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Economic Limits of a Fuel Cell Technology

17 MAY 1962

Prepared by J. I. SLAUGHTER
Materials Sciences Laboratory

Prepared for DEPUTY COMMANDER AEROSPACE SYSTEMS
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
Inglewood, California

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El Segundo, California

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ABSTRACT

Limited world-supply and production of platinum-group metals restrict the potential use of fuel cells using platinum metal catalysts to small-scale, low-volume power sources. Nickel is more abundant, and it is concluded that the development of a fuel cell technology using nickel catalysts depends upon the technology and cost of producing cheap hydrogen from fossil fuels.

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I. INTRODUCTION

In the period 1900 to 1950, Putnam[1] estimates that the world efficiency of raw energy utilization increased from 13 to 23 per cent. During the same period, the utilization efficiency in the United States increased from about 11 to 29 per cent. The effect of the improved utilization efficiency in the United States shows up in the statistics for the thirty-year period, 1920 - 1950. The raw energy input per capita remained nearly constant during this period, but the per capita consumption of energy nearly quadrupled.

It is further estimated[1] that about 58 per cent of the United States energy demand is for work, i.e., transportation, manufacturing, mining, communications, labor saving, etc., compared to 30 per cent for comfort heat and 12 per cent for process heat. The question arises, "Can the fuel cell improve the efficiency of utilization of the 58 per cent of our energy which is used for work?" The purpose of the present paper is to examine this question in the light of the existing state of the art in fuel cell technology and to speculate on the role of fuel cell power in the future. The direct conversion of chemical energy to electrical energy would, in certain cases, represent a substantial gain in utilization efficiency, since high thermal efficiencies may be achieved from fuel cells by proper design and operation.[2]

The case for the fuel cell is evaluated principally on the basis of existing data for the hydrogen-oxygen fuel cell. This seems reasonable on the basis that hydrogen is abundant and cheap (except for transportation and compression costs), cell voltage is high, and thermal utilization efficiency is higher than for most other fuels being considered for large-scale use. Moreover, hydrogen may be produced with better than 90 per cent thermal efficiency from our primary sources of energy, petroleum and coal; viz,

$$C + H_2O = CO + H_2 \qquad (1)$$

and

$$CH_4 + H_2O = CO + 3H_2 \quad . \qquad (2)$$

In order for the fuel cell to contribute in a major way to the total energy demand, it must be obtained efficiently from fossil fuel reserves; otherwise, it will probably never be more than a special applications power source. There is a second, and perhaps more cogent reason for making the comparison on the basis of the hydrogen-oxygen fuel cell. Despite many attempts to effect the direct conversion of coal or petroleum to electricity in a fuel cell, very little practical success has been achieved. Further, there are really no promising leads as to how this conversion might be achieved on either a small or large scale. Thus, the contribution to our over-all energy demand by the hydrogen-oxygen fuel cell might represent the maximum fuel cell power which could be anticipated in the future.

For the present purpose it is assumed that by-product carbon monoxide is separated and consumed economically, so that its energy is neither wasted nor charged against the production of hydrogen. Separation is necessary, since it is unlikely, on theoretical grounds, that the carbon monoxide can be consumed with the hydrogen. In principle, then, fossil fuels may be converted with high thermal efficiency into carbon monoxide and hydrogen, using the hydrogen to produce work in a fuel cell and carbon monoxide for chemical synthesis, process heat, or comfort heat. Thus, by coupling the high thermal efficiency of reactions Eqs. (1) and (2) with the high thermal efficiency of a hydrogen-oxygen fuel cell, a substantial improvement in utilization efficiency could be achieved for the production of work.

Widespread interest in fuel cell technology has been generated by several recent books[3,4] and symposia[5] and the public demonstration of a fuel-cell powered tractor by the Allis-Chalmers Manufacturing Company. Such technical activity supported by about 4 million dollars of government research contracts funded in 1961 has possibly given the fuel cell an atmosphere of reality. This atmosphere coupled with the many attractive advantages of fuel cells, e.g., high efficiency, quiet operation, high kwh/lb, low temperature operation, etc. have caused it to be widely considered for large scale military and industrial use at high power levels.

Because of certain critical materials requirements of hydrogen-oxygen fuel cells, it is important to examine the limitations which materials impose upon the development of a fuel cell technology.

II. BRIEF SUMMARY OF EXISTING FUEL CELL TECHNOLOGY

In addition to the previously cited books,[3,4] the state of the art in fuel cells has been reviewed by Stein,[6] Stein and Cohn,[7] and Slaughter.[8] In reviewing this literature, it is evident that our knowledge, understanding, and progress towards the development of workable fuel cells is far more advanced with the hydrogen-oxygen system than with any other. This is partly confirmed by the fact that the National Aeronautics and Space Agency selected the hydrogen-oxygen fuel cell for further development as the prime power source for the forthcoming Appollo mission to the moon.

In summary, the ingredients of a hydrogen-oxygen fuel cell are:

a) Porous Electrodes - usually carbon or porous nickel

b) Catalyst - most successful are platinum, nickel, silver, and cobalt

c) Electrolyte - sodium or potassium hydroxide

d) Electrolyte support material - ion-exchange resin, fibre, paste, etc., or none, if the electrodes are properly waterproofed

e) Case and plumbing - usually plastic

Fuel cell operation is absolutely dependent upon the proper functioning of a catalyst at the anode and cathode to provide the necessary electron transfer process between the hydrogen and oxygen. Based upon various theoretical arguments and the experiments of Young[9] and Kordesch,[10] it appears that the d electrons of the transition metals are the source of the catalytic activity for the chemisorption and dissociation of hydrogen at the anode. While other catalysts are not ruled out, no success has been reported in finding substitute materials. Nickel and the metals of the platinum group give the maximum catalytic activity as measured by the power and voltage output of experimental fuel cells.

It is instructive to compare the present world energy demand with the fuel cell power which could be developed if the world production of platinum and nickel were diverted completely to fuel cell power sources. Since only an order of magnitude answer is sought, the statistics based upon platinum and nickel are considered to represent the lower and upper limits of power production, respectively.

From the point of view of catalyst requirements, there are basically two types of hydrogen-oxygen fuel cells: nickel and platinum. Although grossly different in design and operation, the Justi[4b] and Bacon[11] fuel cells use nickel electrodes which are about 1/16 in. thick and approximately 50 per cent porous. Under optimum conditions, the Bacon and Justi cells might produce a maximum power of about 400 amp/sq ft at 0.7 v. The other type of hydrogen-oxygen fuel cell uses a catalyst of the platinum-group (Pt, Pd, Rh, Ru, Os, Ir), usually platinum, supported on either carbon or porous metal electrodes. The maximum plausible output based upon current technology is of the order of 0.7 v at 100 amp/sq ft for an application of 10 mg of platinum/sq in. of electrode. These assumed optima are translated into materials requirements/kw in Table 1. It is noted that the costs/kw are approximately 60 dollars for platinum and 8 dollars for nickel. This may be compared with a capital cost of approximately 75 dollars/kw for a modern steam-electric generating plant and approximately 400 dollars/kw for high grade industrial batteries.

The significance of the data of Table 1 may be assessed by examining the United States and world production figures for platinum and nickel.

Table 1

Assumed Minimum Materials Requirement/kw
for Two Types of Hydrogen-Oxygen Fuel Cell

Platinum	0.657 troy oz/kw
Nickel	10.4 lb/kw

III. SUPPLY AND DEMAND OF PLATINUM AND NICKEL

The data appearing in Table 2 show the crustal abundance of some of the more common elements and fuel cell materials. Essentially, the data demonstrate the well-known fact that the price of an element depends upon many factors, principally: supply, demand, and production costs. It may be hypothesized that 1 per cent of the earth's mass of 5.98×10^{27} gm is accessible crust and that this weight multiplied by the abundances in Table 2 would provide for any foreseeable need for any element. Most likely, this is not the case, and the point of diminishing returns in terms of energy gain would be quickly reached because of the distribution and occurrence of platinum and nickel. No doubt, the production of both nickel and platinum could be significantly increased above present levels; nonetheless, it is also true that the United States produces very little of the world's supply of these metals. At the same time, the United States produces and consumes more than one-half[1] of the world energy demand.

The data for the United States production and consumption of platinum-group metals as compiled by Ryan and McBreen[12] appear in Table 3. Note that annual production is of the order of 20,000 oz; but consumption is in the 700,000 to 800,000 oz range. Figure 1, also taken from the data of Ryan and McBreen, shows the distribution of platinum and palladium sales to the various consuming industries over the years. It seems unlikely that the demand for platinum for use in fuel cells could displace more than a fraction of the existing demand without upsetting the price structure of the platinum market. Additionally, it has been estimated by Bell[13] that the total world inventory of platinum is only 22.5×10^{6} oz (troy) and that the total recoverable reserves of platinum in known deposits are only 25×10^{6} oz (troy).

Table 2

Abundance and Cost of Some of the More Common Elements in the Earth's Crust

	Weight[a] (%)	Cost[b] (¢/gm)
O	46.43	0.05
Si	27.77	0.20
Al	8.13	0.06
Fe	5.12	0.13
Mg	2.09	0.088
Ti	0.629	2.4
C	0.027	0.02
Ni	0.008	0.07
Cu	0.007	0.074
Co	0.0023	0.018
Pb	0.0016	0.032
Th	0.00115	0.70
Be	0.001	0.44
W	0.0005	0.77
U	0.0004	11.2
Pt-group	0.000037	600.0
Ag	0.000004	53.0
Au	0.0000005	600.0

[a]N. A. Lange, Handbook of Chemistry, 10th Edition.

[b]J. Greene, "Geochemical Table of the Elements," Bull. Geol. Soc. America, 70, 1127(1959).

Table 3

Production and Consumption of Platinum-Group Metals
(troy oz)

	1949-53 Average	1954	1955	1956	1957	1958
U. S. Production	32,019	24,235	23,170	21,398	18,531	14,322
U. S. Consumption	446,924	581,946	850,811	858,912	744,025	690,373
U. S. Imports	466,832	606,444	1,009,940	1,033,877	682,013	670,431
World Production	700,000	940,000	1,080,000	1,100,000	1,310,000	880,000

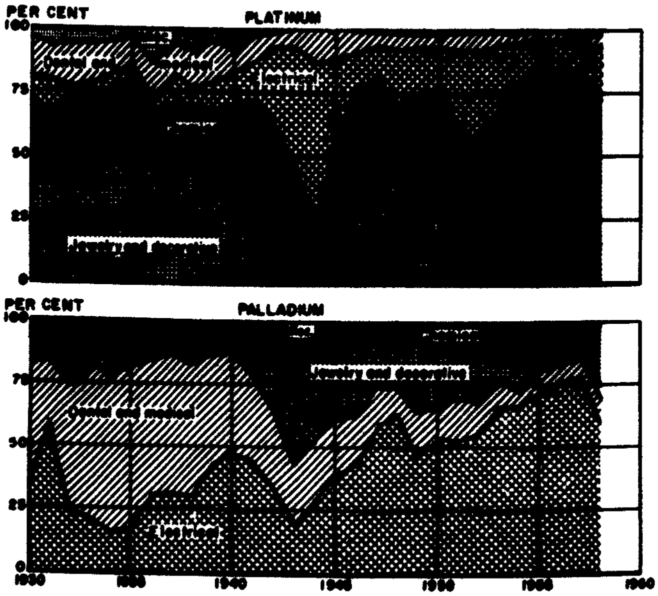

Fig. 1. Sales of Platinum and Palladium to Various Consuming Industries in the United States, 1930-58, as Per Cent of Total

The platinum industry is in the unenviable position of spending large sums for research to find new uses for the platinum metals and to improve product quality while the large customers have comparable research programs to find substitute materials.

The price of platinum metals has trended upwards from about 20 dollars/oz in 1900 to 155 dollars during World War I, to 26 to 45 dollars in 1940, and to approximately 90 dollars/oz at the present time.

The production and consumption of nickel appear in Table 4. These data, compiled by Bilbrey and Long,[14] indicate that the United States is principally a consuming nation; however, in recent years more self-sufficiency is evident as a result of the government subsidy program. Very likely, the production of nickel could be expanded appreciably above present levels to accommodate some of the needs of a fuel cell technology.

Table 4

Production and Consumption of Nickel
(short tons)

	1949-53 Average	1954	1955	1956	1957	1958
U. S. Production	8, 519	11, 442	19, 758	28, 974	35, 007	32, 641
U. S. Imports	102, 000	132, 000	142, 000	143, 000	140, 000	90, 000
U. S. Consumption	92, 676	94, 733	110, 100	127, 578	122, 466	79, 000
World Production	183, 000	238, 000	263, 000	283, 000	314, 000	245, 000

IV. UNITED STATES AND WORLD POWER DEMAND

In order to assess the probable role of the fuel cell in relation to the over-all demand for energy to do work, it is necessary to make a comparison based upon present fuel cell technology, production of nickel and platinum, and the energy demand. Putnam's data[1] for the United States and world demands for total energy and total electric power have been smoothed and plotted in Fig. 2. The two upper curves show that the total energy demands of the United States and the world are increasing at about the same rate, nearly 2.3 per cent per year. Similarly, although relatively much less in terms of millions of kilowatts, the demand for electric power is increasing at a rate of around 7 per cent per year. For Fig. 2, Putnam's original data have been converted from Btu x 10^{12}/yr to kwh/yr, and this figure is converted into what is called the equivalent electric generating capacity in Fig. 2 by the assumption that each installed kilowatt produces about 5000 kwh/yr.

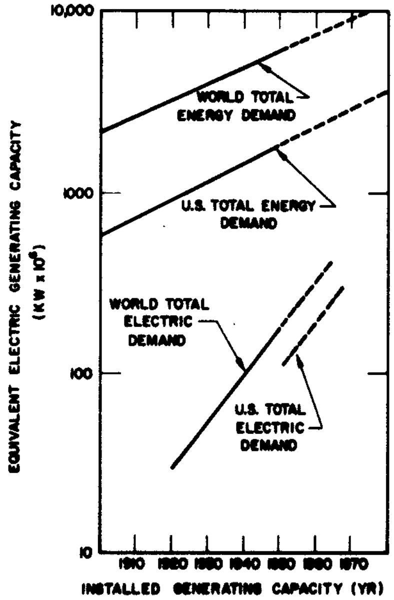

Fig. 2. Smoothed Curves Showing Total Energy and Electric Power Consumption for the United States and the World

Source: P. Putnam, Energy in the Future (D. Van Nostrand Co., Inc., 1953)

V. PROBABLE ROLE OF THE FUEL CELL AS AN ENERGY SOURCE

The amounts of platinum and nickel/kw of power output as computed in Table 1 may now be translated into United States and world fuel cell power production with the production statistics for the metals presented in Tables 3 and 4 and with the further assumption that the entire world production of these metals is used for fuel cell construction. These values are tabulated in Table 5 for comparison with the energy demand and the annual increase in United States and world total and electric energy demands. Inspection of the data in Table 5 indicates that platinum cannot be expected to supply more than a trivial share of the United States and world power demand. The power demand is simply too large for the available platinum to contribute significantly. Moreover, the consumption patterns indicated for platinum and palladium in Fig. 2 suggest that these metals have better uses than to produce power.

With nickel, the fuel cell picture appears more promising on the basis of the comparison in Table 5. In principle, the annual increase of world electric power demand could be met by fuel cell power if current nickel production were increased 44 per cent and the increase used to construct fuel cells. In order for the fuel cell to supply 58 per cent of the annual 2. 3 per cent increase of total world power demand, nickel production 3. 4 times the present level would be required.

It is important to remember that the data in Tables 2 and 5 are highly optimistic and the materials requirements are made more optimistic by making the calculation for hydrogen-oxygen instead of hydrogen-air which is more economical.

Table 5

Maximum Fuel Cell Power Output Based upon 1962 State of the Art and 1958 World Power Demand and World Production of Platinum and Nickel

	Maximum Power (kw x 10^6)	Per Cent of World Total Electric Power Demand	Per Cent of Annual Increase World Electric Power Demand	Per Cent of World Total Power Demand	Per Cent of World Increase in Total Work Demand
Platinum (880,000 oz, 1958)	1.34	0.446	6.38	0.019	1.6
Nickel (245,000 T, 1958)	47.3	15.8	225.0	0.678	58.0

VI. SUMMARY AND CONCLUSIONS

Large-scale use of a platinum catalyst for the production of fuel cell power seems highly improbable. The platinum fuel cell will probably be limited to small power sources in low volume production. This is especially true in the United States because of its low platinum metal production.

In order for the nickel fuel cell to be a large factor in the total power picture, it must operate on air. It also requires the development of a technology for the production of cheap hydrogen from hydrocarbons and the simultaneous, efficient utilization of the by-product carbon monoxide for mobile and fixed power plants; otherwise, there is little to be gained in efficiency over the conventional internal combustion engine and steam turbine. Lacking the cheap hydrogen, the nickel fuel cell is not competitive with the internal combustion engine on either the basis of first cost, dollars/kw, or on the basis of power cost, cents/kwh, despite the superior efficiency of the fuel cell. Accordingly, until cheap hydrogen is available, it must be concluded that the nickel fuel cell will only be competitive with certain types of large industrial batteries. Because of the small magnitude of this market[13] in relation to the over-all energy demand, it is unlikely that fuel cells will contribute to increased efficiency of fuel utilization in either the United States or the world energy demand.

For space exploration, the high kwh/lb for the nickel and platinum fuel cells make them more attractive for certain missions than existing batteries. For some military applications, where silence and low-temperature operation are desirable features, the fuel cell may find some applications; however, if any volume is required, the nickel cell should be selected. New technological developments are needed for fuel cell catalysts and low cost fuel production before fuel cell power can contribute significantly to increased utilization efficiency and to the total demand for work and electric power production.

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