SPACE POWER TECHNOLOGY APPLIED TO THE ENERGY PROBLEM

by

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SUMMARY

A technique using aerospace technology is presented for applicability to large-scale hydrogen production in 1985 energy systems. Photovoltaic energy conversion is baselined with application design data provided. A comparison of hydrogen generation techniques, based on a 1985 scenario, is provided. System performance and costing characteristics are provided for 1985 application.

INTRODUCTION

What has been referred to as the "energy problem" would be more accurately described as the "fuel depletion concern." The word "problem" implies "doubt" and "uncertainty" neither of which are proper descriptors of the doubtless certainty that our fossil fuel resources are rapidly being depleted. To say that we are running out of energy is equally incorrect. By definition, energy is "...the actual exertion of power..." whereas fuel is merely an energy carrier or substance in which energy is stored. Our entire life style is based in large part upon our ability to extract energy from fuel and to cause it to perform work (or other exertions of power) for us. The Designer of the Universe, acting out of infinite wisdom and toward a plan that mankind has yet probably not even begun to understand, provided not only a finite quantity of fuel in the Earth but also an energy source incorporating a fusion nuclear reactor properly located about 93 000 000 miles from Earth.

Until about 200 years ago we knew only how to use the nuclear source. We knew how to use it to make our crops grow, to use the seasons and weather phenomena such as winds and the hydrologic cycle, and we could even heat water with solar energy. With the advent of knowledge of how to locate, extract, and use fossil fuels, our life style as we know it today evolved. Along with the conveniences, comforts, and expediencies of fossil fuel use came the pollution and concern about depleting the supply. With additional knowledge and searching we found that a certain amount of a different kind of fuel was also stored in the Earth. The major problem with its use is that we cannot figure out what to do with the contaminating fission product waste. The major difference between fossil fuel use and nuclear fuel use is that the "polluting" effects of fossil fuel use are short-lived and the environment will "self clean" itself in a decade or two after the pollution stops. Nuclear energy use on the other hand produces a "contamination" that will require several hundred thousand years to dissipate to safe levels in the environment.

These "polluting" or "contaminating" concerns are probably not particularly important (assuming we can continue to contain and guard the nuclear waste) because we have such a small quantity of either that their use cannot continue far into the future. Using the term quad (quadrillions of Btu or 10^{15} Btu) as a convenient energy quantity, one source [1] puts our fossil energy reserve inside U.S. boundaries at about 10 317 quads (335 for oil, 8670 for coal, and 1312 for gas). The "known or expected to be found" fissionable uranium reserves inside U.S. boundaries and obtainable at economically viable prices is only about 884 quads [2]. To look at the fuel use pattern and trends between coal, petroleum, natural gas, etc., over the range of a decade or two or even a couple of hundred years is to miss the big picture. Figure 1 puts the U.S. fossil fuel use [3] in proper perspective in relation to the availability of solar energy [4]. Even if one assumes the 11 201 quads of fossil and nuclear reserve previously mentioned to be consumed at the constant rate of approximately 85 quads per year, the supply will last only 132 years. Assuming a linear increase at the escalation rate, the supply will last about 56 years or until the year 2033.

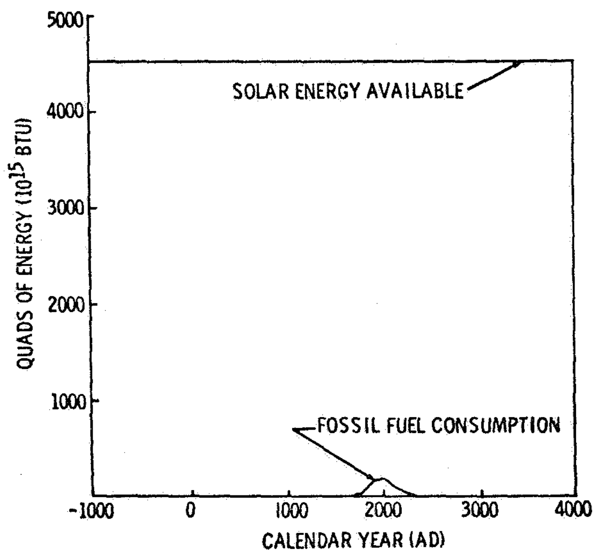

Figure 1. U.S. fossil fuel consumption and solar energy available.

The obvious long range solution is to look to the Sun and to the energy use rate at which the Designer of the Universe has allowed for the planet Earth. The only way to increase this ultimate use rate is to go out in space with large reflectors and direct more of the energy toward us, but then we would probably get too hot. Another alternative is to by-pass the photosynthesis route to fossil fuel resupply and go directly to a synthetic fuel generated from sunlight. The photovoltaic water electrolysis (PWE) system described in this paper converts solar energy into the synthetic fuel hydrogen. A description of the system operation, technologies involved, and predicted economics are contained in the following narrative.

PWE SYSTEM DESCRIPTION

There are two basic technologies involved in converting sunshine into hydrogen fuel. Figure 2 shows a block diagram of the PWE system. Solar energy is converted into dc electrical energy by photovoltaic devices called solar cells and the dc energy is then used to electrolyze water in electrolysis cells. An artist's concept of how a large plant might look is shown in Figure 3. The fuel production plant envisioned here occupies approximately 11 acres and has an annual production capability of about 170 000 lb of hydrogen or an energy equivalence of about 1800 barrels of oil. The solar array form occupies about 10.5 acres of the tract and has a peak output of about 1.5 MW at noon on a sunny day.

The solar cells are silicon devices developed for the space power market and currently beginning to be used in terrestrial applications. Efficiencies of 12 to 16 percent are currently achievable at prices of $10 to $15/watt of peak

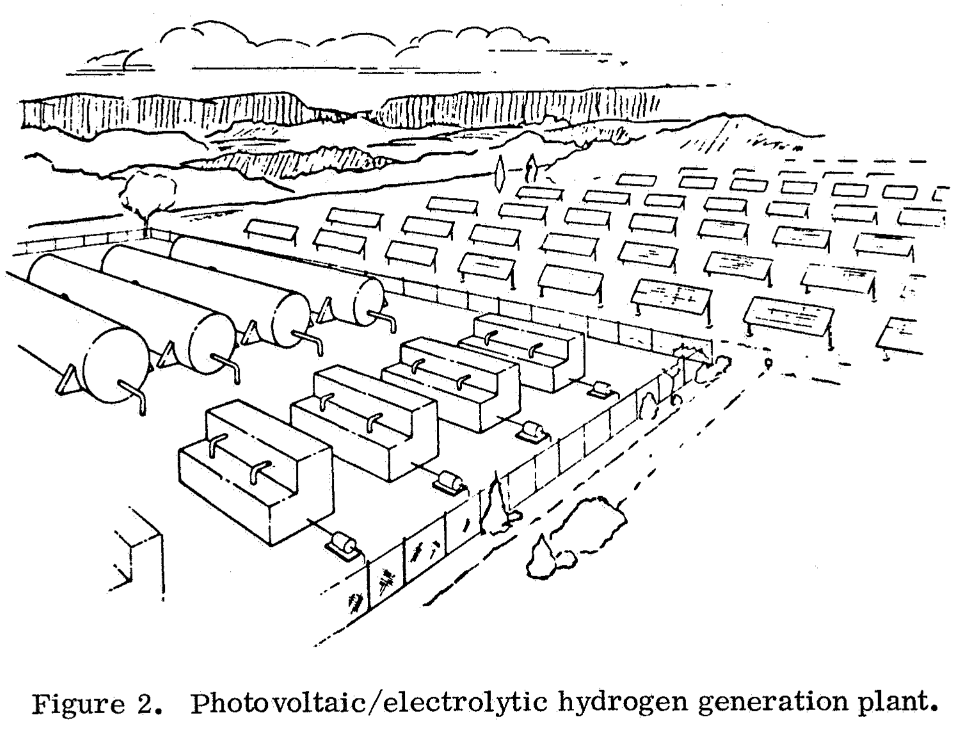

Figure 2. Photovoltaic/electrolytic hydrogen generation plant.

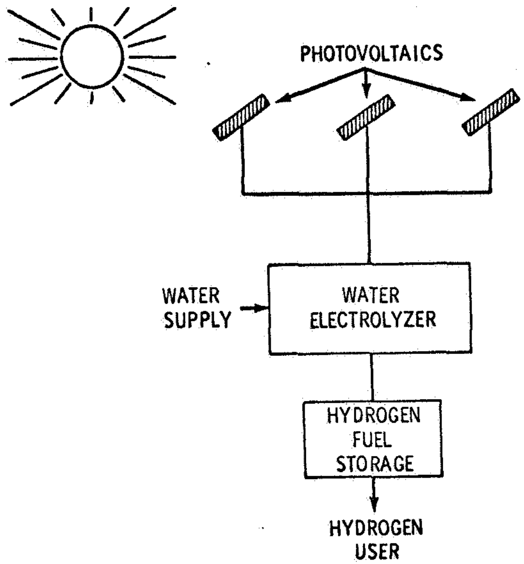

Figure 3. Photovoltaic-electrolytic hydrogen generator.

performance. It is anticipated that by 1985 cell efficiencies of 18 percent at prices between \$0.20 and \$0.50/W of peak performance will be available. The Low Cost Silicon Solar Array Project managed by JPL for ERDA has the objective of bringing the price of an encapsulated solar array to under \$1.60/ft^2 by 1985 with an assured lifetime of over 20 years [5].

Looking at the solar energy available in North Alabama, Figure 4 shows the weekly averages of available energy at a fixed southerly facing angle of 45° on the roof of Building 4487 at the Marshall Space Flight Center. These data were obtained for the entire year of 1975 and show that even the worst weeks have over 100 W-h/ft^2/day available and the best ones range up to 500 W-h/ft^2/day. The overall annual average for the year of 1975 is 360 W-h/ft^2/day. One advantage that a photovoltaic system has over a pure thermal absorber is the fast response time. Figure 5 shows the energy available between 6:00 a.m. and 7:30 p.m. on April 16, 1975, which was a perfect day with 590 W-h/ft^2 integral under the curve. This is an ideal day for either a photovoltaic or thermal absorber system. However, Figure 6 is more typical of the average day. In this case the integrated available energy of 324 W-h/ft^2 has a considerable amount tied up under the sharp spikes which the 10 μs response time of PWE system can extract. Also, solar cells will give a proportional output for the dimly illuminated overcast days of inclement weather.

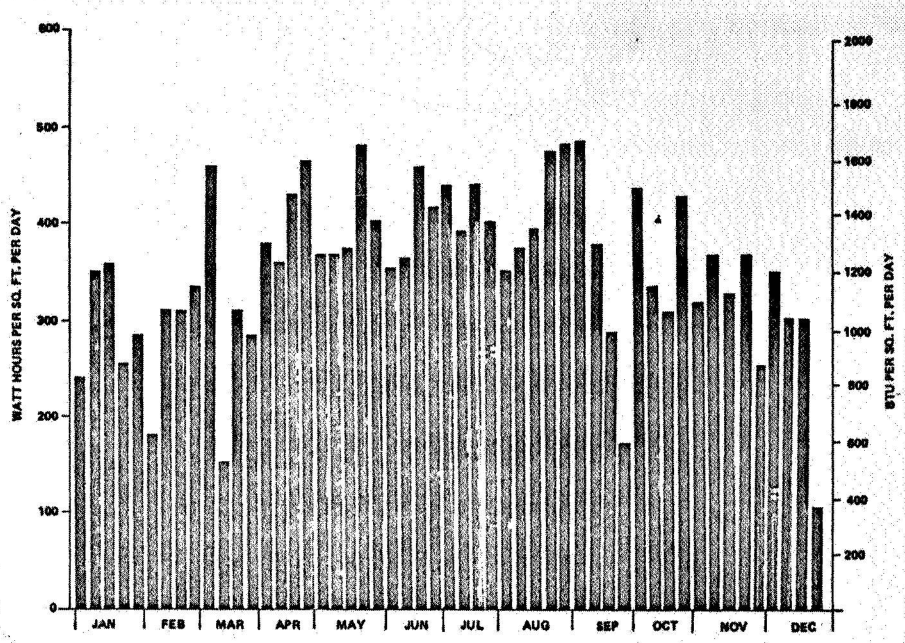

Figure 4. Available solar energy weekly average 45° Huntsville, Alabama, 1975.

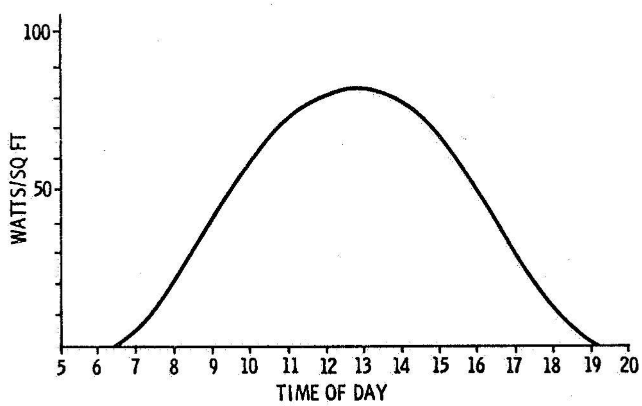

Figure 5. Solar energy available, day 106, April 16, 1975, Q = 590 W-h/ft^2 45° fixed.

To arrive at an economic viability prediction for the 1985 time period, the 1977 situation was used as the point of departure and cost information was generated for both time periods. Figure 7 shows the resulting prediction that costs per kW-h of dc energy generated by solar array forms will decrease from approximately $0.48 to $0.74/kW-h in 1977, to $0.03 to $0.07/kW-h in 1985. The 1977 estimate is based upon the 12 to 16 percent efficiency spread and $ 10 to

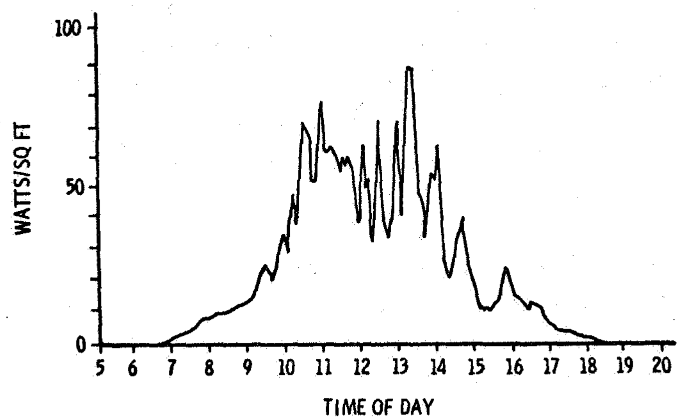

Figure 6. Solar energy available, day 90, March 31, 1975, $Q = 324$ w-H/ft^2 45° fixed.

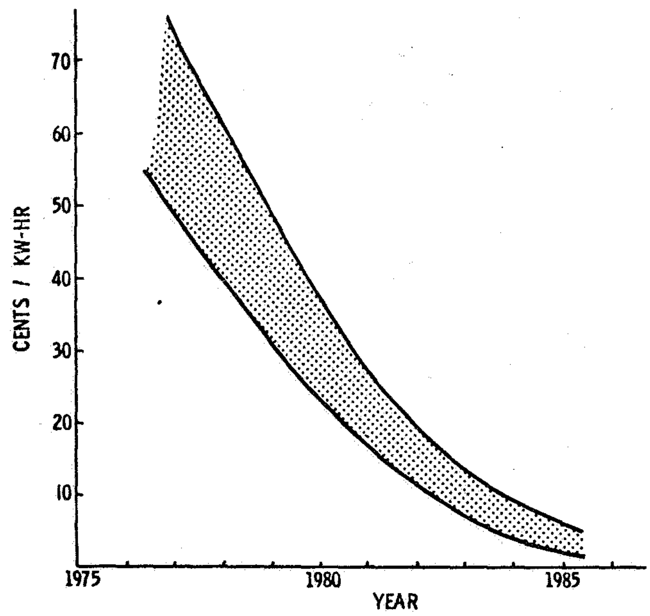

Figure 7. Photovoltaic energy cost trend.

$15/W capital cost information given earlier. The 1985 estimate is based upon 14 to 18 percent efficiency and $0.20 to $0.50/W capital cost. In addition to these estimates, it was assumed that standard panels of 3 ft × 10 ft mounted in clusters of 5 panels per lean-to would be connected by underground wiring to the water electrolysis plant. The lean-to's were assumed to be spaced apart twice their width to prevent shadowing one another. The result is a 33 percent area utilization factor. For an assumed field of 25 rows of 40 lean-to's per row an effective area of 150 000 ft^2 of solar array can be deployed in a field of approximately 10.5 acres. To arrive at a total life cycle cost it was assumed that each lean-to could be built for $100 to $400 and wired into the electrolysis system for an additional $50 to $100. This results in an overall installation cost of $150 000 to $500 000 for the entire field. A fixed maintenance cost of $30 000 per year was assumed.

The capital cost of the solar cell panels was calculated from the expected peak performance and the price per peak watt stated earlier. The performance on a per square foot basis was obtained by calculating the best and poorest cell packing densities achievable with the round terrestrial cell. This range is from 0.78 to 0.87.

Finally, the capital plus maintenance cost on a per square foot per month basis was arrived at by amortizing the capital over an anticipated life of 20 years at assumed interest rates of 8 and 10 percent and then adding the monthly maintenance cost to that. Overall average performance was obtained by multiplying the average energy available by the packing factor and by the cell efficiency.

There are reflective louver concentrator concepts which are attractive and could reduce energy costs in the early timeframe. Description of these alternatives is beyond the scope of this paper. However, assuming a reflective louver cost of $\$2/ft^2$ plus $\$0.33/ft^2$ for installation and an additional $250 per lean-to for a tracker and a 10 year lifetime, the best that can be expected in the 1977 timeframe is $0.30/kW-h. Concentrators offer no advantage in 1985 because the added capital and maintenance cost compared to the anticipated low solar cell array cost results in driving the energy cost upward. Using the same assumptions previously stated for concentrator cost and life in the 1985 time period, the previously stated $0.03 to $0.07/kW-h would increase to $0.04 to $0.09/kW-h. To evaluate the overall 1985 economic viability of the PWE system, a break even transfer cost of $0.03/kW-h was taken as being the most optimistic justifiable number.

Conversion of the solar energy to a useable fuel may be accomplished through several mechanisms [6,7,8]. Considerable research is being conducted in thermal decomposition and photosynthesis of water. However, without a major technology breakthrough, the most promising hydrogen generation technique is water electrolysis. The capital investment and operating cost sensitivities of other generation techniques cannot compete with electrolysis in the 1977 or 1985 markets. Even electrolysis cannot be cost effective for large hydrogen volumes in the 1977 time period when compared with hydrogen generation from fossil fuel sources. With rising fossil fuel costs and their limited availability, electrolysis will prove cost effective in the 1985 or earlier time periods.

There are three candidate electrolyzer technologies being currently developed; alkaline matrix, solid polymer electrolyte, and solid oxide electrolyte. For the 1977 commercial market, the alkaline matrix technology represents the most commercially developed. "Off-the-shelf" units using this technique are currently available for production rates up to 1.4 MBtu hydrogen/h. The solid polymer electrolyte technology will prove most cost effective during the 1980 to 1990 time period. Beyond 1990, the solid oxide electrolyte technology will become commercially available. An artist's concept of a typical hydrogen generation facility is shown in Figure 8.

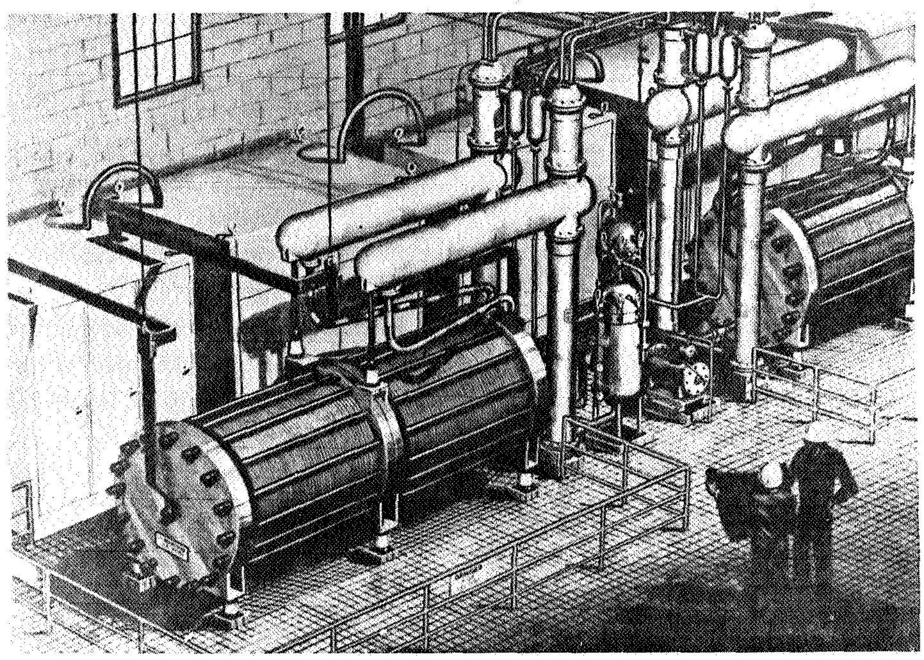

Figure 8. Electrolytic hydrogen generator.

The alkaline matrix technology requires bulky subsystems and recirculation of electrolyte to produce reasonable sized electrolyzer units. For small hydrogen generation rates (less than 1.0 MBtu hydrogen/h) this technique will prove competitive beyond 1985. This system is a derivative of the alkaline matrix electrochemical technology developed by NASA and currently being used in the Space Shuttle fuel cells to provide electrical power.

The solid polymer electrolyte (SPE) technology for electrolysis is a direct derivative from the NASA Gemini program. ERDA is planning extensive development in SPE technology in association with EPRI. EPRI is an organization of electric power utilities which was formed to pool their research funds to meet their common goals. This technology emphasis is expected to reduce capital equipment costs to approximately $30 to $60 per MBtu hydrogen as shown in Figure 9.

Figure 9. Projected SPE electrolyzer capital costs.

Selection of a design operation point is made on a basis of current density, capital equipment costs, and electrical power requirements as shown in Figure 10 [9]. The example shown uses a current density of 1500 mA/cm^2 which results in capital costs of $62/MBtu hydrogen/h and an energy requirement of 298 kW-h/MBtu hydrogen generated. Using these parameters with an

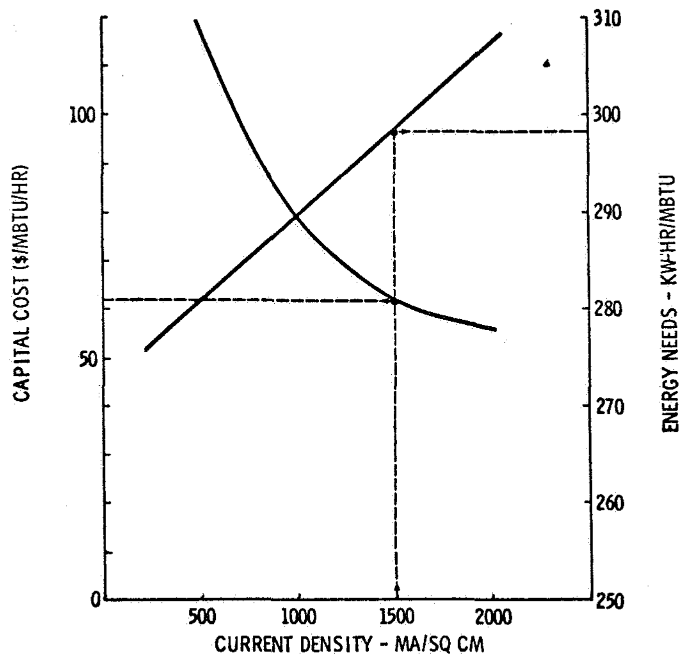

Figure 10. Electrolytic hydrogen costs, 1985 basis.

8 percent amoritization of capital costs over the projected life of 20 years, hydrogen generation costs are determined based on various electrical power costs as shown in Figure 11. Using the 1500 mA/cm^2 operating point and an assumed electrical power cost of $0.02/kW-h, the hydrogen production cost is slightly more than $9.00/MBtu hydrogen.

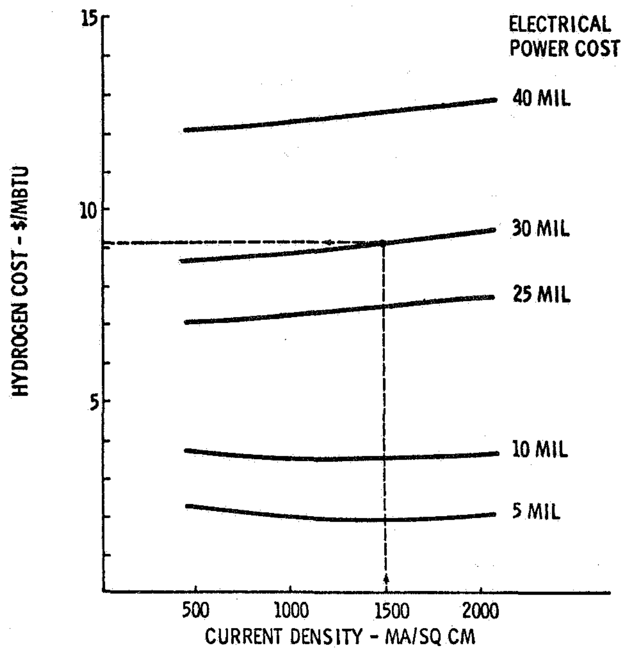

Figure 11. Hydrogen generating cost, 1985 basis.

The cost of producing hydrogen from fossil fuels is shown in Figure 12 [9,10]. Production from natural gas is accomplished by methane reformation. Fuel oil oxidation is used for fuel oil sources. These curves reflect the impact of fossil fuel costs, but do not show labor inflationary factors which will occur between now and 1985. Such factors will increase the slope of the fossil fuel to hydrogen conversion curves. Based on these curves and the projected energy costs of fossil fuels for 1985, it is expected that electrolytic hydrogen production will be cost competitive with fossil fuel hydrogen production techniques [9].

The principle hydrogen users in 1985 are expected to remain as they are today, i.e., industrial consumption for manufacturing semiconductor devices and fertilizer and for heat treatment processing. Residential uses for electrical power and heating/cooling applications are not expected to materialize before 1990. Similarly, transportation users for electrical or internal combustion

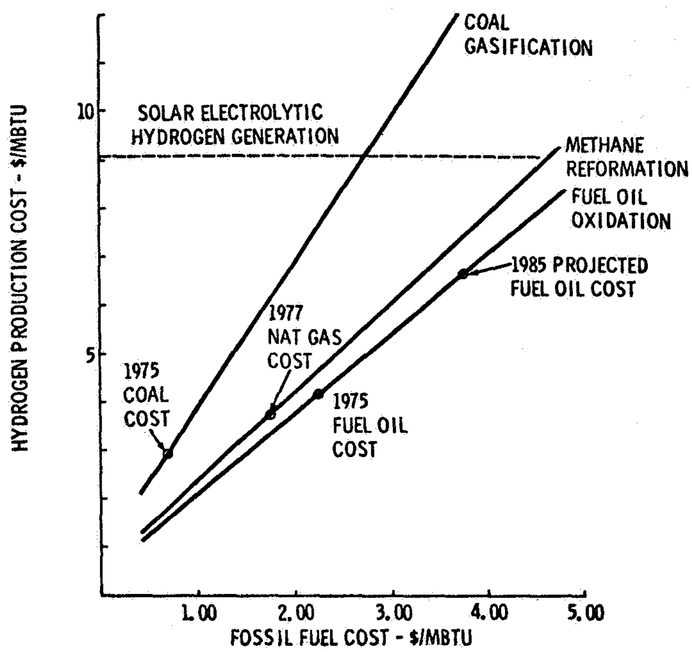

Figure 12. Fossil fuel hydrogen cost.

powered vehicles are not expected to mature by 1985 [10]. With major users being in the industrial market, it is conceivable that small systems of the type described in this paper will provide a substantial portion of these hydrogen consumers.

CONCLUSION

Photovoltaic/electrolytic generation of hydrogen will prove economically feasible by 1985. The physical technologies exist today for such a system, although it is not cost competitive. The extensive development efforts by ERDA and EPRI during the next 5 years will reduce the cost of NASA derived technology to a competitive situation. Photovoltaic generated power will cost in the range of $0.03 to $ 0.07/kW-h and electrolytic hydrogen will be available at $9.00/MBtu which will be competitive with fossil fuel sources.

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