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FUEL CELL POWERED PROPULSION SYSTEMS FOR HIGHWAY VEHICLES

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INTRODUCTION

Over the past thirty-five years, the transportation sector has accounted for approximately 25% of the total gross energy consumption in the United States. Transportation's share of petroleum use in this time frame has ranged from 50-55% (1). Therefore, the use of fuel cell power plants that could possibly operate more efficiently than internal combustion engines in this type of application has been examined. In addition, these fuel cell power plants can operate on methanol produced from indigenous, non-petroleum sources and thereby reduce U.S. dependency on petroleum resources. Fuel cell power plant use in city buses and automobiles has been explored and feasibility determined from both performance and cost viewpoints.

SELECTION OF FUEL CELL SYSTEMS

Fuel cell systems for transportation applications have been selected on the basis of state-of-development, performance (both present and projected), and fuel considerations. In the last 25 years, most of the development work by research organizations and industrial firms has focused on five types of fuel cells, classified according to the electrolyte used (2-6). In terms of the overall state-of-development of systems, the ranking is as follows:

1. Phosphoric Acid
2. Alkaline
3. Proton 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 propulsion applications. In any event, their performance is presently less than or equal to that of phosphoric acid systems, thereby removing any incentive to pursue them for transportation applications at present.

The alkaline fuel cell has shown spectacular performance operating on hydrogen/oxygen for space applications. However, it is severely handicapped in terrestrial applications unless extremely pure hydrogen is acceptable as a fuel Schemes to use processed organic fuels in alkaline cells have been tried, but such methods will not be practical in the near future, if ever.

The fundamental reason for the emergence of phosphoric acid technology is the ability of these fuel cells to operate at high efficiencies on a variety of processed hydrocarbon fuels. The proton exchange membrane (PEM) technology also shows promise for being able to operate on these types of fuels. The fuel cell performance characteristics used in the studies discussed below are summarized for these two systems in Fig. 1. The phosphoric acid fuel cell system is an unpressurized stack and methanol/steam reformer, with a pre-mixed methanol/water fuel. The fuel is approximately 58% methanol by weight. The reformer system is similar for the PEM power plant. In advanced systems, water recovery from the power plant would be used to supply the steam for reforming removing the need for a pre-mixed fuel. The near term phosphoric acid curve is a composite of data from existing power plants, and represents performance which can be easily attained. The two advanced technologies, including PEM, are extrapolated from subscale demonstrations and observed improvements in performance. Both of the advanced performance curves represent modest 5 year expectations.

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 that can be used as fuel by these systems. 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, 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.

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 in terms of high power density, low-temperature operation, rigid and contained electrolyte, and cold start capability 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 (7). This is certainly not satisfactory for vehicle requirements where a fast-response reformer is required for very large power swings. Such fast-response reformers are being developed, but, pending their availability, transient requirements will have to be met by using fuel cell/battery hybrid power sources where the battery supplies power to meet peaking demands.

The motor/controllers, transmissions and differentials used in the following simulations were selected from equipment available off-the-shelf or from those being developed by DOE under the Electric and Hybrid Vehicle program.

NEAR-TERM FUEL CELL BUSES

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 (7,8). 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 performance, which determines the power requirements, is that specified by the Urban Mass Transportation Administration (UMTA) White Book. The fuel cell power in the hybrid system is taken as the average power over the duty cycle, including battery charging capability. For the performance 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 (9,10).

The bus operation was simulated over the selected UMTA duty cycle starting with fully charged batteries. The summary of performance is given in Table 1.

TABLE I

NEAR TERM BUS PERFORMANCE

	Normal	Battery Cut-Out
Energy, kWH		
Propulsion		
Fuel Cell	15.5	14.0
Battery	18.2	15.9
Auxiliary	6.0	6.0
Recharge	56.4	53.4
Final SOC	0.37	0.41
Recharge Time, h:min	5:50	5:36
MPG Methanol	1.67	1.88

The simulation results indicate that charging of the battery with the fuel cell is an inefficient process due to the fact that the natural current drawn is quite low. Not much is gained in terms of charge recovery for the amount of fuel used. It would be possible to use the battery pack only for peaking and not for cruise conditions. In this mode of operation, the battery would be disconnected from the system except when power augmentation is required. The batteries would not be recharged by the fuel cell during the short idle periods. A comparative simulation in this mode is summarized in Table 1 under Battery Cut-Out operation. This is clearly a better way to run the system.

ADVANCED FUEL CELL BUSES

Advanced buses must meet the original DOT composite duty cycle from the UMTA White Book. Advanced buses do not utilize batteries for peaking, the fuel cell power source providing all propulsion and auxiliary power. The performance levels shown for the advanced phosphoric acid and PEM fuel cells in Fig. 1 are assumed. The systems are lighter and therefore the maximum power requirements are reduced. This leads to more efficient energy use. The performance for a bus using an advanced phosphoric acid fuel cell power plant to meet the individual DOT duty cycles is summarized in Table II.

TABLE II

ADVANCED PHOSPHORIC ACID BUS PERFORMANCE ENERGIES IN KWH

Cycle Phase	Fuel Cell Energy	Fuel Energy Use
CBD	0.385	1.01
Arterial	1.53	4.00
Commuter	8.91	23.58
Total Auxiliary	0.7	1.84

The total fuel energy use over the composite duty is 99.7 kWH, giving a methanol mileage of 2.68 mpg.

Performance data for the PEM fuel cell powered bus are given in Table III.

TABLE III

PEM FUEL CELL BUS PERFORMANCE ENERGIES IN KWH

Cycle Phase	Fuel Cell Energy	Fuel Energy Use
CBD	0.36	0.786
Arterial	1.47	3.19
Commuter	8.6	18.86
Total Auxiliary	0.7	1.53

The total fuel energy usage is 79 kWH for a fuel consumption of 3.38 mpg of methanol.

FUEL CELL BUS COST ANALYSIS

Using life-cycle cost analysis, preliminary economic feasibility of fuel cell powered buses was examined along with selected trade-offs for key operating parameters. In addition to the conventional diesel power/drive train, two distinct configurations of fuel cell powered buses were considered. The first was a near-term fuel cell/battery hybrid power system with the bus system sized for the DOT duty cycle used in the simulations above. Most of the analysis centered around this configuration. The second was a pure fuel cell bus using near-term fuel cell operating parameters. The focus of the analysis was on cost targets or goals for the fuel cell powered buses. Because there is limited data on potential costs of fuel cell power systems, and what data there is has been of the cost engineering and exploratory type as opposed to actual full scale production data, the cost target approach allows evaluation of feasibility without requiring detailed and firm cost information. Thus, allowable costs were postulated, cost goals that must be met if the fuel cell powered buses are to be competitive with the conventional diesel powered buses. Two types of cost measures were examined; a total dollars per mile operating cost computation that included fuel, maintenance, fixed overhead, and capital components; and a dollar system cost expressed as allowable power/drive train costs. Comparing the costs of the two systems on a per mile basis was deemed a logical approach. Thus, the "break-even" cost for a fuel cell powered system would be when the cost per mile for the fuel cell bus is the same as for a diesel bus. The cost per mile includes all the costs associated with the operation of a city bus system; initial cost of the buses, maintenance cost, fuel cost, and system overhead costs.

The question addressed by the economic evaluation of the city bus was: What are the fuel cell efficiencies and costs that would allow the fuel cell to be an economic power source for city buses? The economic evaluations focused on two aspects: first, the effect of the bus cost, fuel cost, fuel economy, and maintenance cost on the operating costs of buses; and second, the maximum fuel cell propulsion system costs that would allow a fuel cell powered bus to be competitive with the present diesel driven buses. Because the fuel cell drive train systems for a bus have not been clearly defined as yet, many of the parameters needed to define the economics of a fuel cell powered bus are uncertain. Also contributing to the uncertainties are the unknown future costs of diesel and methanol fuels. Therefore, the economic analysis used a range of values and focused on the "break-even" costs for a fuel cell system and not on what the expected costs of a fuel cell powered bus will be.

To establish benchmarks from which comparative analysis can examine the fuel cell powered bus option, a set of computations was made for the conventional diesel powered bus to provide information on the total operating costs per mile when the bus purchase prices (dollar capital cost) change along with a selected key parameter. Using base-case parameters, that is, $140,000 cost, 3.5 mpg, and $1.10 per gallon figures, maintenance and fixed (overhead) costs, and all other financial and operating assumptions, the total operating cost per mile would be $3.21. For comparison with the base case, fuel efficiency, fuel price, fuel costs per mile, and maintenance costs were changed, one at a time, all other assumptions remaining unchanged. As a function of changes in these parameters, changes in the bus purchase price with the total operating cost per mile maintained at $3.21 and changes in the total operating cost per mile with the bus purchase price held at $140,000 were obtained. Substantial changes to base-case parameters result in large changes in bus cost. However, these same substantial changes cause only small variations in the total operating cost per mile. Therefore, the important item from this simple life-cycle cost look at conventional diesel powered buses is the relative insensitivity of the total expenses, cost per mile, to rather substantial changes in several key operating parameters.

A similar analysis was made for a fuel cell powered bus. The fuel cell base case assumed a methanol cost of $0.50 per gallon and a fuel efficiency of 2.0 mpg. If the bus cost is held at $140,000, the total operating cost per mile is $3.11. Alternatively, at a $3.21 total operating cost per mile (diesel base case), the fuel cell bus could be priced higher than the $140,000 diesel powered bus at approximately $155,000. Again, as a function of changes in key parameters, changes in the bus purchase price with the total operating cost per mile maintained at $3.21 and changes in the total operating cost per mile with the bus purchase price held at $140,000 were obtained. The results are similar to those obtained for the diesel powered bus and, again, the total operating cost per mile is relatively insensitive to substantial changes in key operating parameters.

This information can be used to evaluate direct trade-offs between "allowable" fuel cell system costs and the key fuel cell operating parameters. One set of relationships was constructed addressing "allowable" or target fuel cell costs as methanol fuel efficiency varied. Total fuel cell system and the fuel cell (including fuel processing) itself costs in dollars per kilowatt are presented in Table IV. To obtain the target fuel cell cost, the costs of the three other principal components; the motor, the controller, and the battery, were removed from the power/drive train cost. The component costs for these items were set at $15,000, $23,000, and $33,000 yielding low-, mid-, and high-cost targets for the fuel cell cost. Thus, target costs were developed for the bus with both the fuel cell/battery hybrid and pure fuel cell power plants. In the case of the pure fuel cell power plant, battery costs were removed from the component sum. The pure fuel cell system cost targets are measurably less than those for the hybrid fuel cell systems.

TABLE IV

FUEL CELL COST TARGETS FOR VARYING FUEL EFFICIENCIES
(MPG of Methanol)

Hybrid System (With Battery)	mpg		
	1.0	2.0	3.0
Total Fuel Cell System ($)	0	45,000	55,000
	$/kW		
System	0	763	932
Low-Cost Components	0	588	678
Mid-Cost Components	0	373	542
High-Cost Components	0	203	373
Pure System (Without Battery)	mpg		
	1.0	2.0	3.0
Total Fuel Cell System ($)	0	45,000	55,000
	$/kW		
System	0	375	438
Low-Cost Components	0	258	342
Mid-Cost Components	0	208	292
High-Cost Components	0	142	225

These $/kW figures provide only the first estimates of possible allowances. As more data becomes available, it does provide a reasonable framework under which to carry out further assessments. Basically, the results indicate that at low fuel efficiency values cost targets are nonexistant. At the base or reference fuel efficiency values, the cost target approaches $600/kW for the fuel cell (plus reformer) in a bus powered by a hybrid fuel cell system under low-cost drive train component assumptions. The targets drop by approximately a factor of two for the pure fuel cell propulsion system. Obviously, any factor resulting in an improvement in fuel cell performance increases the cost goals commensurately. A number of arguments can be presented regarding sets of forces that will operate to raise or lower cost targets. The utilities have spoken of cost targets of $1000/kW, considerably above the propulsion cost targets generated. It is premature at this stage of technology R&D and preliminary economic evaluation to offer any final judgement as to the true market prospects for a fuel cell powered bus.

FUEL CELL/BATTERY HYBRID SYSTEMS FOR PASSENGER CARS

The passenger car is obviously the application where the greatest impact on fuel conservation may be realized. For the purpose of specifying a power plant, a baseline model based on the vehicle requirements of the Advanced Electric Vehicle Powertrain is used (11). These basic requirements are:

- 60 mph top speed
- 0-50 mph in 20 seconds
- 30% gradeability
- Driveability

The driveability of the vehicle depends upon having a high transmission step ratio without causing loss of power after an upshift during acceleration. Simulations show that the 0-50 mph in 20 seconds acceleration power is insufficient to meet parts of the Urban Drive Schedule (UDS). The power necessary to accelerate to 60 mph in 20 seconds is closer to the desired value, assuming constant power acceleration. The power plant power outputs necessary for 0-50 mph in 20 seconds, 0-60 mph in 20 seconds, and 60 mph top speed are given in Fig. 2. Also shown in Fig. 2 are lines of constant power plant weight ranging from 15 lbs/kW (projected PEM) to 25 lbs/kW (projected phosphoric acid) to 55 lbs/kW (currently achievable phosphoric acid). These values are derived from the performance levels shown in Fig. 1. The base electric vehicle weight is marked on the graph along with The Advanced Powertrain Vehicle weight with Globe EV-1300 batteries, a reasonable upper limit.

The conclusions drawn from these data are that it is possible to meet performance specifications with a 15 lbs/kW fuel cell power plant, the projected weight for PEM/methanol fuel cells. At 25 lbs/kW, the projected best weight for PA/methanol technology, it is also feasible to meet good performance characteristics. However, at 55 lbs/kW, the currently available PA system weight, fuel cell power plant weights will be too high to be feasible for automobile applications.

The volumes of the fuel cell power plants at the intersections of the 0-60 mph in 20 seconds curve, the point at which a fuel cell could provide the total power, are given in Table V, assuming that 15 lbs/kW represents a PEM fuel cell and that 25 lbs/kW represents a PA fuel cell. At 15 lbs/kW, the required power is 41.3 kW and, at 25 lbs/kW, the required power is 48.5 kW. In the Escort-sized vehicle, the volume available for the power plant is 12.5 ft^3. Thus, it may be possible to configure a full-power PEM fuel cell for this size of car, but even projected PA technology will not be able to meet the complete power requirements. In addition, methanol fuel processors, as presently configured, can not respond to transient requirements. Therefore, until present development efforts on rapid response reformers result in systems that can meet transient response requirements, it will be necessary to meet peaking demands with batteries in a fuel cell/battery hybrid power plant configuration.

TABLE V

FUEL CELL POWER PLANT WEIGHT AND VOLUME
FULL POWER

Fuel Cell Power Plant Weight, lbs/kW	Vehicle Weight, lbs	Total Power Plant Weight, lbs	Power Plant Volume ft^3
15 (PEM)	3099	619	14.9
25 (PA)	3692	1212	29.1

The general approach to assessing a hybrid power plant configuration is to provide a fuel cell power plant which furnishes an average power generation determined by cruise or average duty cycle power requirements and to satisfy peak power demands by means of batteries. Conceptually, the fuel cell will recharge the batteries whenever the power demand is less than the fuel cell nominal power. Simulation studies show that the fuel cell recharging scheme is inefficient in a design where the parallel impedances of the battery and fuel cell are closely matched so that each source can deliver maximum current during peak operation. As a consequence of this design criterion, there is not a sufficient voltage difference between the fuel cell and battery to result in a high current flow to the battery during idle periods. However, some energy is supplied to the batteries by the fuel cell in the natural mode of operation, that is, during zero-load idle times and this mode of hybrid operation is employed. Furthermore, the strategy of not using the batteries during nominal power conditions was found to be the best approach to parallel operation. The study results indicate that battery disconnection during nominal cruise optimizes the trade-off between fuel cell efficiency, fuel cell transient demands, and battery energy range.

The zero-power phases of the duty cycle are divided into coasting and idle, during which fuel cell recharging is feasible, and braking, during which regenerative braking is employed. Regenerative braking accounts for significant battery recovery, which far exceeds natural fuel cell recharging.

The determination of relative fuel cell and battery powers includes the considerations discussed below. The batteries considered are the Delco Remy DR150 nickel-zinc (12) and the Globe EV-1300 lead-acid.

1. The short duration peak power of batteries is better than the projected maximum power of fuel cells on both a weight and

volume basis. The comparative values are:

Batteries (50% DOD)		
NiZn (DR150)	.099 kW/lb	10.2 kW/ft^3
Lead-Acid (EV-1300)	.0735 kW/lb	10.4 kW/ft^3
Fuel Cells		
PA	.04 kW/lb	1.67 kW/ft^3
PEM	.067 kW/lb	2.78 kW/ft^3

2. Fuel cells may be operated at powers above nominal rating provided that fuel processing devices are able to follow the necessary transients. In this study, it is assumed that the fuel cells are able to follow modest transients, such as power reduction at idle and at low speed cruise conditions.

3. Resistive braking is necessary in an electrically-propelled vehicle. The ability of batteries to be regenerated by this method should be utilized because the recovered energy on the UDS is significant.

4. There is an inherent lower limit to the battery size due to the required operating voltage to match impedance with the parallel fuel cell and with the controller input voltage range.

There is a trade-off of nominal fuel cell power versus battery peak power which gives an optimum system where the nominal fuel cell power is the average duty cycle power. At this point, the following effects are evident from simulation studies.

1. The battery capacity is sharply increased at this point, compared to the cases in which the battery supplies more power (less nominal fuel cell power). At fuel cell nominal powers above the average UDS power, increases in battery capacity are marginal.

2. Fuel cell peaking transients are nominal and fuel cell losses due to load drops at idle, when the fuel cell operates at excess fuel conditions, are minimized.

3. With the known and projected weights and volumes of the fuel cells and batteries, a feasible packaging configuration is achieved at this point.

4. The average power of the batteries is approximately the same as the average power of the fuel cell over a wide range of vehicle weights.

5. The nominal fuel cell power is greater than the average vehicle cruise power, but less than the top speed cruise power.

Basic vehicles are formulated with hybrid power sources where the fuel cell systems are based on the average UDS power and the batteries are sized to meet maximum peak-over-average power, and configured to give a nominal 120 V system. The four fuel cell/battery systems considered are PA/lead-acid, PA/nickel-zinc, PEM/lead-acid, and PEM/nickel-zinc.

The maximum volume power plant is found by utilizing all of the available 12.5 ft^3 in the car for batteries, fuel cell system, and fuel. The total volume of batteries and fuel cell for the PA/NiZn system is 13.1 ft^3 without fuel. Because this is 5% greater than the total volume available, it is not possible to package the PA/NiZn system in this vehicle. The problem with systems using NiZn batteries is that instead of the 60 cells needed in the lead-acid system 75 cells are necessary to match the system voltage resulting in a 1.37 ft^3 volume penalty. The data for the other three configurations are given in Table VI. Also given in Table VI are the data for PEM hybrid systems with fixed 10-gallon methanol fuel tanks. In both PEM systems, particularly the lead-acid system, there is enough available volume to allow for larger fuel tanks. Ten gallons of fuel provides for adequate fuel cell range in both cases.

TABLE VI

BASIC FUEL CELL/BATTERY VEHICLES, UDS

SYSTEM	FUEL CELL POWER, kW	FUEL CELL RANGE, MILES	BATTERY RANGE, MILES	METHANOL MILEAGE, MPG	BATTERY ENERGY, kWH/MILE
PA/Lead-Acid	10.1	157	252	29.3	.0347
PEM/Lead-Acid	10.1	799	448	34.4	.0195
PEM/NiZn	10.1	458	897	34.8	.0193
PEM/Lead-Acid, 10 Gal	9.88	351	463	35.1	.0191
PEM/NiZn, 10 Gal	9.95	349	901	34.9	.0192

The effects of reducing the fuel cell weight below the values used in this study are small due to the dominance of the battery weights, which are fixed because of voltage requirements. For example, in the case of PA/lead-acid, a 20% decrease in fuel cell specific weight (to 20 lbs/kW) results in a 1.4% increase in methanol mileage and a 1.2% decrease in battery energy consumption. In the case of PEM/NiZn, a 33% decrease in fuel cell weight to 10 lbs/kW results in a 0.9% increase in methanol mileage and a 1.0% decrease in battery energy consumption.

The battery weight, set by the voltage requirements, makes up a large fraction of the total vehicle weight (somewhat more that 20% in the PEM/NiZn system). Table VI also shows that the DR150 NiZn battery has a capacity of approximately 900 miles of operation in the PEM fuel cell system. Furthermore, the voltage requirement results in a battery which easily meets peak power requirements. The battery capacity could be reduced, with corresponding weight and volume reductions, to meet the peak power requirements and to reduce battery range to more nearly match the fuel cell range. Table VII demonstrates the effect of reducing battery capacity on vehicle performance. This also assumes that some means is available for impedance matching with the fuel cell because the battery pack voltage will be lower. The fuel tank size is held constant at 10 gallons and this, along with battery volume reductions, leads to systems that all fit in the volume available in the vehicle. Efficiencies are also improved because of the reduced weight of the vehicle.

TABLE VII

FUEL CELL/BATTERY VEHICLES WITH REDUCED BATTERY CAPACITY, UDS

SYSTEM	FUEL CELL POWER, kW	FUEL CELL RANGE, MILES	BATTERY RANGE, MILES	METHANOL MILEAGE, MPG	BATTERY ENERGY, kWH/MILE
PA/Lead-Acid	9.61	305	191	30.5	0.0334
PA/NiZn	9.24	315	261	31.5	0.0322
PEM/Lead-Acid	9.34	369	343	36.9	0.0182
PEM/NiZn	8.99	381	458	38.1	0.0177

Cost information is generated for all systems analyzed above. The focus is to provide comparative information for the various fuel cell/battery systems in terms of initial cost and operating cost which could form a basis for system selection. Only fuel cell/battery costs are considered and all other costs for the total vehicle system are assumed to be constant.

In developing a cost for the life of the hybrid power plant, a number of factors are considered. These include:

- initial cost of the fuel cell
- initial cost of the battery
- fuel cost per mile for the fuel cell
- battery recharge cost per mile
- fuel cell replacement cost
- battery replacement cost

No salvage cost benefits were assumed for either the fuel cell or the battery.

Projected fuel cell system costs were based on production runs of 100,000 units/year (13,14). The fuel cell installed cost was estimated to be 1.7 times production cost. Thus, the initial costs used are $425/kW for PA and $280/kW for PEM. Initial battery costs are based on projected manufacturing costs per kWH (delivered to the consumer) of $180/kWH for the lead-acid battery (9) and $200/kWH for the nickel-zinc (15). The cost of methanol per gallon is set at $1.10 (16). For battery recharge cost, the cost of electricity is assumed to be $0.08/kWH (15). Battery recharging efficiency, on an energy basis, is set at 70%.

Replacement costs for the fuel cell and the battery are based on an assumed passenger car life of 100,000 miles. A reasonable value for the fuel cell operating lifetime is 5,000 hours for both the PA and PEM fuel cells (13,14). The average speed over the UDS is 19.6 mph. Using this value and the preceeding assumptions, the fuel cell will not have to be replaced during the lifetime of the automobile for any of the cases analyzed.

Battery replacement cost is based on battery range and cycle life. Battery range, in miles, is obtained by operating the battery in the hybrid system until it reaches 80% DOD. This includes the additional capacity obtained from fuel cell charging and regenerative braking. Battery cycle life in hybrid operation has not been determined, therefore, both the measured and projected cycle life for the EV application will be used. These cycle life values are 229 measured and 800 projected for the EV-1300 (10) and 280 measured and 600 projected for the DR150 (12,15). Replacement battery cost is taken as equal to the initial battery cost.

Using the factors above, a total cost per mile for the power plant can be generated for the systems analyzed in Tables VI and VII. A summary of the data derived for the five hybrid systems using a 120V battery system is given in Table VIII.

The PA/lead-acid system is the most costly both in terms of initial cost and of operating cost over the 100,000 mile lifetime of the vehicle. Of the four PEM systems, the nickel-zinc hybrids are approximately $1500 more initially and have a slightly higher total operating cost. This is obviously due to the cost of the battery. Under the scenario used, no fuel cell or battery replacement is required indicating the power plant lifetime is adequate. Thus, initial cost is a major factor and its reduction should be the target of future development.

TABLE VIII

SUMMARY OF 120V BATTERY HYBRID SYSTEM POWER PLANT COSTS

SYSTEM	FUEL CELL COST, $	BATTERY COST, $	METHANOL COST, $/mile	RECHARGE COST, $/mile	OPERATING TOTAL COST, $/mile
PA/Lead-Acid	4293	2161	0.038	0.004	0.11 (0.13*)
PEM/Lead-Acid	2828	2161	0.032	0.002	0.08
PEM/NiZn	2800	3578	0.032	0.002	0.10
PEM/Lead-Acid 10 Gal	2766	2161	0.031	0.002	0.08
PEM/NiZn 10 Gal	2786	3578	0.032	0.002	0.10

*One battery replacement using measured cycle life

A summary of the cost data derived for the four hybrid systems using battery packs sized to meet the UDS peak power requirements is shown in Table IX.

Initial costs for the PEM systems are approximately $1500 less than thosefor the PA systems, most of which is fuel cell cost. Total operating costs are lower for these systems because of the lower power plant weights, which result in improved performance. Based on total operating cost and the ability to operate for the life of the vehicle without battery replacement, the PEM/NiZn hybrid is the preferred system.

All of these systems assume that control equipment to match battery and fuel cell impedances will be available. The cost of this equipment will be in addition to the standard equipment used in the 120V battery systems. This cost is unknown, but could be sufficient to rule out these systems in favor of the 120V hybrids.

TABLE IX

SUMMARY OF REDUCED CAPACITY BATTERY HYBRID SYSTEM POWER PLANT COSTS

SYSTEM	FUEL CELL COST, $	BATTERY COST, $	METHANOL COST, $/mile	RECHARGE COST, $/mile	OPERATING TOTAL COST, $/mile
PA/Lead-Acid	4084	1532	0.036	0.004	0.10 (0.13*)
PA/NiZn	3927	1737	0.035	0.004	0.10 (0.11**)
PEM/Lead-Acid	2615	1479	0.030	0.002	0.07 (0.09**)
PEM/NiZn	2517	1676	0.029	0.002	0.07

* Two battery replacements using measured cycle life
** One battery replacement using measured cycle life

SUMMARY

Fuel cells possess a number of attributes that make them very attractive for transportation applications. Their high efficiency and ability to use non-petroleum fuels addresses the petroleum dependency problem. Their operational simplicity, safety, and low pollution, although not discussed, are features that make them desirable for use in commercial applications. The fuel cell system chosen for a given application must be selected on the basis of performance and type of fuel required. Based on the state-of-development, fuel considerations, and the inherent restrictions imposed by vehicular applications, only acid fuel cells, phosphoric acid and proton exchange membrane, operating on reformed methanol and air are being considered at the present time.

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 use of new fast-response reformers, which are presently being tested, in advanced fuel cell power plants should lead to pure fuel cell systems that produce much better performance in bus operations. In the interim, the use of available batteries with better charge/discharge characteristics in hybrid systems should provide improved bus performance.

For hybrid power systems for passenger cars, the conclusion is that the optimum system is where the nominal fuel cell power equals the average duty cycle power requirement, at least for the UDS. With this choice and using known and projected weights and volumes of the fuel cells and batteries, feasible packaging configurations that give quite satisfactory performance are achieved.

Cost analysis for the bus systems provides cost targets for the fuel cell power plant system that can be addressed by development programs. Improved fuel cell performance and fast-response reformers are areas that should provide new factors for determining allowable fuel cell system costs. In the passenger car case, determination of total operating cost allows system selection. Initial cost will probably be a key factor because life cycle costs are not usually used in passenger car operation to determine economic feasibility. Developmental areas addressing this will be similar to those for the bus power plant.

Finally, simulation studies indicate that it is feasible to use fuel cell or fuel cell/battery hybrid power plants in city buses and passenger cars. Improvements in technology should enhance this feasiblity of using fuel cells in transportation.

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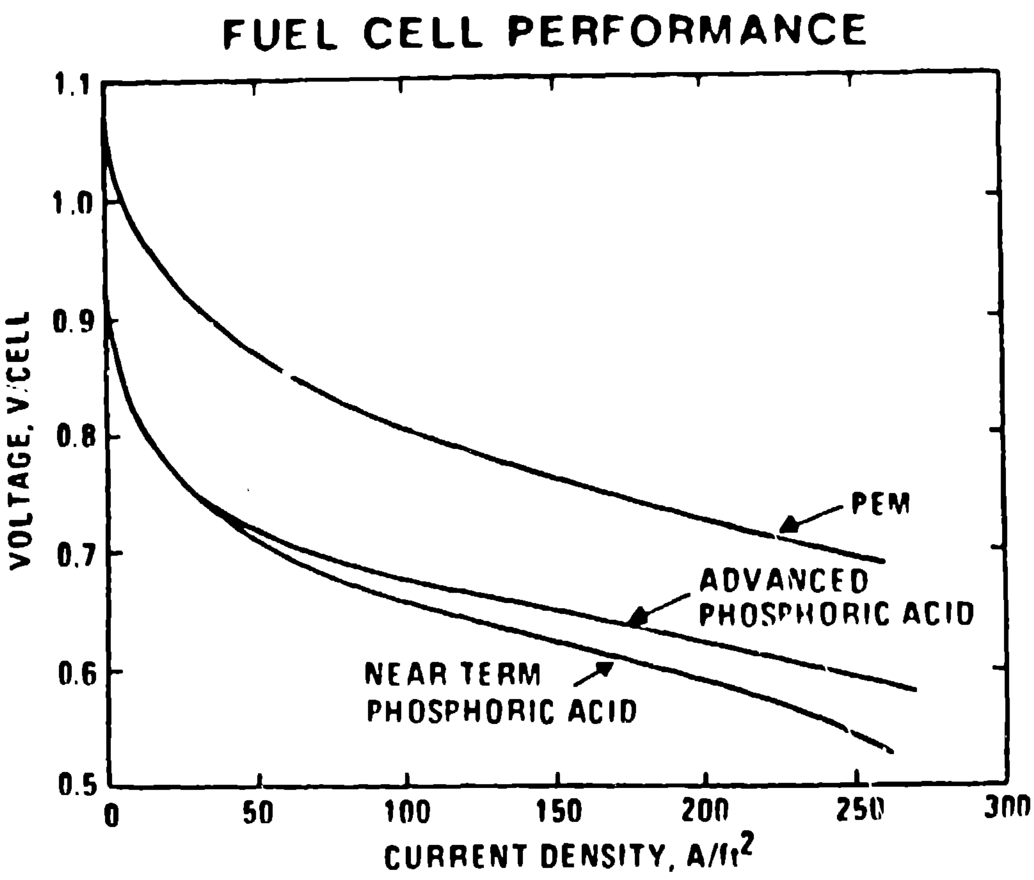

Figure 1

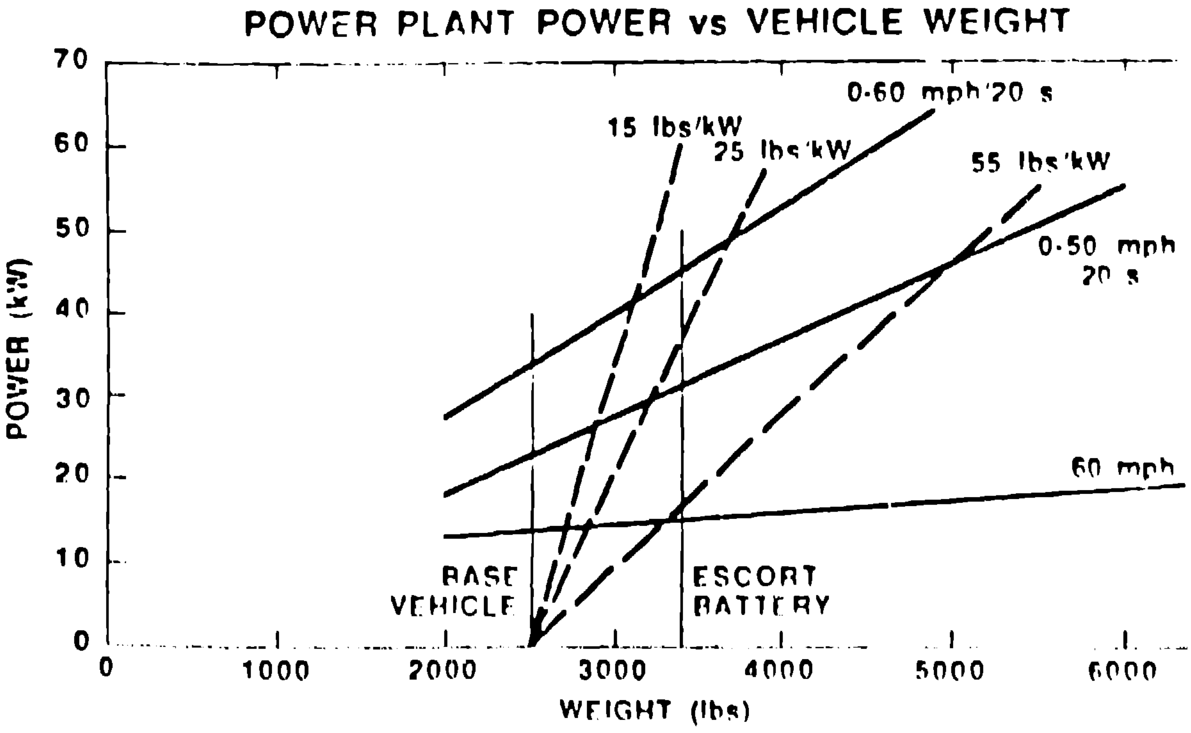

Figure 2