is completed the oceans will rise by about 26 feet, or 8 meters, enough to put many coastal cities and plains under water, where a very large percentage of the earth's population lives. This will result in a shortage of habitable and arable land. The effects are already observable in the North Sea. The Germans and the

Dutch are increasing the height of their dykes to keep the North Sea back. In the United States, the Environmental Protection Agency sent a team of experts to various coastal cities two years ago. They told the local officials that the oceans are rising and that if they are going to put up any structures on the coast or in the water, they should build them higher.

The greenhouse effect is also causing, as we are now observing, climatic changes. The wind patterns are changing. As a result the cloud movements and the locations where rainfalls are changing. This is causing drought in places where historically there was good rainfall and floods in other places where historically there was less rainfall. The consequences are less agricultural produce (higher produce prices) and less hydroelectric power.

In addition to their environmental transgressions, fossil fuels have another fault. They are not distributed evenly among the countries of the world. This unequal distribution, together with the addiction to petroleum, is causing international problems between the suppliers of petroleum and the consuming nations. This is especially hurting the nonpetroleum developing countries, and slowing down their development. Development of nonconventional energy sources will remove this important cause, because they are distributed more evenly around the world, and each country has one or more of the nonconventional energy sources available to meet its requirements almost indefinitely.

When we consider all the detrimental effects and liabilities of petroleum and other fossil fuels, one begins to think that we are fortunate to be running out of them. If there were an interminable supply of fossil fuels, we would eventually turn the planet earth into a desolate graveyard.

3. SHORTCOMINGS OF NONCONVENTIONAL ENERGY SOURCES

In order to make up for the depletion of fossil fuels and meet the growing world energy demand, several alternative and nonconventional primary energy sources are being considered and researched by scientists [4-15], such as direct solar radiation, wind energy, waves, currents, tides, ocean thermal energy, nuclear breeders, fusion reactors and geothermal energy. It may be necessary to make use of several of these primary energy sources. Of course, they do not all have to be used at the same time and/or place. Depending on the economics and availability, different mixes of the primary energies may be used in different parts of the world through different time periods.

Fossil fuels on the other hand have some very useful properties, which are not all shared by nonconventional energy sources. They possess concentrated energy. They are relatively light for the amount of energy contained in them. They can be transported easily using pipelines, railcars, tankers and/or trucks. They are storable. They can be stored for long periods of time without any change in their properties. However, as outlined before, fossil fuels are not renewable. It has taken nature millions of years to produce the fossil fuels which we will be consuming in one century or so.

The nonconventional energy sources, which are being considered, do not possess all the advantages of fossil fuels, although some of them, such as solar, wind and ocean-thermal, are almost unlimited and are environmentally compatible. Some are only intermittently available. For example, solar energy is only available during daytime when the skies are clear. Even then, the intensity of solar radiation is subject to diurnal and seasonal changes. Hence, solar energy needs to be stored to meet the demand when solar radiation is not available. Some of the new energy sources are continuously available, but they are too far away from the consumption centers. For example, the best ocean-thermal energy sites are the equatorial regions of the oceans. In the case of nuclear power plants, because of the potential danger from radioactivity, it would be better to locate them away from the cities and the consumption centers.

None of the new energy sources mentioned can be used as fuel for transportation with, perhaps, the exception of nuclear energy. Nuclear energy is being used to power some ships. However, it has not, as yet, proved itself commercially. None of the new energy sources, with the exception of nuclear, is transportable or storable by itself. Some are not pollution free, such as geothermal which brings out chemical pollution, and nuclear which produces thermal pollution and radioactive waste.

4. HYDROGEN ENERGY SYSTEM

The above-mentioned shortcomings or drawbacks of the nonconventional energy sources point to the need for an intermediary energy system to form the link between the new primary energy sources and the energy consuming sectors or the user. In such an intermediary system, the intermediary energy form or carrier must be transportable and storable; economical to produce; and renewable and pollution free, if possible. It ought to be independent of the primary energy sources used, so that even if the primary nonconventional energy sources are changed from time to time, the intermediary energy system remains intact. This would have the advantage of keeping the storage and transmission systems and conversion devices running on the same intermediary (synthetic) fuel, even though the primary energy sources may have to be changed with geographic location and time.

All the synthetic fuels (hydrogen, methane, methanol, ethanol, ammonia, hydrazine, etc.) are candidates for the intermediary system. Among these, hydrogen meets the above prerequisites best. It is plentiful in the form of water in oceans, lakes and rivers. It is the cheapest synthetic fuel to manufacture per unit of energy stored in it. It is almost pollution free, or the least polluting of all of the synthetic fuels. Over the last decade there have been increasing research efforts to investigate the various aspects of the hydrogen energy system and its implications. Most of the research results have been presented in the proceedings of The Hydrogen Economy Miami Energy (THEME) Conference [16] and in those of the seven World Hydrogen Energy Conferences [17-23] held to date. Books and reports by Bockris [24], Veziroglu [25], Ohta [26], Williams [27], and Skelton [28] cover hydrogen production methods and utilization in some depth.

Table I compares hydrogen (both liquid and gaseous) with gasoline and natural gas. A study of the table shows that for a given amount of energy, hydrogen weighs about one-third of the fossil fuels. But it is bulkier; for a given amount of energy, hydrogen in liquid form occupies 3.8 times the volume occupied by gasoline, and in gaseous form it occupies 3.6 times the volume occupied by natural gas. However, in practice this volume penalty is 20-50% less, since hydrogen can be converted to other forms of energy at the user end more efficiently than fossil fuels. Its high flame speed and wide flammability limits make hydrogen a very good fuel for internal combustion engines, gas turbines and jet engines. High ignition temperature and low flame luminosity make hydrogen a safer fuel than others. It is also nonpoisonous and recyclable.

Figure 2 shows the proposed hydrogen energy system, forming the link between the nonconventional energy sources and the user [29,30]. Hydrogen is produced from water using one or more of the nonconventional primary energy sources. During the changeover period, coal, a relatively abundant fossil fuel, could also be used for hydrogen production with some environmental benefits. Hydrogen can be produced by four main methods: (1) the direct thermal method, (2) the thermochemical method, (3) electrolysis, and (4) photolysis. As a result of using one of these methods, water is separated into its elements, hydrogen and oxygen. Hydrogen is then transported, stored and distributed to energy consumption sectors, where it is used in every application of fossil fuels, with the exception of cases where carbon is specifically needed. After use as fuel, hydrogen turns into water vapor (by combining with oxygen) which is recycled back to earth as rain. The oxygen produced could either be released into the atmosphere, or shipped or piped to industrial and city centers for industrial use and also for rejuvenating the polluted rivers and lakes, and in speeding up sewage treatment.

Hydrogen is a very efficient energy carrier. For distances greater than 400 miles, it is cheaper to transmit energy as hydrogen through pipelines than as electricity via overhead lines. In addition, hydrogen pipelines would need very little right-of-way, take up no land area, and do away with unsightly electricity transmission lines and towers. Also, hydrogen is storable while electricity is not.

In the hydrogen energy system, it is envisaged that from the production plants or the ports, hydrogen will be transmitted by means of underground pipelines and/or supertankers to industry, buildings and homes. There, hydrogen can be used directly for industrial processes needing heat, for space heating, and for cooking. For example, the combustion of hydrogen with oxygen produces steam, which is used in many industries such as the paper and chemical industries. This is an elegant and efficient way of obtaining steam. Hydrogen can be used in the smelting of iron, in lieu of coal, with untold environmental benefits. The electricity needs of industry, buildings and homes can be met by fuel cells, in which hydrogen and oxygen combine, and produce electricity. Today, the conversion efficiency is of the order of 40-70%. It is expected that this figure will be improved upon with further research.

Because of its ideal properties as a fuel and its lightness, hydrogen is a very good fuel for transportation. In internal combustion engines, it can be converted to mechanical energy with higher (10-20%) efficiency than fossil fuels. Additionally, hydrogen-fueled engines do not need pollution control devices and as a result conserve more energy. Because hydrogen is so much lighter than jet fuel, it considerably reduces the take-off weight of airplanes and consequently decreases the fuel consumption. With hydrogen, all the objections to supersonic transport would be eliminated. There will be no damage to the ozone layer since the combustion product is water vapor, the engines will be quieter since they will be smaller, and the passenger per mile cost will be less due to energy conservation.

The nonconventional energy sources are distributed more evenly around the world than fossil fuels. Each country has one or more of the nonconventional energy sources available to it. Consequently, each country will be able to produce the fuel it needs as hydrogen, using the nonconventional energy source(s) it has. As a result, an important cause of international conflicts, that of energy sources (petroleum) being concentrated in a few regions of the world, will be removed, and each country will be able to speed up its economic development by producing the fuel it needs.

5. PRODUCTION AND DELIVERY

Since hydrogen is a synthetic fuel, it must first be produced, stored, transported and distributed, so that it can be utilized. There are four main hydrogen production methods, viz., direct thermal, thermochemical, electrolytic and photolytic.

5.1. Direct Thermal Production

When water is heated to form steam and then steam is superheated to about 2,500° F or above, steam starts dissociating to produce hydrogen and oxygen [31-33]. As the temperatures are increased further the rate of dissociation increases. As the steam pressure is reduced, the rate of dissociation also increases. This can be achieved by mixing the steam with some other non-reacting gas such as nitrogen. In other words, higher temperatures and lower pressures are conducive to direct thermal production of hydrogen.

If sufficient amounts of hydrogen are to be dissociated, temperatures around 5,000 to 6,000° F must be reached. The energy for reaching these high temperatures can be obtained from solar radiation. For this purpose an optical "mirror" system would collect the solar radiation and concentrate it into a smaller area. Parabolic mirrors would then be used to focus the solar energy onto containers of water. Such devices are called solar furnaces since they produce very high temperatures.

There are two problems with the direct thermal method. One is that the containers will not withstand the temperatures in question. Therefore, there must be an efficient means of cooling them down. The second problem is that hydrogen and oxygen must be separated from each other at very high temperatures, because as they cool down they recombine, forming water vapor. Various techniques are being researched to find efficient and economical ways of separating the two gases [34-35]. The centrifugal, magnetic, quenching and membrane methods are among those being considered.

In the centrifugal method the hot gas mixture is rotated very fast. The centrifugal forces cause the heavier gases, such as oxygen and water vapor, to go to the periphery. Hydrogen (the lightest gas) remains in the center. Hydrogen is then extracted by means of a periscopic pipe.

In the quenching method, the hot gases are cooled very fast, showering them with large amounts of water, in order to reduce the temperatures quickly so that the two gases can be cooled down before they have had enough time for recombination. Then they can be separated at lower temperatures much easier.

Some membranes allow the passage of small, light molecules, such as hydrogen, through but not heavier molecules, such as oxygen and water vapor. For example, palladium, which can stand quite high temperatures (melting point: 2,800° F), will let hydrogen through but not oxygen. There are also some ceramics, which can withstand high temperatures, with similar membrane properties. They are being considered for high temperature separation of hydrogen and oxygen, as well.

5.2. Thermochemical Production

It is possible to use lower temperature heat if an intermediary metal or chemical can be used to separate hydrogen and oxygen from water. For example, if hot steam is passed over powdered iron it will absorb oxygen from the steam forming iron oxide and producing hydrogen. Iron oxide can then be heated further to higher temperatures in order to dissociate it. This results in the release of the oxygen obtained from the steam, returning the iron oxide back to iron. In such a way the powdered iron can be used over and over again. After each use, it is regenerated by heating it to higher temperatures.

In research laboratories around the world many such thermochemical cycles are being examined [36-41]. The temperatures required are much lower than direct thermal separation--around 600°F to 2,000°F. Depending on the cycle in question, the projected efficiencies range from 30% to 60%.

Solar heat can easily be used for thermochemical methods, since parabolic concentrators could produce the heat at the temperatures needed. Nuclear heat could also be used for thermochemical hydrogen production.

5.3. Electrolytic Production

The technology for this method of hydrogen production already exists today. In this method, electrolytic cells are used to produce hydrogen and oxygen from water. The cell consists of two electrodes immersed in an electrolyte and connected to a d.c. electricity supply. In this case the electrolyte is mainly water plus some electricity conducting chemicals. When enough electrical potential is supplied between the electrodes to cause current to flow, oxygen is liberated in the anode and hydrogen in the cathode. The net overall effect is to decompose water into its elemental components of hydrogen and oxygen.

There are two main approaches in the physical construction of an electrolyzer that are used today: unipolar cell and bipolar cell construction. Figure 3 shows schematically the layout of each of these. In either case, the voltage impressed across each individual cell, the repeating element involving the anode and cathode, a separator material (usually asbestos), and an electrolyte is of the order of 2.0 V. The lower the voltage, the higher the overall efficiency of the unit, with approximately 1.48 V being equivalent to 100% efficiency.

Today, commercial electrolysis efficiencies range from 70% to 90%; it is expected that advanced electrolyzers using higher temperatures and/or pressures will reach efficiencies of 95% [42-48].

Of course, in order to use the electrolytic method, d.c. electricity must be available. This can be achieved in several ways. Photovoltaic solar cells can be used to convert solar radiation directly into d.c. electricity. Today there are various types of photovoltaic cells on the market, such as amorphous-silicon cells, polycrystalline-silicon cells, single crystal-silicone cells and gallium-arsenide cells. The conversion efficiencies from solar radiation to electricity range from a low of 5-6% to a high of 28%. Research is being conducted to lower the cost by the use of concentrators, which result in large reductions in the photovoltaic materials needed.

There are also novel photovoltaic cells which are being researched, where very thin layers of different cells are placed on each other so that all or most of the solar radiation can be converted to electricity. It is hoped that such combinations of dual or triple cells will reach conversion efficiencies of 35%.

Another way of obtaining electricity is to use tower-top boilers. In this method solar radiation is directed to a central point above a tower by means of heliostats or moving mirrors, which always redirect the solar radiation to the same point above the tower. This can be achieved by computer controlled drives with minimal use of energy.

A boiler, located at the central point above the tower, produces high temperature, high pressure steam. This steam then operates a steam turbine coupled to an electric generator. Of course, if the end product is to be hydrogen through electrolysis, a d.c. generator is used.

With hydro, wind, wave, current, tide and ocean thermal energies, the electrolysis method of hydrogen production should be used, since these primary energies can initially be converted to electricity more conveniently than to heat.

Next to water, most abundant hydrogen is found in hydrogen sulfide (H_2S). It is plentiful in petroleum and natural gas fields, and is considered a nuisance because of its smell. Research results [49-53] indicate that inexpensive hydrogen could be obtained by electrolysis of H_2S.

5.4. Photolytic Production

Solar radiation or the sun's rays can be considered as made up of weightless energy-carrying particles called photons. These energy-carrying photons, under certain circumstances, can be absorbed by water molecules. When the absorbed energy reaches a certain level, the water molecule separates into hydrogen and oxygen. This phenomenon, photolysis, can be used to produce hydrogen through the use of the sun's rays or photons. Photons in the ultraviolet region of the spectrum possess the higher energy needed for the direct photolysis of water. Most of the ultraviolet radiation is absorbed in the upper atmosphere by the ozone layer. Consequently, the intensity of solar radiation reaching the earth is very low in the ultraviolet region of the spectrum, but high in the visible region. Hence, photocatalysts must be used for the photolysis of water on earth [54-59]. The purpose of such a catalyst is to absorb the solar radiation at lower energy levels, and then transmit energy in higher levels to water in order to decompose it into hydrogen and oxygen.

Biochemists have found that biological photocatalysts also exist [60-64]. These include some species of blue-green, green and red algae, and some photo-synthetic bacteria. Basically, solar radiation is absorbed by the light-harvesting chlorophyll protein in the cells of these algae and bacteria. This energy is then transmitted to an electron through the reaction center of the protein. The source of this electron is a hydrogen atom donated by some electron-donor compound such as water. Hydrogen itself becomes ionized and turns into a particle called proton. Under certain physio-chemical conditions, the energized electrons combine with hydrogen ions (protons) to form hydrogen molecules.

Photolytic conversion efficiencies are small. However, the production cost is expected to be low, since there is no need for mechanical parts or machinery in this method of hydrogen production. It is hoped that by the use of genetic engineering it will be possible to increase the conversion efficiencies.

5.5. Storage

To meet the needs of cities, towns and industry, large amounts of hydrogen will have to be produced. This must be stored so that there will always be a regular supply of hydrogen to meet the demand at all times. For such large-scale storage, it would be best to store hydrogen underground [65-68]. This could be the space vacated in petroleum and natural gas reservoirs, as a result of the use of these resources. Man-made caverns resulting from mining and other activities could also be used.

Another underground facility that could be used is aquifers. Aquifers store water in sandy soil under rocky dome-shaped structures. Hydrogen could be pumped into such aquifers under pressure and would replace the water under the dome pushing it further and further down. When needed, hydrogen would flow under its own pressure or under the pressure of the water below it.

The above described methods are already being utilized in some countries. Gaz de France, the French National Gas Company, has stored hydrogen-rich refinery by-product gases in an aquifer structure near Beynes, France. Imperial Chemicals Industries of Great Britain stores their hydrogen in salt mine caverns near Teesside, United Kingdom. Hydrogen losses due to diffusion and pumping are estimated at about 3% of the hydrogen stored.

For small-scale storage (e.g., homes in rural settings where hydrogen is produced at individual homes using solar energy, wind energy, small hydropower, etc.), hydrogen could be stored in pressurized containers or in hydriding materials, which is the recommended method [69-71]. When a hydride is formed by the chemical combination of hydrogen with a metal, an element or an alloy, heat is generated. In other words, the charging or absorption process is exothermic. Conversely, the discharging or desorption process is endothermic, i.e., heat must be supplied to a hydride in order to liberate hydrogen from it. These processes can be represented by the following chemical relationships:

Charging or abscrption:

$$M + xH_2 \rightarrow MH_{2x} + \text{Heat} \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Discharging or desorption:

$$MH_{2x} + Heat \rightarrow M + xH_2 \quad \ldots \quad (2)$$

where M represents the hydriding substance, a metal, an element or an alloy. The rate of these reactions increases with increasing surface area. Therefore, in general, the hydriding substances are used in powdered form to speed up the reaction.

Using the above described properties of hydriding materials, hydrogen can be stored in homes. Figure 4 shows such a storage system filled with a granular hydriding material. The basic storage module is a shell and tube heat exchanger. Granular material is contained on the shell side, and heat is removed and added through tubes spaced throughout the bed of granules, for the storage and extraction of hydrogen, respectively. The heat needed could be obtained through solar collectors, through storing the heat of the hydriding reaction or through combustion of hydrogen. The bed of granules contains an inlet/outlet header connected to porous metal tubes in the tank. This arrangement allows hydrogen to be added and extracted without movement of the granules.

Table II gives a comparison of some hydriding substances with liquid hydrogen, gaseous hydrogen and *N*-octane. As can be seen from the table, all the hydriding substances shown there can store hydrogen atoms more densely than is possible with liquid hydrogen. Another advantage of storing hydrogen in hydriding substances is that a hydride tank would result in almost no fire hazard, which is not true for a pressurized hydrogen gas tank or a gasoline tank.

For small-scale storage of hydrogen, other storage methods are also being considered. Among these are high pressure storage in very small glass spheres, storage in organic liquid hydrides, storage in formate salts, and storage in activated carbon [72-75].

In vehicles, hydrogen could be stored as a pressurized gas in lightweight high strength containers, as a liquid in insulated containers, or in chemical combination with light weight hydriding materials [76-78].

5.6. Transmission and Distribution

Stored hydrogen must be then transmitted to and distributed in the consumption centers. On a small scale, hydrogen can be transported and distributed as a gas in a high pressure container and/or as a liquid in an insulated container. On a large scale, pipelines are being considered for overland transportation, and supertankers (similar to LNG and LPG tankers) are being considered for overseas transportation [79-83].

There are already hydrogen pipelines operating in the United States and in Europe [84,85]. Air Products and Chemical, Inc., operates a hydrogen pipeline in Texas. It consists of 96 km of underground pipes, which range in size from 10 to 30 cm diameter. Pipeline pumping pressures are generated by compressors at the hydrogen production site. No intermediary compressors are used. The Imperial Chemical Industries of England has a 16 km pipeline aboveground in Teesside. Chemische Huls of F.R.G. and L'Air Liquide of France have a hydrogen pipeline system extending some 600 km consisting of 10 to 30 cm diameter pipes. As a result of these commercial operations, there exists a wealth of experience on the safe operation of hydrogen pipelines.

For distances over 200 miles it is cheaper to transport energy as hydrogen than as electricity. Hydrogen also has other advantages. Electricity must be consumed as it is transmitted; otherwise, it is wasted. Hydrogen not consumed remains in pipelines or in storage locations, and is not wasted.

Another advantage for hydrogen is the right-of-way needed for its transmission. For example, consider a small industrial complex, which receives its electrical energy by means of high-voltage transmission lines, say a three parallel high-voltage cable tower system. These would take about a 600-foot wide right-of-way extending miles and miles. Such land sections can usually not be used for agriculture or forestry. The same industrial complex could be supplied with hydrogen to meet all its energy needs, not only electrical needs but the needs of transportation, residential and commercial sectors as well, by means of a 36" underground hydrogen pipeline. As an additional benefit, there would be no unsightly towers and cables, or landscape pollution. Another disadvantage of high tension power lines is the damage it causes to living species, due to the creation of high voltage electrical fields.

Figure 5 compares energy transmission costs by different carriers [86]. As can be seen from the figure, hydrogen transmission costs are somewhat higher than those of natural gas (CH_4) due to higher compression costs resulting from hydrogen's low density, but much lower than electricity transmission costs both for overhead and underground modes of transmission.

Hydrogen in human settlements, whether it is produced and stored *in situ* or arrives by pipeline, must be distributed to the use points. The Institute of Gas Technology has conducted an extensive study [87] to determine suitable piping, valves, fittings, meters, materials and lubricants for such a hydrogen distribution system (see Fig. 6). The results indicate that the pipings and components used in natural gas home distribution systems should be adequate for hydrogen delivery as well. The meters would need larger volumetric capacity and adjustments. Hydrogen did not affect the mechanical and physical properties of metallic or elastomeric materials of system components. There were some indications that plastic products, lubricants and adhesives were somewhat affected by exposure to hydrogen. Although the overall hydrogen-to-natural gas volumetric leaks ratio could range from about 2.9 to 3.5, energy loss from leakage would be similar. Hydrogen leaks would not ignite spontaneously without an ignition source.

6. INDUSTRIAL UTILIZATION

After the Industrial Revolution, energy consuming machines started to replace manual labor. This resulted in lower prices for the goods produced, so that more people were able to afford more goods. Human society was on the way to affluence.

In the two centuries since the Industrial Revolution began, factories have become larger and more numerous in order to meet the growing demands of the growing population, and their energy consumption has increased proportionately. In order to supply the needs of industrial plants, we must have energy sources so that we can continue to enjoy higher standard of living.

At the present time, industry runs on fossil fuels, viz., petroleum, natural gas and coal. However, there is no reason why industry could not run on the hydrogen energy system. It can do so, and it can do so with many environmental benefits [88-92].

We shall first consider how hydrogen can meet the two main energy needs of industry, viz., electrical and thermal energy needs, and then consider some applications.

6.1. Electricity Generation

Using hydrogen, electricity could be generated in conventional ways as well as by new methods. Hydrogen could be used in gas turbine-generator systems in lieu of natural gas, and in steam turbine-generator systems in lieu of fuel oil or coal [93-97]. Conversion efficiencies would be similar to those of the fossil fuel burning power plants. However, if hydrogen is burned with pure oxygen--instead of air--then the steam production efficiency is nearly 100% as there are no flue gases to carry away some 20% of the energy of combustion; consequently, the fuel to electricity efficiency is 25% greater than that of the fossil-fueled plants.

Hydrogen can also be converted to electricity in fuel cells--which are not subject to Carnot cycle limitations--with efficiencies higher than any other fuel [98-102]. Figure 7 shows a schematic diagram of a fuel cell [27]. It has two electrodes separated by an electrolyte. The electrolyte can be a basic solution of sodium or potassium hydroxide, an acidic solution--perhaps of phosphoric acid--or one of the various solid ceramic or polymeric solids that carry electric current in the form of hydroxyl ions or hydrogen ions. At the anode, hydrogen gas reacts to produce hydrogen ions, H^+, and electrons. The electrons are driven through the external circuit producing d.c. electricity, where they can do work, and finally to the cathode, where they react with the oxygen (from the air or from an oxygen supply) and the electrolyte to produce hydroxyl ions, OH^-. In the electrolyte, the hydroxyl ions and the hydrogen ions react to produce pure water. The water is then removed from the cell.

Today's fuel cells have efficiencies of 40% to 70%. It is expected that with further research efficiencies of up to

90% will be possible. No other fuel can be converted to electricity with such high efficiencies.

Another advantage of such in-situ generation of electricity would be a large reduction in electricity distribution losses. Today about 15% of the electricity generated is lost in the distribution systems. These losses could be reduced to a few percentages, by using pipeline hydrogen and fuel cells. Figure 8 shows an experimental fuel cell of 4.5 MW capacity manufactured by United Technologies of Connecticut, U.S.A., and being operated successfully by the Tokyo Electric Utility since 1984.

There is abundant hydropower potential in Alaska which could meet an important part of the energy needs of the United States. These hydropower potentials are not being utilized, since most of the electricity that could be transmitted to the lower 48 states would be lost in transmission. On the other hand, if this indirect form of solar energy, hydropower, is used for hydrogen production and piped to the lower 48 states, only a small fraction of the energy would be lost in transmission. Besides, the energy would be in a stored form, which could be used whenever needed.

There are similar situations around the world. In the Amazon Basin of Brazil, there are many potential hydropower sites which are not being utilized at the present time because, again, most of the electrical energy generated would be lost in transmission lines, carrying the energy to the industrial section of Brazil in and around Sao Paulo. Hydrogen production and transmission systems would be ideal for this situation.

6.2. Thermal Energy and Steam Production

Today's industry uses steam and the hot gases of combustion products extensively. They are used in the textile, paper and chemical industries for cleaning, drying, heat transfer and various other purposes. Hydrogen can be used to produce the thermal energy and steam needed with many advantages [103-106].

In steam generation using fossil fuels, quite a bit of heat or thermal energy--combined with combustion by-products--flows up the chimney, causing pollution, acid rains and the greenhouse effect, in addition to wasting some thermal energy. Steam generating boilers have efficiencies of about 80%, meaning that they waste 20% of the thermal energy generated during combustion.

The German space agency, DFVLR, has recently developed a steam generator [103], which is very small in size compared to conventional, bulky boilers. In addition, it has almost 100% efficiency, which means that it does not waste any thermal energy. This steam generator (see Fig. 9), rated at 40 MW, consists of a heavy-walled sectional steel tube about 6.5 feet in length and 16 inches in diameter, with inlets for hydrogen, oxygen and water, and an exit for steam. The combustion of hydrogen and oxygen produces very high temperature steam at 6,000 F as mentioned earlier. Of course, the steel steam generator cannot withstand such heat, since its melting temperature is 2,600° F. So water is used to lower the steam temperature. By adjusting the amount of water mixed, one can adjust the temperature of the steam generated to the required degree. Such a simple, compact and very efficient device can be used for all of the steam generating purposes mentioned above, as well as for generating electricity.

6.3. Applications

Many industrial applications require a prime mover, an engine, to provide the mechanical energy needed. Such hydrogen-using engines, viz., gas turbines [107-109], spark ignition engines [110-114] and diesel engines [115,116] are being developed by researchers around the world.

In addition, hydrogen can be used in many other industrial applications as diverse as welding where high temperatures are needed, cutting of thick metal plates, iron smelting [117-119], heat treatment [120], and in producing and maintaining oxygen-free environment for computer chip production.

There are also compressors [121] and electric batteries [122] being developed by taking advantage of the properties of hydriding reactions. Hydriding properties are also being employed in producing ultra pure hydrogen [123-126], which is needed in some industrial applications.

7. RESIDENTIAL/COMMERCIAL UTILIZATION

As mentioned earlier, hydrogen can be used in every application which uses fossil fuels today, including the energy for residential/commercial sector [127], such as heating and cooling for comfort, hot water for bathing and washing, cooking and refrigeration of food and food supplies, lighting and electricity for appliances, etc. Of course, before hydrogen can be used to meet these needs, it must be produced.

7.1. Hydrogen Production and Delivery

In the case of residential/commercial sector in urban areas, hydrogen should be produced in large scale at central plants, then stored, transported and distributed as described in Section 5. In rural areas, hydrogen production and delivery could be made as above if a hydrogen pipeline grid or other delivery system is established. Otherwise, hydrogen could be produced in distributed mode in each home or building. Depending on the primary energy source available, the hydrogen needed could be manufactured through a photovoltaic-electrolyzer system, small hydro-d.c. generator-electrolyzer system, wind-d.c. generator-electrolyzer system or through a biological system. Hydride and/or pressurized gas systems could be used for the storage of hydrogen. It is estimated that the photovoltaic produced hydrogen will be able to compete with fossil fuels early in the next century [128].

Biological hydrogen production would especially be suitable for farms, where ponds hosting hydrogen-producing photosynthetic or anaerobic bacteria could be established. Herlevich and Karpuk [129] report of a hydrogen-producing photosynthetic bacteria (*Rhodopseudomonas capsulata*) with quite a high light-to-hydrogen conversion efficiency of 5%. The bacteria are capable of metabolizing waste effluents. It is suggested that the conversion efficiency could further be increased using genetic engineering.

7.2. Electricity Generation

Energy requirements of some basic domestic activities, such as lighting, sewing, ironing, receiving radio and television broadcasts, pumping well water, etc., can be met better by electricity. As the standard of living rises, electricity can also provide the electromotive force for domestic appliances such as air conditioners, refrigerators, water heaters, clothes washers and dryers, cooking ranges and ovens, dishwashers, trash compactors, food mixers, electric shavers, hair dryers, etc. Hence, it is important that electricity must be generated to meet the energy requirements of some or all of these residential/commercial sector activities.

In an urban area, it would be possible to generate the electricity needed in a neighborhood fuel cell facility, or in individual homes and buildings using smaller fuel cells. In a rural area, photovoltaic electricity or wind electricity could be used when they are available. At other times, electricity produced by individual fuel cells--of course, using stored hydrogen as fuel--could be used.

In the United States, several 40 kW phosphoric acid fuel cells are being tested in homes and apartments, achieving combined thermal and electric efficiencies of up to 80% [98]. It is expected that further research work will increase the conversion efficiencies to 85-90%. European and Japanese companies are also experimenting with fuel cells. A fuel cell, about the size of an air-conditioning unit, would meet all the electric needs of a home. Figure 10 shows such a fuel cell of Japanese manufacture.

Another method for producing electricity using hydrogen for the residential/commercial sector is to make use of its hydriding properties in conjunction with a heat source, such as solar heat or waste heat. If passed through a turbine or expansion engine, hydrogen moving from one hydride tank to the other could produce mechanical and electrical power [130].

7.3. Space Heating and Cooling

Homes and offices (and industrial plants) need heating and cooling to create the right climatic conditions for the people to live and work comfortably. This could all be done very easily with the hydrogen energy system. Once the electricity is generated, it could then be used for heating through electrical resistance heaters, for cooling through conventional air conditioning systems, and for heating and cooling through conventional reverse cycle air conditioning systems. If d.c. electricity is generated, then d.c. motors and d.c. controls must be used in the above stated heating and cooling systems. Otherwise, the d.c. electricity generated must be converted to a.c. electricity through converters.

Another, and perhaps more efficient way of achieving space cooling, would be to use hydrogen in lieu of natural gas in the conventional absorption cooling systems. It would only be necessary to make some adjustments to the burners.

If hot water or steam is used in an existing space heating system, then hydrogen could be used instead of natural gas or fuel oil [131]. There is a more efficient way of producing steam through hydrogen, i.e., using an aphodid steam generator. In such a steam generator, hydrogen burns with oxygen producing pure steam at quite high temperatures of around 6,000° F, as mentioned earlier. Then an appropriate amount of water must be added to this high temperature steam in order to bring the steam temperature down so that the boiler, piping and fitting materials can withstand the heat. This is a very efficient way of producing steam, as there are no flue gases going up the chimney and carrying away some 20% of the heat, as in the case of boilers using fossil fuels. If hydrogen is produced by electrolyzers, then the oxygen needed would be readily available.

The catalytic hydrogen combustors could be used for space heating as well [132-134]. This makes use of another unique property of hydrogen not shared by other fuels. Catalytic combustors are composed of porous ceramic plates containing minute amounts of a catalyzer, such as platinum or palladium. When hydrogen and oxygen (or air) are supplied to such a combustor, hydrogen and oxygen are combined forming water vapor and producing heat catalytically and without a flame. This is a very elegant and efficient way of producing heat.

Wall units for space heating have already been designed using catalytic combustors (see Fig. 11). These wall units consist of two porous plates. One plate distributes the hydrogen gas evenly. The second plate includes minute amounts of catalyzing material. Air enters the system through the surface of the catalytic plate, which faces the room or the areas to be heated. Combustion takes place inside this plate. The heat of the reaction is transferred to the surrounding area by radiation and convection. The combustion rate and resulting temperatures depend upon the hydrogen supplied and the active surface area of the catalyst. Room heaters would operate at relatively low temperatures and could be hung onto or built into a wall, and be covered with formica and other paneling materials for esthetics. Catalytic heating efficiencies are extremely high--close to 100%.

Another unique way of using hydrogen for heating and cooling is to use hydrogen with a hydriding material system [130]. As mentioned earlier, hydriding materials are some metals and alloys, which absorb hydrogen as a sponge would absorb water. There are many hydriding materials and alloys, such as lithium, magnesium, titanium, palladium, uranium, iron-titanium, calcium-nickel and lanthanum-nickel to list a few.

When hydrogen is supplied to hydriding materials, they combine to form hydrides in an exothermic reaction (a reaction which produces heat). If heat is supplied to hydrides, hydrogen is released and the hydride returns back to the original hydriding material or alloy. During hydrogen absorption for a given hydrogen pressure, heat is generated at a certain constant temperature; the higher the pressure, the higher the temperature. During desorption, for a given temperature, hydrogen produced is at a certain constant pressure; the higher the temperature, the higher the pressure. Different hydriding materials have different temperature/pressure characteristics.

Using the above described characteristics, hydrogen at a given pressure could be supplied to a hydriding material to release heat at a certain temperature. Then, the hydride (hydriding material + hydrogen) could be subjected to heat at a different temperature, producing hydrogen at a different pressure. These properties have been used to build hydrogen/hydriding-material heat pumps [135-138], e.g., recovering heat from a low temperature source such as the outside atmosphere during the winter and supplying it at a higher temperature to the inside of homes and building. During the summer, the reverse is achieved by pumping high temperature heat from homes and buildings to the outside atmosphere at a higher temperature. This is a very elegant and efficient way of achieving air conditioning as there would be no moving parts, making it quieter than conventional systems. In such heating/cooling systems, solar heat, hydrogen and/or hydrogen electricity can be employed to provide the driving power. Such systems are now being developed in the United States and Japan.

7.4. Water Heating

In homes, offices and public places we need hot water. Four of the space heating methods described in the above section could also be used to produce hot water, viz.:

1. using conventional electrical resistance heaters;
2. using hydrogen instead of natural gas in conventional gas water heaters;
3. using catalytic hydrogen heaters; and
4. using an aphodid steam generators.

A hydrogen water heater operating on a flame-type burner (method 2 above) would have an efficiency of 70%, whereas a natural gas water heater has an efficiency of about 60% [139]. If an aphodid-type steam generator (method 4)is used, then the conversion efficiency would be nearly 100%.

In addition to the above methods, the waste heat from air conditioning systems could be used for water heating. Of course in the tropical, subtropical and temperate regions of the earth, solar radiation could be used directly for producing hot water through solar water heating systems. Solar water heaters are the first economical applications of solar energy. They are quite popular in Mediterranean countries, in the southern United States, and in the solar belt countries.

7.5. Water Pumping

One of the basic needs of human society is water. In rural areas if piped water is unavailable, then underground wells are used. Hydrogen could be used in several ways to pump the underground water up. One way is to use hydrogen electricity with a conventional water pump. Another way is to couple a conventional pump to a hydrogen-fueled internal combustion engine.

If solar energy or waste heat is available, then a hydrogen/hydriding-material system could be used for water pumping [140,141]. Figure 12 illustrates such a system [140]. In this system hot water produced by solar energy (or waste heat) and cool ground water from the well are supplied to a heat exchanger in a hydriding material bed by means of two sequentially operated valves. Hydrogen gas, released from the bed during the heating phase of the cycle, inflates the rubber bladder in the well lifting water through a check valve (the upper check valve) located above the bladder. Ground water then flows into the well through the lower check valve, deflating the bladder and forcing hydrogen back into the hydriding bed during the cooling phase, returning the system to the initial position. After this, the sequence is repeated, and the water is pumped up.

In rural areas if relatively strong winds are available, then a wind-wheel operated pump could be used for pumping up the ground water.

7.6. Cooking

One of the basic energy needs of human society is for cooking--in cooking ranges, ovens, etc. There are three possible ways for hydrogen to provide the required energy. One method is to use conventional electric cooking appliances if hydrogen electricity is available. Another method is to use hydrogen in lieu of natural gas in conventional gas cooking appliances [142,143]. In burners of such appliances (atmospheric burners), all air for combustion is taken from the surrounding atmosphere at atmospheric pressure, and hydrogen is supplied at a relatively low pressure. Usually the hydrogen gas is passed through an orifice (see Fig. 13a), which serves to meter flow and accelerate the velocity of hydrogen. When it enters the mixing tube, it entrains air drawn in through a series of orifices near the base of the burner. In the mixing tube, hydrogen and air are mixed together and then passed through small holes, which are called burner ports. When the gas mixture issues from the port, it is ignited and a flame appears. The atmospheric air diffuses into the flame to complete the combustion. The flame does not propagate back through the burner port because the speed of the issuing gas mixture is adjusted to be greater than the flame speed of the hydrogen/air mixture. A suitable catalytic igniter could be used to initiate combustion.

In another type of the proposed atmospheric hydrogen burners (see Fig. 13b), hydrogen-air mixing is inhibited by blocking all primary air. Then a stainless steel wire mesh is placed around the burner ports. The placement of the wire mesh in a proper configuration will allow a gradual mixing of hydrogen and air throughout the operating flow rates of the burner design. A hydrogen-rich condition exists in close proximity of the burner, with the oxygen concentration increasing when moving away from the burner head. If the stainless steel material is properly configured, there will be a region immediately surrounding the burner openings, consisting of an inflammable hydrogen concentration. This region, referred to as the inflammable zone, will move in and out of the burner head depending on the hydrogen flow rate. A proper burner design would incorporate sufficient stainless steel material so as to ensure that the inflammable limit zone is always located within the outside perimeter of the stainless steel material. The stainless steel also provides a very important secondary function in addition to the mixing inhibiting function. At high temperatures, stainless steel is an excellent catalyst for hydrogen combustion. Shortly after ignition, the temperature of the stainless steel is raised by hydrogen combustion to the region where catalysis begins to occur. At this point, the hydrogen in the inflammable zone begins to react with the dilute quantities of oxygen present through the action and on the surface of the stainless steel catalyst. In this manner, a controlled reaction occurs in the inflammable zone where mixture limitations will not permit the rapid combustion of hydrogen which would occur under normal conditions. Consequently, peak combustion temperatures are maintained below the threshold level for NO_x formation.

The third method is to use catalytic combustion of hydrogen for providing thermal energy for cooking. The primary advantage of catalytic combustion is that combustion can be carried out without a flame and the production of nitrogen oxides from the air is negligible at temperatures below 1,000°F. They transfer more usable heat to food. Temperature ranges are much wider and can be adjusted much more finely, and the heat is distributed more evenly over the entire burner surface. A catalytic burner is self-starting, requiring no pilot, glow coil or spark ignition. Ignition takes place when the hydrogen gas contacts the catalyst (typically a very thin coating of platinum). Catalytic hydrogen combustor efficiencies are 85%, while those of flame burners are 70%, both of which are much higher than those for natural gas flame burners (viz., 60%).

Figures 14a-c present photographs of a hydrogen-flame cooking range, a hydrogen-catalytic combustor cooking range and a hydrogen barbeque.

7.7. Potable Water

In fuel cells, in addition to electricity, pure water is produced as a by-product. The amount of the water produced depends on the electricity consumption. The average household electricity consumption could vary from a low of 7 kWh to 70 kWh per day, depending whether a developing or industrial country is being considered and whether electricity is used only for lighting or for most of the appliances and climate control. Consequently, assuming a fuel cell efficiency of 70%, the pure water produced could vary between 2.5 and 25 l day^{-1}. This amount of water could meet the potable water needs for drinking and/or cooking purposes, especially in areas where potable water might not be available or might be too expensive to obtain.

7.8. Refrigeration

It is important to have refrigerators in order to keep groceries, foodstuffs and food products fresh. If electricity is available, then one way of obtaining refrigeration is to use conventional electric refrigerators. A second method of refrigeration would be to use the hydrogen flame heating of the refrigerant, in lieu of natural gas heating, in the conventional "Servel" type gas refrigerators. These units operate without moving parts, thereby resulting in quiet operation, long life and low maintenance. A third method of refrigeration would be to use hydrogen catalytic combustion heating of the refrigerant in lieu of natural gas heating. This would further improve the energy conversion efficiency and conserve fuel (hydrogen).

7.9. Lighting

Lighting is a major need of human society. During the daytime, the necessary light is usually provided by the sun. Sunlight is the most natural light for human activities, since it is the sun's energy-giving radiation which nurtured the life on this planet in the first place.

It is easy to have daylight in open spaces and in single-family homes with windows on all sides. However, when it comes to high-rise apartments and office buildings, many of the units have little or no daylight. Japan has taken the lead in this area to provide natural sunlight for such cases. They install "sunlight pipes" starting from a point where sunlight is available, such as the roof or sun-facing side of the building. Through the use of hollow pipes with non-absorbing/reflecting surfaces and with sharp bends, they direct the sunlight into interior rooms and corridors. The solar radiation is directed by means of equilateral angled mirrors placed within the pipes at each bend. Sunlight carried through this unique system can be strong enough for people even to sunbathe in their bedrooms.

When the sun is not available, hydrogen produced electricity is the most convenient energy carrier to provide energy for lighting systems through various electric bulbs, such as incandescent, flourescent, sodium vapor, etc.

However, if utility electricity or home-produced electricity is unavailable, then hydrogen could be used to achieve illumination in the same way as gas camping lanterns. It involves a low temperature combustion process of hydrogen for illumination called candoluminiscene [144]. In this process the light emission is generated by molecules, ions and atoms in a phosphorus material coating excited by the hydrogen flame.

7.10. Appliances/Equipment

Many household appliances, equipment and gadgets are dependent on electrical motors or electronics to function. Examples of such equipment are sewing machines, washing machines, dishwashers, electric toothbrushes, saws, drills, radios, televisions and sound systems. This equipment could run on hydrogen produced electricity.

Some appliances and gadgets might also run on a fuel. Such equipment includes clothes dryers and irons, in addition to climate control systems, refrigerators and water heaters mentioned earlier. In such cases thermal energy, produced either through flame or catalytic combustion of hydrogen, could be used.

7.11. Hydrogen Home

Some researchers have considered and developed fully integrated energy systems for homes to run on hydrogen. One, named "Hydrogen Homestead," has actually been built [143]. Figure 15 shows the energy system of the Billings Hydrogen Homestead. Figure 16 shows the energy system concept for a hydrogen home proposed by Buchner and Saufferer [145].

8. TRANSPORTATION

Hydrogen, as mentioned earlier, has many unique properties, including being the lightest fuel known, as well as the fastest burning fuel. These properties make it an excellent fuel for rockets and engines, which all go to make hydrogen the ideal fuel for transportation.

8.1. Space Travel

Spaceships must travel long distances to explore the heavens beyond our planet. In addition, they must travel at very high speeds, something like 30 times the speed of a subsonic jet (or 25 times the speed of sound) in order to escape the earth's gravitational pull and get into orbit around the earth or travel to the moon and beyond. To achieve the desired speeds they must have powerful engines--rocket engines or jet engines. These engines consume large amounts of fuel. Consequently, spaceships must carry all the fuel, as well as the oxidizer, oxygen, with them, so that they can accomplish their missions. Since there is no oxygen in space, spaceships must carry the needed oxygen for their trips. Of course, in order to save weight and therefore fuel, they must carry the lightest possible fuel; and the lightest fuel known is hydrogen. Hydrogen, for a given amount of energy, is three times lighter than jet fuel or petroleum. It is the ideal fuel for space travel.

Because of its excellent combustion properties (fast burning) and because of being the lightest fuel, hydrogen has become the fuel of choice for space programs. The National Aeronautics and Space Administration (NASA) of the United States is the biggest user of hydrogen in the world; it is their main fuel for space travel. They could not have accomplished the amazing feat of putting a man on the moon and bringing him back without hydrogen. The Europeans, the Soviets and Japanese also run their space programs on hydrogen.

NASA is now planning an ambitious space station. It will be carried piece by piece into space by the shuttle spaceplane sometime in the late 1990s. Of course, the main fuel for these trips will be hydrogen. In addition, hydrogen will be used to power the space station through the use of hydrogen-oxygen fuel cells. It was mentioned in Section 7 that hydrogen fuel cells, in addition to producing d.c. electricity (to power the various operations of the space station), will be producing pure water. Electricity produced by solar cells attached to the space station will be used to electrolyze the water, separating it back into hydrogen and oxygen, which will in turn be used to power the fuel cells.

The U.S.A. and the U.S.S.R. are also planning a joint mission to Mars. It must carry all the supplies needed for a trip, which may last as long as eight months to a year and, of course, must be as light as possible. This spaceship will also run on hydrogen. It is planned to put it together and prepare it for the long trip at the space station. The components of the spaceship, its fuel, its oxidizer, its provisions and its crew will be transported to the space station by the space shuttle. It will be assembled on the space station, then loaded to begin its mission. Of course, it will return to the space station, and the crew and Martian samples will be carried to earth by the shuttle. Such trips could not become a reality without hydrogen.

8.2. Airplanes, Aerospaceplanes and Dirigibles

Because of its light weight and excellent combustion characteristics, hydrogen would be the ideal fuel for airplanes and aerospaceplanes, which will fly both in the atmosphere and in space. On 15 April 1988, the first passenger plane flew on a hydrogen-fueled engine near Moscow. It was designated as Tupalev 155--a jet airplane converted from the two-engine Soviet Tupalev 154 jetplane, similar to the DC-9 or MD-80. Only one of the engines was converted to hydrogen fuel. The plane was equipped with a liquid hydrogen storage tank, and a hydrogen supply and control system. The various aeronautical establishments of the Soviet Union and the Tupalev Institute are now working on the design and development of an all-hydrogen supersonic passenger plane designated Tupalev 204.

On 17 June 1988, two months after the flight of the Soviet jet, Bill Conrad, a retired Pan American pilot, flew a hydrogen-fueled single-engine plane in Ft. Lauderdale, Florida. The flight lasted only 36 seconds, but a record, that of take-off, flight and landing on hydrogen power alone, was established.

Actually, Mr. Conrad's plane was to taxi down the runway and return to the starting point, then take-off, fly a few times around the airport and land, all on hydrogen fuel. Due to the higher utilization efficiency of hydrogen, the plane suddenly lifted off the ground while taxiing. Mr. Conrad immediately reduced power, put the plane back on the runway, continued on its taxiing mode and returned to the starting point ready for the flight. The officials from the U.S. Civil Aeronautics Board and other recording agencies told Mr. Conrad that he already established a record and there was no need for him to fly again.

In some ways, this flight is similar to the Wright Brothers' flight. It signaled the beginning of aviation and Bill Conrad's flight signaled the beginning of clean and efficient hydrogen powered flights.

Because of the importance of space as the next frontier, in 1987 President Ronald Reagan charged NASA and the U.S. Air Force with the development of the National Aerospace Plane, which would have speeds of 5 to 25 Mach. The passenger version of this plane is expected to fly from New York to Tokyo or from los Angeles to Sidney in two hours, thereby earning the nickname of the "Orient Express."

The space version of this plane will be able to take-off like an airplane, escape the gravitational pull of the earth, travel outside the atmosphere in space, return back to the earth's atmosphere, and land on a runway just like an airplane. Its engines will use oxygen from the air as an oxidizer during its flight inside the atmosphere, and will use stored liquid oxygen in space. The fuel selected for the National Aerospace Plane is, of course, hydrogen. The first flight is scheduled for 1994.

Other countries are developing their own versions of aerospace planes. The British version is called HOTOL. Sanger, the German version, will consist of two planes, one piggyback on the other. The larger (mother) plane will have air breathing engines and will accelerate up to speeds of five Mach. The smaller plane, running on liquid hydrogen and liquid oxygen, will then take-off from the back of the mother plane, fly into space, then return to earth's atmosphere, and land on a conventional runway. The mother plane, of course, will land, after the aerospace plane has taken off on its flight.

The Japanese government has decided to develop a hypersonic aerospace plane having speeds of 5 to 7 Mach which will take about seven years to develop. They are planning its maiden flight before the end of this century.

Scientists around the world are conducting research into the role of hydrogen for air and space travel in the twenty-first century and into the hydrogen-fueled jet engines [146-149]. It is expected that subsonic, supersonic and hypersonic passenger jets will be flying on hydrogen early in the next century. Studies by Lockheed Company indicate that subsonic jets running on hydrogen would be 19% more efficient than those running on jet fuel [150]. Supersonic jets running on hydrogen would be 38% more efficient than those running on jet fuel [151], such as the present-day, Anglo-French Concorde.

In addition to being the ideal fuel for planes and spaceships, hydrogen, being the lightest element, is the ideal gas for the balloons of dirigibles. Also, the engines of these airships could use some of the hydrogen stored in its balloon for its uplifting, as fuel during its flights. There are plans by some aviation companies to build dirigibles to carry large cargos across the continents and across the oceans at very low cost.

8.3. Trains

Although many nations operate electrified rail systems, the United States railroads are wholly dependent on diesel fuel at the present time. Because we will be running out of petroleum in the near future, and because of the environmental problems caused by petroleum, alternative fuels, among them hydrogen, are presently being examined for feasibility.

Railroads consume about 1.5% of the oil used in the United States, mainly in the form of diesel fuel. However, they carry nearly 50% of the bulk goods on ton-mileage moved across the country, reflecting high energy efficiencies as compared to other transportation modes.

Recognizing that conventional diesel fuels will eventually be a scarce commodity, and in order to protect the environment, the U.S. railroads are examining various future options. Railway electrification is a prominent energy system candidate in this connection and is widely used throughout the world. However, railway electrification conversion in the United States must be viewed in terms of initial capital investment. A conversion can only be justified where there is significantly heavy traffic density, as in the case of the Eastern corridor from Washington, D.C., to New York and Boston, for example.

Whenever and wherever large capital investment for electrification is not justified, hydrogen-fueled diesel locomotives will be attractive alternatives [152]. Studies by such groups as the Federal Railroad Administration, the American Association of Railroads, locomotive builders and railroad companies indicate no major technical barriers to the hydrogen conversion approach.

Actually, hydrogen has been on the railroad scene for a number of years. It is routinely moved across the United

States, from California to Florida and from Louisiana to Florida, as a super cold or cryogenic liquid in insulated rail tank cars of special design for the U.S. space program. This provides a convincing demonstration of the feasibility and routine safe handling of liquid hydrogen under field conditions.

Canadian railroads are also working together with locomotive builders in Canada for a demonstration project of hydrogen-diesel electric locomotive powered train to run between Toronto and Winipeg on the Canada-Pacific railroad.

Hydrogen fuel cell power plants would also be very attractive for locomotives [153]. Fuel cells may not be the power plants of choice in the near future for automobiles, because they are bulkier than internal combustion engines. But, since size and space limitations are not too constraining in the case of locomotives, fuel cells would make an excellent alternative, in fact, a more attractive alternative to replace the diesel locomotive. They would be cleaner and much more efficient.

8.4. Cars and Tractors

Hydrogen is a clean and efficient fuel for obtaining mechanical power through internal combustion engines. In consequence, a large amount of research work has been done on the use of hydrogen-fueled internal combustion engines in cars, buses and farm tractors [143,154-160]. In order to eliminate preignition some researchers used water injection and the others used liquid hydrogen. Various methods of on-board hydrogen storage have been studied, such as pressurized gas, metal hydrides and liquid hydrogen.

A unique property of hydrogen, not shared by other fuels, makes it the ideal fuel for automobile transportation: It burns lean. Gasoline and other petroleum-based fuels, natural gas and other hydrocarbons burn rich. This means that there must be a rich mixture of fuel with air for hydrocarbon fuels to have good combustion. For example, when one stops his/her car at the traffic light or when one slows down, the gasoline flow into the engine is not reduced in proportion to the reduced power demand. Therefore, a lot of fuel is wasted. If the gasoline flow into the engine was reduced, then there would be no combustion and the engine would stop running.

However, in the case of hydrogen, when one stops at the traffic light or slows down, one can reduce the hydrogen flow into the engine and the combustion of hydrogen will continue because of its lean burning characteristics. So hydrogen is not wasted, when it is not needed. Because of this property, hydrogen-fueled automobile engines are up to 60% more efficient than gasoline burning automobile engines, as well as being much cleaner.

Because of the potential of high utilization efficiencies, the application of fuel cells to provide power for vehicles--through electric motors--has caught the attention of several researchers [161-164]. However, fuel cells need more room than internal combustion engines. As a result, their first applications will probably be in bigger vehicles, i.e., trucks and buses.

Figures 17a and 17b show a liquid hydrogen-fueled passenger car developed by Furuhama of the Musashi Institute of Technology, Tokyo, Japan, and its liquid hydrogen storage system. Figure 18 shows a minibus, having metal hydride storage, developed by Daimler-Benz A.G. of Stuttgart, F.R.G. It has three hydride storage tanks, which are used to provide heating and cooling for the bus, in addition to storing hydrogen fuel for the engine. Figures 19a and 19b show a photograph of the Jacobsen tractor and its hydrogen system developed by the Billings Energy Corporation of Provo, Utah, U.S.A.

As mentioned earlier, hydrogen can be stored in three different ways, i.e., as a pressurized gas in high pressure containers, as a liquid in insulated containers, and in chemical combinations with some metals and alloys called hydrides. This last method of storage is unique to hydrogen. No other fuel can be stored in such a way. In a given volume of hydriding metal, they can absorb up to 30% more hydrogen than one would have in the same volume of liquid hydrogen. In other words, hydriding metals or alloys can pack hydrogen very compactly.* Research and development work is being continued around the world to determine which method would be best for hydrogen-fueled cars.

8.5. Ships

Hydrogen will make an ideal fuel for ships, as well, especially because of its hydride storage characteristics. Ships need ballast to keep their center of gravity low and to remain stable. Ballast is usually an additional weight, such as some high density metal. In the case of hydrogen-fueled ships, hydriding materials would be used to provide both the ballast and the medium of storage. A heavy hydride such as titanium-iron alloy could play the dual role. Of course, if needed, pressurized gas storage and/or liquid hydrogen storage could be used, as well. Some of the stored hydrogen could be used in gas turbines, internal combustion

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*This property of hydrogen is now being utilized in cold fusion by packing heavy hydrogen in the hydriding metals palladium and titanium very densely.

engines or fuel cells to propel the ship and provide power for other needs.

It is proposed that supertankers could be used to transport hydrogen from solar belt countries to industrial countries in the form of liquid hydrogen stored in spherical tanks similar to today's LNG (liquefied natural gas) or LPG (liquefied petroleum gas) tankers. In such a case, there would still be need for hydride-type storage of hydrogen with hydriding materials placed at the bottom of the ship along the keel in order to provide ballast. Ballast becomes very important to hydrogen tankers, since liquid hydrogen itself has a very low density (about one-tenth of oil) and cannot provide the mass needed for lower center of gravity.

Hydrogen also makes an ideal fuel for submarines. Nowadays, nonnuclear submarines run on diesel engines when traveling on the ocean surface and on lead-acid electric batteries when underwater. The submarines being developed in Germany today run on hydrogen-oxygen fuel cells. Hydrogen is stored in hydrides, which also provide the ballast as mentioned above, and oxygen is stored in liquified form in insulated containers. The submarine runs on hydrogen and air when traveling on the surface, and on hydrogen and liquid oxygen underwater. It is quieter than diesel-fueled submarines and has a longer range underwater. It does not have dangerous chemicals such as those in lead-acid batteries, and does not produce pollutants.

The German Navy is very impressed with the trial runs of the prototype hydrogen submarine. It has been reported that they have decided that their next generation of submarines to be hydrogen powered.

There are also proposals to build large hydrogen-fueled "merchant marine" submarines for commercial cargo carrying purposes. They would be quite efficient and would be able to avoid rough waters by going under the wave zones.

Of course, the biggest advantage of hydrogen-fueled ships, hydrogen carrying ships, and the hydrogen energy system, will be that in case of an accident or a spill, there will be no damage to the environment. Because hydrogen is not poisonous, it does not pollute waters or beaches, and it evaporates very quickly and disappears. Even if there is a fire, it will only produce water vapor.

9. ECONOMICS

Those who desire continuation of the present fossil-fuel system claim that synthetic gasoline (SynGas), synthetic jet fuel (SynJet) and synthetic natural gas (SNG) could be manufactured through use of the vast deposits of coal, oil shale and tar sands, or even of CO_2 from air and from limestone, when we run out of petroleum and natural gas. Consequently, hydrogen (gaseous and liquid) will be compared with synthetic natural gas, synthetic jet fuel and synthetic gasoline from the viewpoint of real economics; i.e., by taking into account production costs, environmental damage and utilization efficiencies.

9.1. Production Costs

The production costs of interest here are for the large-scale production of the synthetic fossil fuels and hydrogen, so that they may meet large-scale demands. As mentioned earlier, hydrogen can be produced by several methods, using various primary energy sources. Amongst the methods are electrolytic, thermal, thermochemical, photolytic and various "hybrid" methods. Any one of the primary energy sources, including the fossil fuels, can be used as the energy source for the production of hydrogen. As the post-fluid fossil fuel era is under consideration, the main fossil fuel resource of interest would, of course, be coal.

Table III presents the averages of large-scale production costs taken from recent literature [127,128,165-183]. In the case of hydrogen, costs are classified by the primary energy source used in production; namely, coal, hydropower and solar (direct solar, photovoltaics, wind, waves, currents, tides, ocean thermal, etc.), as the estimated prices also group according to this classification. Nuclear energy has not been included, since (1) it would result in much higher hydrogen production cost, and (2) it is not the most desirable energy source for developing countries. In Table III, all the dollar values have been brought up to 1990 U.S.$ by taking into consideration the inflation.

Although gaseous hydrogen can be used in most of the applications where gaseous or liquid (and solid) fossil fuels are currently being used, there are some applications where liquid hydrogen must be used; e.g., in rocket engines for space travel and in jet engines for air transportation. Consequently, prices of liquid hydrogen must also be considered. If conventional liquefaction methods are used, the price has to be increased by about 50% [184] over that of gaseous hydrogen. However, a revolutionary liquefaction process (magnetic liquefaction) is being developed at the U.S. Los Alamos National Laboratory [185], which has a circuit efficiency of 60% as compared with only 30% in conventional systems. Preliminary studies show that the magnetic liquefaction process will need less capital investment and less maintenance than conventional systems. It then becomes reasonable to assume a 25% add-on for liquid hydrogen produced by the new method, which could be available in the 2000s.

As can be seen from Table III, the estimated production costs of coal GH_2 (gaseous hydrogen) and coal LH_2 (liquid hydrogen) are lower than those for the synthetic fossil fuels, while GH_2 from other energy sources is more expensive than SNG. SynJet is the second least expensive liquid synthetic fuel, followed by hydro LH_2 SynGas and solar LH_2. Coal has been added to the list, since it could by itself (without converting to a synthetic fuel) be used in some applications, with cost benefits.

9.2. Environmental Damage

In calculating the cost of fuels to society, their environmental effects and damages must be considered. As described in Section 2, investigations are being conducted in many parts of the world to estimate those damages [182,186-235]. Detailed estimates of the fossil fuel damage on various elements of the biosphere are presented in Table IV. Table IV indicates the type of damage and the damage per unit of modified fossil fuel consumption, which is defined as the total of the petroleum and coal consumption plus one-third of the natural gas consumption (i.e., it has been assumed that the environmental damage caused by natural gas is one-third that of the liquid or solid fossil fuels).

As can be seen from Table IV, the total environmental damage of fossil fuels is \$10.62 per GJ, which is quite a large figure. This is what the society pays, in addition to the market prices, for using fossil fuels. On a worldwide basis, it amounts to about U.S.\$1,900 billion, or 12.7% of the world's projected total Gross Domestic Product in 1990. It should be noted that the figure of \$10.62 per GJ ought actually to be greater, as it does not include the costs of human discomfort and any induced climatic changes.

The figure \$10.62 refers to the environmental damage caused by 1 GJ of coal or oil. When 1 GJ of a synthetic fuel is produced from coal, more than 1 GJ of coal is consumed. Consequently, the environmental damage due to 1 GJ of a synthetic fuel manufactured from coal is greater than \$10.62. This can be expressed as follows:

$$E_s = E_f \frac{p_s}{p_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where E_s is the environmental damage due to 1 GJ (or one unit) of a synthetic fuel produced from coal, E_f (= \$10.62) the fossil fuel environmental damage, p_s the synthetic fuel pollution factor, and p_f the fossil fuel pollution factor. Because of the dearth of data, total CO_2 generated has been taken as a measure of the pollution factor. Table V presents the pollution factors for various synthetic fuels, as well as for coal, gasoline, natural gas and the average between coal and oil [128].

9.3. Utilization Efficiency and Effective Cost

In comparing the fuels, it is important to take into account the utilization efficiencies at the user end. For utilization by the user, fuels are converted to various energy forms, such as mechanical, electrical and thermal. As mentioned in Sections 6, 7 and 8, in almost every instance of utilization, hydrogen can be converted to the desired energy form more efficiently than the fossil fuels (or the synthetic fossil fuels). In other words, conversion to hydrogen would result in energy conservation owing to its higher utilization efficiencies.

As a result of the foregoing, in order to compare the synthetic fuels under consideration, we could define a societal (effective) cost, which takes into account the production cost, environmental cost and utilization efficiency, as follows:

$$S_s = \{C_s + E_s\} \frac{\eta_3}{\eta_s} \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where S_s is the societal or effective cost of the synthetic fuel under consideration, C_s the production cost, E_s the environmental damage, η_s the utilization efficiency, and η_f the utilization efficiency of the fossil fuels. Substituting equation (3) in (4), one obtains:

$$S_s = \{C_s + E_f \frac{p_s}{p_f}\} \frac{\eta_f}{\eta_s} \ldots\ldots\ldots\ldots\ldots \quad (5)$$

Using the above equation with the data developed earlier, Tables VI, VII, VIII, and IX have been prepared to give the effective costs for various types of applications for thermal energy generation, electric power generation, surface transportation and air transportation respectively. Table VI shows that the catalytic combustion of GH_2 would produce the most economical thermal energy, while the synthetic fossil fuel produced heat would be most expensive. Coal generated heat is reasonably low, since there are no conversion (to synthetic fuels) losses. Another point to note is that amongst GH_2, the effective cost of coal GH_2 is the highest, although its production cost was the lowest. This is of course due to the addition of the environmental damage.

When electric power generation is considered (see Table VII), hydro GH_2 and solar GH_2 with fuel cells would be the most cost effective, followed by hydro GH_2 with aphodid steam generator and coal electricity. In the case of surface transportation (see Table VIII), GH_2 with fuel cells is the most cost effective, followed by GH_2 with I.C. engines and LH_2 with I.C. engines. Fossil-fueled surface transport becomes the most expensive. When air transportation is considered (see Table IX), hydro LH_2 is the most economical, followed by solar LH_2 and coal LH_2. SynJet is the most expensive fuel when societal cost is considered.

9.4. Comparison of Two Scenarios

In order to compare the real economics of the post-petroleum (and natural gas) era energy systems, two possible scenarios will be assumed:

1. Coal/Synthetic Fossil Fuel System: In this case it is assumed that the present fossil fuel system will be continued by the substitution of the synthetic fossil fuels wherever convenient and/or necessary. On a worldwide basis for the years 2000s, it will be assumed that out of the total "fuel" energy consumption, 40% will be used for thermal energy generation, 30% for electric power generation, 20% for surface transportation and 10% for air transportation. Of course, there will be additional electricity generation by hydropower and nuclear power, which does not enter or effect the comparison. It will further be assumed that two-thirds of the thermal energy generation will be achieved using coal and one-third using SNG, electric power generation will be achieved by coal burning thermal power plants, one-half of the surface transportation will run on SNG and the other-half on SynGas, and one-half of air

transportation will be subsonic and the other-half supersonic--both running on SynJet.

2. Solar Hydrogen Energy System: In this case, it is assumed that the conversion to the hydrogen energy system will take place, and one-third of the hydrogen needed will be produced by hydropower and two-thirds by direct and other (other than hydropower) indirect solar energies. On a worldwide basis for the years 2000s, the same percentages of energy demand by sectors as the first (above) scenario will be assumed. It will further be assumed that two-thirds of the thermal energy generation will be achieved by flame combustion of GH_2 and one-third by catalytic combustion of GH_2, electric power generation will be achieved by fuel cells, one-half of the surface transportation will use GH_2 burning I.C. engines and the other-half fuel cells, and one-half of the air transportation will be subsonic and the other-half supersonic--both running on LH_2.

Using the above assumptions and the data generated earlier, Tables X, XI and XII have been prepared. As can be seen from Table X for the Coal/Synthetic Fossil Fuel System, the overall effective cost of energy (by taking the weighted averages for all the sectors considered) will be \$19.63/GJ, whereas Table XI shows that the overall effective cost for the Solar Hydrogen Energy System will be \$10.73/GJ. In other words, the Solar Hydrogen Energy System's societal cost will be 45% less than that of the Coal/Synthetic Fossil Fuel System.

Table XII presents the data for the comparison of the utilization efficiencies by considering worldwide energy consumption by sectors. It can be seen that on a weighted average basis, the Solar Hydrogen Energy System is 26% more efficient that the Coal/Synthetic Fossil Fuel System. This means that out of the total savings of 45% for hydrogen, 26% is due to utilization efficiency advantage and the difference of 19% is due to environmental compatibility advantage.

9.5. Energy-Environment Resolution

When the advantages of the Solar Hydrogen Energy System are brought to the attention of decision-makers, legislators and government officials, their answer is "Hydrogen sounds good, but just now it is more expensive than petroleum. Let the free market forces decide what the energy system will be." The answer is fine, if the rules of competition are fair. At the present time, they are not. The rules favor the lower production cost products, irrespective of their environmental effects. We need new and fair laws which take into account the cost of the environmental damage, as well as production costs. Products must be liable for their damages.

In order to elucidate the above stated ideas, some 65 energy and environment scientists from around the world have drafted the following "Energy-Environment Resolution":

> WHEREAS the countries of the world are striving to increase their living standards, and thus--in addition to adopting all appropriate conservation measures--must increase their energy consumptions in the long run,
>
> WHEREAS the main energy sources at present are fossil fuels,
>
> WHEREAS fossil fuels are finite in amount and will eventually be depleted, with the downturn in production

expected to start early in the next century, if not before,

WHEREAS it is prudent to plan and begin conversion to the next energy system by making use of the remaining fossil fuel sources (and also other conventional energy sources, such as nuclear, etc.) to achieve a smooth changeover, which is expected to take half-a-century or so,

WHEREAS it is also prudent to preserve the diminishing supplies of the fossil fuels for non-fuel applications (such as lubricants, synthetic fibers, plastics and fertilizers), for which there may be no substitutes,

WHEREAS the combustion products of fossil fuels are causing growing damage to our Biosphere (the only known domain in the Universe to be supportive of life) and especially to its living components through pollution, acid rain, CO_2 and carcinogens,

WHEREAS the combustion products and their harmful effects do not stop at the national boundaries,

WHEREAS it is of the utmost importance to keep the Biosphere clean and fit for life, and hence the energy sources and energy carriers as clean as possible,

WHEREAS there exist "clean" primary energy sources,

WHEREAS there is a need for two types of energy carriers, viz., electricity (meeting about one-quarter of the demand at the consumer end) and fuel (meeting about three-quarters of the demand),

WHEREAS there exists technology for the production and utilization of the environmentally most compatible and most efficient fuel energy carrier, i.e., hydrogen,

WHEREAS there is a necessity for a self-regulating system, to ensure that man-induced factors (energy or otherwise) do not harm the Biosphere or threaten life,

IT IS HEREBY RESOLVED:

THAT products (energy carriers and otherwise) be made responsible for the harm they cause to the Biosphere and to life, directly or through their waste or their manufacture.

THAT the price of each product include an "environmental surcharge" to cover its environmental damage,

THAT the environmental surcharge be used by appropriate authorities to undo the damage to the Biosphere, life and structures; to cover related medical, restoration and relief expenses; and to compensate the victims,

THAT there must be international cooperation to ensure equitable and uniform application of the environmental surcharge.

IMPLEMENTATION OF THE ABOVE WILL RESULT in the following lasting and universal benefits:

ENSURE that eventually the present fossil fuel system would be replaced by a clean and environmentally compatible energy system, the Hydrogen Energy System,

ENSURE that energy (fossil, nuclear, etc.) would be available for the changeover, thus resulting in a smooth change with no upheavals,

ENSURE that some supplies of fossil fuels would be preserved for non-fuel applications, for which there might be no substitutes,

PROMOTE worldwide economic development and hence international harmony as progressively less unproductive work would be required to undo the environmental damage, and through the utilization of an efficient and renewable energy carrier, and

SAVE the Biosphere and life from extinction by ensuring that products, their manufacturing methods and wastes would be environmentally compatible.

The principal expressed in the resolution is already applied on a small scale; for example, if the emission from a factory is damaging farm produce around it, then the farmers are compensated. What we are proposing is that this principle should be applied universally, and not only for the immediate near term damages, but also for the long-term cumulative damages which may take place far away from the source and over a period of time. Under such a system, in costing a product, a surcharge necessary to cover environmental damage would be added to its production cost. This surcharge could then be used, by the appropriate authorities, to undo the damage caused by "dirty" products to the Biosphere, life and structures; to cover related medical, restoration and relief expenses; and to compensate the victims. Once such a principle is legislated, then no energy company will produce and sell fossil fuels, but will begin to manufacture solar hydrogen, since it will be by far the cheapest fuel. This will not only initiate the establishment of the clean and abundant Solar Hydrogen Energy System, but will have other important benefits: It will force all the products to be clean and environmentally compatible; it will save the Biosphere from slow death and preserve the life on this planet; and it will also provide higher quality of life for its dwellers--humans, flora and fauna.

10. SAFETY

We have seen that the Solar Hydrogen Energy System is more cost effective than the Coal/Synthetic Fossil Fuel System. But, is it safe? In the Solar Hydrogen Energy System, the primary energy source under consideration, solar energy, is environmentally the most compatible. It is the life giver to this planet earth. However, when the safety of the energy carrier, hydrogen, is discussed, the Hindenburg accident is immediately brought up. People will say hydrogen causes explosions and big fires, and that it is a very dangerous fuel. Contrary to this belief, extensive studies show that hydrogen is the safest fuel.

The U.S. National Aeronautics and Space Administration, (NASA) is the world's biggest hydrogen consumer. Since hydrogen is their basic energy carrier, NASA has sponsored many studies to compare hydrogen with other fuels, such as petroleum. All of these studies show that, when everything is taken into consideration, hydrogen is the safest fuel [191,236-241].

10.1. Hindenburg Syndrome

The Hindenburg dirigible was the biggest passenger airship of its time in 1937. Since hydrogen is the lightest element, its balloon was filled with hydrogen to keep it afloat. On its eleventh crossing of the Atlantic from Europe to New York, it had some 100 passengers and crew members. As it was getting ready to land in Lakehurst, New Jersey, a fire started in the balloon. Nobody knows for sure how the fire started. Some say it was because of a malfunction of an electrical contact. Others say it was sabotage. In any case, the dirigible was on fire with some 100 people in the gondola.

People panicked. Thirty-five persons jumped from a height of several hundred feet and perished. The others remained in the gondola. Incredibly, they were not hurt by the flames, although the balloon above them was ablaze. The reason is that hydrogen flames radiate very little heat. On the other hand, fires from fossil fuels radiate very intense heat due to the high radiation characteristics of the heated carbon particles. Petroleum fires burn with a red-orange glow. Hydrogen fire is almost invisible with a faint bluish color.

The remaining passengers stayed in the gondola as the balloon lost its hydrogen and started to descend. After some moments the gondola touched the ground, and the passengers and crew made a hasty retreat from the burning airship. They were all saved.

Should the fire have been a petroleum fire, most of these remaining people would have died from intense radiation heat, as well as from smoke inhalation.

10.2. Safety in Aerospace Transportation

It is expected that one of the earliest commercial uses of hydrogen will be in aerospaceplanes and in hypersonic airplanes, which travel at several times the speed of sound and will be able to cross the oceans in a couple of hours. The fuel selected for such transportation is hydrogen.

Regardless of the precautions taken and the safety features built into any aerospace transport, there are occasionally unforeseen accidents on the ground and during the flight. Even a plane fueled with hydrogen could experience such an accident.

Let us consider a ground accident. Forty years after the Hindenburg accident, in 1972, the worst aviation mishap in history took place in Santa Cruz de Tenerife, the Canary

Islands, when a KLM B-747 jumbo jet collided with a Pan Am B-747 jumbo jet on the runway. Both planes burst into flames. The splattered jet fuel from the two planes was burning fiercely, and flames and smoke filled both planes. Some 583 persons perished, mainly from the intense heat of radiation and from smoke inhalation.

If these planes had been hydrogen fueled, a disaster of this magnitude could not have happened, because most of the passengers would have been able to walk out the exit doors. There would have been no suffocating or breathing difficulty, since hydrogen has no toxic combustion products. Everyone, except those engulfed in flames, would have been saved.

Now let us consider a mishap during the most dangerous time of any flight, i.e., right after the takeoff. Today, when there is an emergency right after a takeoff, the plane has to circle for hours to empty its fuel tanks, or dump the fuel, before landing. The reason is that the landing gears would collapse if a landing was attempted with the full force of the weight of an airplane plus a full load of fuel. It should be mentioned here that for long flights about 60% of a plane's takeoff weight is fuel. If the plane were fueled with hydrogen, this additional weight would only amount to 20%. So the pilot could land right away, avoiding the possibility of further complications. If any of the hydrogen fuel were dumped, it would dissipate into the air with no poisonous effects. However, the dumped jet fuel (or SynJet fuel) would pollute the atmosphere, oceans and the land.

So hydrogen-fueled airplanes and spaceplanes would be safer than synthetic fossil-fueled planes in many respects.

10.3. Safety in Surface Transportation

Every year thousands of people die in accidents directly related to gasoline or diesel fuels used in automobiles. On cold winter nights, when teenagers return from the movies they often pull into the family garage. Sometimes they sit in their cars talking or courting and, of course, leave the engine running to keep warm. Unfortunately, they are found in the morning overcome by the toxic effects of carbon monoxide intoxication. But it does not happen to only inexperienced young people. In 1988 a Dade County (Miami, Florida) policeman was found dead in his car, apparently of carbon monoxide poisoning. Even a public official, knowledgeable in all kinds of dangers, is not immune to the hazards of fossil fuels. There are 1,800 deaths a year because of this cause in the United States alone.

With cars running on hydrogen, nothing like the above tragedies could happen. The by-product of the combustion of hydrogen is water vapor. Water vapor, or steam, is not poisonous and does not kill people. It does not affect the nervous system, so people do not become unconscious from breathing it.

If a collision occurs between cars running on gasoline or diesel fuels, the fuel lines frequently burst, spattering fuel all over. In many instances a fire starts. The intensity of radiating heat and poisonous gases again prove to be lethal.

As mentioned earlier, the storage system for hydrogen-fueled cars could be either a hydriding bed or a liquid hydrogen, or a pressurized gas storage system. Of the three, the hydriding system is the safest. Even very violent collisions, puncturing the hydriding tank, would not start a big fire. A small flame would flicker from the tank as hydrogen was slowly released from the hydriding material. Some experiments show that when bullets are shot at hydriding tanks, only a small flame comes out of the bullet hole.

There are some prototype cars running on liquid hydrogen, which have reported accidents. One such accident occurred in California where a car, with a full tank of liquid hydrogen, was overturned in a collision and the storage tank was punctured. The cold liquid (-440°F) quickly spilled out and evaporated due to the heat in the atmosphere. There was no fire.

Cars running on hydrogen stored in pressurized containers pose more danger than those with hydrides or liquid storage. There would be a possibility of fire, but not necessarily an explosion. Explosions can occur when hydrogen and oxygen or hydrogen and air are mixed in a confined space. If hydrogen is escaping from a broken pipe or a punctured tank, a fire could be ignited by a spark or by the hot surface of the engine. Again, those near the fire but outside the flames would not be burned or overcome by toxic fumes, and could walk away from it. Those touched by the flames would, of course, be hurt.

In conclusion, it can be stated that when all factors are considered, hydrogen is a much safer fuel for cars than fossil fuels or synthetic fossil fuels.

10.4. Safety in Homes and Kitchens

In homes natural gas is used for heating and cooking. Also, fuel oil and coal are used for heating, and sometimes for cooking. If for any reason a leakage of natural gas or fuel oil vapor occurs anywhere in the house, a large concentration can be fatal. Every winter, in closed up homes, families are found dead from the inhalation of toxic fumes.

Cooking ranges using natural gas or oil can be dangerous, too. Fires resulting from natural gas or fuel oil produce toxic smoke, as well as heat radiating flames. Many accidents of this nature can cause bodily injury, can even prove to be fatal. A home running on hydrogen for cooking, heating and cooling would not have mishaps as described above. Neither hydrogen itself nor its combustion product, water vapor, is poisonous. Catalytic burners using hydrogen are the best choice for cooking since they would not cause a fire. A finger touched on a catalytic burner would suffer a much milder burn as compared to a burn from a natural gas or fuel oil burner. Catalytic combustion temperatures are much lower (300° F) than the flame temperatures of fossil fuels (2500° F). Rooms heated by catalytic hydrogen burners would be much safer than rooms which use a fireplace fueled by natural gas, fuel oil or coal.

Of course, all fuels, including hydrogen, can cause fires. If a hydrogen fire occurs in a house, no one would be burned unless they were in direct contact with the flames. They would not be overcome by inhaling toxic fumes either, and could quickly and easily escape. They would also be able to help those injured by the flames, since they would not be in immediate danger.

However, in the case of fires caused by fuel oil, natural gas or coal, the situation is quite different. The fossil-fuel flames radiate intense heat, burning everyone in close proximity. The poisonous smoke and fumes produced by fossil fuels can quickly suffocate people. Every year in the United States alone, 800 persons die in such a way in homes, hotels, offices, warehouses and other buildings.

In summary, a hydrogen-fueled home is safer than a fossil (or synthetic fossil) fueled home. Even in the event of a fire, the residents of a hydrogen-fueled home stand a greater chance of escaping injury and/or death.

10.5. Leaks

All fuel storage facilities and transportation pipelines are subject to leakage. Hydrogen, being the lightest and smallest element, leaks easier than other fuels including natural gas. However, hydrogen is a bulkier fuel; that is, for a given amount of energy it occupies more space than fossil fuels. It occupies three times more space than natural gas. It is not immediately obvious whether hydrogen would be more or less dangerous than natural gas or petroleum under similar leakage conditions.

When hairline cracks develop, gases first escape from their containers or pipelines by diffusion. When the crack becomes a little bigger, the gas flow becomes laminar. A further enlargement of the crack makes the flow faster, and the turbulent flow ensues.

Studies have been carried out to compare hydrogen and natural gas flow rates under the same conditions for the three leakage types described above. For the case of diffusion, hydrogen volume flow rate would be about 2.8 times greater than that of natural gas. Hydrogen flow rate would be 1.5 times greater than natural gas if the flow through the crack was laminar, and 3.3 times greater if the flow was turbulent. The greater hydrogen flow rates are due to the lower viscosity of hydrogen as compared with natural gas; the lower the viscosity, the greater is the flow rate.

However, this does not make hydrogen more dangerous than natural gas. To compare them from the point of view of potential danger, we must consider the amount of energy flow through the leaks. Since for a given volume hydrogen contains less energy than natural gas, higher volume flow rate does not necessarily mean higher energy leaking out of the container or the pipeline. Of course, energy content would be a way to measure the damage, in case leaking gases ignite, causing a fire.

Again, studies show that for a hairline crack, the hydrogen energy leak would be 15% less than that of natural gas. If the flow was laminar, the hydrogen energy leak would be 56% less than that of natural gas. In the case of turbulent leaks, they are about even. This means that if the leaking gases from a larger crack were ignited, the damaging forces of the resulting fires would be about the same for both hydrogen and natural gas. For smaller cracks, the damaging force of natural gas would be worse than that of hydrogen. However, when one takes into account the greater radiation heat from natural gas fires and the noxious fumes generated, hydrogen is the safer of the two fuels for all three types of leaks.

Every year, it is estimated that five million gallons of diesel oil, gasoline and fuel oil leak from their storage tanks in gas stations and from pipelines. They enter the ground water and make it unsafe for drinking. If underground water flows into any lakes and rivers, they will also poison the aquatic life in those places. This cannot happen with hydrogen. If there is a hydrogen leak from a storage tank or a pipeline, it will seep up through the ground and diffuse into the air.

Across the oceans, it is proposed that hydrogen be transported in supertankers similar to today's LPG (Liquefied Petroleum Gas) and LNG (Liquefied Natural Gas) tankers. LPG and LNG are carried on tankers in huge insulated spherical containers. Liquid hydrogen would be carried in the same way. If the ship were damaged or if the tanks leaked, hydrogen would readily evaporate into the atmosphere, which would not harm any living creature or the environment. This cannot be said for fossil fuels.

Let us consider the oil spill of the Exxon *Valdez* which occurred in April 1989 in Prince William Sound, Alaska, U.S.A. It ran into a reef spilling in excess of 10 million gallons of oil with great loss of life to seals, otters and birds; damaged spawning grounds and nursery areas for salmon and other fish; and polluted the waters and beaches of Prince William Sound and the Alaskan Gulf. Nothing like this can or could happen with hydrogen.

All in all, when one considers the above facts, we can safely say that hydrogen is the safest fuel, as already concluded by many reports on the safety of fuels.

11. CONCLUSIONS

As a result of the foregoing study, the following conclusions are reached:

(a) The Solar Hydrogen Energy System is renewable and will provide the world with a permanent energy system, while the Fossil Fuel System is not renewable.

(b) The Solar Hydrogen Energy System is environmentally more compatible than the Fossil Fuel System.

(c) The utilization efficiencies of the Solar Hydrogen Energy System are greater than those of Fossil Fuel system.

(d) The Solar Hydrogen Energy System is more cost effective than the Synthetic Fossil Fuel System.

(e) Most of the technology for the near term applications of the solar Hydrogen Energy System exists. With further research and development work, there should be improvements in utilization efficiencies and costs.

(f) In addition to the above reasons (which are applicable worldwide to all the countries), the Solar Hydrogen Energy System is especially attractive to the developing countries for two more reasons:

    (i) Almost all of the developing countries have abundant indigenous direct and/or indirect forms of Solar Energy available to them, while this cannot be said for the fossil fuels.

    (ii) Since the developing countries are just starting to build their energy infrastructures they could avoid the mistakes of the industrial countries, by basing their energy infrastructure on the Solar Hydrogen Energy System, rather than a nonrenewable and environmentally incompatible system. Hence, they would have a permanent and cost effective energy system to speed up their development, while saving their environment.

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TABLES

Table I

PROPERTIES OF GASOLINE, NATURAL GAS AND HYDROGEN

PROPERTY	GASOLINE	NATURAL GAS	HYDROGEN
Density (g/cm^3)	0.73	0.78x10^{-3}	0.84x10^{-4} (gas) 0.71x10^{-1} (liquid)
Boiling Point (°C)	38 - 204	-156	-253 (20K)
Lower Heating Value:			
Gravimetric (kJ/kg)	4.45x10^4	4.8x10^4	12.50x10^4
Volumetric (kJ/m^3)	32.0x10^6	37.3x10^3	10.4x10^3 (gas) 8.52x10^6 (liquid)
Stoichiometric Composition in Air (Volume %)	1.76	9.43	29.3
Flammable Limits (% in Air)	1.4 - 7.6	5 - 16	4 - 75
Flame Speed (m/sec)	0.40	0.41	3.45
Flame Temperature in Air (°C)	2197	1875	2045
Ignition Temperature (°C)	257	540	585
Flame Luminosity	High	Medium	Low

Table II

COMPARISON OF HYDROGEN STORAGE MEDIA

MEDIUM	HYDROGEN CONTENT WT %	STORAGE CAPACITY g/ml of Vol	ENERGY DENSITY HEAT OF COMBUSTION** (HIGHER)	
			cal/g	cal/ml of Vol
MgH_2*	7.0	0.101	2373	3423
$MgNiH_4$	3.16	0.081	1071	2745
VH_2	2.07		701	
$FeTiH_{1.95}$	1.75	0.096	593	3245
$TiFe_{.7}Mn_{.2}H_{1.9}$	1.72	0.090	583	3050
$LaNi_5H_{7.0}$	1.37	0.089	464	3051
$R.E.Ni_5H_{6.5}$	1.35	0.090	458	3050
Liquid H_2	100	0.070	33900	2373
Gaseous H_2 (100 atm pressure)	100	0.007	33900	244
N-Octane			11400	8020

*Starting alloy 94% Mg-6%Ni

**Refers to H only in metal hydrides

Table III

ESTIMATED AVERAGE PRODUCTION COSTS OF SYNTHETIC FUELS AND COAL

FUEL	ESTIMATED AVERAGE COST 1990 $/GJ
Coal GH_2	8.58
Hydro GH_2	11.51
Solar GH_2	15.44
SNG	8.85
Coal LH_2	10.73
Hydro LH_2	14.39
Solar LH_2	19.30
Syn - Gas	17.25
Syn - Jet	13.05
Coal	2.19

Legend and Information:

Hydro: Hydropower
Solar: Direct & Indirect Solar, except hydropower
SNG: Synthetic Natural Gas
Syn - Gas: Synthetic Gasoline
Syn - Jet: Synthetic Jet Fuel
G: Gaseous
L: Liquid

Table IV

SUMMARY OF THE ESTIMATES OF THE FOSSIL FUEL DAMAGE

TYPE OF DAMAGE	DAMAGE PER UNIT OF FOSSIL FUEL ENERGY 1990 $/GJ
1. Effect On Humans	3.76
2. Effect On Fresh Water Sources & Resources	0.59
3. Effect On Farm Produce, Plants & Forests	1.25
4. Effect On Animals	0.40
5. Effect On Buildings	0.73
6. Effect On Coasts And Beaches	0.17
7. Effect Of Rising Oceans	0.37
8. Effect Of Strip Mining	0.15
9. Effect Of Rising Temperatures	3.20
TOTAL:	$10.62/GJ

Table V

POLLUTION FACTOR

FUEL	POLLUTION FACTOR CO_2 Emission kg/GJ
Coal GH_2	116.3
Hydro GH_2	- 0 -
Solar GH_2	- 0 -
SNG	116.3
Coal LH_2	145.4
Hydro LH_2	- 0 -
Solar LH_2	- 0 -
Syn - Gas	131.6
Syn - Jet	131.6
Coal	85.5
Gasoline	76.5
Natural Gas	48.4
Mean Fossil (Coal + Gasoline)	81.0

Table VI

EFFECTIVE COST OF SYNTHETIC FUELS AND COAL FOR THERMAL ENERGY GENERATION

APPLICATION	FUEL	UTILIZATION EFFICIENCY η_f or η_s	EFFECTIVE COST 1990 $/GJ
Fossils — Flame Combustion	SNG	0.800	24.10
	Syn - Fuel Oil*	0.800	30.30
	Coal	0.800	13.40
GH_2 — Flame Combustion	Coal GH_2	0.800	23.83
	Hydro GH_2	0.800	11.51
	Solar GH_2	0.800	15.44
GH_2 — Catalytic Combustion	Coal GH_2	1.000	19.06
	Hydro GH_2	1.000	9.21
	Solar GH_2	1.000	12.35

* Considered to be the same as Syn - Jet.

Table VII

EFFECTIVE COST OF SYNTHETIC FUELS AND COAL FOR ELECTRIC POWER GENERATION

APPLICATION	FUEL	UTILIZATION EFFICIENCY η_f or η_s	EFFECTIVE COST 1990 $/GJ
Fossils — Thermal Plant	SNG	0.380	24.10
	Syn - Fuel Oil	0.380	30.30
	Coal	0.380	13.40
GH_2 — Thermal Plant	Coal GH_2	0.380	23.83
	Hydro GH_2	0.380	11.51
	Solar GH_2	0.380	15.44
GH_2 — Thermal Plant With Aphodid Steam Generator*	Coal $GH_2 + GO_2$	0.475	21.46
	Hydro $GH_2 + GO_2$	0.475	11.61
	Solar $GH_2 + GO_2$	0.475	14.75
GH_2 — Fuel Cells	Coal GH_2	0.700	12.94
	Hydro GH_2	0.700	6.25
	Solar GH_2	0.700	8.38

* $3/GJ Has Been Added To Fuel Cost As Oxygen Cost.

Table VIII

EFFECTIVE COST OF SYNTHETIC FUELS FOR SURFACE TRANSPORTATION

APPLICATION	FUEL	UTILIZATION EFFICIENCY η_f or η_s	EFFECTIVE COST 1990 $/GJ
Fossil Fueled Transport — I.C. Engines	SNG	0.250	24.10
	Syn - Gas	0.250	34.50
GH_2 Fueled Transport — I.C. Engines	Coal GH_2	0.300	19.86
	Hydro GH_2	0.300	9.59
	Solar GH_2	0.300	12.87
LH_2 Fueled Transport — I.C. Engines	Coal LH_2	0.330	22.57
	Hydro LH_2	0.330	10.90
	Solar LH_2	0.330	14.62
GH_2 Fueled Transport — Fuel Cells	Coal GH_2	0.700	8.51
	Hydro GH_2	0.700	4.11
	Solar GH_2	0.700	5.51

Table IX

EFFECTIVE COSTS OF SYNTHETIC FUELS FOR AIR TRANSPORTATION

APPLICATION	FUEL	UTILIZATION EFFICIENCY RATIO: η_f/η_s	EFFECTIVE COST 1990 $/GJ
SUBSONIC JET TRANSPORT	Coal LH_2	0.840	25.02
	Hydro LH_2	0.840	12.09
	Solar LH_2	0.840	16.21
	Syn - Jet	1.000	30.30
SUPERSONIC JET TRANSPORT	Coal LH_2	0.725	21.59
	Hydro LH_2	0.725	10.43
	Solar LH_2	0.725	13.99
	Syn - Jet	1.000	30.30

Table X

COAL/SYNTHETIC FOSSIL FUEL SYSTEM

APPLICATION	ENERGY CONSUMPTION FRACTION	FUEL	EFFECTIVE COST 1990 $/GJ	(FRACTION) X (COST) 1990 $
Thermal Energy	0.30	Coal	13.40	4.02
Thermal Energy	0.10	SNG	24.10	2.41
Electric Power	0.30	Coal	13.40	4.02
Surface Transport	0.10	SNG	24.10	2.41
Surface Transport	0.10	Syn - Gas	34.50	3.45
Subsonic Jet Transport	0.05	Syn - Jet	30.30	1.51
Supersonic Jet Transport	0.05	Syn - Jet	30.30	1.51
TOTALS:	1.00	Overall Effective Cost = $19.63/GJ		

Table XI

SOLAR HYDROGEN ENERGY SYSTEM
$(\frac{1}{3}$ HYDRO $H_2 + \frac{2}{3}$ SOLAR $H_2)$

APPLICATION	ENERGY CONSUMPTION FRACTION	FUEL	EFFECTIVE COST 1990 $/GJ	(FRACTION) X (COST) 1990 $
Thermal Energy — Flame	0.30	GH_2	14.13	4.24
Thermal Energy — Catalytic	0.10	GH_2	11.30	1.13
Electric Power — Fuel Cells	0.30	GH_2	7.67	2.30
Surface Transport — I.C. Engines	0.10	GH_2	11.78	1.18
Surface Transport — Fuel Cells	0.10	GH_2	5.04	0.50
Subsonic Jet Transport	0.05	LH_2	14.84	0.74
Supersonic Jet Transport	0.05	LH_2	12.80	0.64
TOTALS:	1.00	Overall Effective Cost = $10.73/GJ		

Table XI-I

UTILIZATION EFFICIENCY ADVANTAGE OF SOLAR HYDROGEN SYSTEM OVER SYNTHETIC FOSSIL FUEL SYSTEM

APPLICATION	ENERGY CONSUMPTION FRACTION	FUEL	UTILIZATION EFFICIENCY RATIO η_f/η_s	(FRACTION) X (η_f/η_s)
Thermal Energy — Flame	0.30	GH_2	1.000	0.300
Thermal Energy — Catalytic	0.10	GH_2	0.800	0.080
Electric Power — Fuel Cells	0.30	GH_2	0.543	0.163
Surface Transport — I.C. Engines	0.10	GH_2	0.833	0.083
Surface Transport — Fuel Cells	0.10	GH_2	0.357	0.036
Subsonic Jet Transport	0.05	LH_2	0.840	0.042
Supersonic Jet Transport	0.05	LH_2	0.725	0.036
TOTALS:	1.00		Overall $\frac{\eta_f}{\eta_s} = 0.740$	

FIGURES

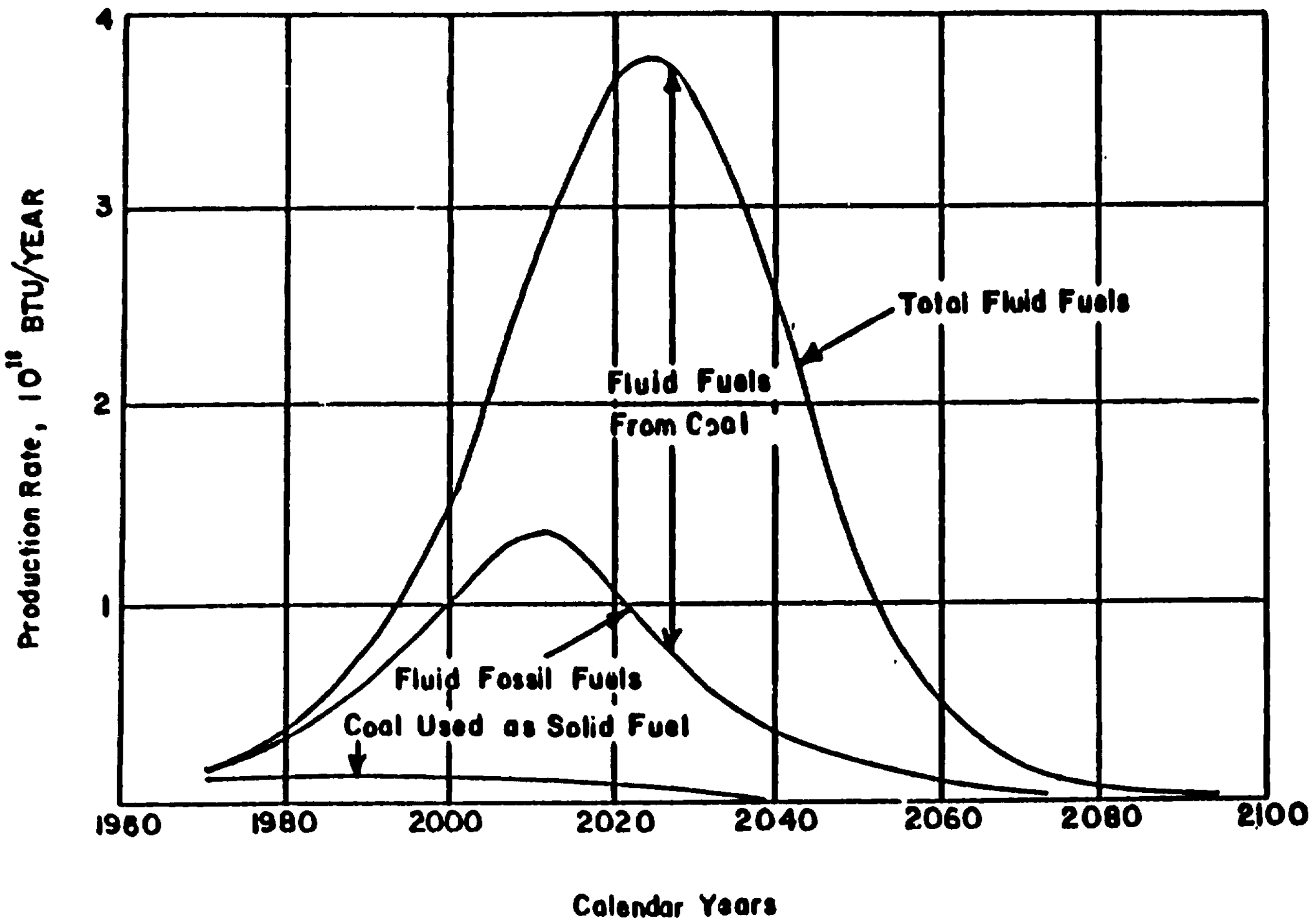


Fig. 1 - Projected Rates of Production of World Fossil Fuels.

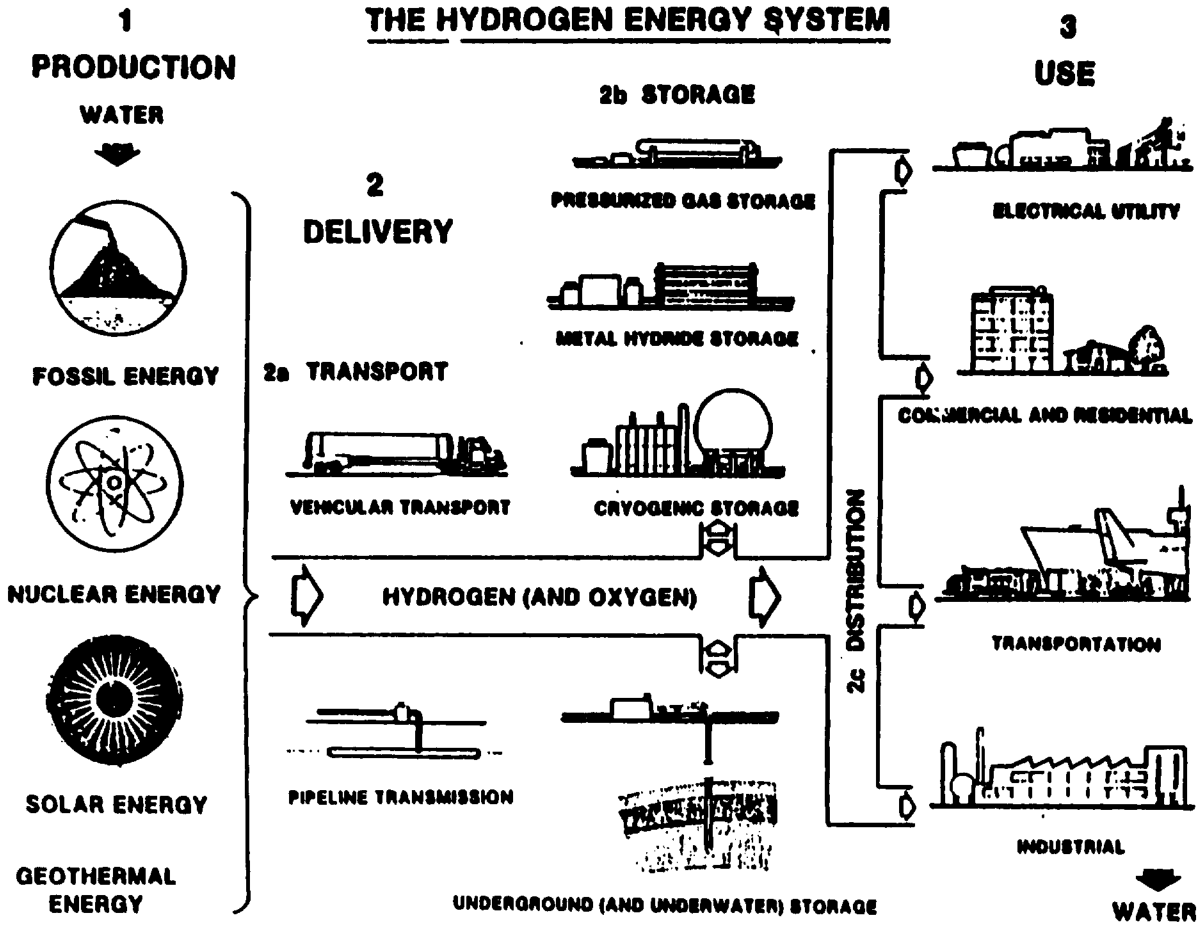
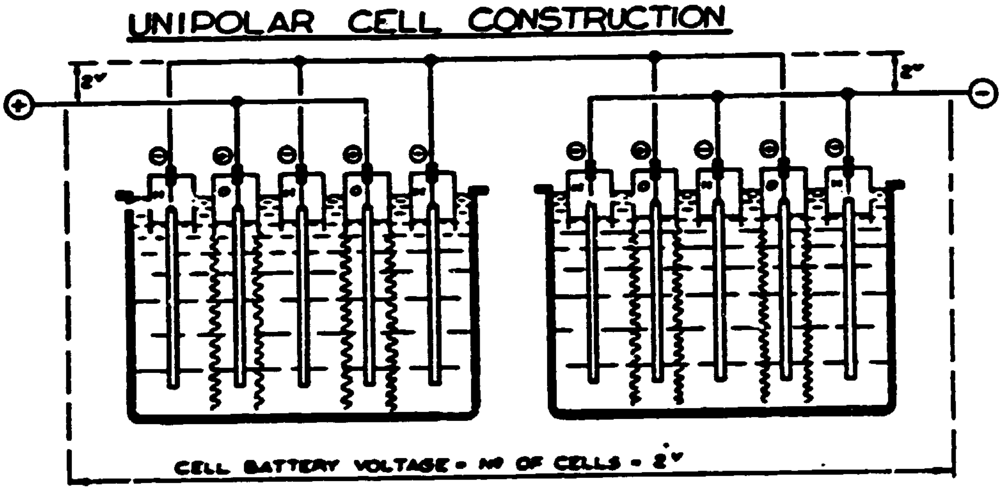


Fig. 2 - Hydrogen Energy System.



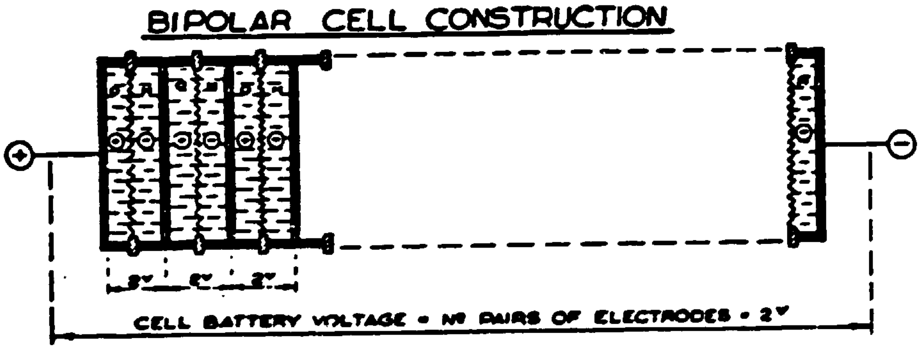


Fig. 3 - Schematic Diagrams of Unipolar and Bipolar Electrolysers.

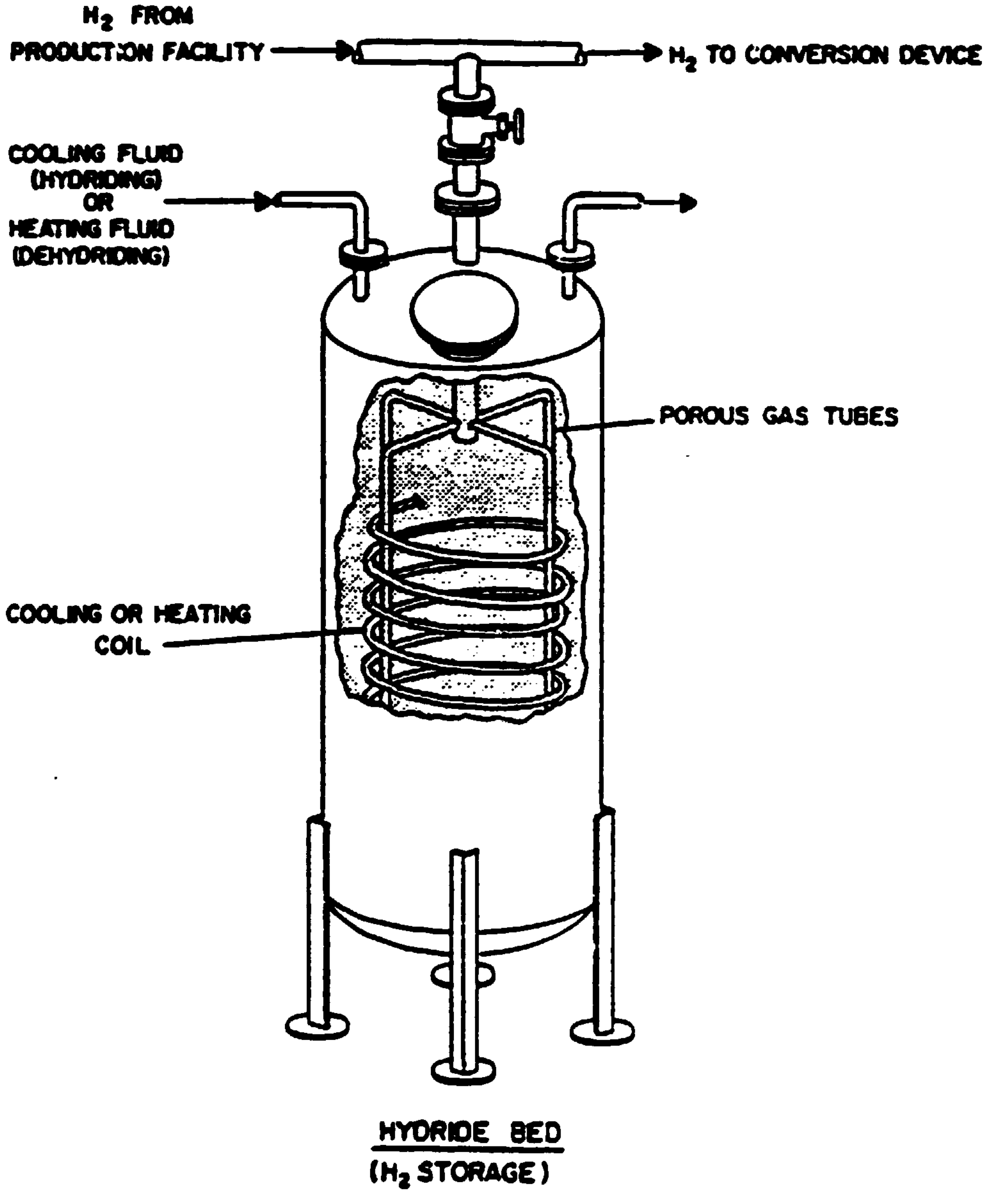


Fig. 4 - Hydrogen Storage Hydride Tank.

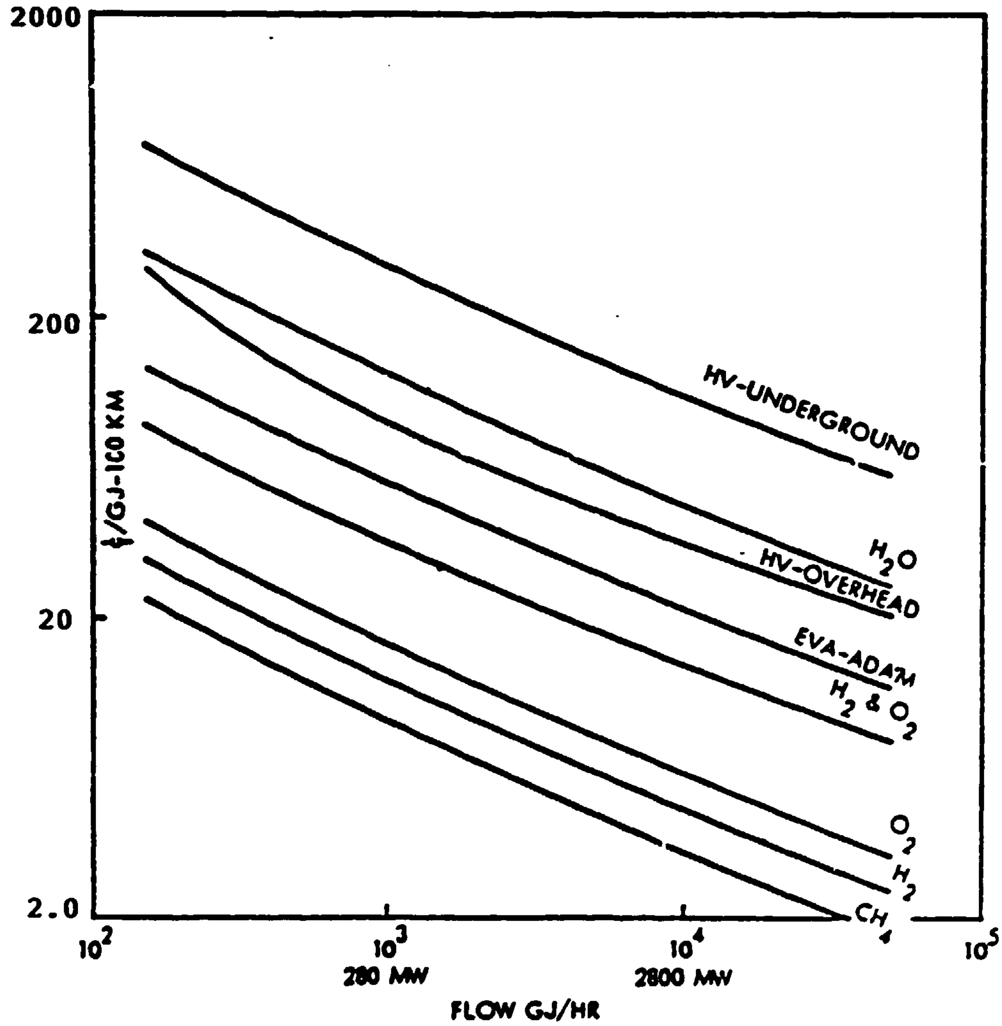


Fig. 5 - Energy Transport Costs (1990 $).

HYDROGEN TECHNOLOGY FOR HUMAN SETTLEMENTS

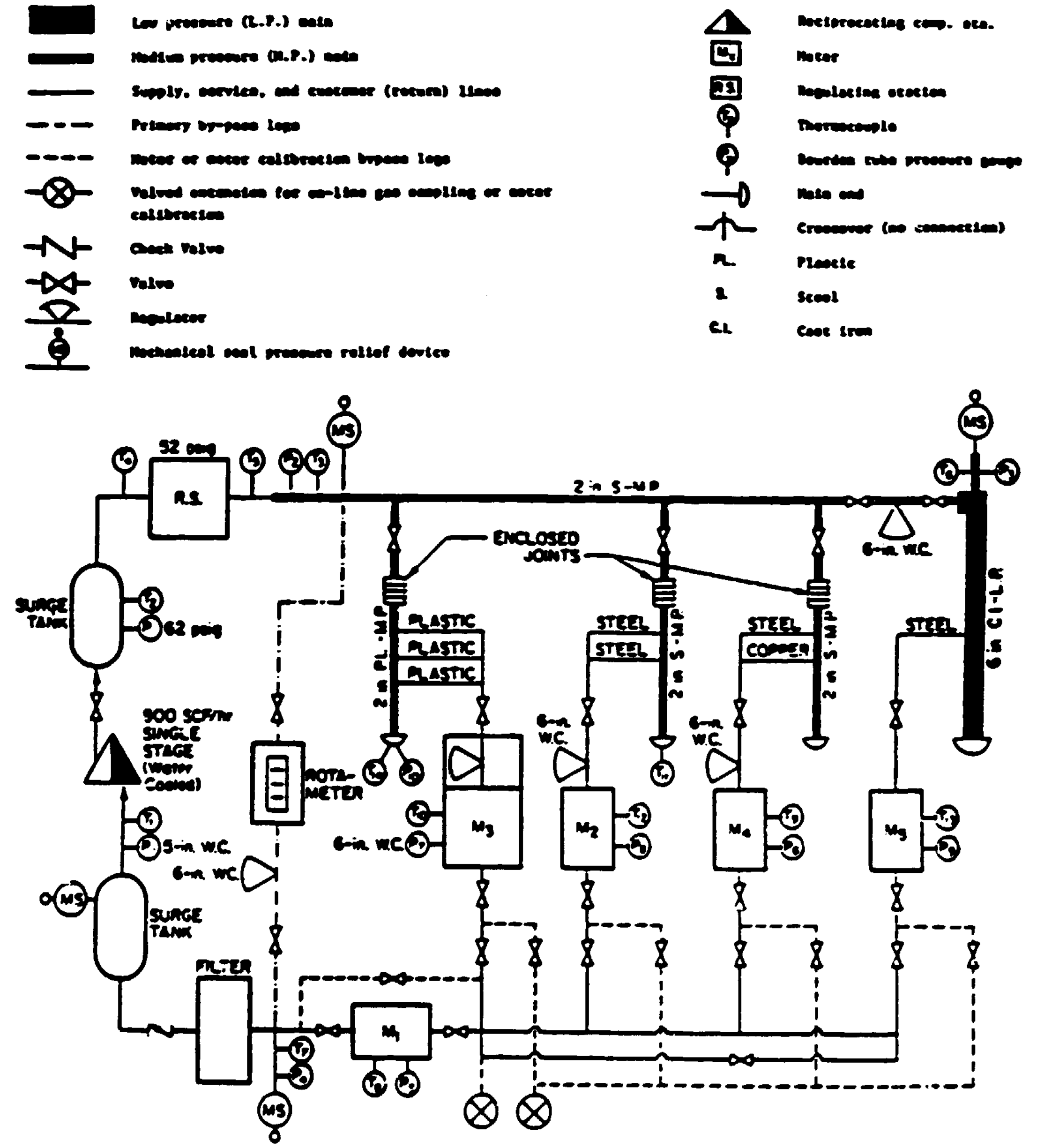


Fig. 6 - Residential Hydrogen Distribution Test System.

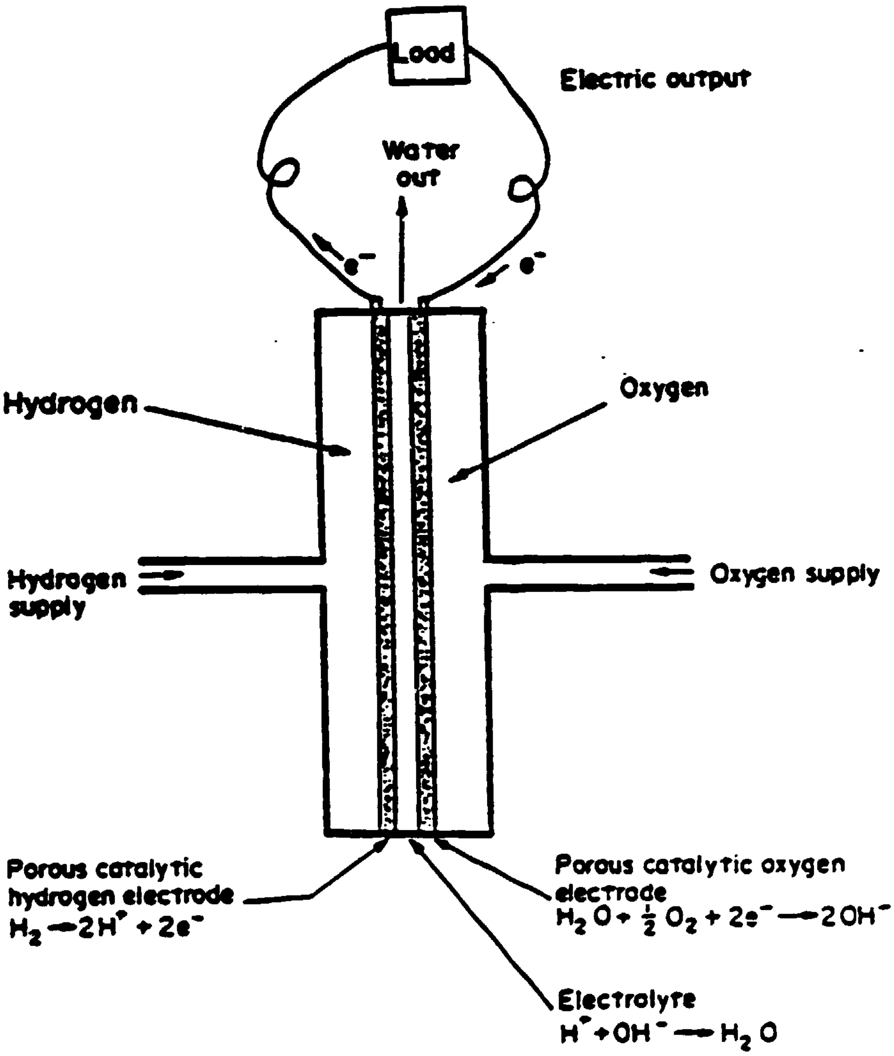


Fig. 7 - Hydrogen Fuel Cell.

Fig. 8 - 4.5 MW_e Fuel Cell Operated by Tokyo Electric Utility.

Fig. 9 - DFVLR Steam Generator.

Fig. 10 - A Home Fuel Cell Unit.

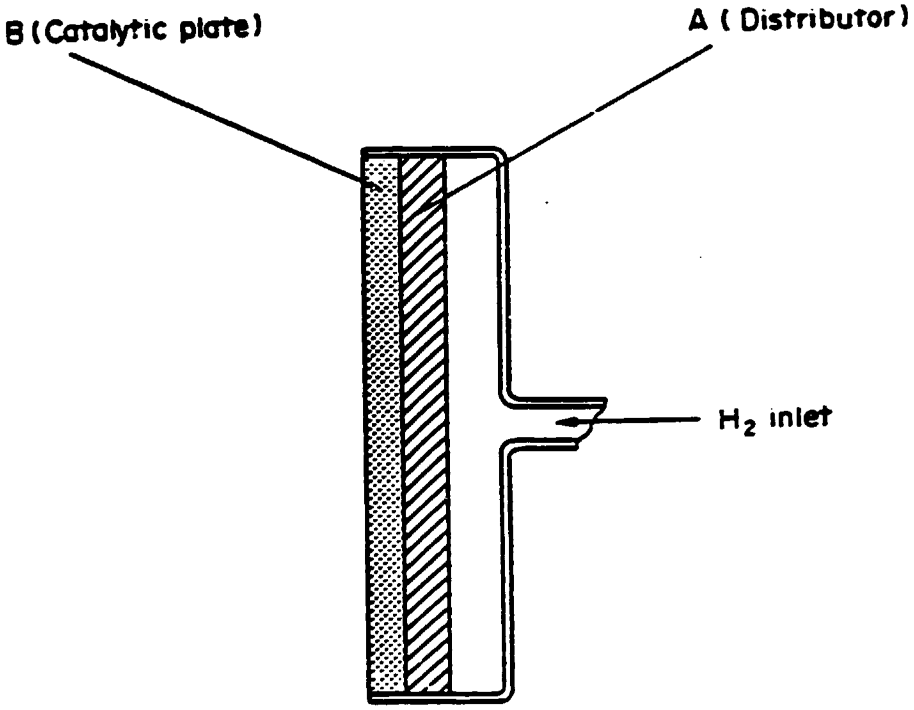


Fig. 11 - Catalytic Wall Combustor.

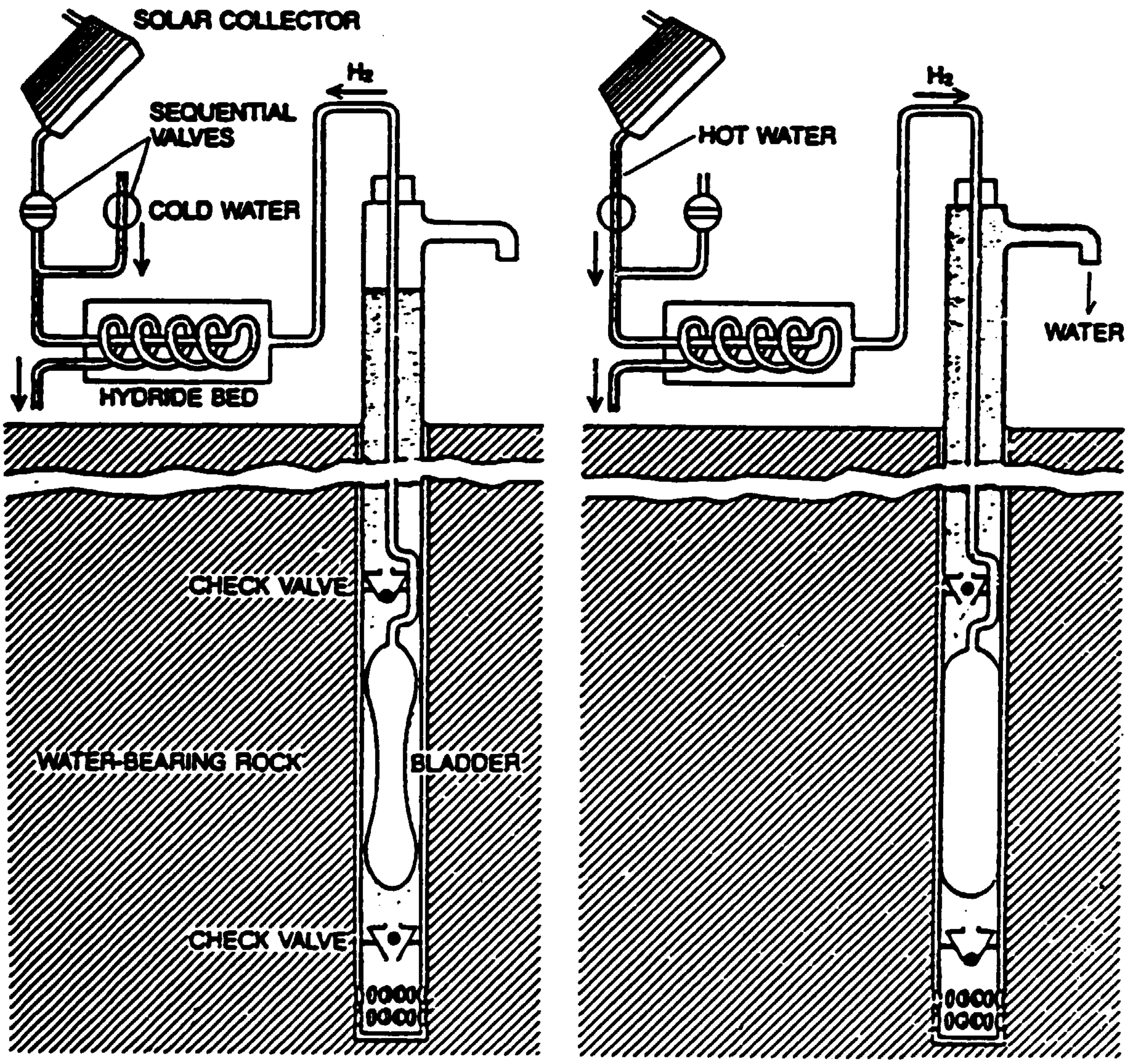


Fig. 12 - Hydrogen/Hydride Water Pumping System.

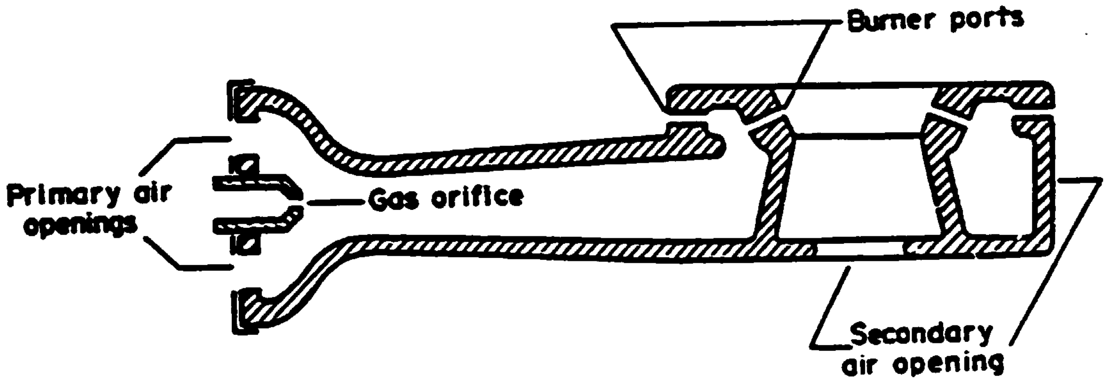


Fig. 13a - Typical Atmospheric Burner.

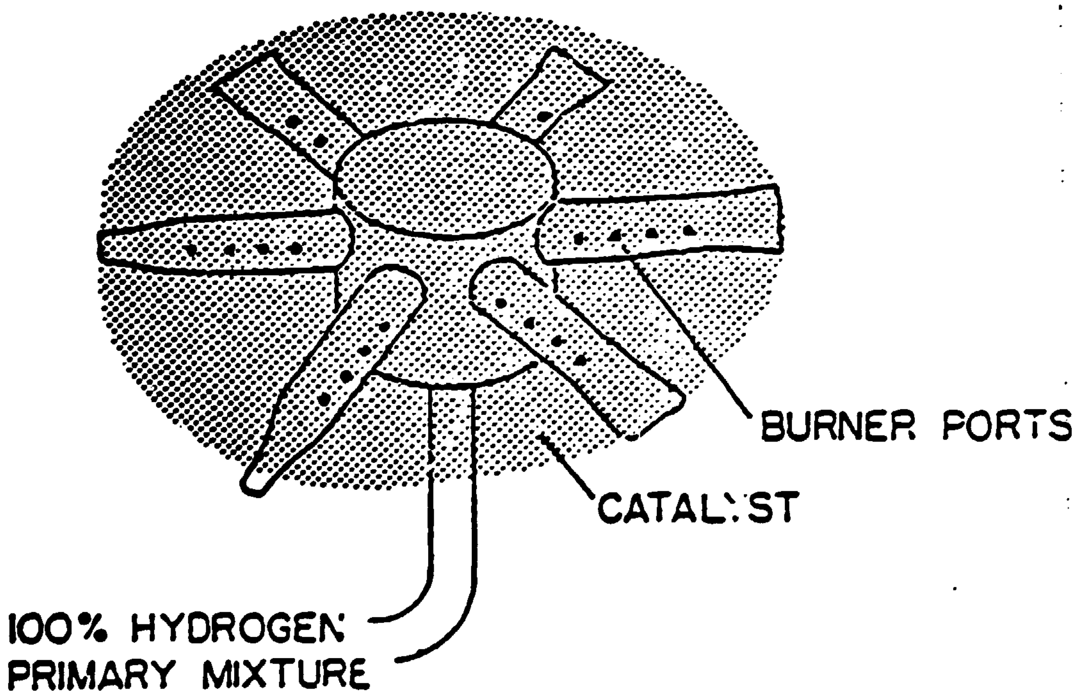


Fig. 13b - Atmospheric Burner with Stainless Steel Catalyst.

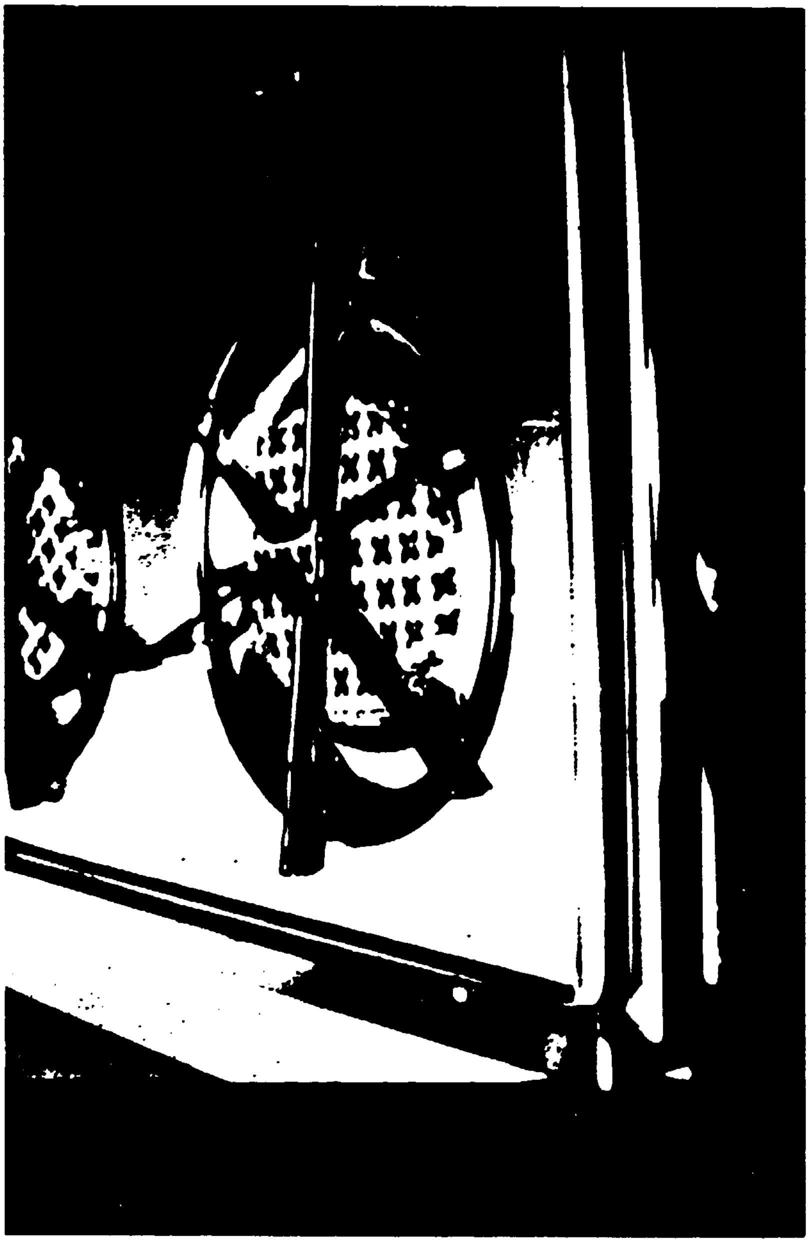


Fig. 14a - Hydrogen Flame Stove Top.

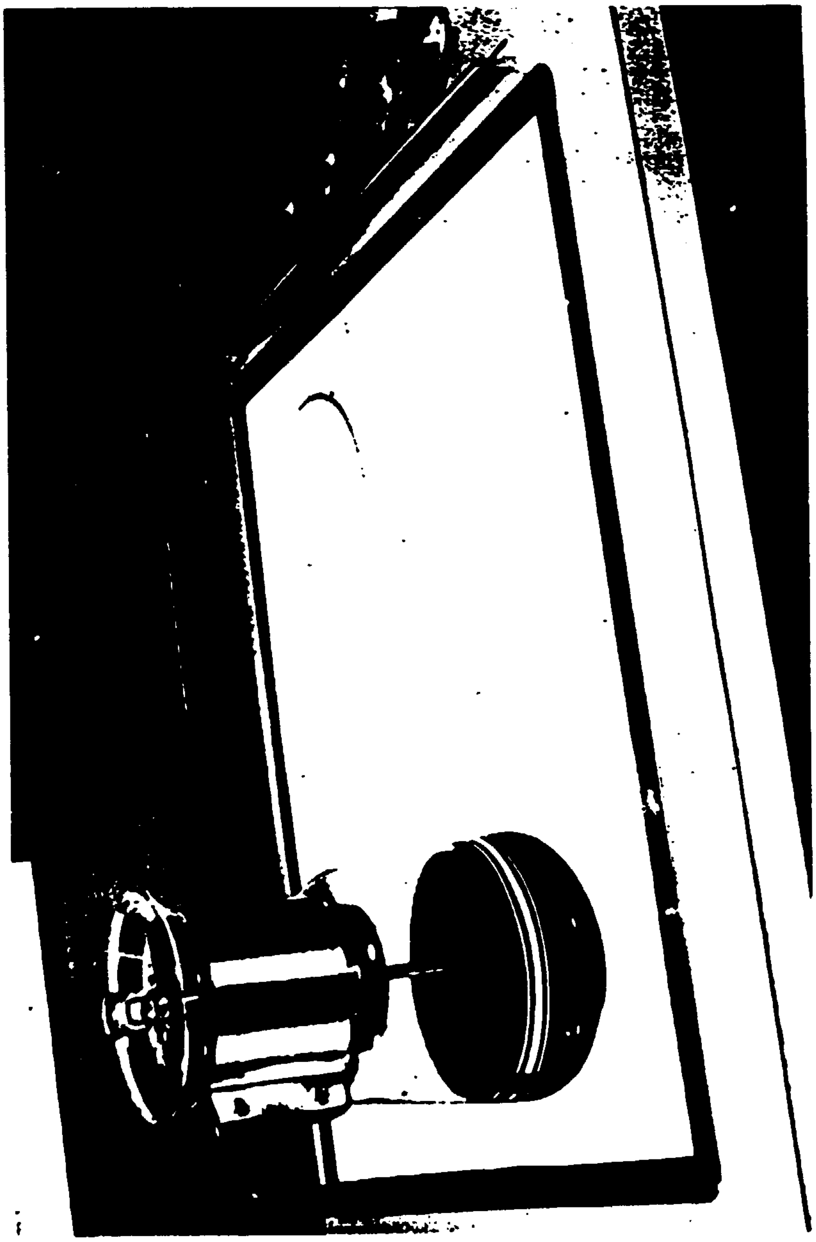


Fig. 14b - Hydrogen Catalytic Combustor Stove Top.

Fig. 14c - Hydrogen Barbeque.

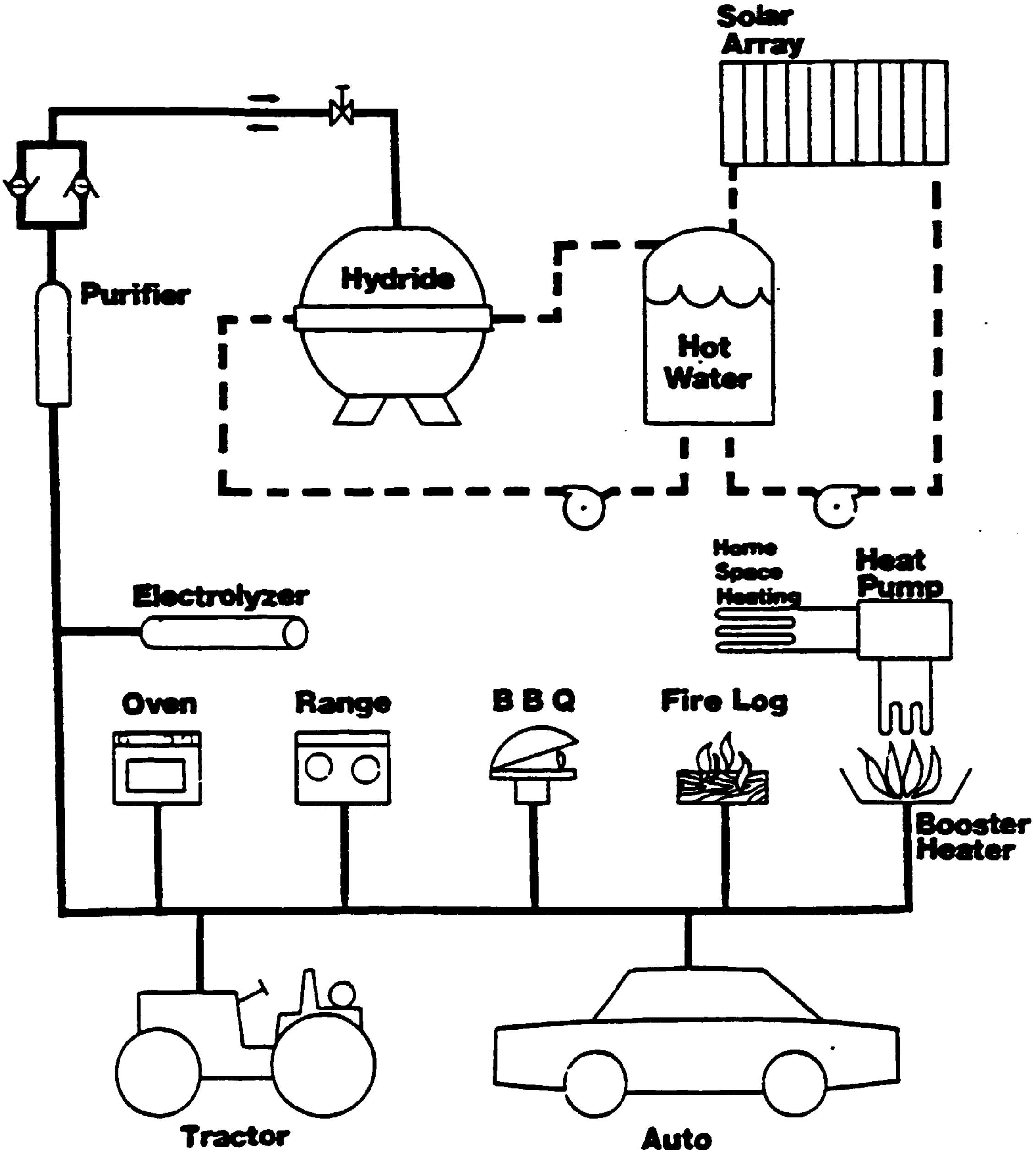


Fig. 15 - Billings Hydrogen Homestead Energy System.

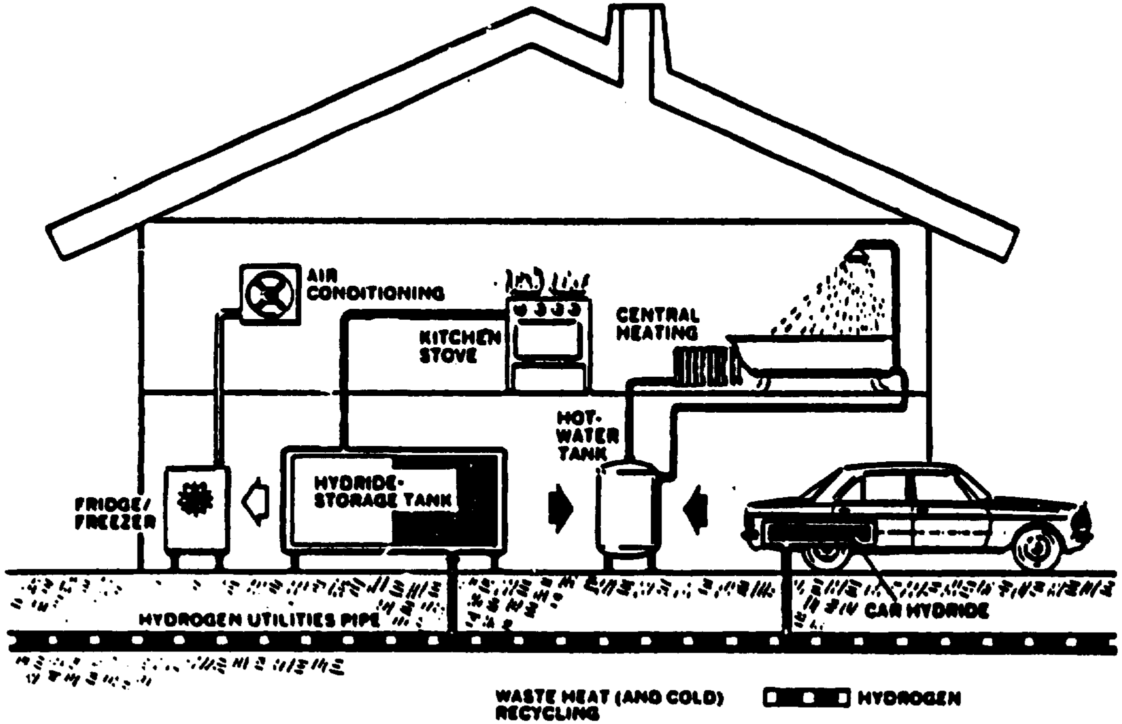


Fig. 16 - Residential Hydrogen/Hydride Energy System.

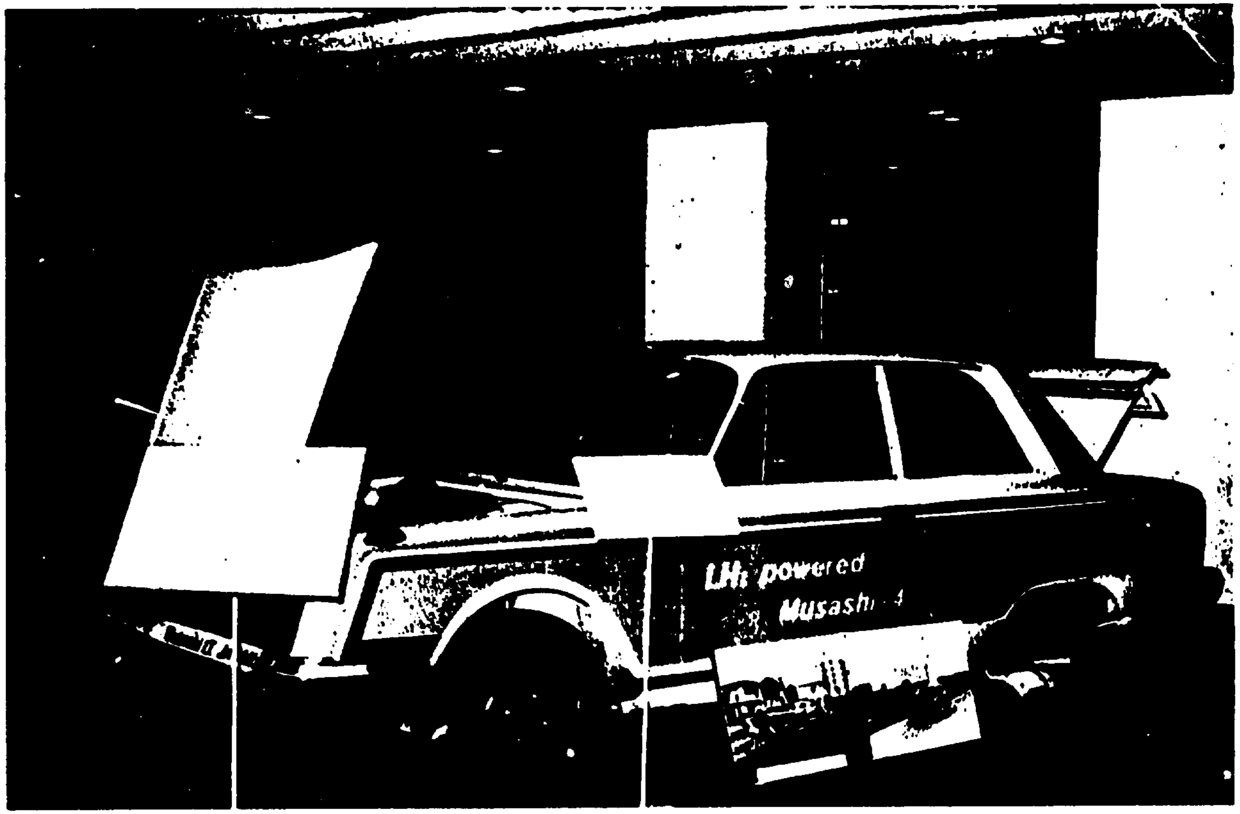


Fig. 17a - Suzuki Car Converted to Run on Liquid Hydrogen.

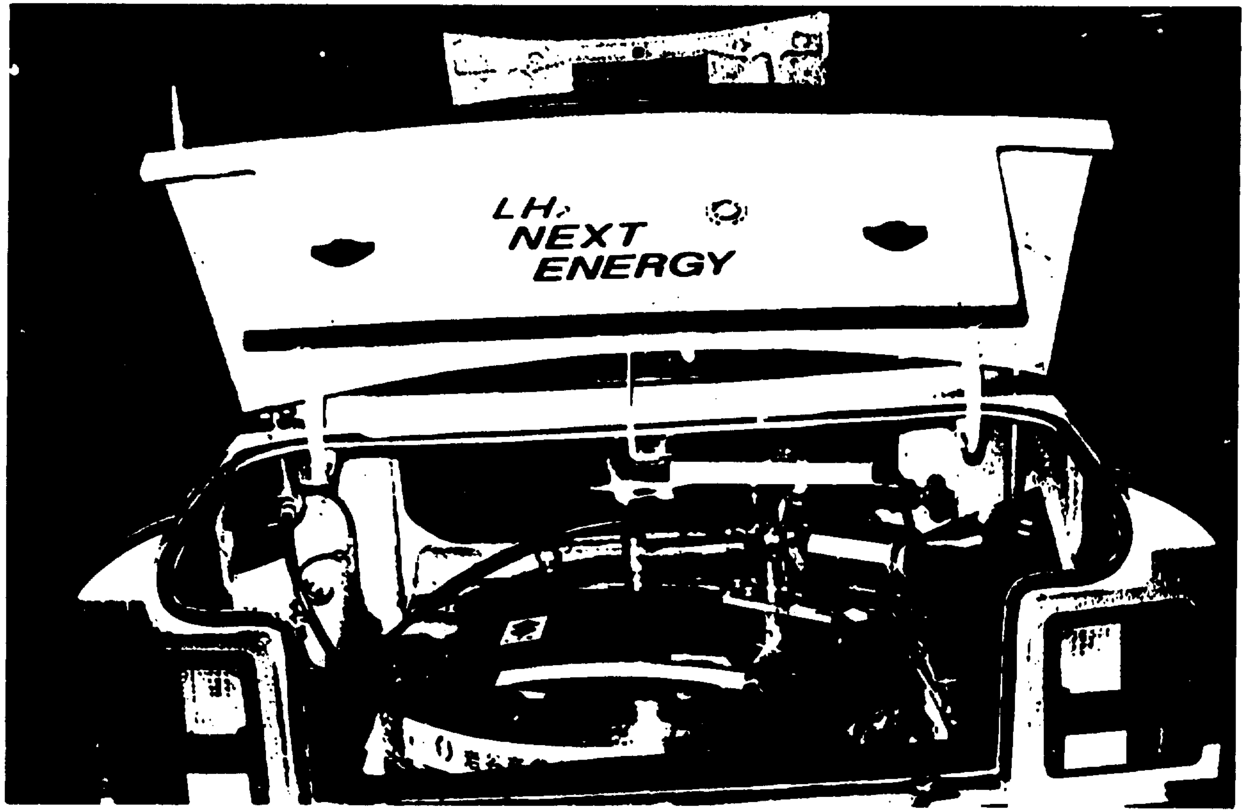
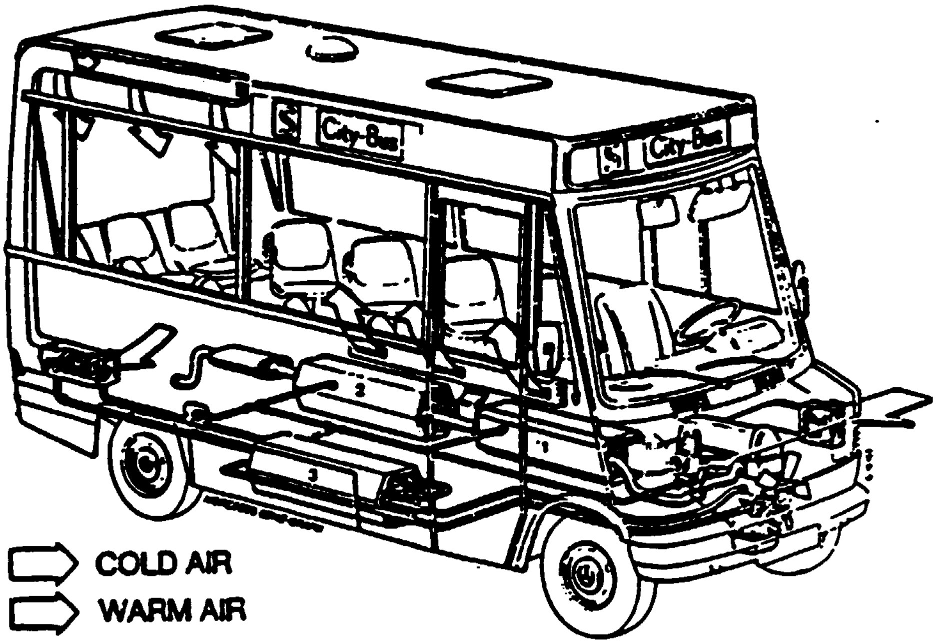


Fig. 17b - Suzuki Car Liquid Hydrogen Storage System.



1 HIGH TEMPERATURE HYDRIDE STORAGE TANK, HEATED BY EXHAUST GAS (AUXILIARY HEATER)
2 LOW TEMPERATURE HYDRIDE STORAGE TANK, HEATED BY EXHAUST GAS (WATER CONDENSATION)
3 LOW TEMPERATURE HYDRIDE STORAGE TANK WITH LIQUID HEAT EXCHANGE (AIR CONDITIONING)

Fig. 18 - Mini-Bus Running on Gaseous Hydrogen with Hydride Storage, and Hydrogen/Hydride Heating-Cooling System.

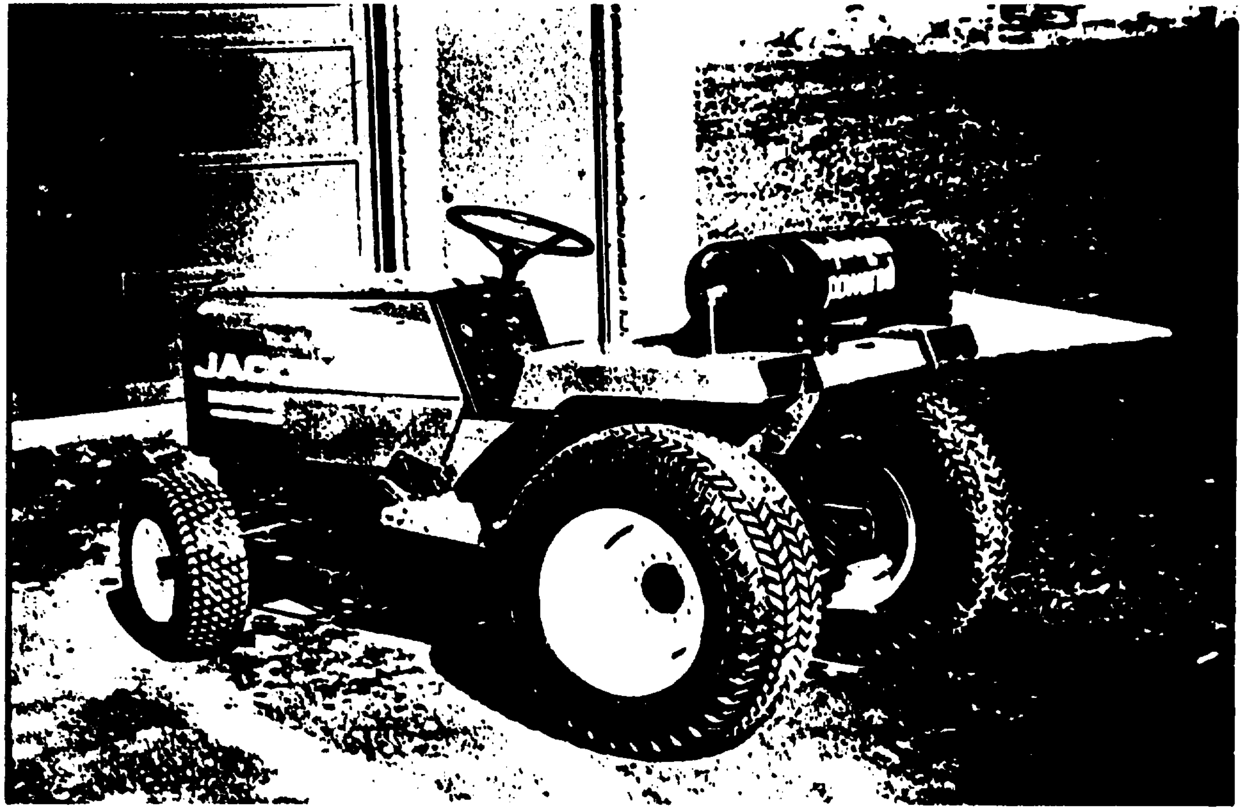


Fig. 19a - Hydrogen Fueled Jacobsen Tractor.

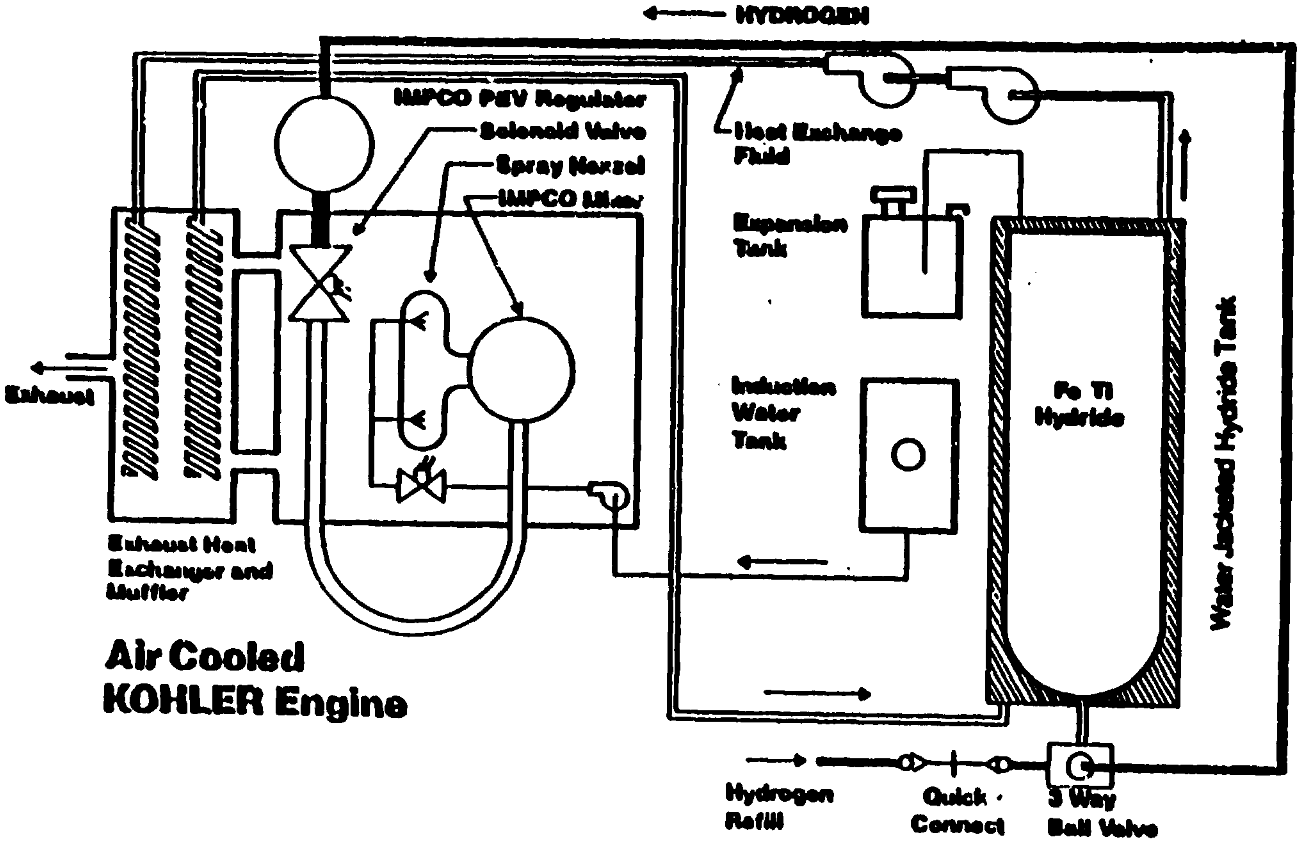


Fig. 19b - Jacobsen Tractor Hydrogen System.