

HYDROGEN GENERATION BY SOLID POLYMER ELECTROLYTE WATER ELECTROLYSIS

J. H. Russell, L. J. Nuttall and A. P. Fickett

General Electric Company
Direct Energy Conversion Programs
Lynn, Massachusetts 01910INTRODUCTION

A number of recent studies (1 - 11) have concluded that hydrogen is a most promising future means of energy storage and transmission, as fossil fuel supplies diminish and nuclear energy usage increases. These conclusions are based on the premise that a reliable, efficient and cost-effective means of generating hydrogen from water will be available. Electrolysis is presently the most practical generation method, and offers the greatest promise of meeting required capital and operating cost objectives without requiring a major technological break-through. The most common water electrolysis units in the past used a liquid caustic (potassium hydroxide) electrolyte and were relatively inefficient and required frequent maintenance. During the past five years, however, the General Electric Company has developed a unique solid polymer electrolyte (SPE) water electrolysis technology. The SPE system combines high efficiency with exceptionally long, maintenance free life (over three years of continuous operation have been accumulated to date on one of the early single-cell units). While this development was prompted primarily by requirements for oxygen generation in aerospace and submarine life support systems, the design can readily be adapted and scaled to large-size hydrogen generation plants.

It is the purpose of this paper to summarize the present and projected capabilities of the SPE water electrolysis technology, and to consider the applicability of the SPE technology as a generator of hydrogen for use as a fuel, for energy transmission, and for energy storage.

In view of the considerable attention given the "future hydrogen economy", it would seem important that a projection of the costs of the potential hydrogen applications in that economy be considered. This paper attempts to deal with such considerations in a manner that is not overly dependent upon indeterminate factors such as future energy costs, location of nuclear plants, etc. This has necessitated that the respective analyses be kept somewhat general and simplistic.

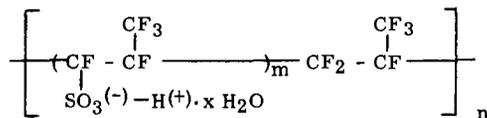
SOLID POLYMER ELECTROLYTE TECHNOLOGY

Details of the technical background describing the performance improvements, demonstrated operating lifetimes, and hardware developments related to this technology have been previously described (12). The following is a summary of this technology and its inherent characteristics.

Solid Polymer Electrolyte

The electrolyte used in the SPE electrolysis cell is a solid plastic sheet of cation exchange membrane about 12 mils thick. This membrane when saturated with water is an excellent ionic conductor (≤ 15 ohm-cm resistivity) and is the only electrolyte required. There are no free acid or alkaline liquids in the system. A typical cell is shown schematically in Figure 1.

The ion exchange membrane (SPE) is a perfluorinated sulfonic acid membrane which has all of the stability and performance requirements for a long-lived electrolysis system. Chemically, the polymer approximates:



Ionic conductivity is provided by the mobility of the hydrated hydrogen ions ($\text{H}^+ \cdot x \text{H}_2\text{O}$). These ions move through the polymer sheet by passing from $\text{---}(\text{SO}_3^-) \text{---}$ to $\text{---}(\text{SO}_3^-) \text{---}$. The sulfonic acid groups $\text{---}(\text{SO}_3^-) \text{---}$ are fixed and do not move, thus the concentration of the acid remains constant within the SPE.

Water is supplied to the oxygen evolution electrode (anode) where it is electrochemically decomposed to provide oxygen, hydrogen ions, and electrons. The hydrogen ions move to the hydrogen evolving electrode (cathode) by migrating through the SPE. The electrons pass through the external circuit to reach the hydrogen electrode. At the hydrogen electrode, the hydrogen ions and electrons recombine electrochemically to produce hydrogen gas.

An excess of water is usually supplied to the system and recirculated to remove any waste heat.

The gases are generated at a stoichiometric ratio of hydrogen and oxygen at any pressure required of the system. The SPE can withstand large differential pressures (> 1000 psid) as well as high generating pressures which can easily be attained simply by back-pressuring the system.

The use of the SPE results in the following advantages:

- a) The cell can operate with high differential pressures (> 1000 psid) in addition to high gas generating pressures.
- b) The concentration of the electrolyte is fixed and the electrolyte is not mobile.
- c) There is no possibility of acid carry-over into the effluent gas.
- d) There are no corrosive electrolytes to control or leak in the system.
- e) The electrolyte is essentially invariant in operation.
- f) The acid SPE electrolysis unit results in a minimum power requirement per unit of gas generated.

Catalytic Electrodes

An additional feature of the SPE water electrolysis cell is the simplicity of the catalytic electrodes. Since the electrolyte is a solid, the catalytic electrodes are not required to retain the electrolyte and may therefore be optimized for catalytic activity at minimum cost. Presently, a thin layer of platinum black ($1 - 5 \text{ mg/cm}^2$) is attached to the

SPE surface to form the hydrogen electrode and a similar layer of a proprietary alloy catalyst forms the oxygen electrode. The improvements in the oxygen electrode catalyst over the past five years have resulted in substantial reductions in the voltage requirements for a fixed hydrogen generation rate. These improvements are shown in Figure 2.

Stack and Hardware Design

Figure 3 illustrates the basic components of a cell. The design uses a flat gasket concept for sealing the gas compartments and manifolding the feed water and generated gases between cells. The active area of the membrane is supported by expanded screening on each side. This screening forms the hydrogen and oxygen/water compartments and provides sufficient membrane support to allow operation at 500 - 1000 psid across the membrane. Bipolar current collection is maintained between each cell by means of the screen layers contacting a 3 mil separator sheet.

These cells are in turn stacked between end plates as shown in Figure 4. The particular hardware shown in this figure has operated for more than 12,000 hours with no change in operating characteristics.

Generally the metallic components within the cells are either titanium alloy or niobium to eliminate corrosion. Titanium alloy would be used almost exclusively for ground applications to take advantage of its lower cost. As can be seen, this particular design concept can readily be scaled-up either in terms of the number of cells in a stack or the area of a cell. SPE fuel cell stacks of 78 cells have been made and tested for over 5000 hours. Likewise, 1 x 2 ft fuel cells have been tested. One unit with approximately 1 x 0.5 ft cells has operated for more than 15,000 hours without problems.

Present SPE Water Electrolysis Capability

Status of the SPE water electrolysis technology in 1972 - 1973 is best depicted in Figure 5, which shows the performance attained with "state-of-the-art" SPE electrolysis cells. The cell used to determine these curves has operated for 7000 hours to date with no change in its performance capability.

Based upon this technology, an electrolysis stack operating at 1000 ASF would require 22.2 KWH to produce a pound of hydrogen. Capital costs would be \$3000/lb/hr of hydrogen capacity (equivalent to \$167/KW capacity based upon the higher heating value of hydrogen).

Projected SPE Water Electrolysis Capability

Titterington et al (12) have examined the potential for further reductions in both energy requirements and the capital cost of producing hydrogen by SPE water electrolysis. Figures 6 and 7 summarize these projections.

The projections through 1985 are straightforward extensions of the present SPE technology. Input energy reductions will be obtained through further anode improvements and the increase in operating temperature to 300°F. The SPE has been operated at this temperature for 800 hours and has been shown to be stable at this temperature condition. Capital cost reductions will be achieved by modest reductions in the quantity of noble metal required per cell and the use of lower cost hardware materials. For example, materials are presently available to achieve the capital costs projected for 1977. Since these

materials have not undergone extensive testing in the actual electrolysis environment for periods in excess of three years, they have not been used to calculate the 1973 capital cost basis.

Beyond 1985, it has been assumed that an inorganic solid electrolyte, similar to the zirconia technology (13 - 14) studied in some depth in the 1967 - 1968 time period, will become available. In the 1968 time period, the energy requirements and capital costs for the zirconia technology were similar to those projected for the SPE in the 1980 - 1985 time period. This technology was severely limited by the temperature of operation (1800°F) and resulting materials problems. It has been assumed that an oxide conductor operating in a temperature range below 1800°F and above that of the β aluminas (650°F) could be developed within the 1985 - 2000 time frame.

Thus the projections through 1985 are based on extensions of the present SPE technology through increased temperatures of operation and lower cost materials. In the 1985 - 2000 time period the development of a \sim 1000°F oxide conductor is assumed.

APPLICATION OF WATER ELECTROLYSIS IN FUTURE POWER SYSTEMS

In recent months, ever increasing attention is being given by industry, utilities and government agencies to the search for alternative energy sources to meet the energy crisis. The impetus behind this effort is the prospect that in the foreseeable future, if the energy demand increases at the anticipated rate, fuels such as natural gas, fuel oil and coal will either be depleted or prohibitively expensive. This concern is coupled with environmental regulations which prohibit the direct burning of high sulfur coal (which is reasonably plentiful) and restrict the amount of local thermal pollution resulting from close-by nuclear installations. The location of nuclear generating plants in remote locations, such as off-shore islands or platforms, effectively attacks the thermal pollution concern but incurs the expense of transmitting power for long distances.

As the severity and ramifications of the energy shortage become better defined, the utilization of hydrogen as a fuel and/or a means of transmitting or storing energy comes into contention. Hydrogen as a fuel is clean and its product of combustion is pure water when reacted with either oxygen or as a hydrogen-rich air mixture. It also offers the highest specific energy density (Btu/lb) of any potential fuel. Piped hydrogen as a future means of transmitting large amounts of energy for relatively long distances offers the potential advantages of:

- a) Plentiful supply since the basic requirement is water.
- b) Compatibility with remote nuclear plants located off-shore where thermal environmental effects are minimal.
- c) Lower cost, to the extent that the savings in transmission and distribution costs more than offset the cost of generating the hydrogen.
- d) Improved visual environment since hydrogen pipes are underground and can utilize existing natural gas networks.
- e) Flexibility, since hydrogen can be used directly in home and industry with minor modification to natural gas burning equipment, converted to electricity via gas turbines or fuel cells, or it can be liquified and distributed for automotive or aircraft use.

- f) Storage, either in gaseous or liquid form which allows: 1) utilization of power at the off-peak periods where desirable (nuclear or conventional fossil fuel plants); or 2) utilization of cyclic or periodic electrical power sources (such as wind power systems, solar energy systems or tidal systems).

In addition to the above advantages, the electrolysis of water produces oxygen as a byproduct along with the hydrogen. This "free" oxygen could potentially be utilized for sewage treatment, fresh water purification, or sold for industrial use.

Many studies of the economics of various aspects of the hydrogen energy cycle compared to present and predicted fossil fuel cycles have been performed by utilities, industry and government agencies (1 - 8). Most studies conclude that based on present technology, energy in the form of hydrogen could be transmitted at less cost than electrical energy and by 1985, local re-conversion of hydrogen to electric power via combustion turbines would be competitive with underground transmission of electrical energy.

All of the present studies assume electrolysis energy requirements in the area of 22 to 28 KWH/lb H₂ and capital costs in the range of \$785/lb H₂/hr output capacity.

Based on the projected performance and cost estimates discussed previously, we see energy requirements of 18 to 20 KWH/lb H₂ in the 1985 - 1990 time period, dropping as low as 15 KWH/lb H₂ by the year 2000. A capital cost of \$785/lb H₂/hr capacity is reasonable for the 1985 time period with reduction to \$250 - 350/lb H₂/hr capacity by the year 2000.

Conceptual Hydrogen Utility System

A conceptual hydrogen utility system is depicted in Figure 8. Electricity is generated in a large-scale power plant located in a remote, unpopulated land area or an off-shore platform where environmental pollution effects are minimized and a ready supply of water (either sea, river or lake) is available. The power plant produces DC power directly (utilizing homopolar generators) for use by the electrolysis plant located at or close by the power plant. This avoids the requirement of AC-DC conversion equipment. The waste heat from the nuclear plant is utilized to desalinate the water utilized in the electrolysis process.

In the electrolysis plant the water is electrolyzed into hydrogen and oxygen. The hydrogen can be stored in sub-surface tanks, either under pressure or as liquid H₂, in sufficient quantity to compensate for load fluctuations while allowing the power plant and electrolysis plants to operate at full capacity at all times. The hydrogen, which can be generated under pressure, is then transmitted through sub-surface pipe lines to local distribution points where it can be 1) distributed and used directly as fuel by domestic and industrial customers, 2) re-converted to electricity via either gas turbine generators or fuel cells, or 3) liquified and distributed in the liquid form for automotive or aircraft use.

The attractiveness of such a system is based not only on the fact that hydrogen is an alternative to the dwindling fossil fuel supply or that it has important environment advantages, but that it is potentially less expensive to transmit large amounts of energy for long distances in the form of hydrogen than as electric energy and, since hydrogen can be stored, it offers the cost advantage of steady load operation. The following discusses each of these options in more detail.

Hydrogen as a Fuel

Hydrogen as a fuel has several advantages over natural gas and other fossil fuels, such as:

- . Low pollution levels; hydrogen produces much less pollution than hydrocarbon fuels and can be used in combustion equipment with little, if any, modification.
- . High specific heat; the heat content of hydrogen is almost three times as great as gasoline on a weight basis.

Based on the predicted energy requirements and capital equipment costs discussed previously, the cost of hydrogen generated by SPE electrolysis can be expressed for the year 1985 as:

$$C_{GF} = 0.312 C_o + 0.227 \quad \$/10^6 \text{ Btu}$$

where C_o , the cost of electrical energy, is expressed in mils/KWH.

For the year 2000, the cost of generated hydrogen drops to

$$C_{GF} = 0.250 C_o + 0.090 \quad \$/10^6 \text{ Btu}$$

The above costs include the cost of desalinated water at a cost of 32 cents per 1000 gallons (9) or about 0.006 $\$/10^6$ Btu.

The fixed cost factor represents the capital equipment cost of the electrolysis cells (exclusive of ancillary pump and control cost) depreciated at 15% per year (6.67 years of continuous operation or 58,4000 hours).

An approximate total cost including ancillary costs and pumping requirements can be obtained by adding 10% to C_{GF} . This factor is small relative to the uncertainty regarding future electrical energy costs and has, therefore, been excluded. Likewise, no credit has been taken for the potential cost offset of the oxygen which is a byproduct of the electrolysis process.

Based on a DC electricity cost of 5 mils/KWH, the cost of SPE-generated hydrogen would be $\$1.79/10^6$ Btu by 1985 and $\$1.35/10^6$ Btu by the year 2000.

Figure 9 shows the predicted cost of SPE electrolytically generated hydrogen through the year 2000 with electrical energy costs of 5 and 10 mils/KWH. Shown also are typical costs of other gaseous fuels. It is apparent that during the 1990's, local electrolytically produced hydrogen could be competitive with foreign natural gas transported to the United States via LNG tankers, natural gas transmitted from Alaska by pipeline or locally produced synthetic natural gas generated from either oil or naphtha or the gasification of coal.

The real cost of the hydrogen, of course, will be directly influenced by the cost of electrical energy. A deciding factor in the use of hydrogen will be the relative rates of electrical energy cost increase vs. fossil fuel cost increase.

Energy Transmission by Hydrogen Pipe Line

Figure 10 is a model used for comparing the cost of energy transmission by piping hydrogen vs. both overhead and underground electric cabling. As in the model for hydrogen generation, electrical energy at cost C_o mils/KWH is fed to a water electrolysis plant and desalinated water is fed to the plant at a cost of 32 cents per 1000 gallons or about 0.02 mil/KWH. Again, for the purposes of this analysis the oxygen is assumed dumped to the atmosphere and no credit is given for potential use of the oxygen such as water purification, sewage processing, etc. The hydrogen is transmitted through sub-surface pipe lines at 750 psi to distribution points at a cost of 3.5 cents/MBtu/100 miles or 0.12 mil/KW/100 miles (7) assuming a compressor station every 65 miles.

Based on this model, the cost of energy at the distribution point can be expressed as:

$$C_{DF} = 1.064 C_o + 0.77 + 0.12 M \text{ in the year 1985, and}$$

$$C_{DF} = 0.854 C_o + 0.31 + 0.12 M \text{ in the year 2000}$$

where M is the distance in hundreds of miles between the electrolysis plant and the distribution point. The fixed cost factor represents capital equipment cost depreciated at 15% of the original capital per year (6.67 years of continuous operation).

Assuming the cost of DC electricity via homopolar generator is the same as AC electricity, the above cost at the distribution point can be compared directly to the cost of electrical transmission estimated at 21 cents/MBtu or 0.714 mil/KWH/100 miles for overhead high voltage wires (10) and 5 mils/KWH/100 miles for underground wires (1).

This comparison is shown graphically in Figure 11 based on a cost for electricity at the generating plant (C_o) of 5 mils/KWH. This shows that in 1985, the transmission of energy in the form of hydrogen would be competitive with overhead wires for distances greater than 190 miles and with underground wires for distances greater than 20 miles. By the year 2000, hydrogen energy transmission will be less expensive than electrical transmission regardless of transmission distance.

For that portion of hydrogen energy which must be re-converted for use as electrical energy, the cost and efficiency of the conversion equipment (combustion turbine/generator or fuel cell/inverter) must be added to the hydrogen energy cost. Based on predicted gas turbine/generator costs and efficiencies of

	<u>1985</u>	<u>2000</u>
\$/KW _{out}	\$120/KW	\$120/KW
η	55%	70%

the cost of electrical energy at the distribution substation (C_{DE}) can be expressed as

$$C_{DE} = 1.94 C_o + 3.78 + 0.12 M \text{ in 1985 and}$$

$$C_{DE} = 1.22 C_o + 2.50 + 0.12 M \text{ by the year 2000.}$$

These relationships are shown in Figure 12, again compared against overhead and underground electrical transmission and assuming a generation cost of 5 mils/KWH. This shows that even with the cost of re-conversion to electricity factored in, energy transmission by piped hydrogen will be less expensive than by underground wires for distances of 175 miles or greater in 1985, and for distances of 75 miles or greater by the year 2000.

The above analyses show that energy transmission by hydrogen pipe line could offer significant cost advantage over electrical energy transmission in the not too distant future. It should also be recognized that a cost of generated electricity above the 5 mils/KWH assumed would make hydrogen energy transmission less attractive relative to electrical energy transmission. Thus the cost of future electrical energy remains the determining factor in the use of hydrogen for energy transmission.

Energy Storage - In Hydrogen Energy Transmission

One of the major advantages apparent in the use of hydrogen as a method of energy transmission is that it can be stored either as a gas or cryogenically. This storage capability makes hydrogen generation advantageous in systems where either the energy load is cyclic or periodic, or the energy source is periodic. In the case where the load is cyclic, the utilization of stored hydrogen allows the power and electrolysis plants to operate at a constant level close to full capacity at all times, with load peaks being supplied from the storage tanks which are then recharged during off-peak hours.

In the case where the energy source is periodic or cyclic such as a solar energy system, some of the hydrogen generated during the "on" period can be stored to supply the "off" period load.

Storage of hydrogen as a low pressure gas requires very large storage volumes (one lb of hydrogen requires 190 cu ft at sea level ambient pressure or 17.5 cu ft at 150 psi), but may be practical for limited storage. Such schemes as large undersea balloons have been suggested (3), as have underground cap rock aquifers similar to those used for natural gas (7).

However, by liquifying hydrogen the storage volumes are greatly reduced, to the point where large quantities of energy can be stored in very small dewars (at -423°F, one lb of hydrogen occupies only 0.225 cu ft).

Liquid hydrogen dewars as large as 0.9 million gallons have been built at costs of approximately \$2 per gallon capacity (11). This is approximately a \$55.40/10⁶ Btu or 189 mils/KWH storage capacity. Large-size tanks have boil-off rates as low as 0.03 to 0.05% per day. Boil-off, as such, has minimal effect on storage costs since any boil-off can be returned to the main supply and does not necessarily represent waste. The heat required to reheat the liquid hydrogen for transmission as a gas would be readily available from the waste heat of the electrical generation plant.

Assuming 1% of the annual output is stored, storage dewars amortized over 35 years, and a liquification cost of \$0.70/MBtu stored, leads to an additional cost on delivered energy of \$0.023/10⁶ Btu (or 0.08 mil/KWH). This small cost could be greatly overshadowed by the savings in capital equipment costs due to being able to size the plant for nominal load rather than peak load.

Energy Storage - As Part of Existing Electrical Power System

At the substation level, energy storage as hydrogen may be competitive as a means of utilizing off peak power to meet peak load demands. Consider the case where the typical daily load curve has: 1) an 8-hour off peak period from midnight to 8 AM where demand is below the nominal load level; and 2), an 8-hour peak load period in the afternoon and evening when the load level is higher than the nominal load level. Off peak electricity is available at a cost of C_{op} mills/KWH.

A water electrolysis/storage/gas turbine or fuel cell-inverter system could utilize the off peak power to form hydrogen, store it in either gaseous or liquid form, and utilize it to generate electricity during the peak load period.

Such a system, shown in Figure 13, would have an overall energy efficiency of about 52% in 1985 and around 82% by the year 2000. Capital costs are estimated at approximately 7.8 (1985) to 4.9 mills/KWH daily output (2000) if gaseous storage is used, with an additional 4.3 (1985) to 3.4 (2000) mills/KWH if cryogenically stored to allow for liquification. This method of storage would be attractive if the actual cost of off peak (C_{op}) electricity at the substation is sufficiently less than the cost of peak load electricity (C_p). The relationships are shown at the bottom of Figure 13.

Future Applicability

It seems apparent, due to its cleanliness as a fuel, capacity for energy storage, ease of transmission and the availability of its raw material (water), that hydrogen may become an extremely important element in tomorrow's utility power system. The degree to which it will find application largely depends on the degree to which water electrolysis hardware costs can be reduced and efficiency increased, and on the future costs of electrical energy relative to fossil fuels.

General Electric's water electrolysis technology holds the promise of both the low capital cost and high efficiency required for future power system application.

REFERENCES

- (1) W. Hausz, G. Leeth, C. Meyer, "ECO-ENERGY", conference proceedings - 7th Intersociety Energy Conversion Engineering Conference, 1972.
- (2) L. Lessing, "The Coming Hydrogen Economy", Fortune, November 1972.
- (3) L. O. Williams, "The Cleaning of America", Astronautics and Aeronautics, February 1972.
- (4) Business Week, "When Hydrogen Becomes the World's Chief Fuel", September 23, 1972.
- (5) C and EN, "Hydrogen: Likely Fuel of the Future", June 26, 1972.
- (6) C and EN, "Energy: The Squeeze Begins", November 13, 1972.
- (7) D. P. Gregory, J. Wurm, "Production and Distribution of Hydrogen as a Universal Fuel", conference proceedings - 7th Intersociety Energy Conversion Engineering Conference, 1972.

- (8) E. C. Tanner, R. A. Huse, "A Hydrogen-Electric Utility System with Particular Reference to Fusion as the Energy Source", conference proceedings - 7th Intersociety Energy Conversion Engineering Conference, 1972.
- (9) P. H. Sager, J. M. Kruse, "Combined Nuclear Gas Turbine Power and Desalination Plant", conference proceedings - 7th Intersociety Energy Conversion Engineering Conference, 1972.
- (10) W. E. Winsche, K. C. Hoffman, F. J. Salzano, "Economics of Hydrogen Fuel for Transportation and Other Residential Applications", conference proceedings - 7th Intersociety Energy Conversion Engineering Conference, 1972.
- (11) J. R. Bartlet, F. J. Edeskuty and K. D. Williamson, Jr., "Experience in Handling, Transport and Storage of Liquid Hydrogen - The Recyclable Fuel", conference proceedings - 7th Intersociety Energy Conversion Engineering Conference, 1972.
- (12) W. A. Titterington, A. P. Fickett, "Electrolytic Hydrogen Fuel Production with Solid Polymer Electrolyte Technology", presented at 8th Intersociety Energy Conversion Conference, Philadelphia, August 13, 1973.
- (13) Chem Eng News, Vol 46, No. 47, 1968.
- (14) H. S. Spacil and C. S. Tedman, Jr., "Electrochemical Dissociation of Water Vapor in Solid Oxide Electrolyte Cells", Journal of Electrochem. Soc., Vol 116, No. 12, 1969.

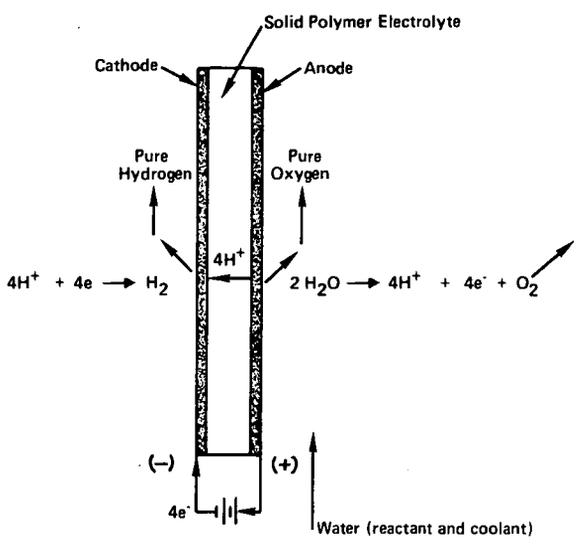


Figure 1. SPE Electrolysis Cell Schematic

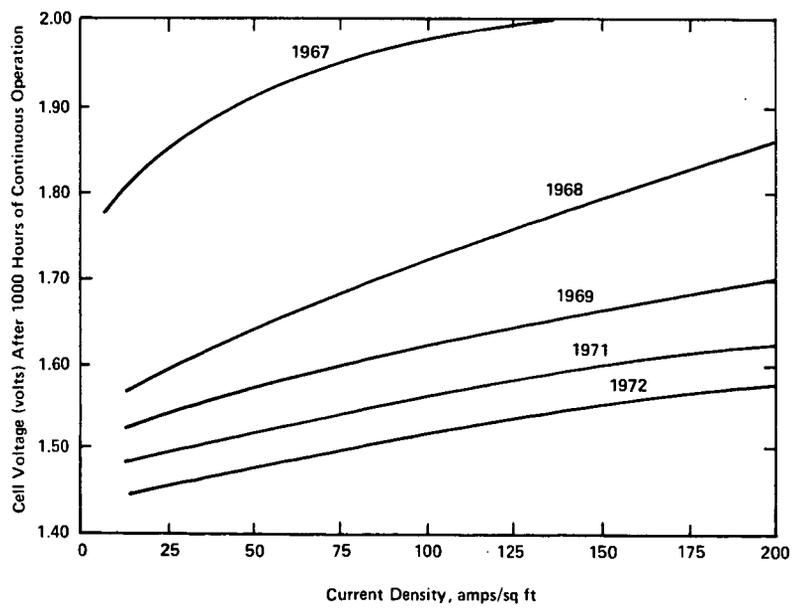


Figure 2. SPE Electrolysis Performance at 120°F and Ambient Pressure

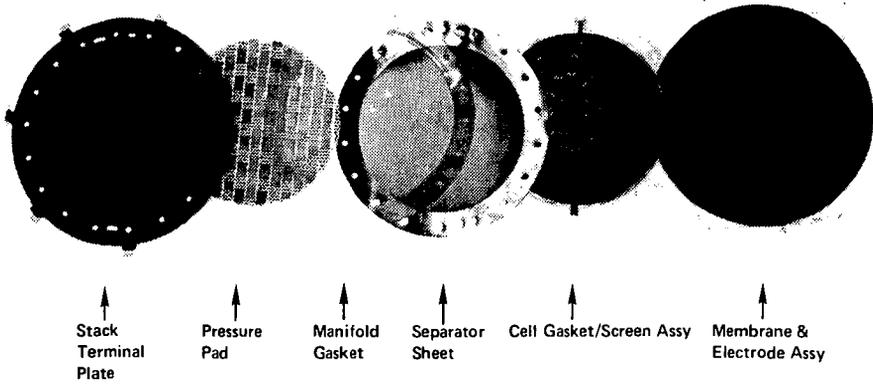


Figure 3. Electrolysis Cell Component Parts

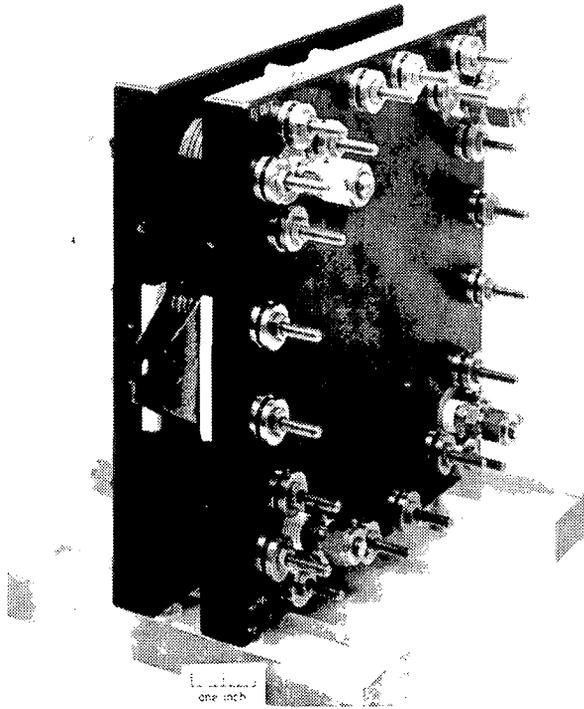


Figure 4. Seven-Cell NASA/LRC Electrolysis Stack

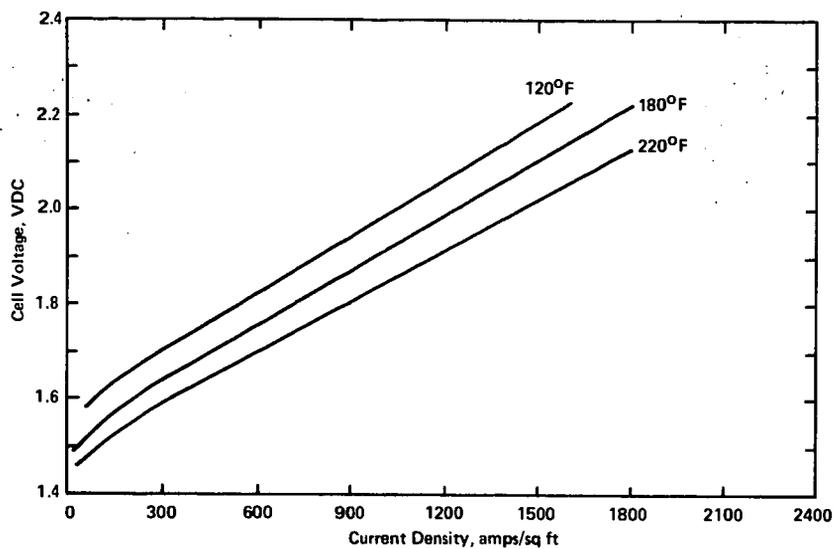


Figure 5. 1972 SPE Water Electrolysis Capability

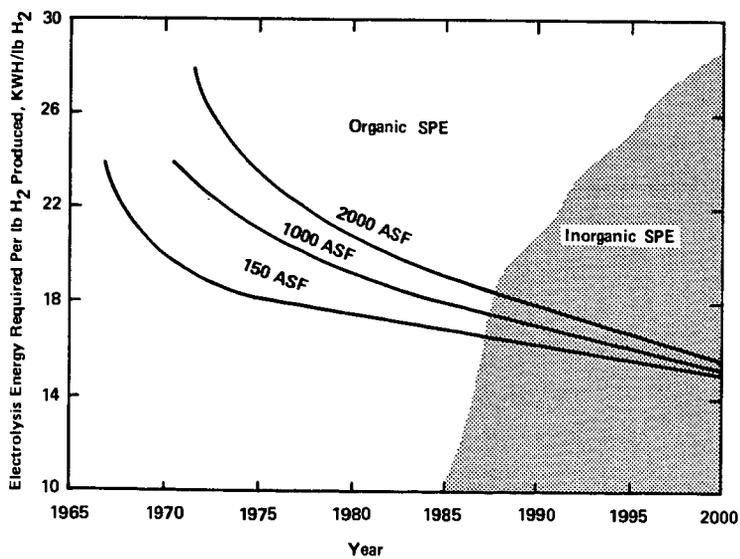


Figure 6. Energy Requirements for SPE Electrolysis

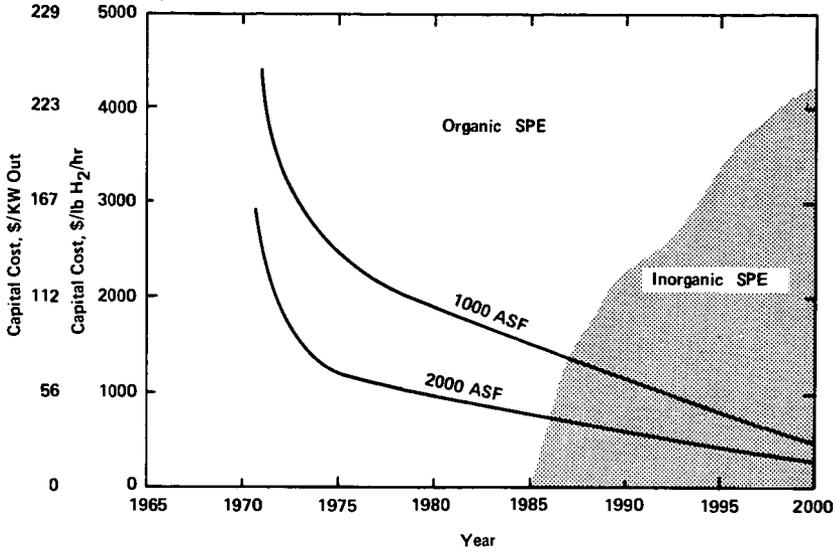


Figure 7. Capital Cost Requirements for SPE Electrolysis

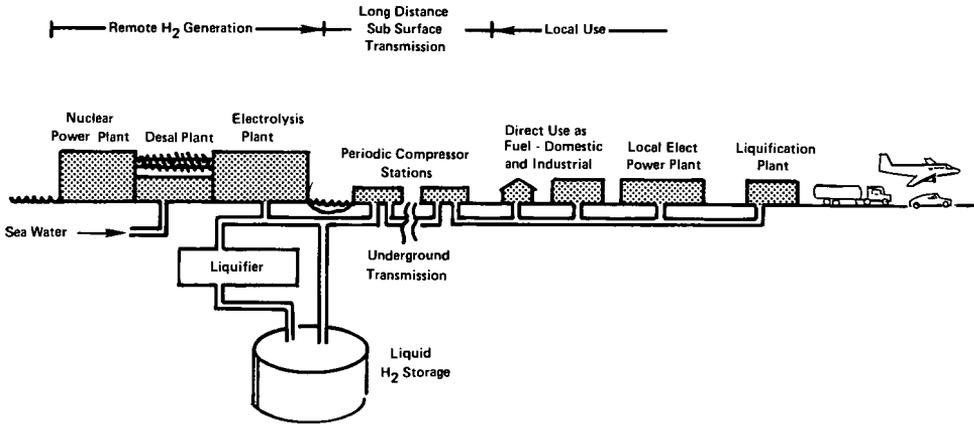


Figure 8. Conceptual Hydrogen Utility System

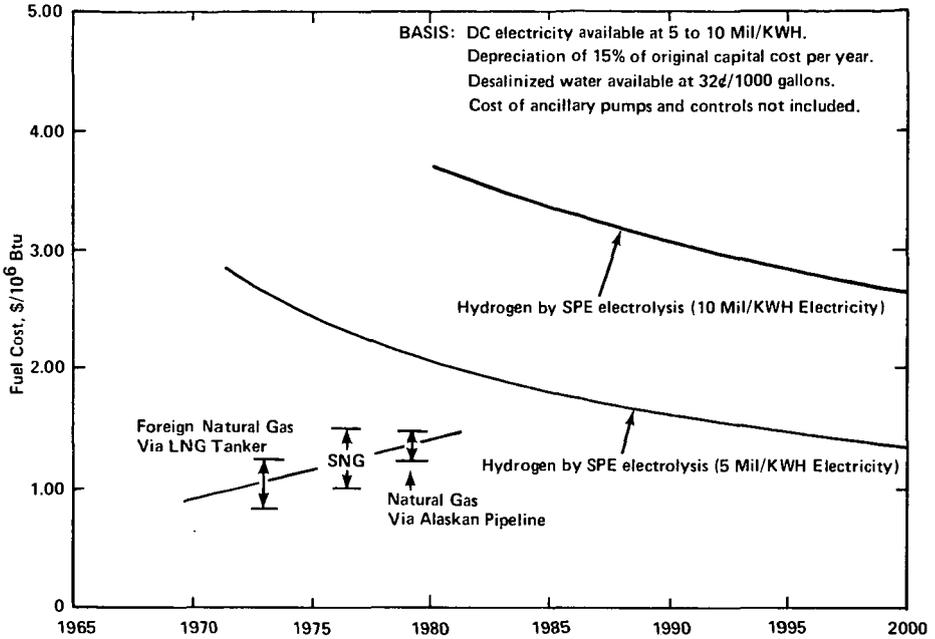


Figure 9. Projected Cost of Hydrogen Production by SPE Electrolysis

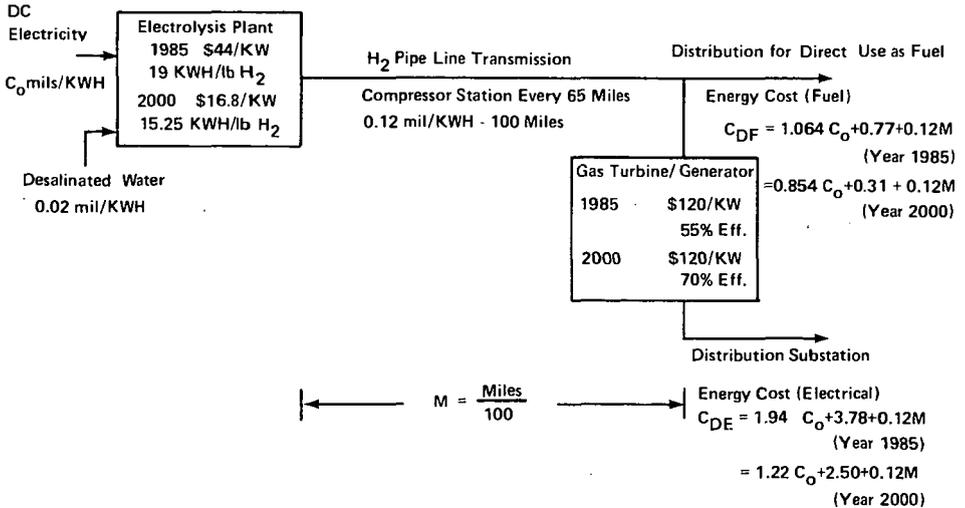


Figure 10. Model of Hydrogen Pipe Line Energy Transmission

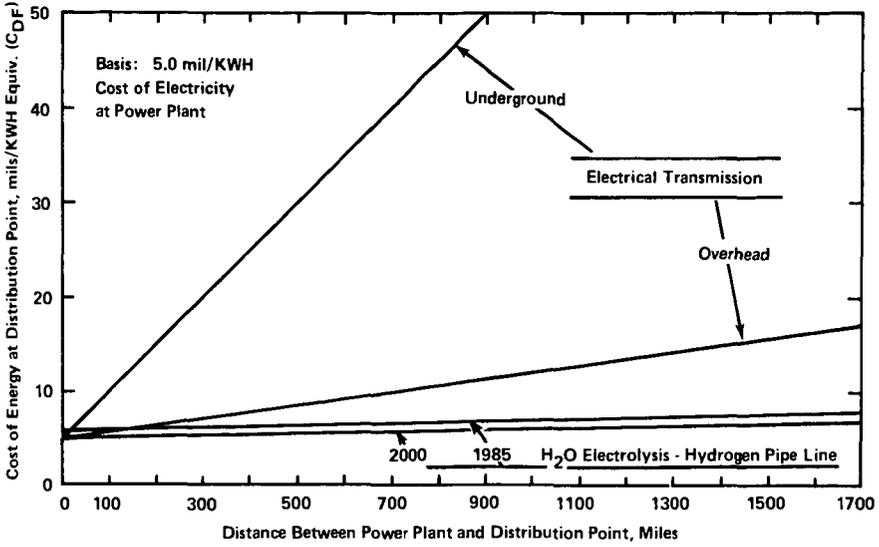


Figure 11. Comparison of Cost of Energy at Distribution Point for Electrical vs. Hydrogen Pipe Line Transmission

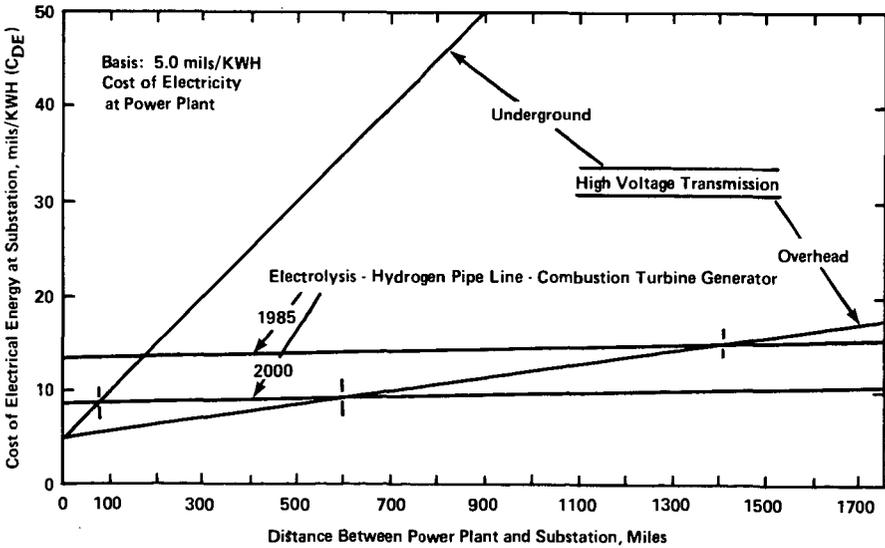
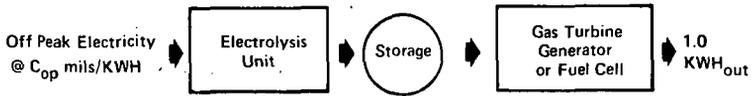
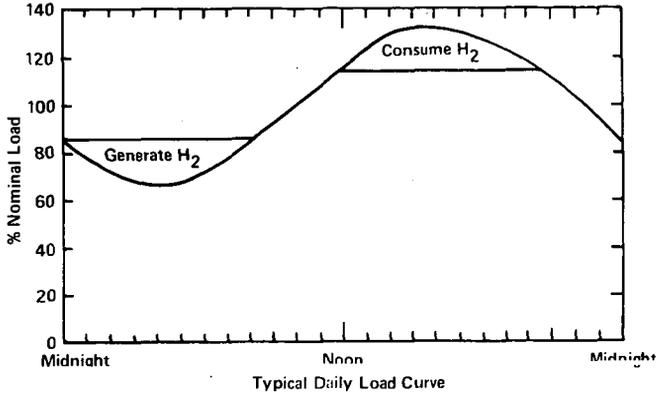


Figure 12. Comparison of Cost of Electrical Energy at Distribution Substation for Electrical Transmission vs. Hydrogen Pipe Line



1985	\$44/KW _{out} 19 KWH/lb H ₂	Tankage Cost 0.02 mil/KWH	1985	\$120/KW _{out} 9.8 KWH/lb H ₂
2000	\$17/KW _{out} 15.25 KWH/lb H ₂	Liquification 4.3 mils/KWH (1985) 3.4 mils/KWH (2000)	2000	\$120/KW _{out} 12.5 KWH/lb H ₂

COST RELATIONSHIPS

Gaseous H ₂ storage $C_{op} \leq 0.52 C_p - 7.8$ mils/KWH	$C_{op} \leq 0.82 C_p - 4.9$ mils/KWH
Liquid H ₂ storage $C_{op} \leq 0.52 C_p - 11.3$ mils/KWH	$C_{op} \leq 0.82 C_p - 8.3$ mils/KWH

Figure 13. Typical Bulk Storage System