

RECENT ADVANCES IN FUEL CELLS AND THEIR APPLICATION
TO NEW HYBRID SYSTEMS

E. J. Cairns and H. Shimotake

Argonne National Laboratory
9700 S. Cass Avenue
Argonne, Illinois

INTRODUCTION

In our rapidly-advancing technological society, there is an increasing need for versatile sources of electrical energy. Some of the desired characteristics of these power sources are:

1. High specific energy (watt-hours/lb)
2. High specific power (watts/lb)
3. Fast refuel (or recharge)
4. Fast response to load changes
5. Cleanliness (no pollution)
6. Low cost
7. Silence

Some fuel cells have some of the desired characteristics, and some secondary cells have others; no known power source possesses all of them. One possible solution is to take advantage of the desirable characteristics of both fuel cells and secondary cells by using a composite power source containing both of these devices. In considering the characteristics of fuel cells, it becomes clear that some fuel cell systems can provide high specific energy (greater than 500 watt-hours/lb for cells operating on air), none can provide very high specific power (all fuel cell systems are below 30 watts/lb), most can be refueled quickly, some will respond quickly to load changes (systems using reformers respond slowly), most can be made to operate at a very low level of emission of pollutants, none are low-cost yet, and many are quiet. Some of the shortcomings of fuel cells can be compensated for by an appropriate secondary cell having a reasonable specific energy (greater than 40 watt-hours/lb), a high specific power (greater than 150 watts/lb), and fast charge acceptance (15 minutes for full charge). In their present state of development, neither fuel cells nor high specific power, fast-recharge secondary cells are low-cost devices. In applications where the other characteristics are essential, however, a price-premium is justified as for remote power and military and space applications.

The recent advances in fuel-cell development will be summarized below, in order to include the best performance, endurance, and cost estimates in considering some applications. Because fused-salt secondary cells show the most promise for high specific power and high specific energy applications requiring fast charge acceptance, the secondary cells considered will be of this type. Specifically, the Li-Te and Li-Se cells, with which the authors have the most experience, will serve as the basis for the calculations.

RECENT ADVANCES IN FUEL CELLS

In considering the areas where improvement in fuel cells is needed, the three most prominent are: a) Electrocatalysts, primarily as they affect cost and performance, b) Electrode structure, as it affects cost, endurance and weight, and c) Engineering, as it affects endurance, weight, and volume. Of course, improvements in these three areas are desired while maintaining at least the present level of performance.

The fuel cells which are expected to find the most widespread application are those operating on air. For this reason, only cells with air cathodes will be discussed here. In addition, because of the trouble and expense involved in storing hydrogen, either as a liquid or as a gas, only fuel cell systems using fuels normally

stored as liquids will be considered. These fuel cell systems can be classified as indirect (those using a reactor to produce hydrogen which is then consumed in the fuel cell), and direct (those in which the unaltered fuel is fed directly to the cell).

Indirect Fuel Cells

Indirect fuel cell systems can be arranged so that: a) only very pure hydrogen is fed to the anode (most expensive), or, b) hydrogen of almost any degree of purity (including the untreated reformer exit gas) is fed to the anode. Some of the indirect fuel cell systems which have been investigated are diagramed in Figure 1. The indirect systems which use very pure hydrogen at the anode (parts a and b of Figure 1) are the most well-developed and make use of high-performance fuel cells. Furthermore, because of the high reactivity of hydrogen and the absence of chemical and electrochemical complications due to impurities, a great deal of progress toward the elimination of expensive platinoid-element electrocatalysts has been made for these cells.

The amount of platinoid element electrocatalysts necessary in hydrogen fuel cells has been reduced from 35-50 mg/cm² a few years ago^{1,2,3} through intermediate loadings^{4,5} to values as low as 0.5-2 mg/cm² (on each electrode) in low-temperature alkaline systems^{4,5} and 0.5-4 mg/cm² (on each electrode) in low-temperature acid systems.^{8,9,10} This decrease in the amount of platinum required has been made possible largely by the use of electrocatalyst supports such as high-area carbon, ^{6,7,8,9,10} resulting in very small platinum crystallites having a high specific area.

It is not only possible to minimize the amount of platinum in hydrogen anodes, but for alkaline-electrolyte cells, the platinum can be eliminated by using nickel (high-area, ^{11,12} or Raney form^{13,14}) or nickel boride.^{15,16} High area nickel has disadvantages, however, such as the irreversible loss of activity after being used at too high a potential (oxidation of the nickel occurs). Nickel boride, formed in various ways, ^{15,16} seems to be less sensitive to overvoltage excursions than nickel, and may be an acceptable hydrogen anode electrocatalyst for operation near 80°C at a modest performance penalty.¹⁵

It is also possible to eliminate platinoid elements from air cathodes for alkaline electrolyte systems. Some of these cathodes use silver^{7,17,18} or spinels such as CoAl₂O₃, ⁷ or phthalocyanines such as cobalt phthalocyanine¹⁹ instead of platinum, providing an additional saving. It should be noted, however, that the advantage of the more flexible electrocatalyst requirement for the alkaline electrolyte cell is at least partially offset by the need for CO₂ removal from the air (or periodic electrolyte replacement).

Almost as important as the advances in electrocatalyst use are the improvements in electrode structure, particularly at the air cathode. In the last few years, the trend has been towards very thin electrodes (0.006 to 0.03")^{1,2,6} with relatively high porosity^{4,5} providing for limiting current densities of several hundred ma/cm² on air at only moderate air flow rates ^{4,8,9} (1.5-3 times stoichiometric). Thin, highly porous electrodes are also essential in those systems which remove product water by evaporation through the porous electrodes.

The requirement of minimum cell internal resistance has led to the use of thin, porous, absorbent matrices to hold the electrolyte, resulting in inter-electrode distances of 0.010" to 0.030". The use of thin electrodes (about 0.020" each) and thin absorbent electrolyte matrices (0.020") allows the construction of ²⁰ relatively compact fuel batteries, with cell stacks of about seven cells per inch. This stacking factor corresponds to stack power densities in the range 7-8 kw/ft³ for 160 w/ft² cells. The density of the stacks is estimated to be about 140 lb/ft³, corresponding to 18 lb/kw for future fuel cell stacks. The weights and volumes should be increased by 10 to 20 percent for cells with liquid electrolytes.

The present state of fuel cell engineering can be appreciated by consulting the papers describing the design, development and operation of the GM Electrovan^{21,22} which is powered by Union Carbide hydrogen-oxygen cells.²³ This is a

remarkable achievement, especially when one considers the relatively sophisticated control system²⁴ and the high performance of the vehicle. The most notable disadvantage of this fuel-cell powered vehicle is the excessive weight of the fuel cells (3,380 lb!) made necessary by the peak power requirement (160 kw) of five times the nominal rating (32 kw). This weight penalty could be minimized by use of a fast charge, high specific power secondary cell. This point will be discussed in more detail below. Despite the disadvantages, the Electrovan proves that fuel cell engineering has progressed to the point that vehicles can be powered by hydrogen fuel cells and can retain reasonable performance and range.

The combined effect of improved use of electrocatalysts, thinner, high-porosity electrode structures, and small interelectrode distances yields the performances shown in Figure 2. The upper curves correspond to alkaline electrolyte cells, using thin matrices and moderate catalyst loadings (9-10 mg Pt/cm²) on thin, PTFE-bonded electrodes.^{3,5,20} Replacement of the Pt at the anode with Ni₃B¹⁵ yields slightly lower voltages as shown. The next lower curve corresponds to the substitution of H₂SO₄ for KOH as the electrolyte. The poorer performance of oxygen cathodes in acid electrolytes is responsible for this decrease in cell voltage. The next lower set of curves with the somewhat higher slopes corresponds to the use of liquid electrolytes, with larger interelectrode distances and consequently a higher internal resistance.^{1,6,10} The lowest curve of Figure 2 corresponds to the use of dual ion exchange membranes.²⁵ The higher internal resistance of this arrangement is evident.

Based on the results shown in Figure 2, it seems reasonable to adopt the uppermost curves for design purposes, assuming a catalyst loading of 1 mg Pt/cm² (or its cost equivalent of Ni₃B and Ag or CoOAl₂O₃) on each electrode. Only a small performance penalty would be paid if the platinum in the cathode were replaced by silver or CoOAl₂O₃,⁷ and the platinum in the anode by nickel boride.^{15,16} This performance is what would be expected from the cell in any indirect system supplying pure hydrogen (or hydrogen with non-adsorbing inerts, such as N₂) to the anode.

A five-kilowatt indirect system using a KOH electrolyte and an air scrubber has been constructed by Englehard (reformer) and Allis-Chalmers (fuel battery) and has been tested at Fort Belvoir.^{26,27} This system operates on a sulfur-free hydrocarbon fuel (JP 150, a Udex raffinate),²⁷ and uses a silver-palladium alloy diffuser to purify the hydrogen (an expensive method). The operating point was 0.83 V at 135 ma/cm². A second 5 kw indirect system using a silver-palladium diffuser, but methanol as the fuel to the reformer, was constructed by Shell Research, Ltd.²⁸

For indirect systems involving the use of unpurified gases (H₂, CO, CO₂, CH₄, H₂O), as in case c of Figure 1, acid electrolytes must be used if the anode is porous, in order to reject the CO and CO₂. The strong adsorption of CO on platinum, and the low rate of electrochemical oxidation of the CO make platinum an unsuitable anode electrocatalyst at temperatures below about 130°C, as shown by the lowest curve in Figure 3. At higher temperatures, with H₃PO₄ as the electrolyte, Pt will provide adequate performance as shown by the upper curve of Figure 3. At 150°C, about 110 ma/cm² can be obtained at 0.75 V using 90% H₂ and 10% CO with an anode containing 2.8 mg Pt/cm², supported on boron carbide.³ At 85°C, Pt-Ru alloys show moderate activity with CO-containing reformer gases and H₂SO₄ as the electrolyte, as indicated in Figure 3, but the electrocatalyst loadings used (34 mg Pt-Ru/cm²)²⁹ must be considered to be about an order of magnitude too high to be practical. For the present, it appears that the oxidation of reformer gases containing more than a few ppm of CO requires the use of acid electrolytes at temperatures near 150°C. The improvements in CO tolerance shown by Pt-Ru alloys are encouraging, however, and it is expected that alloy catalysts will be improved further, making the use of unpurified reformer gases practical at temperatures below 100°C.

The same thin, highly porous electrode structures found to be useful with hydrogen/air cells are also useful in reformer gas/air cells. The lower performance

obtained from the latter cells is primarily related to electrocatalytic problems at both electrodes, and not electrode structure problems.

Engineering work resulting in the construction of fuel batteries or complete fuel cell systems operating on reformer gas is just beginning. Several systems are probably being built, and only one low-temperature battery has been reported.²⁵ Significant performance losses were observed, with only 20 ppm of CO in the feed to the fuel battery, which used 9 mg Pt/cm² electrodes and H₂SO₄ electrolyte at 65°C (see Figure 3). It is likely that the indirect systems² built in the near future will use fuel cells which operate at temperatures above 100°C, and will have performances like that shown by the uppermost curve in Figure 3.

The molten carbonate cell, operating at temperatures in the range 600 - 750°C is capable of consuming reformer gases containing relatively large amounts of CO (10-20%) with excellent performance. At an operating temperature of 750°C, it is conceivable that the cell and reformer might be integrated in such a manner that the reject fuel cell heat is used by the endothermic reforming reaction, increasing the overall system efficiency. Furthermore, the carbonate cell employs relatively inexpensive electrocatalysts such as nickel at the anode and copper oxide (or silver) at the cathode,³⁰⁻³⁴ making this an economically attractive system. During the last few years, considerable improvements in performance³¹ and operating life^{30,34} have been made, bringing this system to the point where it is ready for an increased engineering effort. A reasonable design point for a molten carbonate system would be 200 ma/cm² at 0.75 V, as shown in Figure 4. The life expectancy for a single cell is now more than six months,³⁰ and 36-cell modules operate for about 1000 hours.³⁵

An interesting recent approach to the indirect fuel cell is the integration of the fuel cell and the reformer, placing the reforming catalyst in the fuel compartment of the cell³⁶ (case d of Figure 1). This is best done when the anode is a non-porous hydrogen diffusion electrode (Ag-Pd activated with Pd black on both sides).³⁶⁻³⁸ These electrodes are expensive, their materials costs being equivalent to that of about 20 mg Pt/cm² for a 0.001" thick electrode activated on both sides.

Because of the fact that the fuel battery and integrated reformer operate at the same temperature (200-250°C, 85% KOH electrolyte), the reject heat from the fuel battery can supply the endothermic heat for the reforming reaction. In addition, since the fuel cell reaction extracts hydrogen directly from the reforming zone, the response of the reformer to the demands of the fuel cell is relatively rapid. Start-up is not very fast, however, and external heating energy must be supplied.

The best-performing integrated system is that operating on methanol,^{36,38} the performance of which is given in Figure 5. The corresponding indirect hydrocarbon cells show poorer performance and short catalyst lifetimes, even at the higher temperature of 250°C,^{36,39} as shown in Figure 5. These systems, especially the methanol system, could gain popularity during the interim period before direct methanol or hydrocarbon cells show high performances at capital costs comparable to those for present hydrogen-air cells.

In choosing among the various indirect systems, the operating requirements of the application will probably dictate the optimum combination of reformer, hydrogen purifier (if any) and fuel battery. For fast start-up, a low-temperature fuel battery is desirable. This may require the use of pure hydrogen (as from a silver-palladium diffuser), but it is possible that a cell using a Pt-Ru anode electrocatalyst could be started quickly from room temperature on unpurified reformer gases. Where steady operation without shut-down is needed, the molten carbonate system probably offers the lowest capital cost and highest efficiency. A reasonable compromise system with medium start-up time and medium cost, using no scrubbers or purifiers would be a cell with 2-3 mg Pt/cm² at the anode, H₃PO₄

electrolyte, and 3-4 mg Pt/cm² at the cathode.³ This seems to be the simplest system in concept, and could be the simplest in practice.

Direct Fuel Cells

The direct fuel cell which shows the highest performance on a liquid fuel is the hydrazine cell. This cell has received more engineering attention than any other except for hydrogen-oxygen.^{40,41} Typical performance curves for hydrazine-air cells are shown in Figure 6. Both platinoid element electrocatalysts^{40,42} (Pt and Pd) and nickel-based electrocatalysts⁴² (high-area nickel and nickel boride) have been used successfully with hydrazine hydrate as the fuel. Because hydrazine reacts with acids, an alkaline electrolyte is necessary. This means that the CO₂ must be removed from the air fed to the cathode. As in the hydrogen cells, thin, porous electrodes are used, and the electrolyte is usually held in a matrix.

Several complete hydrazine fuel cell systems have been built for vehicle applications, including a 20 kw system for an Army M-37 truck.⁴¹ Because nickel boride can be used at the anode and silver or a spinel at the cathode, the hydrazine cell looks promising from a capital cost viewpoint, but the high cost of hydrazine will probably restrict this cell to special applications. Strong points are the admirable performance obtained with relatively simple systems and the use of non-platinoid electrocatalysts.

All other non-hydrogen direct fuel cells show poorer performance than hydrazine cells, and require unreasonably large amounts of precious-metal electrocatalysts. These other systems must still be considered to be in the research stage and should not be included in any designs involving cost as an important criterion for the near-term future.

Several advances in the direct use of carbonaceous fuels are notable, however. A few years ago, large amounts of platinum (~ 50 mg/cm²) were necessary in order to obtain current densities near 100 ma/cm² from propane at cell potentials of 0.2 to 0.3 volt.⁴³⁻⁴⁸ It has been reported recently that electrocatalyst loadings as low as 5 to 10 mg Pt/cm² can be used with propane, while still obtaining current densities of 100 ma/cm² at cell potentials of 0.4 volt.^{49,50,51} Some of the recent data are summarized in Figure 7. The liquid hydrocarbons which yield the highest performance are propane and butane; the higher molecular weight fuels give decreasing performance with increasing molecular weight.^{44,47-49,54} Some of the problems which remain to be solved are the cycling behavior of the anode reaction rate when phosphoric acid is used as the electrolyte,⁵⁵ and the conservation of water, in addition to the obvious problems of electrocatalysis and corrosion.

No presently-known hydrocarbon cells will start up from room temperature, so external heat for start-up must be provided. No appreciable amount of fuel battery or systems work has been done yet, but the time is approaching when this will be appropriate.

The direct methanol cell has not shown the progress that might have been expected of it a few years ago. This cell still requires electrocatalyst loadings of 20 to 40 mg/cm² of platinoid electrocatalysts^{56,57} at the anode. Even with these loadings, the performance is still relatively modest, as shown in Figure 8. In spite of this disadvantage, some engineering work has been completed, resulting in a battery delivering 300 watts⁵⁸, and a compact system delivering about 100 watts at a regulated voltage.⁶⁰

Summary of Fuel Cell Performance

The present state of affairs, with respect to cell choices, reflecting all of the recent advances discussed above incorporating new, low electrocatalyst loadings, and improved performances on air (in some cases estimated by the authors)* is

* All asterisks in the figures identify those current density-voltage curves which have been converted from oxygen performance to air performance by the authors, based on published data.

summarized in Table I. The performance values for the indicated electrocatalyst loadings may be slightly optimistic. The systems which are expected to have the lowest capital cost are the molten carbonate (indirect) and the hydrazine (direct), followed by the reformer gas (indirect) and the integrated methanol reformer-fuel cell. The hydrazine system is the most well-developed, followed by reformer gas (indirect), the other direct cells being farther behind. Direct hydrocarbon and direct methanol cells still contain too much expensive electrocatalyst and require a great deal more engineering work before they can compete with the other systems.

The current status of the systems just discussed is also presented in Table I, together with the authors' estimates of the specific power of the fuel cell stacks and systems (including reformers and plumbing but not fuel and tank) which could be constructed using the present research and engineering results. The specific power values for some of the systems of Table I, together with the specific energy values (watt-hr/lb) of the fuel plus tank allow the direct calculation of specific power (watts/lb) versus specific energy (watt-hr/lb) curves for fuel cell systems containing various weight fractions of fuel cell and fuel. These results are summarized in Figure 9. This figure is particularly useful in selecting fuel cell systems which must meet specific power and energy requirements. This will be discussed in more detail below.

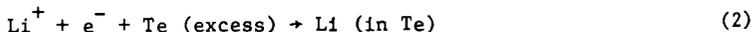
SECONDARY CELLS WITH FUSED-SALT ELECTROLYTES

In order to augment the characteristics of fuel cells to form a high-performance hybrid system, it is necessary that the secondary cell have the ability to deliver large amounts of power per unit weight, on a repeated basis, with no damage to the cell. Specific power values above 100 watts per pound are necessary for many applications, and values as high as 500 watts per pound are desirable. Furthermore, it is necessary that the secondary cell have the ability to accept charge very rapidly without detrimental effects. This feature is important in vehicle propulsion and other applications where fast recharge is essential. A full charge should be achievable in 15 minutes or less for some applications.

The lithium-tellurium and lithium-selenium cells possess both of the characteristics discussed above.^{66,67} These cells are still in the early stages of development, but laboratory-model cells have indicated that these systems have the required fast charge-discharge characteristics and high specific powers.^{61,62}

The lithium-tellurium cell makes use of molten lithium as the anode (negative electrode), fused lithium halides as the electrolyte, and molten tellurium as the cathode (positive electrode). The minimum operating temperature is set by the melting point of the tellurium (449.8°C),⁶⁸ hence thermal insulation must be provided to prevent excessive heat loss. Under normal operating conditions, the internal heat generation will be sufficient to maintain operating temperature, while on stand-by, the cell temperature may be maintained by means of a small heater.

The overall cell reaction is the electrochemical transfer of lithium through the electrolyte into the tellurium, resulting in the formation of a lithium-tellurium alloy at the cathode. On recharge, the lithium is electrochemically extracted from the cathode alloy and returned to the anode compartment. The electrode reactions on discharge are:



Typical steady-state current density-voltage curves for two Li-Te cells operating at 470°C are shown in Figure 10. The open circuit voltage of 1.7-1.8 volts is in good agreement with the values reported by Foster and Liu.⁶⁹ Current densities in excess of 7 amp/cm² were obtained on both charge and discharge. Because of the fact that the open circuit voltages of the cell are in good agreement with the published reversible emf values, and because the voltage-current density data lie

on straight lines, it is concluded that there are no significant activation or concentration overvoltages present. Furthermore, since the slopes of the voltage-current density curves agree with the measured cell resistance, the only appreciable irreversibilities in the operation of the Li-Te cell at current densities up to 8 amps/cm² are those associated with ohmic losses. The ohmic losses arise from the electrolyte resistance and the resistances associated with current collection from the electrodes, primarily the tellurium electrode.

The maximum power density obtained from the cells, whose results are shown in Figure 10, was 3.5 watts/cm², indicating that high power densities can be obtained. The use of charging current densities up to 7 amp/cm² shows that fast recharge rates can be used. In addition, operation at even higher power densities can be achieved for short periods of time. Figure 11 shows the cell performance for short discharge times (within one minute after start of discharge from the fully-charged condition), corresponding to a cathode composition of about 5 a/o Li in Te. The peak power here was 5 watts/cm²; the short-circuit current density was 12.7 amp/cm².

The Li-Te cells were charged and discharged repeatedly over periods of up to 300 hours at temperatures of 450 to 500°C with no signs of degradation. The charge-discharge coulombic efficiencies at the 1-hour and 45-minute rates were 85 to 91 percent.

A lithium-selenium cell was also operated using the same cell parts as for the lithium-tellurium cell. The operating temperature was reduced to 350°C, since the melting point of Se is only 217°C. The current density-voltage curve for this cell is shown in Figure 12.

Based on the voltage-current density curves of Figure 10, secondary batteries can be designed. The designs include bipolar current collectors and rigid paste electrolyte⁷⁰ of minimal thickness (~1 mm). A realistic design, allowing for 5 cells per inch corresponds to a specific energy of 80-100 watt-hr/lb for the Li-Te battery at a 1.5-hr discharge rate, and a specific power of 300 watts/lb at the 1/5 hour rate. The curve of specific power vs specific energy on which these points lie is shown in Figure 9, together with several other curves corresponding to various cell spacings. The method used for calculating the Li-Te battery curves in Figure 9 is explained in detail elsewhere.⁶⁶ These curves and those for the fuel cell systems are used in preliminary design calculations. The important features of Figure 9 are the high specific power values obtainable at reasonably high specific energies, since high-performance hybrid systems depend upon the secondary cell for high peak-power capability.

FUEL CELL-SECONDARY CELL HYBRID SYSTEMS

As can be seen by inspection of Figure 9, fuel cell systems have the ability to deliver low to moderate specific powers for long periods of time, but are not able to provide specific powers in the range of 100 watts/lb or higher. In fact, sustained power densities in excess of 30-35 watts/lb are not possible with present-day air-breathing fuel cell systems. Furthermore, air electrodes in general cannot support heavy overloads for even a few minutes because of oxygen diffusion limitations. This situation results in the necessity of designing fuel cell systems around the peak power requirements of the anticipated application. The disadvantage of this practice is that the fuel cell system then is very heavy and bulky, and has a significantly higher capital cost than would be required if the design were for the average power demand.

By combining a fuel cell system with a high specific power secondary cell, a hybrid system is obtained. The hybrid system is designed to take advantage of the high specific power secondary cell to supply the peak load requirements, while the fuel cell system is designed to meet only the time-average power requirements. This results in a total system which is lighter than either a fuel cell system or a secondary battery designed to do the job alone. In vehicle applications of the

hybrid system, it is possible to take advantage of the fast-recharge characteristics of the secondary cell by using regenerative braking. This practice can recover a large fraction of the energy expended in acceleration, providing an extended vehicle range. Thus, fuel cell-secondary cell hybrid systems provide the following features:

- 1) The high energy:weight ratio of fuel cells.
- 2) The high power:weight ratio of bimetallic cells.
- 3) The high charge-discharge rate of bimetallic cells.

These features permit the design of compact portable power sources, particularly well-suited for applications where power profiles having high peak to average power ratios are encountered. These points will be illustrated in the following section by means of practical designs relating to applications in automobiles, homes, and submarines.

Automobile Power Sources

The electric propulsion of automobiles has been viewed as a potential means for reducing air pollution and other urban irritants.⁷¹ However, because of range limitations due to the low specific energy of present batteries⁶⁶, it is unlikely that an economically competitive electric automobile with a range of more than 40 miles powered by presently-available secondary cells will be available in the near future.

Fuel cells have also been proposed for automobile propulsion, but the severe limitation of a low overload capability requires that the fuel cell system be sized according to peak power requirements, resulting in a heavy, bulky system.

The hybrid design provides a combination of the high specific power capability of secondary cells and the high specific energy of fuel cells. This will be illustrated by the following calculations for an automobile suited for urban driving where an air pollution problem exists and where the fuel cell fails to meet the requirements of the frequent stops and starts in the driving pattern which require a high specific power. For this driving pattern, a light automobile, like the Volkswagen (1960) was chosen. Pertinent data for the Volkswagen (1960)⁷² are listed below:

Unladen car weight *	1,600 lb
Laden car weight (passengers inclusive) *	2,000 lb
Engine brake horsepower	36 hp at 3,700 rpm
Engine weight* (transmission inclusive)	250 lb

* Numbers have been rounded off.

As a design specification for the electrically-powered automobile, the weight of the power source was set at 400 lb or 25% of the unladen car weight, including fuel and tank.

The traction required to drive the automobile consists of tire resistance F_f , air resistance F_a , gravity resistance $Mg \sin \alpha$, where M is the mass of the car and $\sin \alpha$ is grade, and acceleration $M \frac{dv}{dt}$, where v is the car velocity and t is time. The total traction required is therefore:

$$F_t = F_f + F_a + Mg \sin \alpha + M \frac{dv}{dt} \quad (3)$$

The power requirement is obtained by multiplying each term by the car velocity:

$$P_t = P_f + P_a + Mgv \sin \alpha + Mv \frac{dv}{dt} \quad (4)$$

The tire resistance for passenger-car tires, with various percentages of synthetic rubbers lie in the range 1.2 to 1.4% of the load carried, and increases to 1.6-2.0% at 70 mph.⁷³ The air resistance varies with the square of the car velocity and may

be expressed by

$$F_a = C_D \cdot A_f \cdot \rho \frac{v^2}{2g} \quad (5)$$

where C_D is the drag coefficient of the car (0.6 for a Volkswagen), A_f is the frontal area of the car (20 ft² for a Volkswagen) and ρ is the air density (2.38 x 10⁻³ lbs-sec²/ft⁴). From the above equations, it follows that for a Volkswagen at 30 mph on a 1% grade, having a typical acceleration of 15 to 30 mph in 4 seconds requires 26.6 hp, 20.9 hp of which is required for acceleration.

The traction requirements at various speeds calculated from Equation 3 are plotted together with the performance of the Volkswagen (1960) using four standard gear ratios in Figure 14, illustrating the power requirements for this automobile.

The simplified urban driving profile presented in Figure 13a has been adopted for the present design purposes.

The power profile calculated from this figure and Equation 4 is shown in Figure 13b. This power profile shows that in typical urban driving, the power requirement at the wheels consists of

continuous power:	5 hp	(3.75 kw)
pulse power:	25 hp	(18.8 kw)

By providing a 25 hp electric motor, the design will essentially produce the performance of the Volkswagen as can be seen from the curve labeled as 25 hp in Figure 14. Table II summarizes the design specifications for the urban auto which will perform according to the driving profile of Figure 13a.

The design calculations for the urban automobile powered by the hydrogen/air fuel cell - Li-Te secondary cell hybrid system are summarized in Table III. The weight, energy, and power capabilities of this hybrid system are compared to those for other power sources in Table IV. Note that no fuel cell system used alone could meet the specific power requirement of .58 watt/lb. However, if the car is redesigned to allow more weight for the fuel cell, it is possible to build an automobile powered solely by fuel cells as shown in column 3 of Table IV and demonstrated by the Electrovan. The lead-acid battery may be the least expensive power source at present, however, no lead-acid batteries can meet the specific energy required for a practical range (column 4, Table IV). The silver-zinc and lithium-tellurium systems are both very attractive with respect to the power-to-weight ratio. In particular, the fast charge-acceptance capability of the lithium-tellurium cell presents interesting possibilities including regenerative braking,⁷⁴ which is not practical for cells unable to accept charge very rapidly. In the present analysis Ag-Zn batteries show only a marginal range. In summary, Table IV clearly illustrates the superior features of the hybrid system over the other systems.

Power Source for the Home

In many areas, the largest component of the consumer's cost of electricity is the cost of transmission from the power generating station. For the home owner purchasing power from a large utility, this cost is approximately 50% of the consumer price for the electricity. While this cost seems to be a large fraction of the total, it is still acceptable when the economics of central power generation are considered. At present, or in the near future, it is unlikely that any type of fuel cell will be economical enough to be used for supplying electrical power to homes, replacing available power lines. However, because of the very rapid progress made in the last few years, some fuel cells, particularly molten carbonate cells, are becoming attractive in special situations such as areas which are not already serviced by power lines. Under these conditions, fuel cells and hybrid systems may be suitable and economically attractive, with the advantage that the transmission of a fuel such as natural gas is much more economical than transmission of electricity.

The energy and power requirements for a home exhibit a cyclic profile, as shown in Figure 15. Four peaks appear, corresponding to breakfast time, lunch time, afternoon work, and the evening hours. A detailed listing of the power and energy demands,²⁵ is shown in Table V. Because of the high ratio of peak power to average power shown in Figure 15, it is to be expected that a hybrid system will have an advantage over a fuel cell system. It is seen from Table VI that the hybrid system weighs less than half that of the fuel cell system. A lower system weight means in general a lower initial investment and a lower maintenance expense. In addition, one may take advantage of the high flue temperature of the molten carbonate cell in the hybrid system by using it to maintain the operating temperature of the Li-Te cell. The heat balance shown in Figure 16 indicates that under the given conditions assuming 30% fuel cell efficiency,³¹ and using an after-burner to combust the residual hydrogen in the flue, the flue gas from the after-burner will have a thermal energy of approximately 12,000 BTU/hr. This energy can be used to operate an ammonia absorption refrigeration unit to produce approximately 6000 BTU/hr refrigeration, which is more than enough to run several refrigerators and dehumidifiers but not sufficient to provide central air conditioning (which requires 36,000 BTU/hr refrigeration for an average home). The additional energy for central air conditioning and heating would be supplied by direct combustion of natural gas, and would be independent of the hybrid system.

Submarine Power Source

The use of fuel cells for propulsion of combat submarines is rather unlikely in view of the almost unlimited submergence capability of nuclear-powered submarines. However, many unique features of fuel cells make them attractive for special-purpose submarines. Some of the attractive features are: low fuel and oxidant weight requirements resulting in smaller displacement vehicles with greater depth capability, quiet operation, and simplicity. From the point of view of buoyancy and weight-displacement ratio, the high energy density of fuel-cell systems makes them very attractive in applications where weight-to-energy and volume-to-energy ratios are critical. Although secondary cells are superior from the standpoint of power-to-weight ratio, they are only suited for missions of a few hours' duration. As the mission length increases to days or weeks, the weight of the battery pack increases much more rapidly than that of fuel cell systems.

A power source for a small submarine requiring 10^3 kw of power for propulsion and 10^4 kw as pulse power for sonar can make good use of the fast-charge fast-discharge capabilities of the Li-Te cell, as shown by the results in Table VII.

Other Applications

As illustrated in the preceding three examples, the hybrid system surpasses the other energy and power sources, including the system with a fuel cell alone or storage batteries alone in applications where periodic high peak energy demands exist. Since the bimetallic battery is capable of being charged and discharged at high rates, it can be combined with a regenerative braking system which recovers a part of the energy which would otherwise be wasted. These unique features of the hybrid system make many possible applications for the fuel cell much more attractive. For example, industrial trucks, commuter buses, commuter trains, passenger boats, speed boats, submarines, hydrofoil boats, portable communication units, and electrolytic machining equipment are all potential applications of fuel cell-high rate secondary cell hybrid systems.

CONCLUSIONS

The recent advances in fuel cells have placed them in a much more competitive position than they were just a few years ago. The previous requirements for large amounts of platinoid metal electrocatalyst have been drastically reduced to the point where platinoid elements can be eliminated from hydrogen-air cells using alkaline electrolytes, and only 1-4 mg/cm² of platinoid elements are required when acid electrolytes are used in hydrogen-air cells. The direct use of unpurified reformer gases (containing more than about 20 ppm CO) is presently only

feasible with low-loading (< 5 mg platinoid metal/cm²) electrodes at temperatures above 130°C. The direct use of hydrocarbon fuels is not yet practical, although very encouraging progress has been made, reducing the electrocatalyst loadings by a factor of about 10 from the original requirements of a few years ago. Molten carbonate cells have improved significantly in both performance and endurance, to the point where they can compete with other fuel cells on a performance basis, and are most attractive from an economic viewpoint.

The choices among the most advanced fuel cells are governed by the specific requirements of each application. For simplicity and high power density, direct hydrazine cells are attractive; for use with conventional carbonaceous fuels, indirect systems operating either on pure or impure hydrogen appear to be the best at present. In choosing between acid and alkaline electrolytes, the gain in system weight due to the necessary air scrubber for the alkaline electrolyte is counterbalanced by the lower performance of the air electrode in the acid system, so that the choice should be based on system simplicity (acid) or system cost (alkaline).

Since fuel cells are still relatively low specific power devices (maximum of 30 watt/lb for a system), the specific power requirements of many applications cannot be satisfied by fuel cell systems, unless a method is available for providing the peak power. Design calculations indicate that a fuel cell-high rate secondary cell hybrid system should provide the ability to meet the demands of high peak-to-average power profile with a system weight lower than that available using either fuel cells or secondary cells alone. These hybrid systems provide an attractive opportunity for the early use of fuel cells in high specific power applications.

Work performed under the auspices of the U. S. Atomic Energy Commission, operated by the University of Chicago under Contract No. W-31-109-eng-38.

ACKNOWLEDGMENTS

We thank Mr. G. L. Rogers for his help in performing the experiments. The encouragement and support of Drs. A. D. Tevebaugh and R. C. Vogel are appreciated. Mr. B. S. Baker of the Institute of Gas Technology kindly provided some of the information relating to power demands for homes.

References

1. L. W. Niedrach and H. R. Alford, J. Electrochem. Soc., 112, 117 (1965).
2. W. P. Colman, D. Gershberg, J. DiPalma, and R. G. Haldeman, in Proc. 19th Ann. Power Sources Conf., PSC Publications Committee, Red Bank, N. J., (1965).
3. G. R. Frysinger, in 20th Ann. Power Sources Conf., PSC Publications Committee, Red Bank, N. J. (1966).
4. H. I. Zeliger, J. Electrochem. Soc., 114, 236 (1967).
5. R. G. Haldeman, W. P. Colman, S. H. Langer, and W. A. Barber, in "Fuel Cell Systems", Adv. in Chem. Ser. 47, R. F. Gould, Ed., American Chemical Society, Washington, D. C. (1965).
6. M. B. Clark, W. G. Darland, and K. V. Kordesch, Electrochem. Tech., 3, 166 (1965).
7. K. V. Kordesch, in "Hydrocarbon Fuel Cell Technology", B. S. Baker, Ed., Academic Press, New York (1965).
8. E. J. Cairns and E. J. McInerney, in "Technical Summary Report No. 9, ARPA Order No. 247, Contract No. DA-44-009-AMC-479(T), to USAERDL, Jan. 1 - June 30, 1966, AD 640, 521.
9. W. T. Grubb and L. H. King, in "Technical Summary Report No. 9", ARPA Order No. 247, Contract No. DA-44-009-AMC-479 (T), to USAERDL, Jan. 1 - June 30, 1966, AD 640, 521.
10. M. A. Christopher, in Proc. 20th Ann. Power Sources Conf., PSC Publications Committee, Red Bank, N. J., (1966).
11. A. M. Adams, F. T. Bacon, and R. G. H. Watson, in "Fuel Cells", W. Mitchell, Jr., Ed., Academic Press, New York (1963).
12. R. A. Wynveen and T. G. Kirkland, in Proc. 16th Ann. Power Sources Conf., PSC Publications Committee, Red Bank, N. J. (1962).
13. E. W. Justi, Proc. IEEE, 51, 784 (1963).
14. E. W. Justi and A. W. Winsel, "Cold Combustion Fuel Cells", Franz Steiner, Publisher, Wiesbaden (1962).
15. R. Jasinski, in Proc. 18th Ann. Power Sources Conf., PSC Publications Committee, Red Bank, N. J., (1964).
16. I. Lindholm, in Proc. International Meeting on The Study of Fuel Cells, SERAI, Brussels, June 21-24, 1965.
17. J. Platner, D. Ghere, and P. Hess, in Proc. 19th Ann. Power Sources Conf., PSC Publications Committee, Red Bank, N. J. (1965).
18. H. M. Dittman, E. W. Justi, and A. W. Winsel, in "Fuel Cells", Vol. 2, G. J. Young, Ed., Reinhold, New York (1963).
19. R. Jasinski, J. Electrochem. Soc., 112, 526 (1965).
20. R. F. Buswell, in Proc. 19th Ann. Power Sources Conf., PSC Publications Committee, Red Bank, N. J. (1965).

21. C. Marks, E. A. Rishavy and F. A. Wyczalek, Presented at Automotive Eng'g Congress and Exposition, Detroit, Jan. 9-13, 1967, SAE Paper No. 670176.
22. F. A. Wyczalek, D. L. Frank and G. E. Smith, Presented at Automotive Eng'g Congress and Exposition, Detroit, Jan. 9-13, 1967, SAE Paper No. 670181.
23. C. E. Winters and W. L. Morgan, Presented at Automotive Eng'g Congress and Exposition, Detroit, Jan. 9-13, 1967, SAE Paper No. 670182.
24. P. D. Agarwal and I. M. Levy, Presented at Automotive Eng'g Congress and Exposition, Detroit, Jan. 9-13, 1967, SAE Paper No. 670178.
25. F. B. Leitz, W. Glass and D. K. Fleming, in "Hydrocarbon Fuel Cell Technology", B. S. Baker, Ed., Academic Press, New York (1965).
26. T. G. Kirkland and W. G. Smoke, Jr., in Proc. 19th Ann. Power Sources Conf., PSC Publications Committee, Red Bank, N. J. (1965).
27. T. G. Kirkland, in Proc. 20th Ann. Power Sources Conf., PSC Publications Committee, Red Bank, N. J. (1966).
28. K. R. Williams, Ed., "An Introduction to Fuel Cells", Elsevier, New York (1966).
29. L. W. Niedrach, D. W. McKee, J. Paynter, and I. F. Danzig, Presented at Electrochem. Soc. Meeting, Philadelphia, Oct. 1966, Abstr. No. 14; See also Extended Abstracts of The Battery Div., 11, 32 (1966).
30. G. H. J. Broers and M. Schenke, in "Hydrocarbon Fuel Cell Technology", B. S. Baker, Ed., Academic Press (1965).
31. B. S. Baker, L. G. Marianowski, J. Zimmer and G. Price in "Hydrocarbon Fuel Cell Technology", B. S. Baker, Ed., Academic Press, New York (1965).
32. A. D. S. Tantram, A. C. C. Tseung, and B. S. Harris, in "Hydrocarbon Fuel Cell Technology", B. S. Baker, Ed., Academic Press, New York (1965).
33. J. Millet and R. Buvet., in Proc. Journées Internationales d'Etude Des Piles A Combustible, SERAI, Brussels, June, 1965.
34. I. Trachtenberg, in "Hydrocarbon Fuel Cell Technology", B. S. Baker, Ed., Academic Press, New York (1965).
35. J. Truitt, in Proc. Journées Internationales d'Etude Des Piles A Combustible, SERAI, Brussels, June, 1965.
36. M. A. Vertes and A. J. Hartner, in Proc. Journées Internationales d'Etude Des Piles A Combustible, SERAI, Brussels, June, 1965.
37. S. M. Chodosh, N. I. Palmer, and H. G. Oswin, in "Hydrocarbon Fuel Cell Technology", B. S. Baker, Ed., Academic Press, New York (1965).
38. A. J. Hartner and M. A. Vertes, in Preprints of the AIChE-ICChem.E Joint Meeting, London, June 13-17, 1965, Paper 5.3.
39. D. P. Gregory and H. Heilbronner, in "Hydrocarbon Fuel Cell Technology", B. S. Baker, Ed., Academic Press, New York (1965).
40. P. Terry, J. Galagher, R. Salathe, and J. O. Smith, in Proc. 20th Power Sources Conf., PSC Publications Committee, Red Bank, N.J. (1966).

41. E. A. Gillis, in Proc. 20th Ann. Power Sources Conf., PSC Publications Committee, Red Bank, N. J. (1966).
42. R. Jasinski, Electrochem. Tech. 3, 130 (1965).
43. H. Binder, A. Kohling, H. Krupp, K. Richter, and G. Sandstede, J. Electrochem. Soc., 112, 355 (1965).
44. W. T. Grubb and C. J. Michalske, in Proc. 18th Ann. Power Sources Conf., PSC Publications Committee, Red Bank, N. J. (1964).
45. E. J. Cairns, Nature, 210, 161 (1966).
46. E. J. Cairns, in "Hydrocarbon Fuel Cell Technology", B. S. Baker, Ed., Academic Press, N. Y. (1965).
47. E. J. Cairns, Presented at San Francisco Meeting of the Electrochemical Society, May, 1965, Abstract No. 140; See also Extended Abstracts of the Electro-Organic Division, 2, 6 (1965); J. Electrochem. Soc., 113, 1200 (1966).
48. E. J. Cairns, and G. J. Holm, Presented at Washington, D. C. Meeting of the Electrochem. Soc., Oct. 1964, Abstract No. 30; See also Extended Abstr. of the Battery Div., 9, 75 (1964).
49. E. J. Cairns and E. J. McInerney, J. Electrochem. Soc., Submitted; See also Extended Abstracts of the Industrial Electrolytics Div., 2, 1 (1966).
50. E. J. Cairns and E. J. McInerney, Presented at Electrochem. Soc. Meeting, Philadelphia, Oct. 9-14, 1966, Abstract No. 8; See also Extended Abstracts of the Battery Div., 11, 19 (1966).
51. O. J. Adlhart and A. J. Hartner, in Proc. 20th Ann. Power Sources Conf., PSC Publications Committee, Red Bank, N. J. (1966).
52. W. R. Epperly, in Proc. 19th Ann. Power Sources Conf., PSC Publications Committee, Red Bank, N. J. (1965).
53. G. R. Frysinger, in Proc. 19th Ann. Power Sources Conf., PSC Publications Committee, Red Bank, N. J. (1965).
54. E. J. Cairns, Science, 155, 1245 (1967).
55. E. R. White and H. J. R. Maget, in Proc. 19th Ann. Power Sources Conf., PSC Publications Committee, Red Bank, N. J. (1965).
56. E. J. Cairns and D. C. Bartosik, J. Electrochem. Soc., 111, 1205 (1964).
57. B. L. Tarmy, in Proc. 19th Ann. Power Sources Conf., PSC Publications Committee, Red Bank, N. J. (1965).
58. O. J. Adlhart, in Proc. 19th Ann. Power Sources Conf., PSC Publications Committee, Red Bank, N. J. (1965).
59. K. R. Williams, M. R. Andrew, and F. Jones, in "Hydrocarbon Fuel Cell Technology", B. S. Baker, Ed., Academic Press, New York (1965).
60. G. Ciprios, in Proc. Intersociety Energy Conversion Engineering Conf., Amer. Inst. Aeronautics and Astronautics, New York (1966).

61. G. E. Evans, in Extended Abstracts of the Symp. on Power Systems for Electric Vehicles, Columbia Univ., N. Y., April, 1967.
62. A. Levy, "Final Tech. Report", Contract No. DA-44-009-AMC-747(T), to USAERDL, July 27, 1964 - July 27, 1965, AD 473143L.
63. L. W. Niedrach and I. B. Weinstock, Electrochem. Tech., 3, 270 (1965).
64. N. I. Palmer, B. Lieberman and M. A. Vertes, in "Hydrocarbon Fuel Cell Technology", B. S. Baker, Ed., Academic Press, New York (1965).
65. H. Binder, A. Köhling and G. Sandstede, in "Hydrocarbon Fuel Cell Technology", B. S. Baker, Ed., Academic Press, New York (1965).
66. H. Shimotake and E. J. Cairns, Presented at the Intersociety Energy Conversion Engineering Conf., Miami Beach, August, 1967.
67. H. Shimotake, G. L. Rogers and E. J. Cairns, Presented at Electrochem. Soc. Meeting, Chicago, October, 1967.
68. A. D. Tevebaugh and E. J. Cairns, J. Chem. Eng. Data, 9, 172 (1964).
69. M. S. Foster and C. C. Liu, J. Phys. Chem., 70, 950 (1966).
70. G. H. J. Broers, in "Fuel Cells", A CEP Technical Manual, Amer. Inst. of Chem. Engrs., New York (1963).
71. Bureau of Power, Federal Power Commission "Development of Electrically Powered Vehicles" (February 1967).
72. Volkswagenwerk Ag., "Instruction Manual Sedan and Convertible" (1959).
73. N. MacCoull, in "Mechanical Engineer's Handbook", T. Baumeister, Ed., 6th ed., McGraw-Hill, New York (1958), p. 11-5.
74. W. G. Hudson, in "Mechanical Engineer's Handbook", T. Baumeister, Ed., 6th ed., McGraw-Hill, New York (1958), p. 10-4.
75. F. R. Innes, in "Standard Handbook for Electrical Engineers", A. E. Knowlton, Ed., 9th ed., McGraw-Hill, New York (1957) p. 17-622.
76. Am. Soc. Heating, Refrig. and Air-Cond. Engrs., "ASHRAE Guide and Data Book Fundamentals and Equipment for 1965 and 1966", p. 486.

TABLE I
Estimated Performances for Some Fuel Cell Systems

Index	System	Anode $\frac{mg}{cm^2}$	Electrolyte	Cathode $\frac{mg}{cm^2}$	$\frac{mA}{cm^2}$	t °C	E_{volt}	i $\frac{mA}{cm^2}$	Operating point	Stack Life, Hr	Specific Power $\frac{W}{lb}$	Stack System	Remarks	References
HC Fuel/Reformate/H ₂ /Air	Pt/C	1	KOH, Matrix	Pt/C	1	80	0.80	200	10 ³	55	25	Air scrubber; Ag-Pd diffuser.	3, 6, 7, 17, 20, 22, 23, 26, 27	
HC Fuel/Reformate/H ₂ /Air	Ni ₂ B	10	KOH, Matrix	Ag/C	1	80	0.80	140	10 ³	38	20	Air scrubber; Ag-Pd diffuser.	6, 7, 12, 15-20	
HC Fuel/Reformate/H ₂ /Air	Pt/C	1	H ₂ SO ₄ , Matrix	Pt/C	2-3	80	0.70	150	10 ³	36	23	Ag-Pd diffuser.	3, 4, 8, 9, 10, 25, 29	
H ₂ /H ₂ -H ₂ /Air	Pt/C	1	KOH, Matrix	Pt/C	1	80	0.80	200	10 ³	55	30	Air scrubber.	3, 6, 7, 17, 20-23, 26, 27, 62	
HC Fuel/Reformate/Air	Pt/C	2-3	H ₃ PO ₄	Pt/C	2-3	150	0.70	150	10 ³	36	23		3, 51	
HC Fuel/Reformate/Air	Pt-Ru	34	H ₂ SO ₄	Pt/C	2-3	85	0.60	150	?	31	21	High catalyst loading.	29, 63	
HC Fuel/Reformate/Air	Ni	20	(LINAK) ₂ CO ₃	CuO	20	650	0.80	150	10 ³	12	10	Inexpensive, but heavy.	30-35	
CH ₃ OH/Integrated Reformer/Air	Pd	5	KOH	NiO/Ni	100	200	0.70	190	10 ³	21	16	Ag-Pd anode; air scrubber.	36-38, 64	
HC/Integrated Reformer/Air	Pd	5	KOH	NiO/Ni	100	250	0.75	80	2x10 ²	9.6	8	Ag-Pd anode; air scrubber.	36, 39	
Direct H ₂ /Air	Ni ₂ B	10	KOH, Matrix	Ag/C	2	80	0.80	150	2x10 ³	42	30	Air scrubber.	40-42	
CH ₃ OH/Air	Pt-Ru	20-40	H ₂ SO ₄	Pt/C	10	70	0.40	50	10 ³	7	6	Too much Pt; low power.	57-60	
CH ₃ OH/Air	Pt-Ru	20-40	Cs ₂ CO ₃	Ag/C	2-3	125	0.40	50	>6x10 ²	7	6	Too much Pt; low power.	7, 56, 65	
LPG/Air	Pt/C	5-10	H ₃ PO ₄	Pt/C	3	150	0.50	60	?	10	8	Too much Pt; low power.	9, 44, 51-53, 55	
LPG/Air	Pt/C	5-10	HF	Pt/C	3	105	0.50	60	?	10	8	Too much Pt; low power.	8, 45-50	

* This is the weight of electrocatalytically active material only; e.g., Pt, Ni₂B, etc.

† The estimates are for systems of 10-50 kw power output.

** Includes catalyst in reforming anode.

TABLE II

Design Specifications for Power Sources
For a Light Urban Automobile.

<u>Design Requirement</u>	
Unladen car weight	1600 lb
Laden car weight	2000 lb
Maximum speed on level road	60 mph
Acceleration 0 to 30 mph	8 sec
Brake horsepower (pulse)	25 hp
Power source (pulse)	23.2 kw
Brake horsepower (continuous)	5 hp
Power source (continuous)	4.65 kw
Weight allowance for power source*	400 lb
System specific power (peak)	58 watt/lb

* Exclusive of motor, controls and gear train. The motor and controls will weigh 90 lb.²⁴

TABLE III

Hybrid System for the Urban AutomobileFuel Cell

System $N_2H_4 \cdot H_2O/Air$	
Continuous power required	4.65 kw
Specific power of fuel cell	30 watt/lb (From Table I)
Weight for 4.65 kw	155 lbs

Battery

System Li-Te	
Power Requirement	23.2 kw - 4.65 kw = 18.55 kw
Design specific power (with 3.6 cell per inch from Fig. 9)	300 watt/lb
Specific energy	58 watt-hr/lb
Weight for 18.55 kw	62 lb
Energy stored	(58)(62) = 3.6 kw-hr

Fuel and Tank

Weight allowance	400 - 155 - 62 = 183 lb
Energy available	(183)(680.2)* = 125 kw-hr
Total energy available	3.6 + 125 = 128.6 kw-hr
System specific energy	$\frac{(128.6)(10)^3}{400} = 322$ watt-hr/lb
System specific power (peak)	$\frac{(23.2)(10)^3}{400} = 58$ watt/lb
Range in the typical urban driving (from Figure 13a)	(128.6 kw-hr)(3.75 miles/kw hr) = 481 miles

* Specific energy of fuel and tank for the $N_2H_4 \cdot H_2O/Air$ fuel cell is taken as 680.2 watt-hr/lb.

TABLE IV

Comparison of Various Electric Power Sources for an Urban Automobile

<u>System</u>	<u>Hybrid</u>	<u>Fuel Cell</u>	<u>Lead-Acid</u>	<u>Ag-Zn</u>	<u>Li-Te</u>
	$N_2H_4 \cdot H_2O/Air$ and Li-Te	$N_2H_4 \cdot H_2O/Air$			
<u>Weight</u>					
Fuel cell and fuel, lb	338	970	-	-	-
Battery, lb	62	-	400	400	400
Total, lb	400	970	400	400	400
<u>System Power</u> , kw	23.2	23.2	23.2	23.2	23.2
<u>System Energy</u> , kw-hr	128.6	66	0.96	28	56
<u>Range</u> *, miles	481	246	3.6	105	210
<u>Recharging time</u>	<15 min	<15 min	> 8 hr	>8 hr	<15 min

* Based on a typical urban driving profile shown in Figure 13 a, 3.75 miles/kw-hr is obtained.

TABLE V

Power Requirements for a Home

<u>Continuous Loads</u>	<u>Thermal BTU/Hr</u>	<u>Electric, Watts</u>	<u>Duration, Hr</u>
Heating ⁷⁶	80,000	-	24
Home appliances	-	1,000	24
<u>Pulse Loads</u>			
Cooking	10,000	-	2
Household chores	-	2,000	0.5
Clothing dryer	15,000	-	0.5
Home appliances	-	3,000	0.5
TV and Radio	-	600	7
Lights	-	1,000	7

TABLE VI

Designs of Power Sources for a HomeDesign Requirements

Electric power and energy requirements:

Continuous power	1 kw
Pulses integrated over 24 hr period	22.5 kwh
Energy of largest pulse	16 kwh
Peak pulse power	6.6 kw

Calculations are made for both hybrid system and fuel cell system.

Hybrid System

Fuel cell system: Molten carbonate cell with a reformer.

Cell operating temperature	650°C
Fuel: Natural gas (methane) from gas supply line	
Average power requirement:	$\frac{24 + 22.5}{24} = 1.95 \text{ kw}$
Specific power of the fuel cell system (Table I) (reformer inclusive)	10 watt/lb
Weight:	$(1.95)(10)^3 / (10) = 195 \text{ lb}$

Battery system: Li-Te

Peak power requirement	4.65 kw
Energy storage requirement (from Figure 15)	8 kwh

From the definition of specific energy, σ_E and specific power, σ_p^*

$$\frac{4.65}{\sigma_p} = \frac{8}{\sigma_E} \quad \text{or} \quad \sigma_p = 0.58 \sigma_E$$

By finding the intersection of the above equation and the Li-Te line in Figure 9, we have the following points for the Li-Te battery with 2.1 cells per inch.

specific energy	136 watt-hr/lb
specific power	68 watt/lb
weight required	$(8)(10)^3 / (136) = 59 \text{ lb}$
combined weight	$195 + 59 = 254 \text{ lb}$

Fuel Cell System

Fuel cell:	molten carbonate cell with a reformer
Fuel:	natural gas (methane)
Power requirements:	6.6 kw
Specific power:	= 10 watt/lb (reformer inclusive)
Weight:	$(6.6)(10)^3 / (10) = 660 \text{ lb.}$

* σ_E is watt-hr/lb and σ_p is watt/lb.

TABLE VII

Designs of Power Sources for Small SubmarinesDesign Requirements

Search, rescue, salvage or research missions with sonars

Continuous power requirement:	1,000 kw _A 48 hours
Total propulsion energy:	4.8×10^4 kw-hr
Pulse power requirement:	10,000 kw for 10 seconds
	1,000 pulses at 100 second intervals
Total pulse energy:	2.78×10^4 kw-hr
Total mission energy requirement:	7.58×10^4 kw-hr

Hybrid System

Battery

System	Li-Te
Power requirement	10,000 kw
Energy requirement for a sonar pulse	27.8 kw-hr
Specific power (for the Li-Te battery with 8.5 cells per inch)	500 watt/lb
Weight for 10,000 kw	20,000 lb
Specific energy (from Figure 9)	20 watt-hr/lb
Energy stored	$(20,000)(20) = 400$ kw-hr

The stored energy is more than sufficient
to produce several pulses without recharge.

Fuel Cell

System	Ammonia (Dissociator)/Air
Energy requirement	7.58×10^4 kw-hr
Power requirement	$\frac{7.58 \times 10^4}{48} = 1,580$ kw

From the definition of specific energy and power

$$\frac{7.58 \times 10^4}{\sigma_E} = \frac{0.158 \times 10^4}{\sigma_P} \quad \text{or} \quad \sigma_P = 0.0208 \sigma_E$$

By drawing the above relation on the coordinates of Figure 9,
we find the line intersects with the ammonia (dissociator)/air
line at the following points

Specific energy	605 watt-hr/lb
Specific power	12.5 watt/lb

These numbers correspond to the fuel cell system consisting of
43 w/o fuel cell and 57 w/o tank plus fuel

Weight required	$\frac{7.58 \times 10^7}{605} = 1.25 \times 10^5$ lb
Power available	$1.25 \times 10^5 \times 12.5 \times 10^{-3} =$ 1.56×10^3 kw

This power is sufficient to meet the mission requirement.

Total system weight	$= (0.2 + 1.25)10^5 = 145,000$ lb
---------------------	-----------------------------------

TABLE VIII

Submarine Power Source Designs

<u>System</u>	<u>Hybrid</u>	<u>Fuel Cell</u>	<u>Ag-Zn</u>	<u>Li-Te</u>
	NH ₃ /Air and Li-Te	NH ₃ /Air	Ag-Zn	Li-Te
<u>Weight</u>				
Fuel cell, lb	125,000	398,000	-	-
Battery, lb	20,000	-	1,080,000	525,000
Total, lb	145,000	398,000	1,080,000	525,000
<u>System Power</u> , Mw	10	10	10	10
<u>System Energy</u> , Mw-hr	75.8	75.8	75.8	75.8

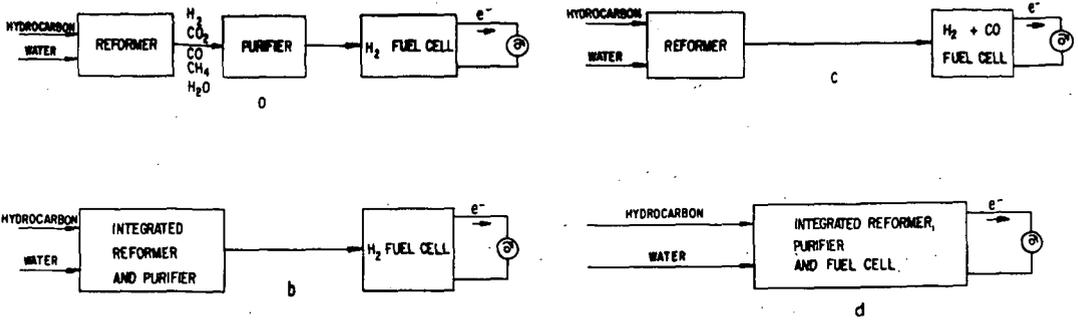


Fig. 1 Some indirect hydrocarbon fuel cell systems.

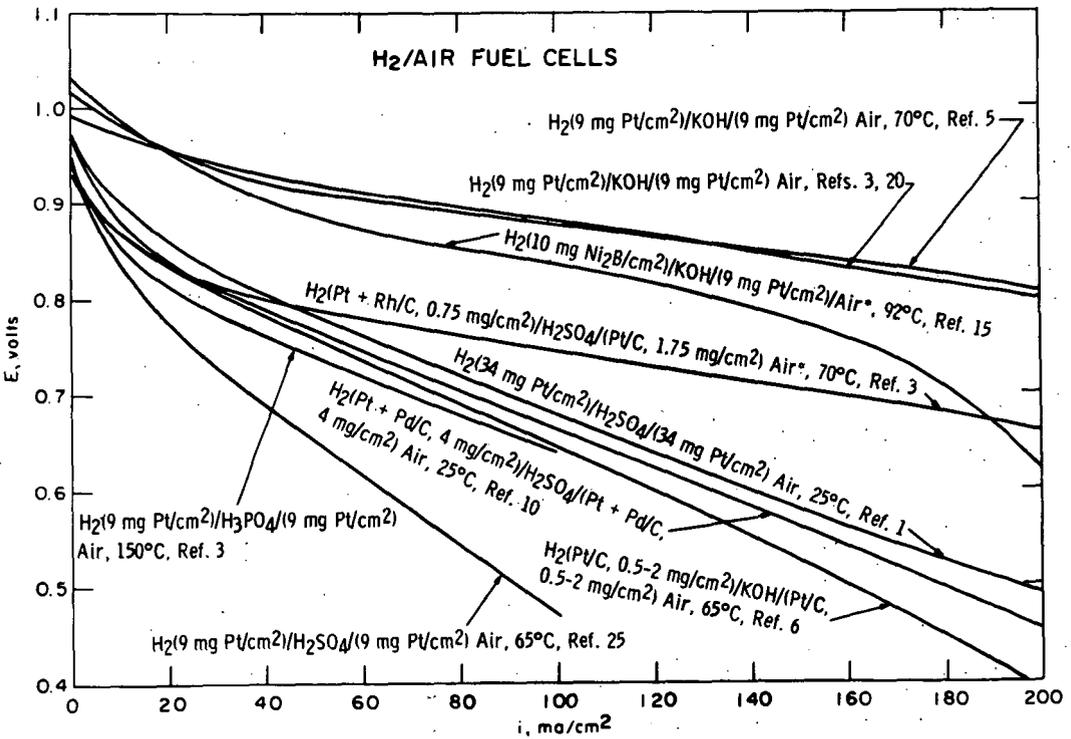


Fig. 2 Voltage-current density curves for hydrogen/air fuel cells.

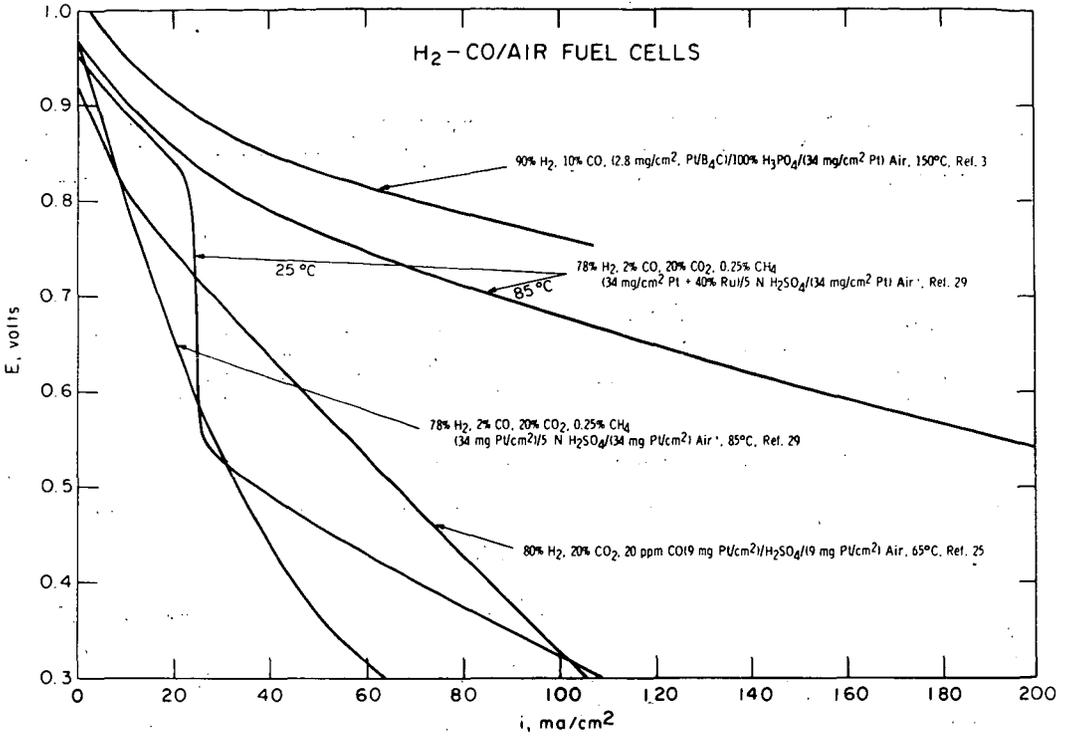


Fig. 3 Voltage-current density curves for H₂-CO/air fuel cells.

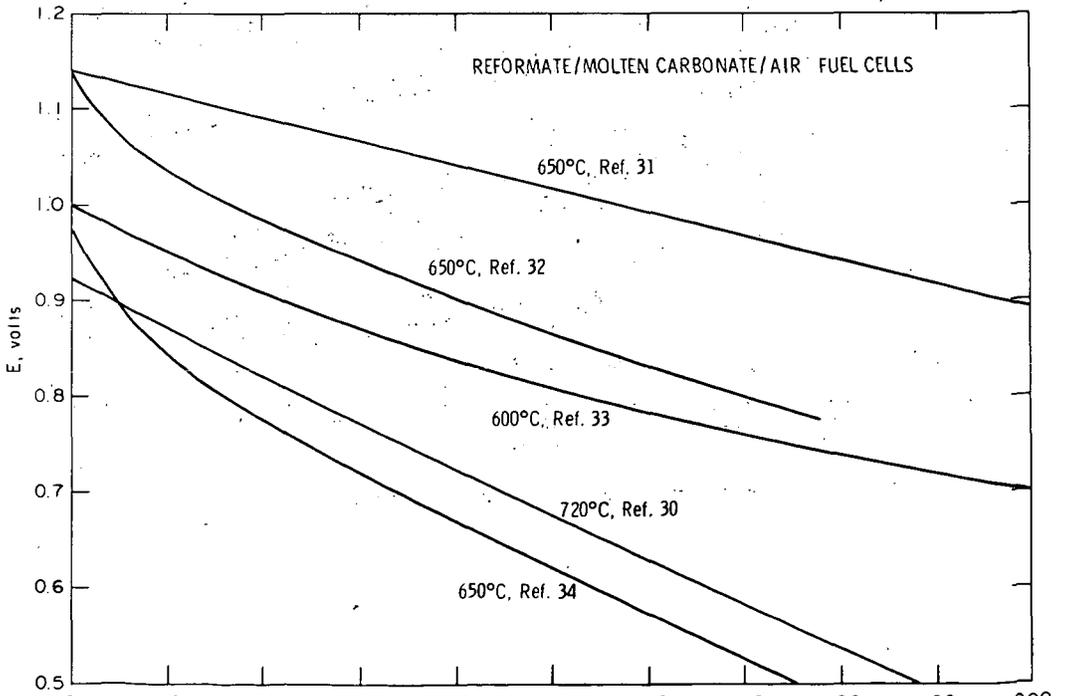


Fig. 4 Voltage-current density curves for molten carbonate cells operating in reformer gases and air.

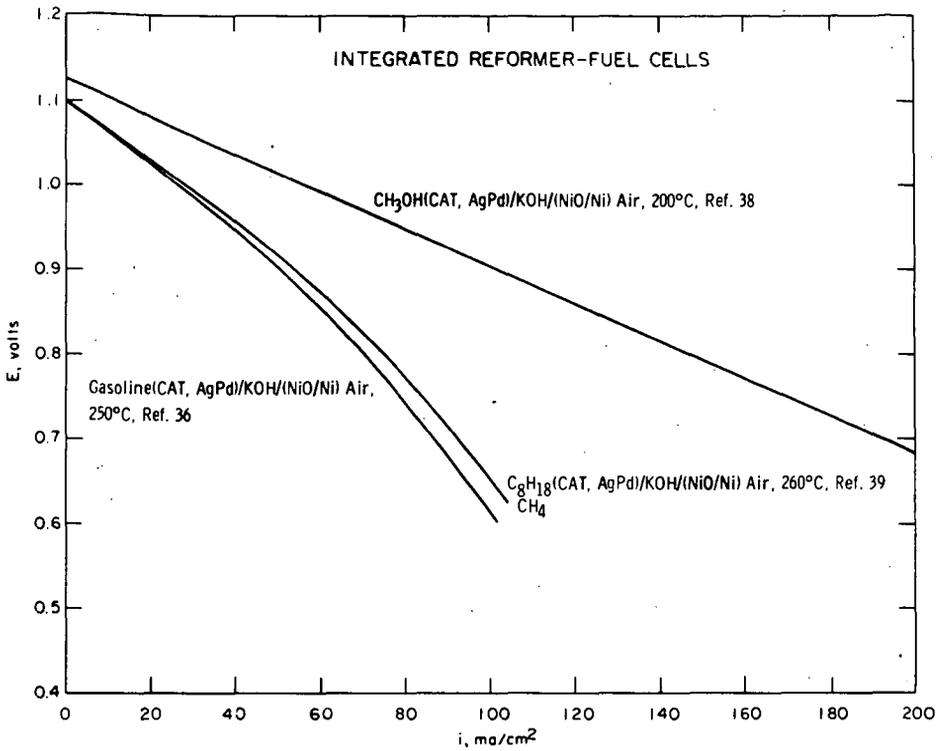


Fig. 5 Voltage-current density curves for integrated reformer/air fuel cells.

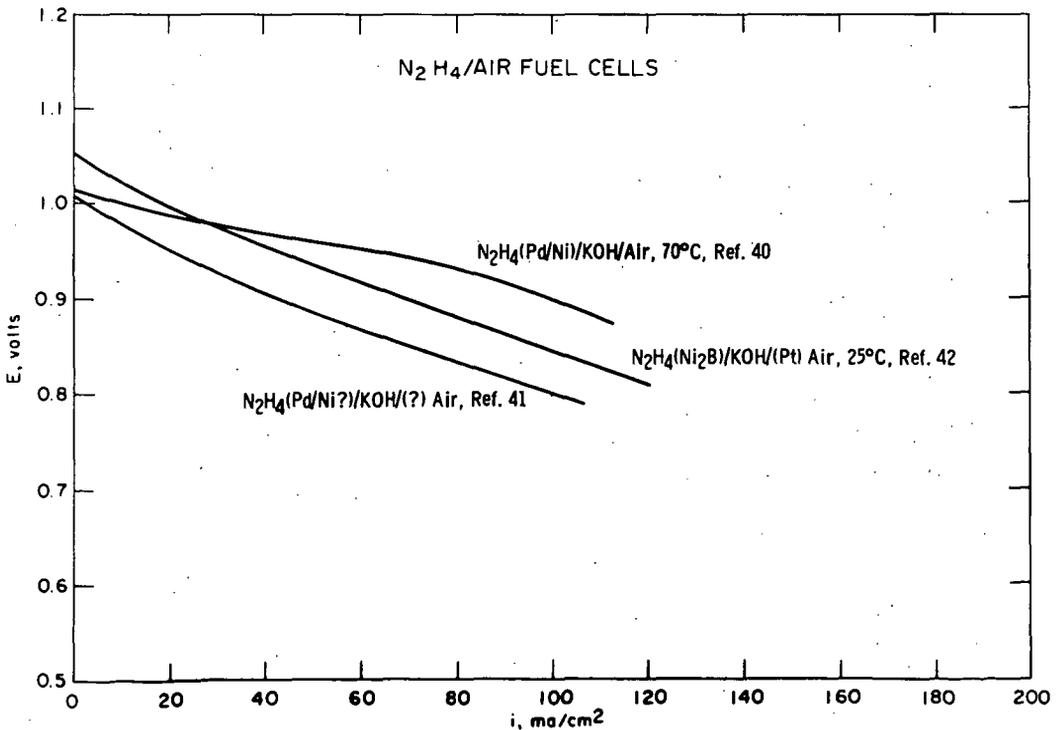


Fig. 6 Voltage-current density curves for direct hydrazine/air fuel cells.

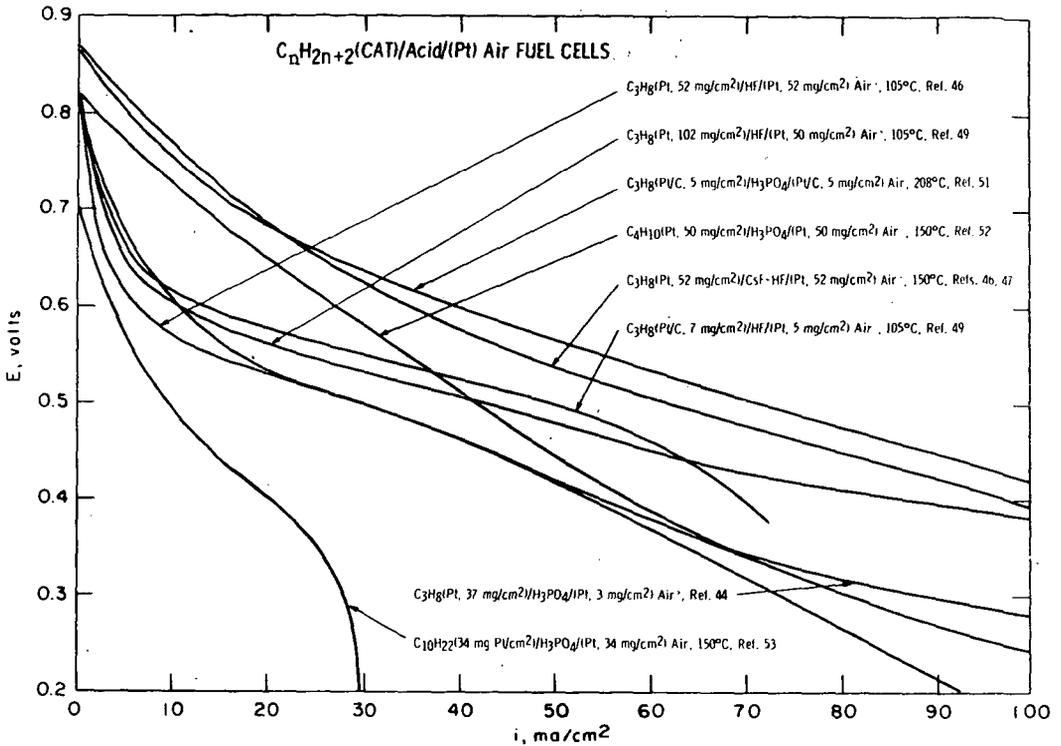


Fig. 7 Voltage-current density curves for direct hydrocarbon/air fuel cells with acid electrolytes.

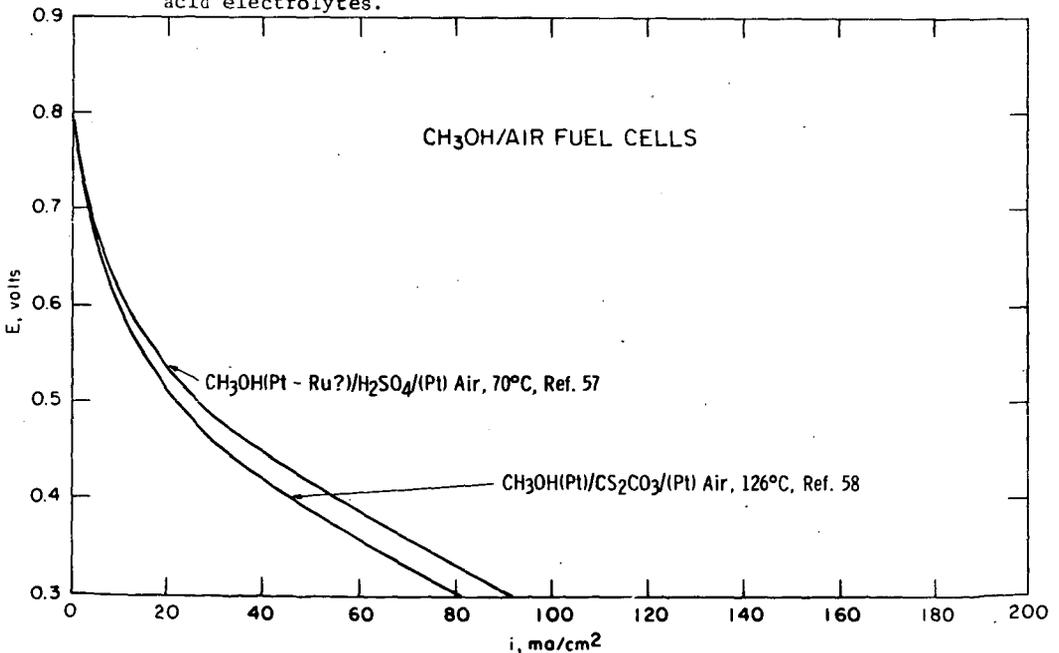


Fig. 8 Voltage-current density curves for direct methanol/air fuel cells.

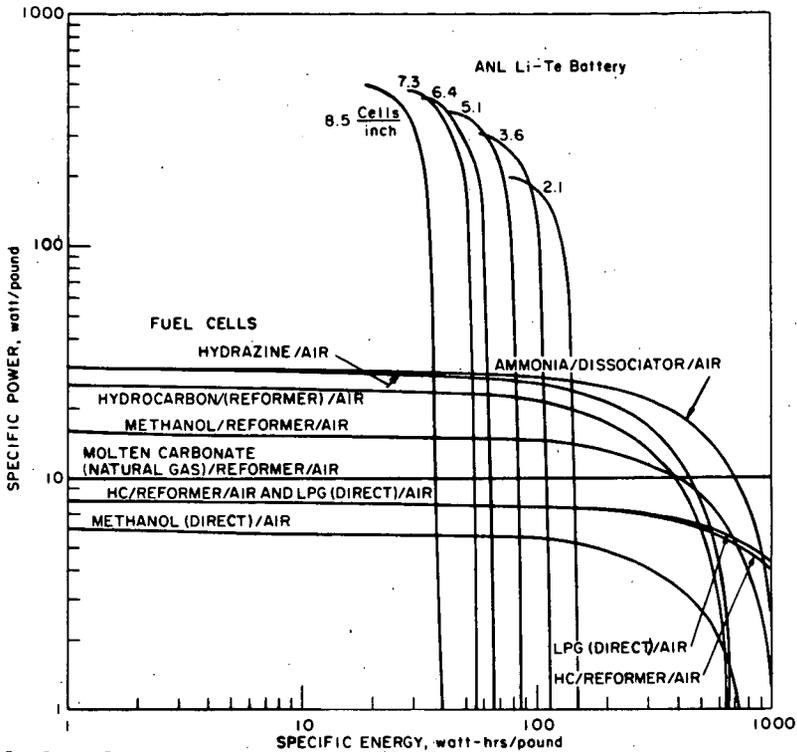


Fig. 9 Specific power-specific energy curves for fuel cell systems and Li-Te batteries.

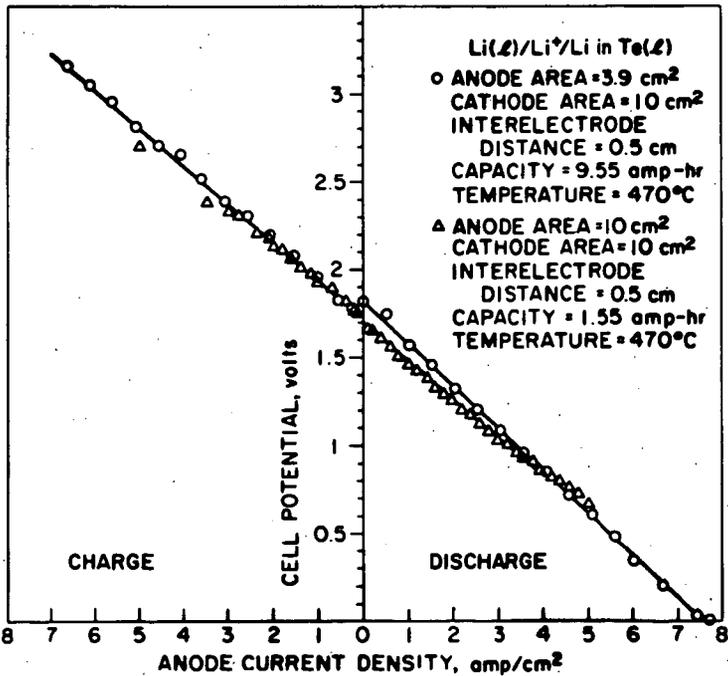


Fig. 10 Steady-state voltage-current density curves for Li/Te cells.

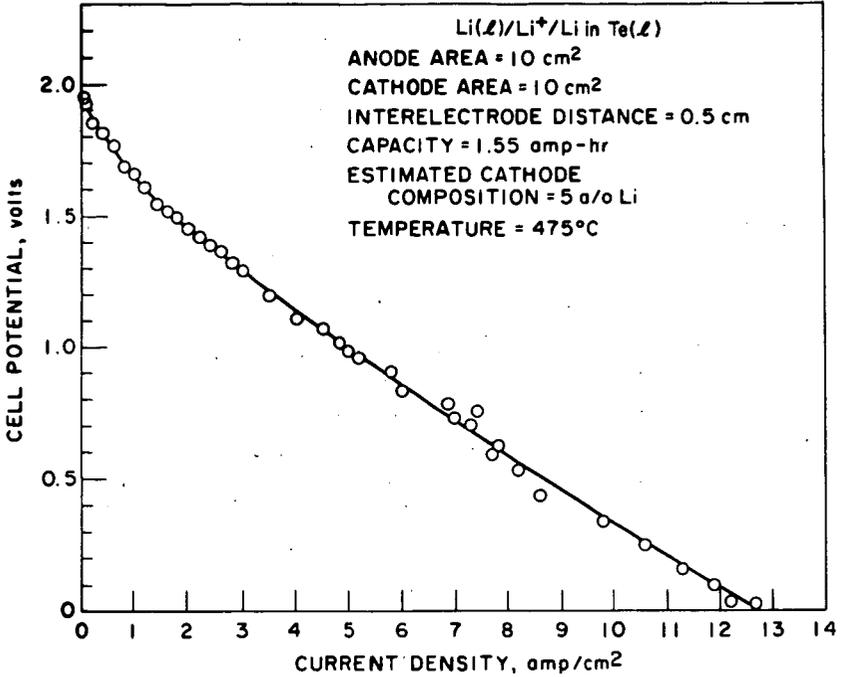


Fig. 11 Short-time voltage-current density curves for a Li/Te cell.

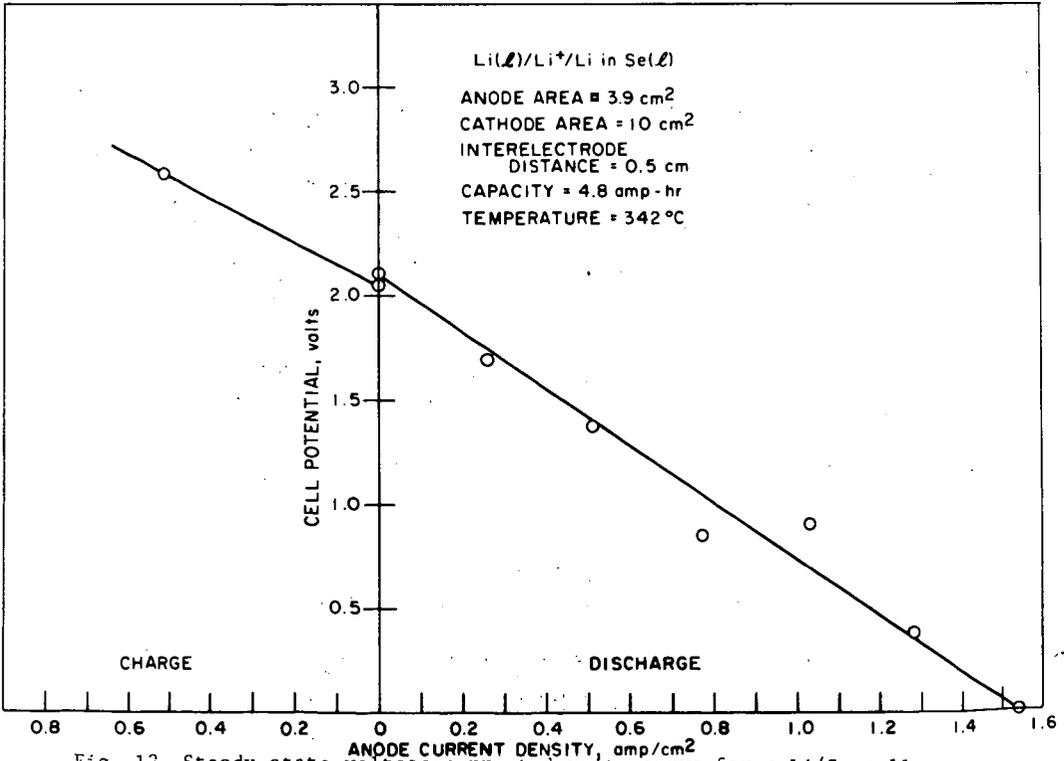


Fig. 12 Steady-state voltage-current density curve for a Li/Se cell.

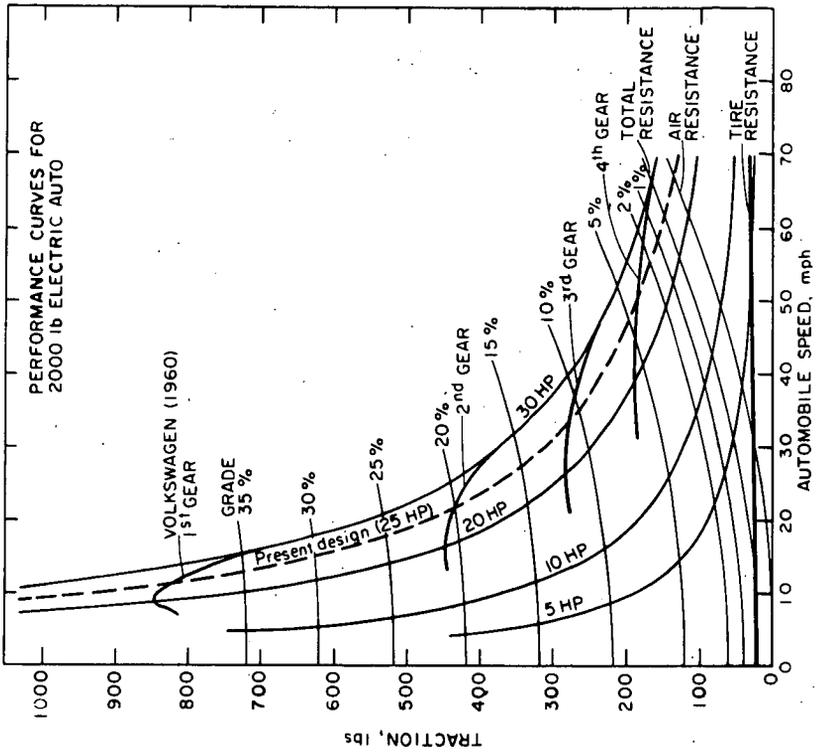


Fig. 14 Performance Curves for 2000 lb. Electric Auto.

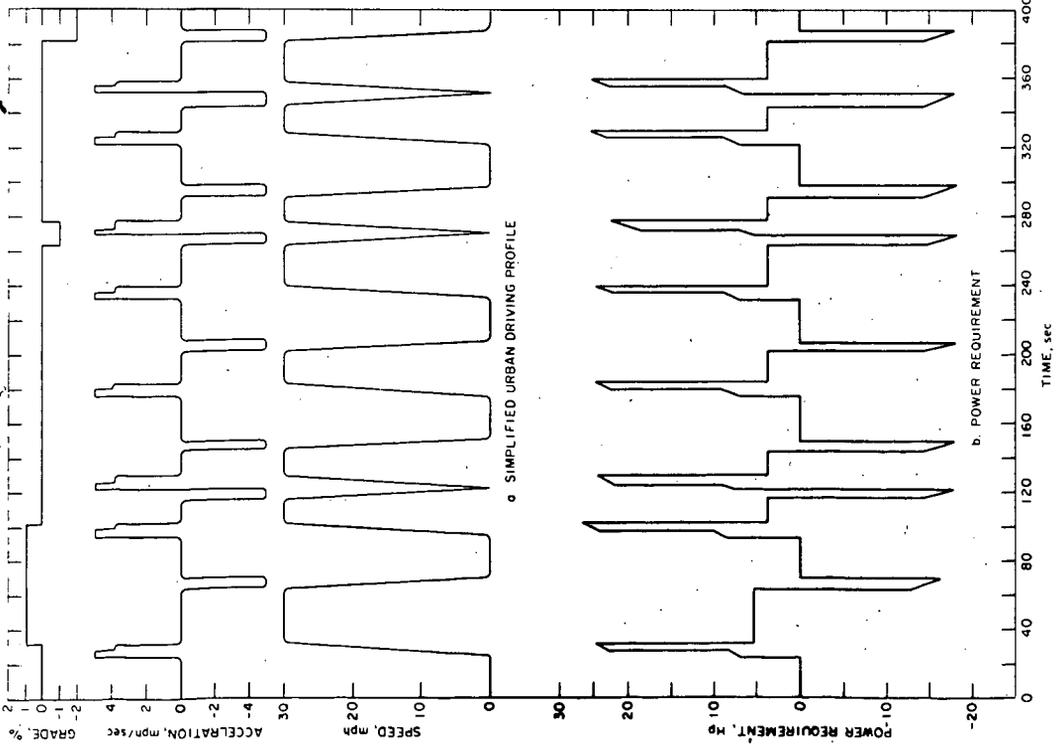


Fig. 13 Driving profile and power requirements for small urban auto.

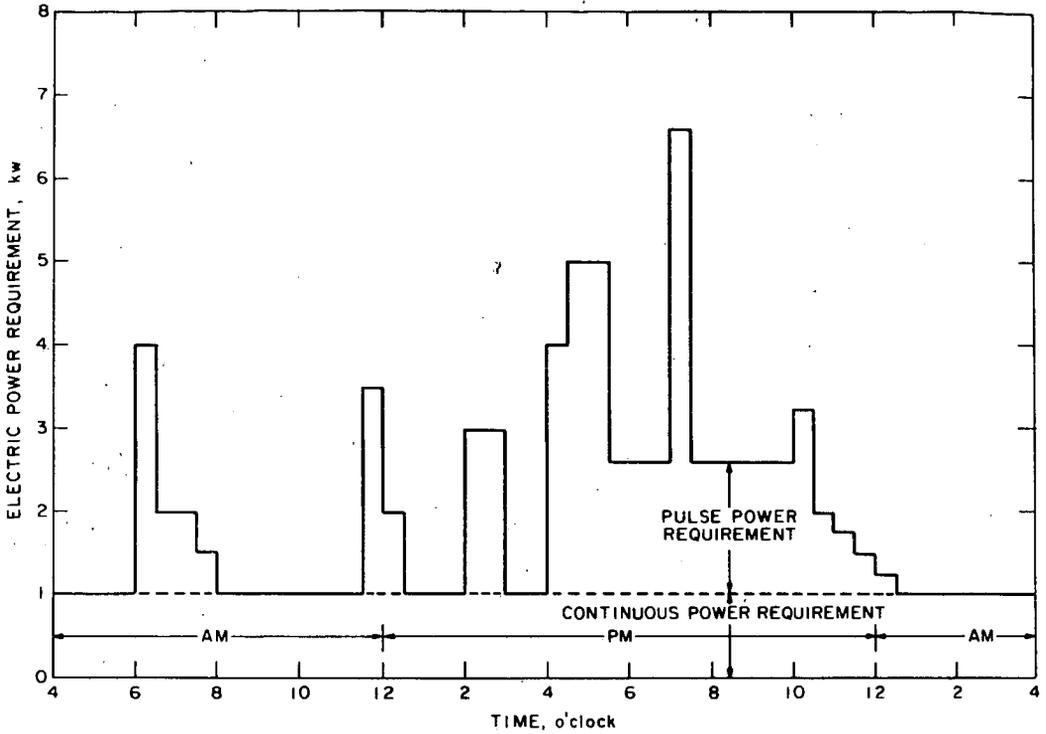


Fig. 15 Electric power requirements for a home.

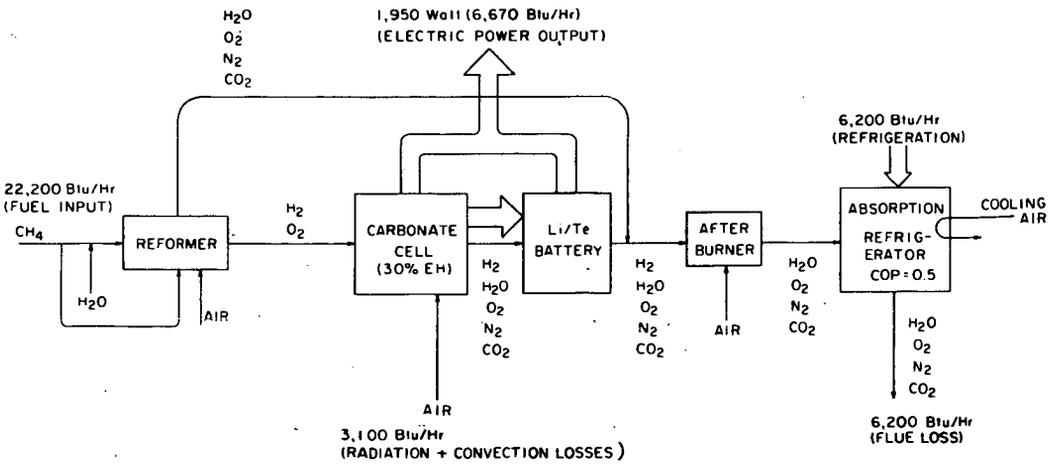


Fig. 16 Schematic diagram of a home hybrid power source.