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FUEL CELLS IN TRANSPORTATION

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ABSTRACT

Fuel cells have been considered for use in transportation applications for a number of years. They are attractive because they offer a mode of reducing U.S. dependency on petroleum. Fuel cell performance at present has been assessed for applicability to vehicle power plants. Types of fuels that might be used and their effect on selection of a fuel cell technology have been considered. Simulation of a city bus using a hybrid fuel cell/battery power plant indicates that adequate performance can be obtained with current technology.

INTRODUCTION

One of the attributes of fuel cells that has made them attractive for use in a wide variety of stationary and mobile power requirements is their efficiency in converting chemical to electrical energy. One area where more efficient use of fuel could have considerable impact is that of transportation. Of the approximately 71 quadrillion Btu total gross energy consumption in the United States by all sources in 1975, 18.3 quadrillion Btu was consumed by the transportation sector for both military and civilian purposes. This represents slightly over 25% of the total energy consumed in the U.S., and this share has remained quite steady during the 26-year period between 1950 and 1975 (1). If one looks at petroleum consumption in this same time frame, transportation accounts for well over 50% of the petroleum used in this country. Thus, there is the incentive to reduce the petroleum dependency of the U.S. by developing a more efficient power source for transportation applications. An alternative approach is to use fuels that can be derived from indigenous resources, such as methanol from coal or natural gas, in these advanced power sources. Fuel cells offer an approach to advanced propulsion power plants that encompasses both of these alternatives.

FUEL CELL STATUS

In the period 1980 to 1985, the worldwide development of fuel cells has grown considerably. The applications of fuel cells that have stimulated continued interest are: on-site, utility power plants; transportation and propulsion; spacecraft power; and small, low-emission, portable electric generators. Without a doubt, the highest level of activity has been in the development of phosphoric acid fuel cells for on-site and stationary power generation. This has led to a greatly expanded technology base for phosphoric acid, with large scale demonstrations of utility and on-site power plants, increased life, improved performance, and refined systems features. In addition to phosphoric acid, development work by research organizations and industrial firms has focused on four other types of fuel cells, also classified by the electrolyte used. In terms of the overall state-of-development of these systems, the ranking is as follows:

1. phosphoric acid
2. alkaline
3. ion exchange membrane
4. molten carbonate
5. solid oxide

On the basis of observed progress, it is not expected that molten carbonate or solid oxide fuel cell technologies will advance to the point that a viable system can be demonstrated in the next 5 to 10 years. They are fragile in their present forms and perhaps not suited to mobile applications. Their high temperatures of operation would be a safety hazard in a vehicle. They are attractive for utility applications because they are a source of high-grade heat for cogeneration use, a feature that is not needed in the propulsion application. In any event, their performance is presently equal to or less than that of phosphoric acid systems, thereby removing any incentive to presently pursue them for transportation applications.

Perhaps the most significant indicator of progress and present status of the three remaining systems is cell performance measured in current density and cell potential. Thus, graphs have been developed that depict this progress (2). With the exception of the proton exchange membrane fuel cell, there has not been any significant change reported for the various technologies since 1984. A 1984 one-atmosphere air-reformate (or H_2) reference is provided for each technology so that the technologies can be compared with each other.

As can be seen in Fig. 1, the alkaline fuel cell operating on H_2-O_2 is a spectacular performer at 100°C and 10 atm. Data for 1984 are essentially the same as for 1978 and represent a dramatic improvement over 1960 capabilities. Note, however, that on H_2-air at 65°C, where reasonable lifetimes might be expected, the performance is not as good as might be expected.

The phosphoric acid fuel cell progress (Fig. 2) has been good, but the major performance improvements have derived from increasing the temperature and pressure of the system. Thus, the real improvement has been in obtaining more stable materials, which have allowed operation under these more severe conditions.

The solid polymer system (Fig. 3) shows very good performance on H_2-O_2, having improved from 15 A/ft^2 at 0.7V in 1965 to 500 A/ft^2 at over 0.8V today. Operation on H_2-air, reported in 1986 (3), shows considerable improvement to over 500 A/ft^2 at 0.7V. Under the conditions shown, there was no apparent problem with water management.

FUEL PROCESSING

The fuel cell systems discussed above use pure hydrogen or a hydrogen-rich mixture as the fuel. Hydrogen can be supplied in its pure form as a gas, compressed gas, or a liquid. Hydrogen-rich fuel may be derived from the catalytic decomposition of hydrocarbons or other hydrogen-containing compounds. Interest in acid electrolyte fuel cells is due to numerous organic hydrogen compounds that may be readily reformed into hydrogen-rich mixtures. Hydrocarbon fuels that have been used are natural gas, naphtha, methanol, and jet fuel. Methanol decomposes at relatively low temperatures (200°C) using inexpensive catalysts (CuO-ZnO) and a simple apparatus. This makes it an attractive source of hydrogen for fuel cells. The other, heavier hydrocarbons, including diesel fuel, require complex equipment and much higher temperatures for reforming. This leads to higher weights and volumes, which are critical parameters in transportation applications.

During reforming, varying amounts of carbon monoxide (CO) are produced and efforts have been made to reduce these amounts. The methods of CO reduction include varying the amount of water used in the reaction and controlling the temperature of reaction. The CO content of the reformate is critical to fuel cell operation because CO is preferentially adsorbed over H_2 by the fuel cell catalyst, thus poisoning the fuel electrode and reducing performance. At the moderately high temperatures (200°C) encountered in phosphoric acid fuel cells, several percent CO can be tolerated (2 to 3%), but in low-temperature fuel cells, such as the proton exchange membrane (PEM), allowable CO concentrations will be much lower (<0.5%).

Also, during reforming, carbon dioxide (CO_2) is formed as one of the major products (20-25%). Acid electrolyte fuel cells reject the CO_2 but alkaline electrolytes react with it to form carbonates that eventually precipitate in the electrodes and destroy electrochemical performance. Thus, alkaline fuel cells are not able to use hydrogen derived from hydrocarbons but require pure hydrogen as fuel. At the present time, it does not appear feasible to supply hydrogen through the transportation infrastructure.

PROJECTED FUEL CELL ADVANCES

The efforts of developers of phosphoric acid fuel cells are now concentrated on manufacturing and mass production at lower cost. This is especially true in Japan. Over the last 10 years, catalyst loadings in phosphoric acid fuel cells have steadily gone down. There does not seem to be any concerted effort to reduce these loadings further in existing utility systems, although fundamental research on the O_2 reduction reaction continues. There is also work being done on porous plate construction to improve reactant transport and to increase the effectiveness of catalysts by depositing them in the region of maximum reaction probability in the pores. In the next few years, evolutionary improvement in phosphoric acid fuel cells in terms of performance and cost are expected as a result of these efforts.

Although there has not been as much activity in PEM fuel cell system development for terrestrial applications, this technology has some advantages over liquid acid or alkaline fuel cells. The inherent advantages of PEM fuel cells are:

High power density
Low-temperature operation
Rigid, contained electrolyte
Cold start capability

As a result of these features, interest has increased in the past few years. It is expected that prototypical systems will be developed within five years for stationary or portable applications in the power range of a few kilowatts using reformed methanol as the fuel.

PREFERRED FUEL CELL SYSTEMS FOR TRANSPORTATION

The indicated state-of-development and the overall results of fuel considerations leave only the phosphoric acid fuel cell as a choice for near-term use. The phosphoric acid fuel cell represents the only technology that has demonstrated full stack operation on reformed fuel. By the 1990's, sufficient improvements in performance and power density will be realized to consider an advanced phosphoric acid system for future applications. Also, a PEM fuel cell system should be considered at the same time. The potential of the PEM fuel cell for transportation applications dictates its consideration even though the system technology development is immature for terrestrial operation on reformed fuel.

FUEL CELL PROPULSION SYSTEM CONSIDERATIONS

One of the prominent aspects of contemporary phosphoric acid fuel cell systems is that the systems are designed to produce power at a steady-state condition, or at most, at a few fixed operating points. The transportation application, however, requires rather large and rapid changes in power source output to meet the duty cycles. The limiting factor in fuel cell systems for meeting transients is the reformer.

It is doubtful that existing reformer systems will be able to respond adequately to the severe transient load requirements of transportation duty cycles, particularly in urban operation. To quantify the degree of the problem, the time constant for changes in the catalyst bed temperature in response to changes in fuel flow in a Los Alamos 20-kW methanol reformer experiment, was 15 min. This is certainly not satisfactory for vehicle requirements where a fast-response reformer is required for very large power swings.

NEAR-TERM TRANSPORTATION SYSTEM EXAMPLE

One possible near-term application for a fuel cell powered vehicle is the 40-ft city bus. Simulations have been conducted to determine the feasibility of this application (4). With the restriction that current technology be used, a hybrid fuel cell/battery system is the necessary solution to the fuel cell electric bus propulsion system. The reasons for this conclusion are:

1. Contemporary reformer designs are not suited to transient operation on vehicular duty cycles.
2. Available power densities in fuel cells are not adequate to provide peak power requirements without excessive weight and volume penalties.

The fuel cell power in the hybrid system is taken as the average power over the duty cycle, including battery charging capability. For the duty cycle selected, the fuel cell power is 59-kW. The peak power requirement is 143-kW; the battery pack is capable of supplying the difference.

The fuel cell system used is an unpressurized phosphoric acid stack and a methanol/steam reformer. The battery used is a Globe EV-1300 lead-acid electric vehicle battery selected for its peak power capability.

Bus operation is simulated over a DOT duty cycle with this power plant. Some of the overall findings are:

1. There is a fuel cell/battery combination that will allow the bus to meet the duty cycle.
2. The amount of recharging of the batteries during the low power parts of the cycle is not nearly enough to allow continuous operation.
3. In terms of economy of operation and performance, systems with a higher fuel cell-to-battery ratio (comparatively fewer batteries) are favored.
4. There are long recharge times in the natural fuel cell/battery configuration (fuel cell and battery directly connected in parallel with no fuel cell voltage regulation).
5. Discharge/charge efficiencies for the battery pack are quite low due to the fact that the batteries are discharged at relatively high currents.
6. The use of new fast-response reformer designs, which are presently being tested, and available batteries with better charge/discharge characteristics, should produce much better performance in bus operations.

SUMMARY

Fuel cells possess a number of attributes that make them very attractive for transportation applications. The fuel cell chosen for a given application must be selected on the basis of performance and type of fuel required. From simulations of city bus operation, using a fuel cell/battery hybrid power plant, a system can be designed using current technology that will provide adequate operation. The improvements in technology, particularly of the reformer response time, should enhance the feasibility of using fuel cells in transportation.

ACKNOWLEDGMENT

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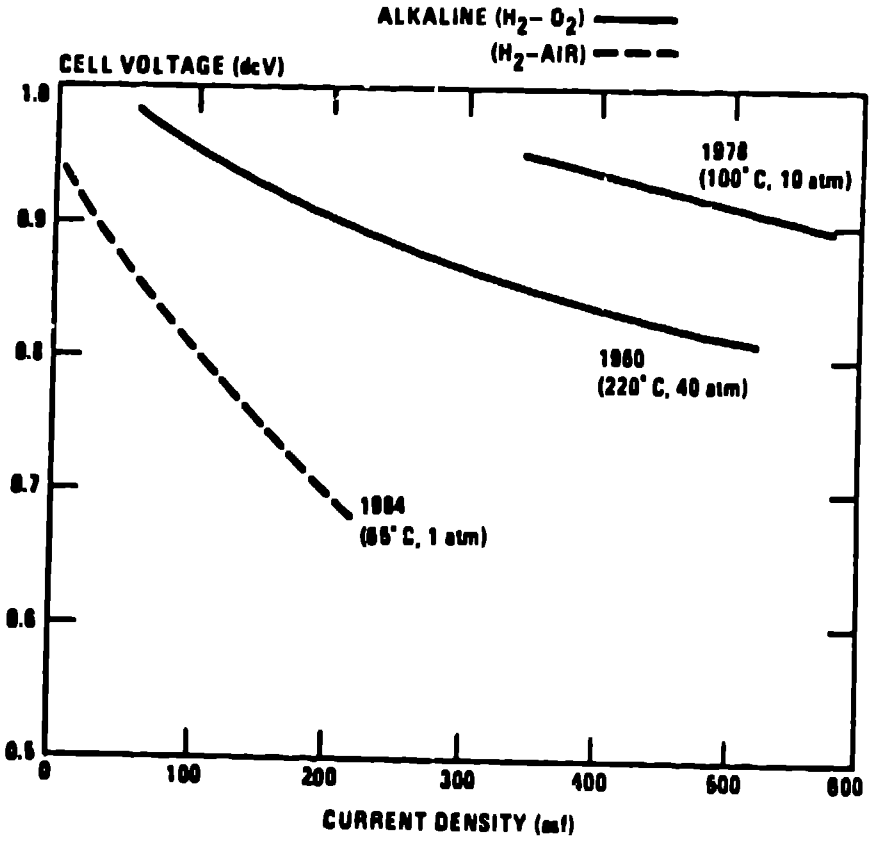

Fig. 1.
Performance curves for alkaline fuel cell systems.

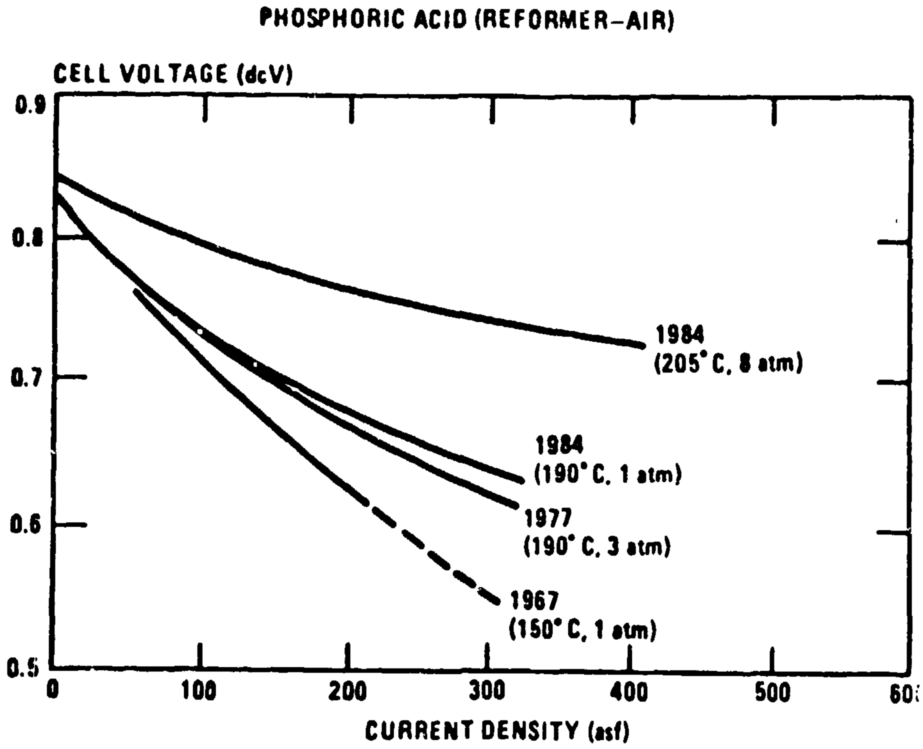

Fig. 2.
Performance curves for phosphoric acid fuel cell systems.

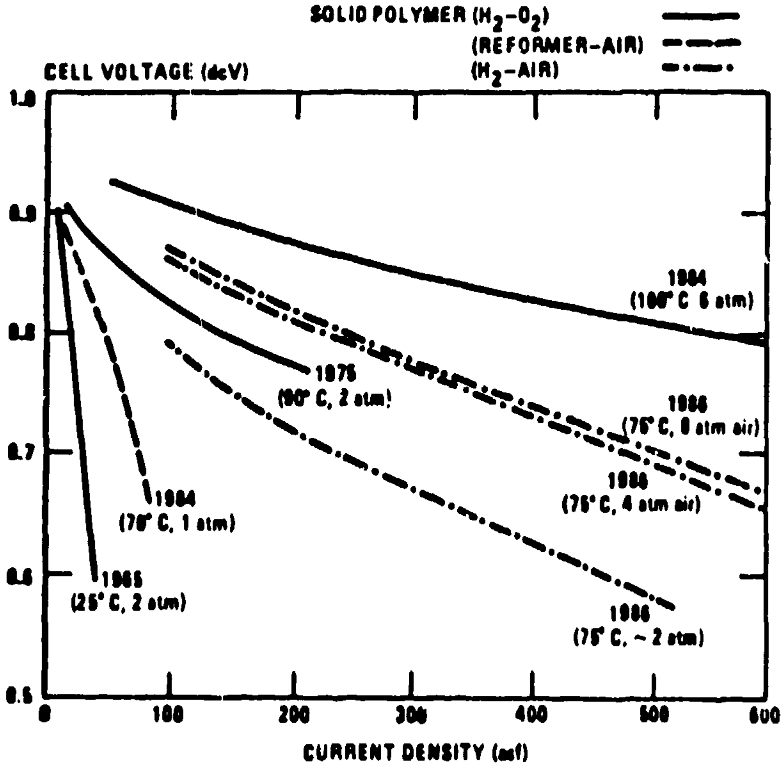

Fig. 3.
Performance curves for solid polymer fuel cells.