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POWER SOURCES FOR ELECTRIC CARS

by

Galen R. Frysinger

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POWER SOURCES FOR ELECTRIC CARS

by

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JANUARY 1968

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### ABSTRACT

Based on extensive experience with battery and fuel cell power sources during various Army programs, the author extrapolates into the future world of the electric car and speculates on the power sources most suited as the electrical energy source. The conclusion is that both the battery and the fuel cell have their place when combined uniquely in a hybrid configuration which by proper design can provide outstanding characteristics.

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## POWER SOURCES FOR ELECTRIC CARS

The electric car is seen as a possible attractive alternative to the existing internal combustion engine because of its inherently lower pollution product emission. The big question is whether an electric car can provide a transportation means which will be accepted by the American public and which will become a vital factor in the planning of transportation patterns within our big cities or across the country in general. Since in almost all cases the electrical power to provide the propulsion energy for the future electrical cars will come from energy stored within the car, rather than from a trolley-like overhead wire or third rail, it comes down to a consideration of how the energy can be stored. The power source which may become possible for future electric cars and the means for recharging them with the energy required will be considered in detail.

### INTRODUCTION

The first vigorous public debate on electric cars was associated with the Senate hearings which were held last year to explore the possible

alternatives in vehicle transportation. During this debate two basic groups emerged, both of which saw the electric car as the answer to particular transportation problems. The first group, the hear and now group, see the electric car meeting a variety of short-range transportation needs in specific urban and suburban situations. They study the average rate of travel of a vehicle in Manhattan and its average distance of travel and determine that there are many deep urban zones which could be fully converted to electrical cars and meet the requirements for business and pleasure transportation in "smog free" zones. This group has also considered the housewife in her daily trips to and from the shopping centers, schools, and family recreation areas and foresees an application for a short-range electrical car. In most of these studies the total energy capacity of the car is between 10 and 20 kilowatt hours so that the overnight recharge in the family garage, the plug-in at parking meters or combination commuter parking and recharge stations is completely feasible. Discussions extend to the all rental fleet of cars where a person simply places his charge card in the vehicle's ignition system and is billed at the end of the month for the extent of use of the "core of city" fleet of transportation vehicles. The design challenge in the local short-range limited energy use of electrical cars is not in the creation of new power sources or even new power trains, but in the way in which people would use cars and in the total planning of interchange and localized integrated transportation systems. Most of the electrical cars now being offered to the public by a number of companies as semi-experimental lines are of this

type and utilize conventional batteries, usually of the lead-acid type, which have been successfully used for many years in golf carts.

The second major group is endeavoring to extend the range of electric cars by increasing the energy storage capability of existing power sources and by making major adaptations and modifications in the design of an automobile to optimize its design around the concept of electrical propulsion. It is noted that the recent parade of press announcements by the automobile companies, together with some battery development groups, each promise the electric car which can go a little faster, a little farther, and be a little more comfortable. It is in this area where the real design challenge lies and where concerted improvements of both the power source and the power train and mechanical design of the vehicle can be expected to lead to drastically improved electrical cars.

When one considers the fully competitive electric car most of the discussion comes down to the battery. Can we provide in the battery sufficient power and energy to have an electric automobile which can do all the things and provide all the conveniences which the present gasoline engine powered car does for the average person today? One can dismiss the possibility of utilizing low performance local electric cars since they will not be acceptable as a total solution because it requires people to make major changes in the way they would go about their daily routine. Therefore, for major conversion and wide impact over the total general transportation system, the much more difficult technical problem

must be undertaken: to develop the electrical automobile which has all the capabilities of our present high power gasoline driven cars. This means that the scientists and engineers must invent new battery systems which will allow us to overcome some of the limitations which have been present in electric cars since the days of Thomas Edison. To accomplish this, not only are new batteries required, but also considerations must be given to the whole aspect of applying a power source to do the best job to give optimum performance on the specific duty cycle which our vehicle demands. The design challenge is then to determine how one would use high energy battery systems most effectively in powering a full performance electrical car.

#### WHAT IS EXPECTED FROM THE FAMILY CAR

The number of miles that an automobile can travel before getting a refill of its tank of gasoline depends on the amount of gasoline which is carried in the tank. Normally our cars have gasoline tanks which are large enough so that we can travel approximately 300 miles before refueling at a gas station. If a battery is to do the same job, it must carry enough electrical energy stored inside it to run the car for a distance of about 300 miles. The size of the engine in normal gasoline burning automobiles depends on how fast the car is supposed to speed away from a stop light or how much energy reserve is required for high-speed passing of other cars on main highways. Normally, automobile engines are designed so that the full horsepower is very rarely used. The engine in normal driving is almost at idle. The battery for the future electric car must

therefore be capable of allowing electrical current to be drawn at a normal rate, but also must provide high rates of electrical current when racing away from a stop light, or climbing steep grades, or for high-speed passing.

When your present automobile runs out of energy you stop at a gasoline service station, and in 5 to 10 minutes are ready to go again for another 300 miles of operation. This is the point where use of batteries becomes most difficult. Normally, batteries which are used in small vehicles, such as lift trucks in industrial plants, are allowed to recharge overnight or during the shift when they are not being used. This means that in the conventional manner the electric car would have to be plugged in overnight to be ready to move the next day. This, of course, would put a serious limitation on long cross-country traveling because one could only travel 300 miles during the day and then must plug in at a friend's house or at a service station overnight so that one could go again the 300 miles for the next day's trip. What is then needed is a new type of battery which would not only have the full energy reserve for 300 miles of traveling, but which also could be fully charged in about 5 to 10 minutes, which would be the equivalent time that you would take to fill your car with gasoline.

#### NEW BATTERIES

Within the last year you have probably noticed that both the Ford Motor Company and General Motors Corporation have announced work on new

batteries for use in future electric cars. Both of these batteries, which are still at very early stages of development, use completely new battery principles. They no longer use the acid, which is commonly employed as the electrolyte, in normal automobile batteries. These new batteries run at temperatures equivalent to those now found in the inside of gasoline engines so that the conversion of chemical to electrical power can go much more readily. The chemicals normally used in these batteries are lithium or sodium metal as the anode materials, and sulphur or chlorine materials as the depolarizers or cathodes. Melted salts of these chemicals are used as the ionic conducting electrolyte. These chemicals all have very high electrical energy equivalents and are very lightweight. If packaged properly and used efficiently, these chemicals can provide a battery which could propel the normal automobile beyond the present 300-mile range with a weight of total battery less than the present weight of the engine and the fuel tank combined. Because these batteries run at higher temperatures (250 to 600°C) they allow the conversion of chemical to electrical energy to proceed very rapidly and therefore result in a battery which can deliver very high currents for spinning the wheels at a stop light, to climb very steep grades, or to undertake normal high-speed driving on super highways, including passing with ease and safety. Another advantage of the ease of chemical reaction is that not only can the chemicals be converted to electrical current, but also that electrical current from the outside can be applied to the battery to recreate the chemicals and therefore recharge the total battery system. This is what

is accomplished when you plug in the automobile battery to your house electrical current to recharge. Because this reaction proceeds very quickly, it is possible with proper design and packaging of the battery to produce a battery which can be fully recharged in from 10 to 20 minutes. This, however, creates a very serious problem. The electrical distribution system in a normal household is designed for a normal usage not to exceed approximately 3 kilowatts of power. If we design the system to accomplish an overnight recharge of your electric automobile, this would increase the requirements to about 15 or 20 kilowatts to be drawn during the overnight recharging period. The electrical distribution and switches required for this overnight recharging could be easily contained in your garage. If, however, we use the battery's capability to be recharged in a period of approximately 10 to 20 minutes, this means that a major substation must be installed in every garage. To have a distribution system for from 600 kilowatts to over 1,000 kilowatts in each individual residence is, of course, impractical just because of the cost alone, if for no other reason. This means that these new batteries in future vehicles would have to be recharged at special recharging stations, which would require a new capital investment in a whole series of electrical recharging stations similar to what we now have invested in our nation-wide chain of gasoline stations. But let us first examine what the requirement to recharge these new batteries in 10 minutes does to the design of the batteries themselves and the way they are placed in an electric car. If the car is to have equal range and capability with present automobiles,

this means that we must have in the battery approximately 200 kilowatt hours of stored electrical energy. If the battery system is designed to run at approximately 200 volts, this means that in recharging within 10 to 20 minutes, 3,000 to 6,000 amps must be passed through the wires connecting the battery with the recharge station. For this quantity of current, the switch alone may weigh as much as the present engine in the car, and the weight of metal required to carry the current inside the car from the switch to the battery would be so heavy that very little space and weight would be available for the battery. Even with the very high energy and lightweight chemicals of these new battery systems, it would not be practical to try to incorporate all the metal and conductors needed to try to recharge these batteries at the very high rate. It is therefore impractical to think of the average automobile being recharged in this manner. It is therefore obvious that batteries alone are not sufficient to solve the power source problem.

#### FUEL CELLS

Another approach to creating the electrical power needed to drive an electric automobile is the fuel cell. Fuel cells were first used successfully in the Gemini space explorations. Here a fuel cell created continuous electrical power from stored chemicals. In this case hydrogen and oxygen gases which were liquified and kept stored in cooled containers were used in the fuel cell to provide the power required over extended periods in orbit of from 4 to 14 days. The fuel cells which

have been manufactured to date for the space program have all used hydrogen gas and oxygen gas. For fuel cells to work on the ground, the oxygen can be obtained directly from the air around us. Likewise, hydrocarbon fuels such as presently used in existing engines can be a source of hydrogen to be used in the fuel cell. Over the last three to four years, work which has been largely carried on and sponsored by the U.S. Army research laboratories has shown the feasibility of making electrical power straight from gasoline-type fuels and air in a fuel cell. It is projected that these fuel cells could be used to replace the engines in future electric automobiles. Even though the fuel cell can very efficiently convert the energy contained in a gasoline fuel to electric power, the fuel cell itself is relatively heavy and bulky compared to the present gasoline engines. So, if today, or within the next five years we would create a fuel cell which would have the same ability to convert gasoline to energy as the existing gasoline engine, it would be far too heavy to carry in an automobile. This is assuming that we would pick the size of the fuel cell to be identical to that of the existing engine, i.e., to give fast acceleration, to permit the climbing of steep grades, and high-speed passing in turnpike traffic. From the excitement caused by the advantages of both of these approaches, the new higher energy, lighter weight batteries and the hydrocarbon converting fuel cell, it appears that the best way to solve the problem of the most versatile and best type of electrical power plant for future cars is to combine both the new type of battery and the new type of fuel cell together in a hybrid

system. The fuel cell is best when it continuously converts gasoline and air to electrical power at a steady constant rate. The battery is best for providing a wide range of currents to meet small or large electrical demands of the motors, but has the limitation that it only carries a small amount of total reserve energy. Therefore, to overcome this immense battery charging problem which was previously mentioned, each electric car of the future would carry a gasoline tank and a small fuel cell which can convert this gasoline to electrical power continuously to recharge the batteries. The stored energy of the battery would be used to accelerate or speed the car away from stop lights and to provide the burst of speed needed for in-traffic maneuvering and for the sustained high amounts of current needed on steep upgrades or driving through mud or other difficult road conditions. The fuel cell would be used to supply an average level of electrical power which could be used to sustain normal driving under normal highway conditions and which would be used to recharge the batteries while the automobile is motionless in traffic or during periods when the car is parked, waiting for the next trip. Because the battery and the fuel cell are both electrochemical systems which have very similar characteristics, they can be made to work together very well. The fuel cell will automatically keep the battery at its full charge of electrical power and ready to instantly provide the power required for any function of the automobile. The fuel cell would almost be like the pilot light in your home gas furnace, always keeping the fuel cell and battery system at the proper operating

temperature and ready to give instantaneously the power required. Even under the most adverse weather conditions, no additional warm-up would be required. The parts of the fuel cell and the storage battery could be so arranged in a common package so that each would be extremely simple and would require only a minimum of auxiliary controls and accessories. Since the fuel which would be used in this hybrid battery and fuel cell package would be the same fuels which are now used in existing gasoline engine cars, the same nation-wide network of service stations could be used. A traveler making a long distance trip across country could be refueled in the same time that it now takes for him to normally refuel his car at a service station. The traveler would then suffer no inconvenience or change in driving pattern because he now has an electric car rather than a conventional car. The advantage, of course, is that the electric car will now utilize the hydrocarbon in a fuel cell which insures complete combustion of all of the fuel components because it is a continuous operating electrochemical conversion whose products are exclusively water and carbon dioxide. Because the fuel cell is not dependent on rejecting heat at a lower temperature, it has a much higher energy conversion efficiency and therefore can provide much more electrical energy per gallon of fuel. For the type of total system, including fuel cell and battery which would be used in a private automobile, between 37 and 47 per cent of the energy in the gasoline would be converted to motion of the car, depending upon the efficiency of the particular motors used in the wheels of the car. This means that your future electric car would go approximately 60 miles per gallon of gasoline and therefore represent

a great saving in cost to its owner.

The particular fuel cell which would be used in this system would have to be low in cost and very simple to operate. This type of fuel cell has not yet been built, but based on research results now being obtained, should be possible within the next three to four years. Likewise, the new lithium chloride batteries have only been tested in the laboratory and would take approximately the same amount of time before they are available to put in an experimental electric car.

#### HYBRID POWER SYSTEM

A hybrid power source system (Figure 1) would consist of approximately an equal weight of hydrocarbon fuel, fuel to electrical converter (fuel cell) and energy storage (battery). The theoretical energy of the fuel 5.5 KWH/lb becomes useful when the fuel cell converts it for immediate needs or stores it in a battery for later use. The fuel cell's high conversion efficiency (40-50%) will allow more miles to the gallon using an equivalent refinery produced liquid hydrocarbon fuel. The fuel cell and battery elements could be configured in the series-parallel arrangement shown in Figure 2. The voltage across this parallel arrangement of battery and fuel cell would be applied to the pulse code modulator in the vehicle propulsion control system. The voltage at these bus terminals will be a function of the current drawn. Figure 3 shows the fuel cell V vs. I curve which would be followed until sufficient amperes are drawn to reduce the fuel cell module voltage to the battery discharge

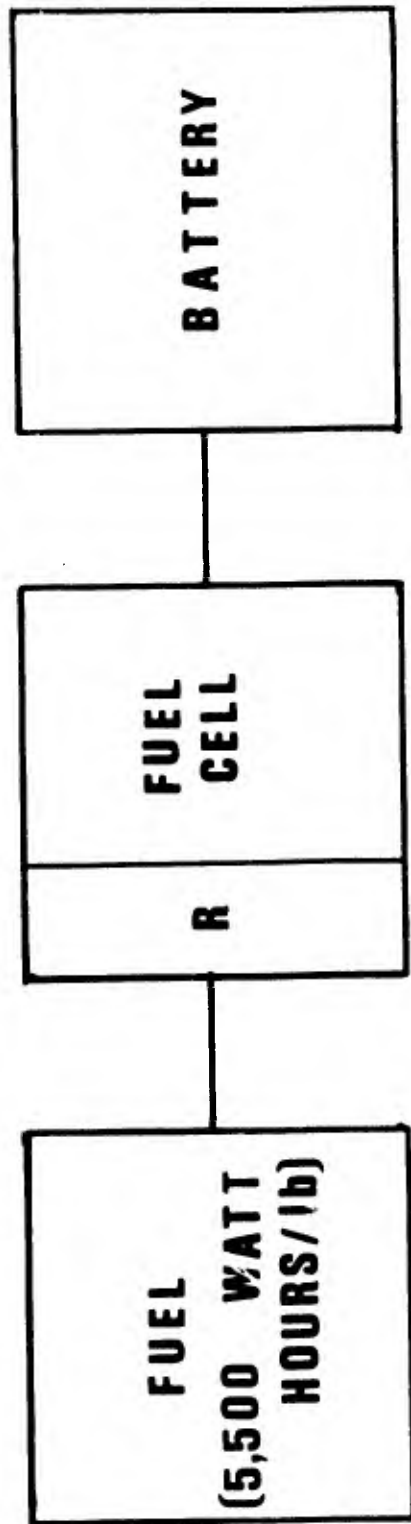


FIGURE I

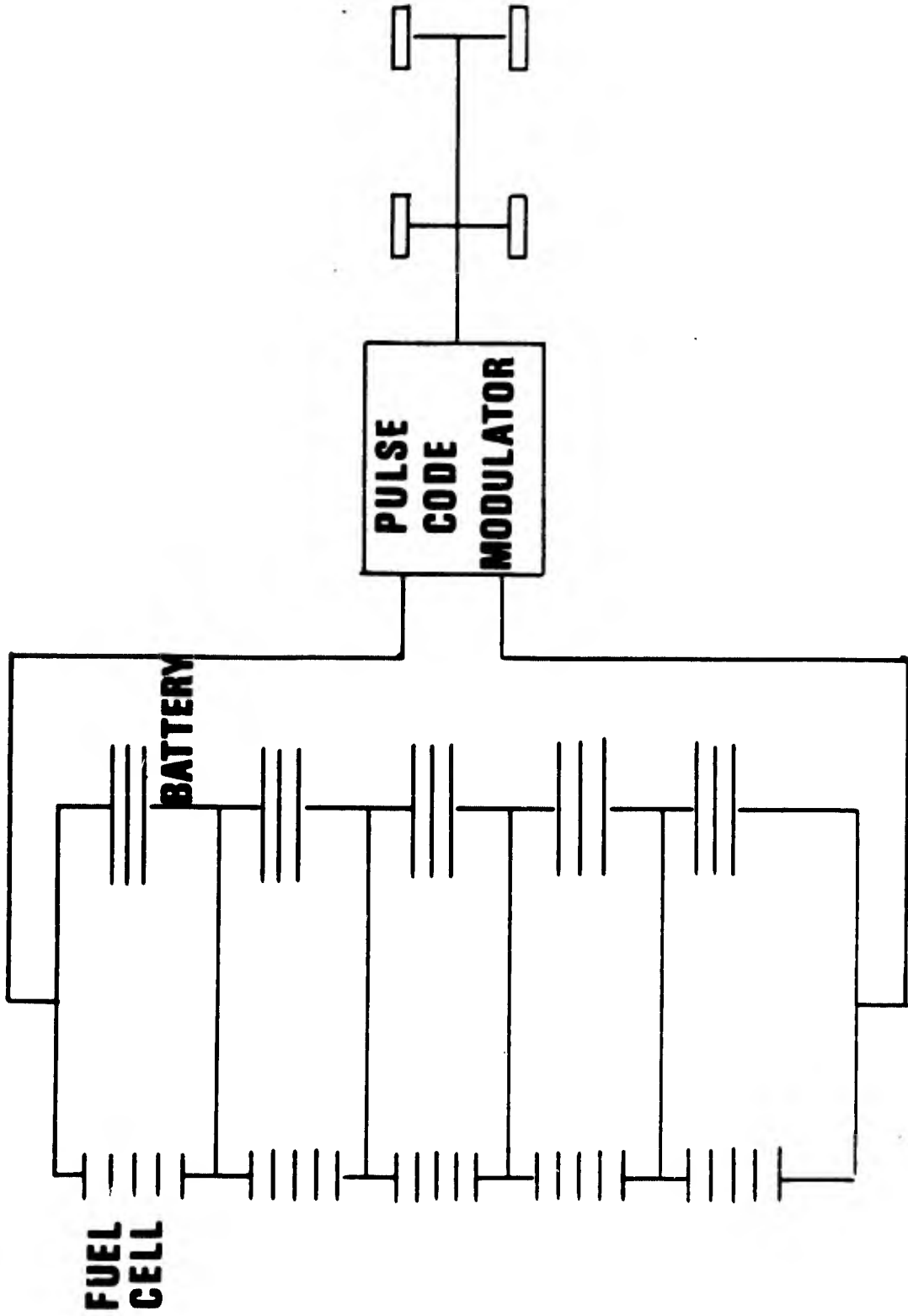


FIGURE 2

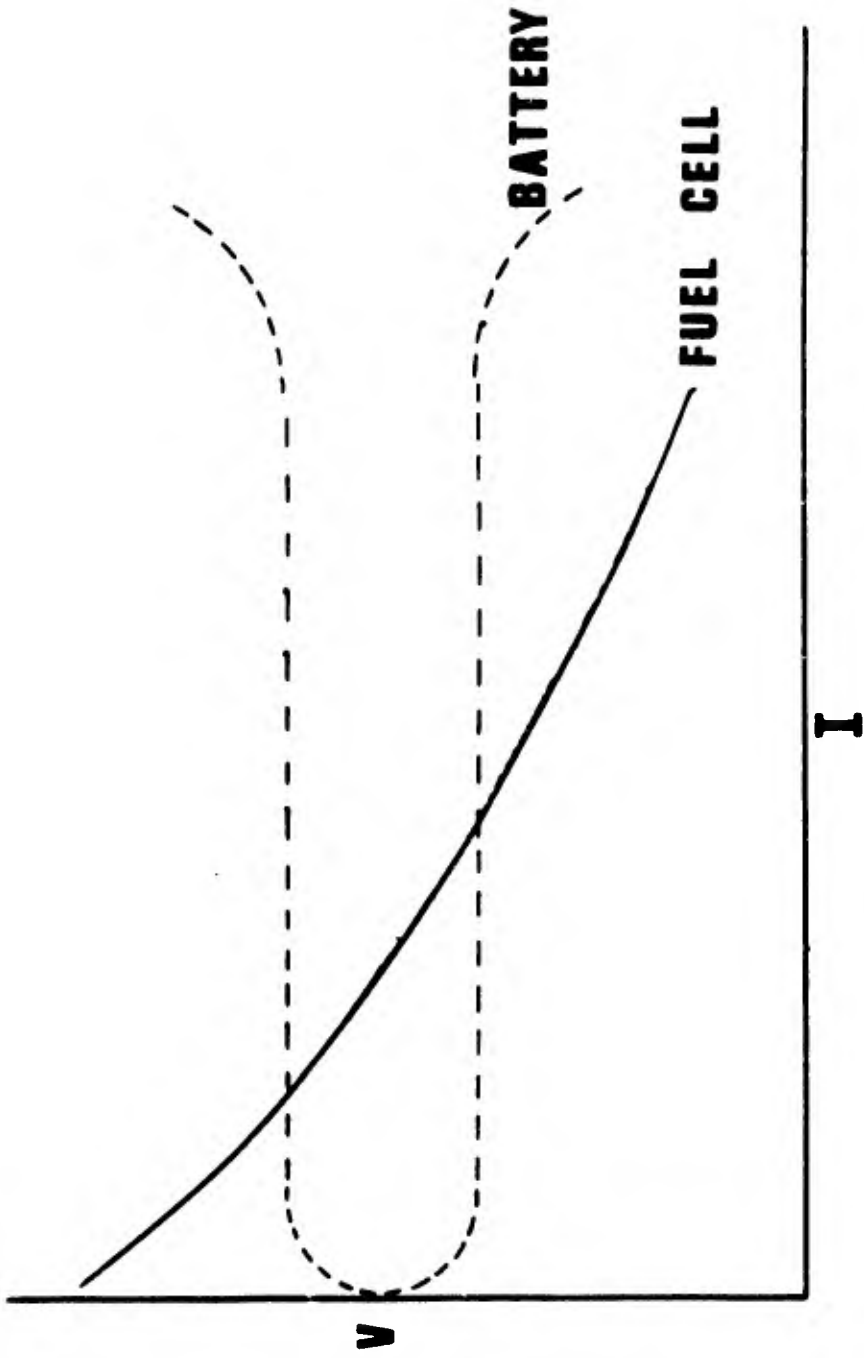


FIGURE 3

voltage. From this point to maximum rated power the voltage across the pulse code modulator will be the battery's discharge voltage. As the required external current is reduced the voltage rises to the point where the fuel cell starts to recharge the battery. When the external load is reduced to zero, internal current flows as the fuel cell fully recharges the battery.

Figure 4 is a schematic of a possible modularized hybrid system. Each module would consist of a hydrocarbon to hydrogen reformer, the fuel cell and the battery storage unit. A typical system may use the molten electrolyte lithium-chlorine battery which operates at 450-600°C, together with a reformer and a molten carbonate matrix electrolyte fuel cell operating at the same temperature. For control simplicity, the fuel cell fuel feed could have a variable flow pump regulated to maintain a constant excess hydrogen partial pressure at the exit of the fuel cell converter. The small amount of excess hydrogen could be combusted in a catalytic burner to provide the quantity of heat needed to keep the hybrid system at its operating temperature. Likewise, the flow of air in the fuel cell combustion air stream could be adjusted to maintain the proper temperature during periods of activity when heat must be dissipated. Since excellent electrical transient response is provided by the storage battery energy, the lag time of the reformer and fuel cell can be rather lengthy, thus allowing very simple, largely self-regulating controls.

By proper attention to design criteria, a battery-fuel cell power source can be (a) less polluting, (b) more silent, (c) more efficient in

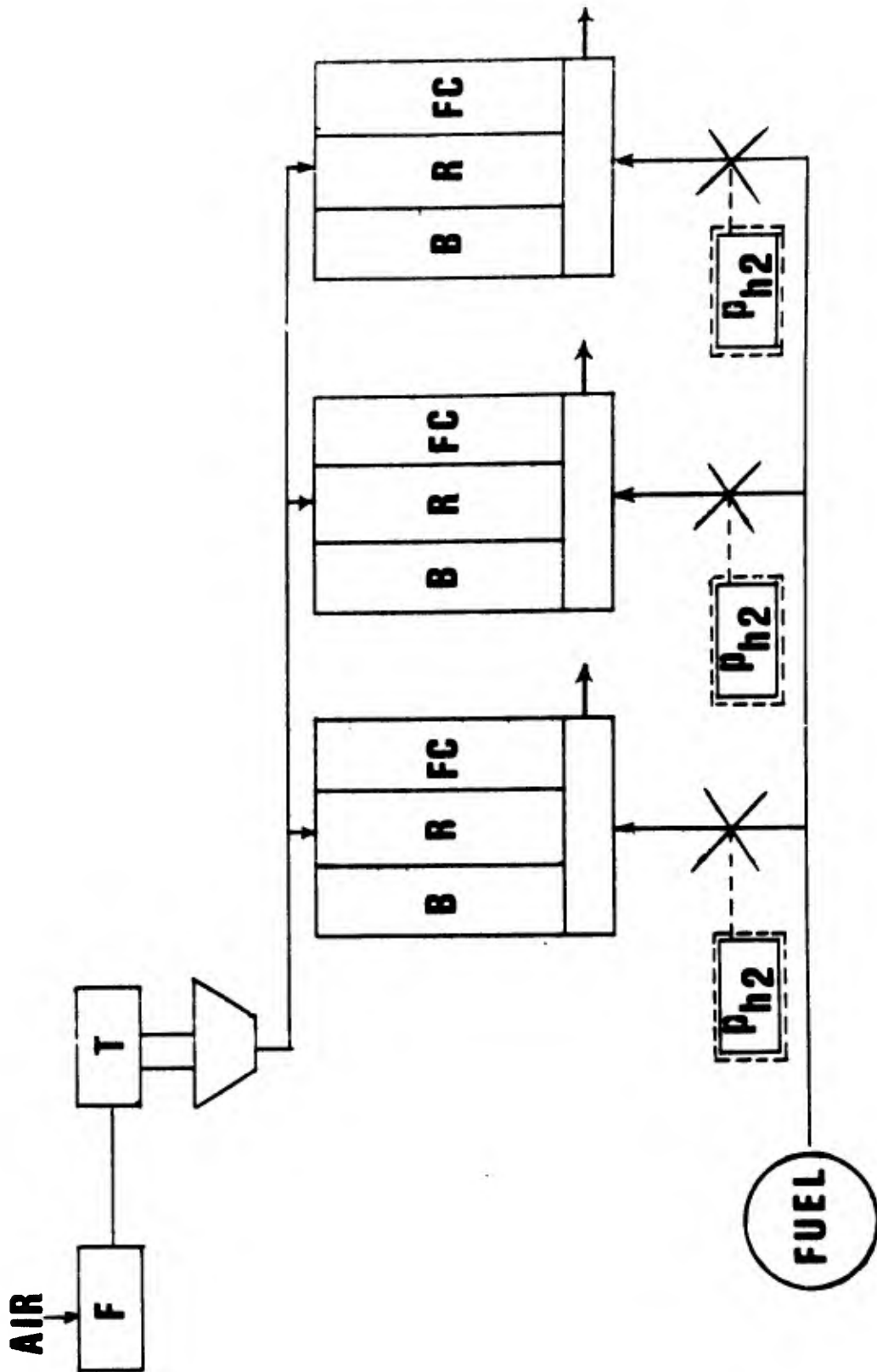


FIGURE 4

using energy from liquid hydrocarbons, (d) lighter weight, (e) simpler and (f) more reliable than internal combustion engine vehicle power plants. The most important design criteria for optimizing the hybrid power source are (a) minimum power plant weight by proper sizing of the fuel cell and battery component, (b) proper efficiency matching, and (c) thermal integration and control simplicity.

#### OPTIMUM RATIO OF FUEL CELL POWER TO BATTERY STORED ENERGY

The key to the optimum hybrid system is to minimize unused capacity. The fuel cell should cover the steady average power requirements with the battery providing the peak or above average currents which are required. To determine the average power required over a given operating period and to establish the optimum energy reserve, detailed consideration must be given to the way in which the vehicle will operate. Army estimates have shown that a "standard vehicle" will spend approximately 30% of any 24-hour period at idle, 20% undergoing cross-country travel, 20% on secondary road travel, 25% on higher speed highway travel, with 5% allowance for peak power required in obstacle crossing, fast acceleration, and on steep inclines. This type of duty cycle information is sufficient for a design of an optimum fuel cell-battery hybrid system if the specific power requirements in each mode are known. In order to minimize any reduction in the performance capabilities of the vehicle, the design must provide for the total time at peak power to be available at any time within the 24-hour period. This means that the energy stored in the battery would be

sufficient in combination with the energy continuously available from the battery charger to run the vehicle at peak power for the first 1.2 hours of its duty cycle. This, of course, would be a very unusual case.

As an example of the sizing of the fuel cell battery charger and the battery for a specific power plant, we will consider a 2½-ton truck. The first column in Figure 5 shows the standard duty cycle which was previously described and the power requirements of this truck in each of these modes. To meet this duty cycle, a 20-kilowatt fuel cell was selected, together with a battery containing 9½ kilowatt hours of stored energy capacity. Note that the fuel cell alone can power the truck fully during secondary road travel and has adequate overload capacity to provide the 2½ kilowatts needed for highway travel. The energy reserve of the battery is only required for peak power operation. The ratio of battery to fuel cell capacity is not too critical. For example, the second column of Figure 5 shows the estimated duty cycle for a light convoy operation, with a significant increase in the percentage of time on secondary and highway travel. The same ratio of fuel cell to battery capacity would again be appropriate for this application. If the truck must be designed for heavy duty convoy operation where 70% of the time would be required at high-speed highway travel with up to 20% of the time at full peak power, it would, of course, be necessary to increase the kilowatt rating of the fuel cell from 20 to 30 and to increase the total energy content of the battery somewhat. The ratio allows operation for almost five continuous hours at peak power during

2-1/2 TON TRUCK

<u>Standard Duty Cycle</u>	<u>Light Convoy</u>	<u>Heavy Duty Convoy</u>
30% Idle	10%	10%
20% Cross Country (11 KW)	10%	0
20% Secondary (20 KW)	35%	0
25% Highway (24 KW)	40%	70%
5% Peak (108 KW)	5%	20%
20 KW Fuel Cell (0.8v)	20 KW	30 KW
30 KW Fuel Cell (MAX.)	30 KW	45 KW
94 KWH	94 KWH	120 KWH

FIGURE 5

any portion of the duty cycle. These are probably unrealistically severe design criteria.

The range of duty cycles which may be of interest for commercial applications run everywhere from the "milk truck" to high-speed highway operation. The first column in Figure 6 shows the same  $2\frac{1}{2}$ -ton truck with a "milk truck" duty cycle of 50% idle and 50% of the time at an estimated power requirement of 20 kilowatts which is equivalent to secondary road travel. For this application a much smaller (10 KW) fuel cell can be used with only 20 KWH of battery energy capacity. This is, of course, one of the most attractive applications for a hybrid system and results in a very low weight power plant. This is not a low speed limited vehicle since it can provide periodic peak demands of up to 100 kilowatts out of its energy reserve. There is no limitation on the instantaneous performance of this vehicle. It only requires a significant portion of idle time during any given operating period. In the second column of Figure 6 is the other extreme which demands an almost continual 25-kilowatt power. A battery of 10-kilowatt-hour capacity is included mainly as a means of simplifying the fuel cell system, providing more flexible operation with a minimum of control, and to provide immediate load capability. This is the same fuel cell as the military design except that the energy reserve in the battery has been significantly reduced to get a lower weight power plant. This vehicle is capable of high-speed highway operation, but with its constant kilowatt rating will have reduced speeds on steep grades. In these five example duty cycles for the  $2\frac{1}{2}$ -ton

2-1/2 TON TRUCK

Simulated Commercial Duty Cycle

<u>"Milk Truck"</u>	<u>High Speed Highway (Limited Performance)</u>
50% Idle	10% Idle
50% Secondary (20 KW)	90% Highway (25 KW)
10 KW Fuel Cell (0.8v)	20 KW Fuel Cell (0.8v)
15 KW Fuel Cell (Max.)	30 KW Fuel Cell (Max.)
20 KWH Battery (Capable of Periodic Peak Demands)	10 KWH Battery

truck, the energy capacity to power density ratio was varied over a factor of 10. The effect of this ratio on total power source weight is shown in Figure 7 for the four variations of the hybrid power source. Of these only the heavy duty convoy design has a total power source weight exceeding that of the conventional internal combustion engine. The ratio between total battery stored energy capacity and battery charger capability is not the only factor in determining a weight optimization. The weight of the fuel which must be carried is very directly a function of the efficiency of the total system. To obtain an optimum low weight of fuel plus power source, both considerations must be taken into account.

#### EFFICIENCY

A high degree of precision is required in defining and estimating the efficiency of a particular power source. In a fuel cell-battery hybrid system the efficiency with which the energy of a hydrocarbon fuel can be converted to effective power to the drive train is very dependent on the rate at which the energy is required. The most significant index is the efficiency vs. the kilowatt demand curve. To determine the thermal efficiency of a hybrid system, detailed knowledge must be obtained on the battery energy storage efficiency, the battery charger efficiency, and knowledge of the relative contribution of the battery charger and the battery in providing current at given load levels.

Confusion has arisen because of the way efficiencies have often been stated in the literature. The efficiency of a given battery is often

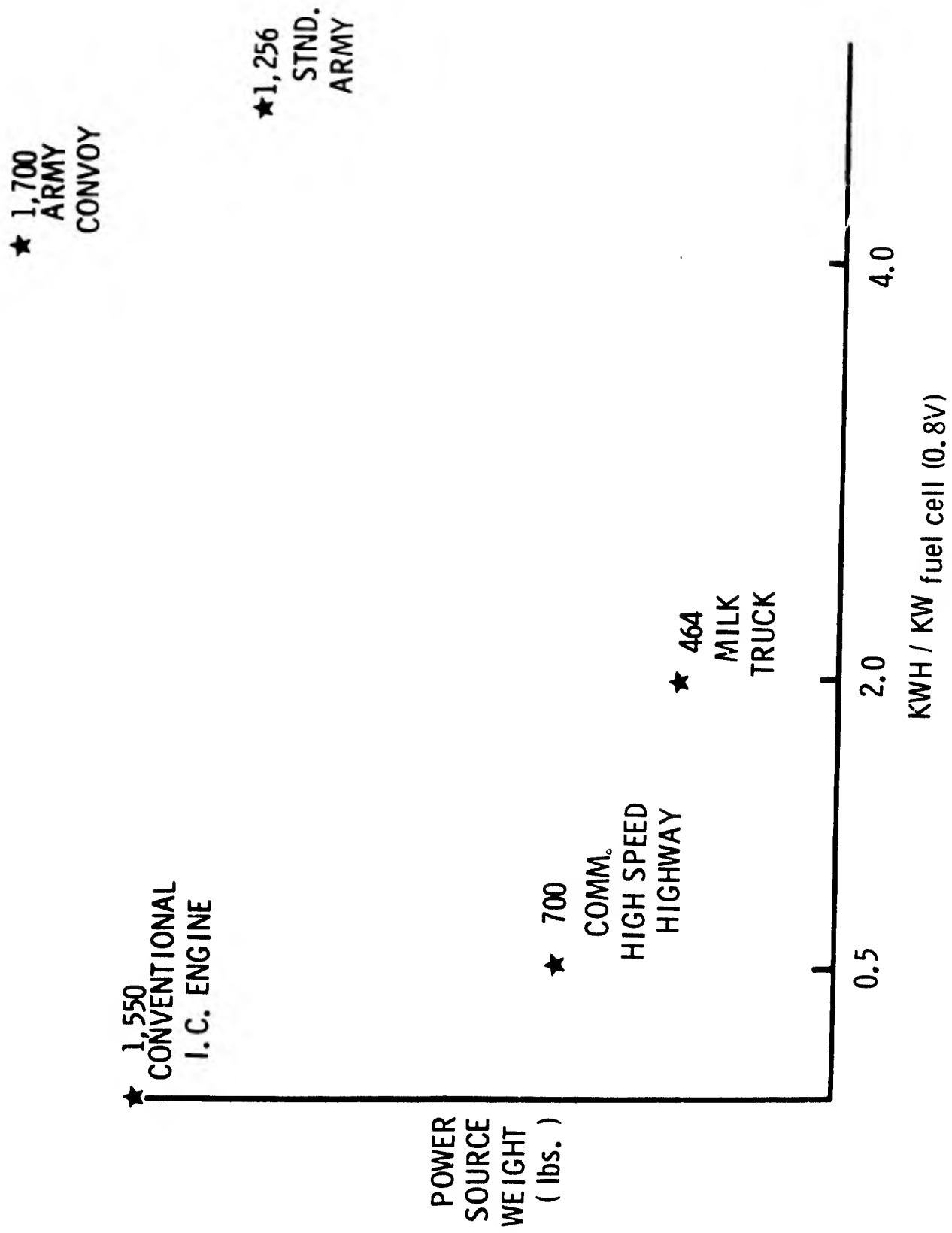


FIGURE 7

puted as a Faradaic efficiency which is only a comparison of the ampere hours obtained during discharge of a battery to its cut-off voltage compared to the number of ampere hours given to this same battery during its charge period. In Figure 8 this would result in a comparison of the distance BC to BA. The attainment of a high Faradaic efficiency for a secondary battery indicates only that the principal reaction is the charging reaction, but does not give a true indication of the overall energy efficiency. The true measure of energy efficiency for a secondary battery system is the comparison of the area under the discharge portion of the volts vs. ampere hour curve (I) to the area under the charge portion of the same curve (II).

The simplified curve in Figure 8 indicates a discharge period immediately following the charge period. If, however, a significant period of time elapses between the end of the charging period to the beginning of the discharge period, another factor, self-discharge, due to migration and chemical recombination or reactants without participation in the principal electrochemical reaction, can significantly reduce the amount of energy remaining in the battery for eventual discharge. This must, of course, be taken into account in the calculation of a complete energy storage efficiency.

In the hybrid system the battery would principally be floated between 25 and 90% of full capacity. In this regime the principal energy loss is due to resistances in the cell's current collectors and electrolyte resistivity, particularly where porous electrode materials are utilized,

# CHARGE-DISCHARGE EFFICIENCY

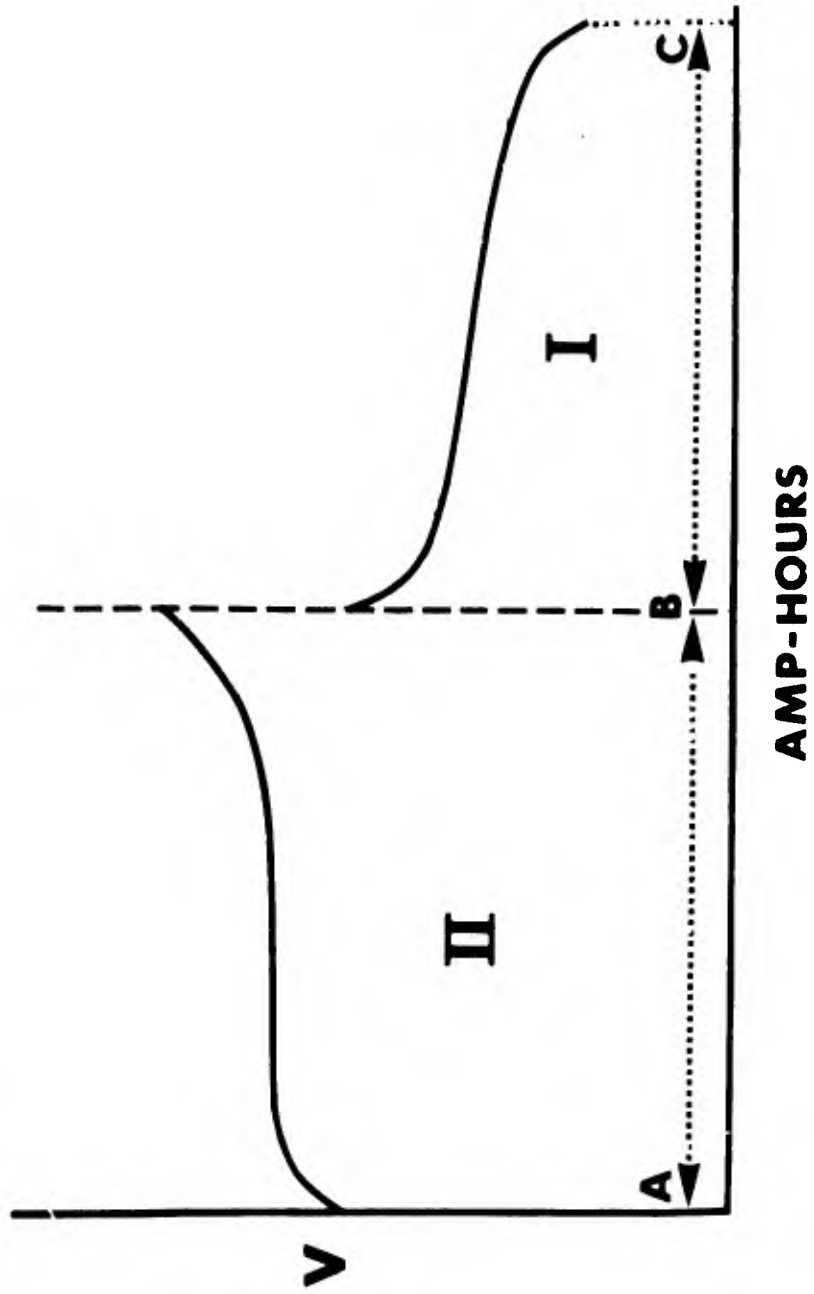


FIGURE 8

assuming that self-discharge rates have been reduced to negligible proportions. Chemical polarization losses which are present in all lower temperature systems can be significantly reduced in molten electrolyte batteries. The only true measure of a battery's energy storage efficiency is to determine the watt hours of useful energy which are discharged from the battery during its normal operation and compare that to the watt hours of energy required to bring it back to its previous charged state. Many conventional batteries (lead acid, for example) have far too low energy storage efficiencies and would not be suitable in a hybrid application. The most attractive battery for hybrid use appears to be a molten salt system where Faradaic efficiencies of 100% and duty cycle energy storage efficiencies of 70-80% should be achievable.

The efficiency with which a fuel cell can directly generate electrical power for supply to the drive train or for recharging of the energy periodically removed from the battery is determined by (a) the single cell operating voltage at the load point, (b) the fuel preparation efficiency, and (c) the amount of parasitic power which must be wasted in the conversion process. Figure 9 shows the volt ampere curve for the fuel cell battery charger. The single cell voltages are shown together with the total fuel cell system thermal conversion efficiencies corresponding to these single cell voltages.

One of the principal advantages of the fuel cell-battery hybrid system is that it significantly reduces the complexity of the fuel cell portion. By achieving complete thermal integration and a simplified control system, the fuel preparation section (hydrocarbon-steam reformer)

# BATTERY CHARGER EFFICIENCY

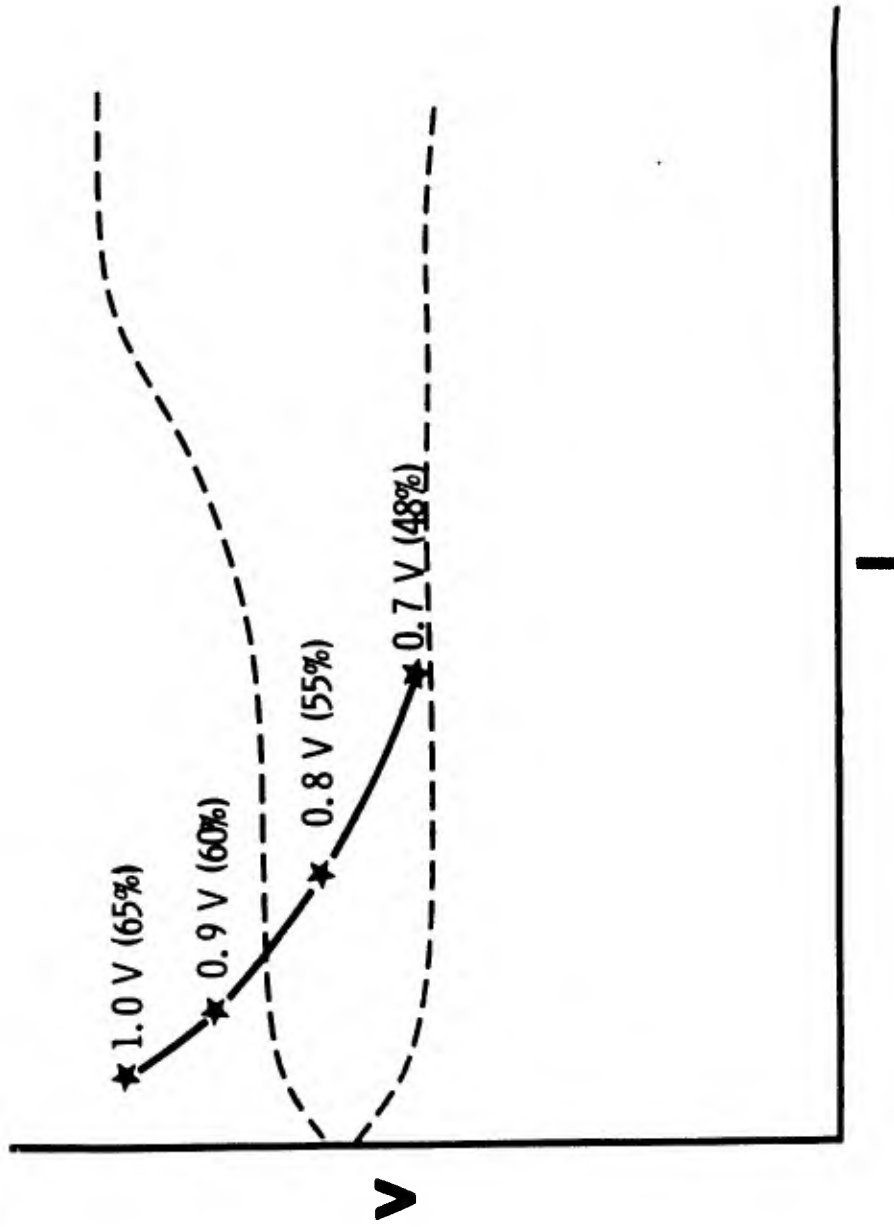


FIGURE 9

can maintain a high efficiency even at very low levels of gas production. Also since the total parasitic power requirements are negligible the all-over thermal conversion efficiency is in direct proportion to single cell voltages. Since the fuel cell and the battery are directly connected in parallel to the load, the lowest single cell voltage which the fuel cell would experience is the preselected battery crossover voltage. This means that the lowest thermal conversion efficiency of fuel to electrical power can be set at a fuel cell maximum overload point of 0.7 volts per single cell and is 48%. At zero or very low external power demands the fuel cell system will internally recharge the battery at a single fuel cell voltage between 0.9 and 1.0 volts where the battery charger efficiency is between 60 and 65%. Based on the synthesis of these two efficiency patterns the efficiency of the total hybrid system vs. the power to the drive train is shown in Figure 10. The initial decreasing portion of the efficiency curve is in direct proportion to the reduction of the single cell operating voltages of the fuel cell. The minimum in this curve indicates the full participation of the fuel cell at its maximum overloaded point. As the power requirements increase even higher, more of the energy is withdrawn from the battery with a slight increase in all-over thermal efficiency because of the combination of higher efficiency involved in the initial placement of this energy in the battery and its efficient delivery for this application. As power requirements increase to overload the complete hybrid system, the thermal efficiency will, of course, drop again

**EFFICIENCY Vs. POWER TO DRIVE TRAIN**  
( HYBRID SYSTEM )

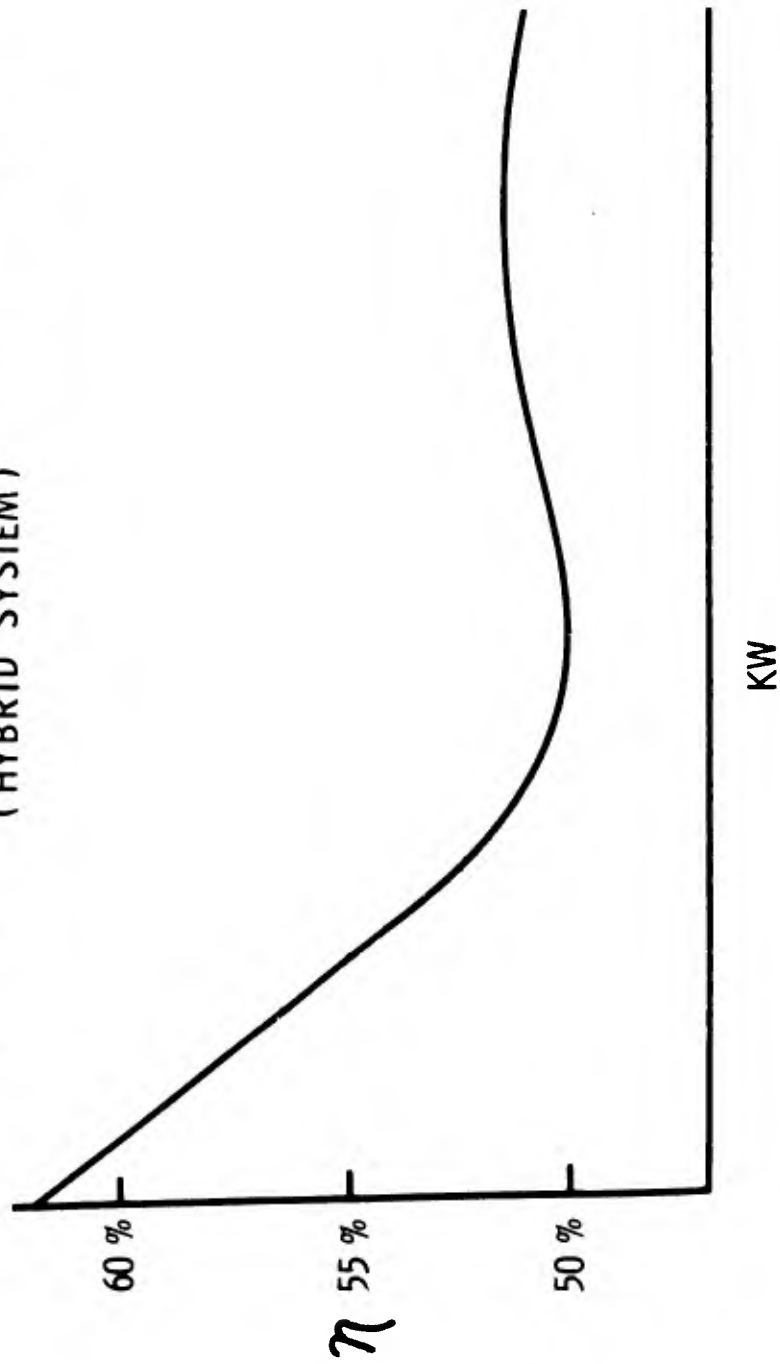


FIGURE 10

as the battery seriously polarizes. It must be noted that this curve is for external power to the drive train. During periods of reduced vehicle activity the hybrid system will have a significant internal current for battery recharging operations.

Because the fuel cell battery hybrid system is highly regenerative, using its own waste heat for fuel preparation and to maintain operating temperatures, the severely lowered efficiencies which are characteristic of fuel cells by themselves are not experienced with this system. Figure 11 is an efficiency vs. load curve for an ammonia-air fuel cell. Note that the power plant efficiency drops significantly below 30% of rated operation. This is partially due to the parasitic power required for the auxiliaries which must be sized to operate at the 40-kilowatt level, but is principally a function of lower efficiency of the hydrogen generator. This same loss in efficiency at part load will be encountered in a hydrocarbon-air fuel cell which is not integrated in a hybrid system.

#### HYBRID SYSTEM DESIGN

All of the design calculations are based on a hydrocarbon-air fuel cell portion which would weigh 30-35 pounds per kilowatt and a battery with an energy density of approximately 150 watt-hours per pound. As previously indicated, any fuel cell with this power density, or any battery with this energy storage density would not necessarily be the optimum candidates for the best hybrid system for vehicle propulsion applications. Maximum advantage is obtained when the fuel preparation, the fuel cell

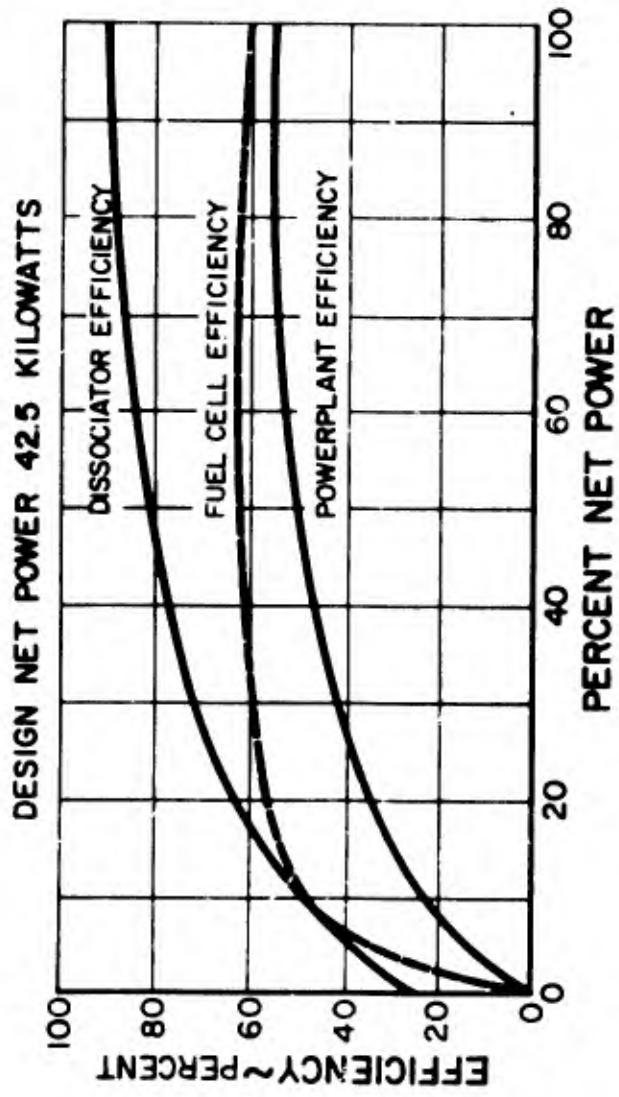


FIGURE 11

reaction, and the battery reactions are all carried out at the same temperature. According to this concept the unit building block contains the fuel reforming, fuel cell conversion, and energy storage components. These hybrid modules could be standard repeatable units which could be paralleled in larger power sources. The fuel preparation section contains a conventional reformer catalyst which is located in thermal contact with the heat stored in the heat capacity of the battery electrolyte. The fuel cell could utilize a molten salt electrolyte immobilized in a suitable high density matrix. Laboratory models of these fuel cells have been fabricated and shown performance equivalent to the voltages, currents, and efficiencies described in Figure 9. The battery could utilize the lithium molten salt reactions, preferably in a design which would use sealed single cells.

A large amount of attention must still be given to the high temperature materials, the devising and optimizing of specific cell configurations, and total system integration and control schemes. Engineers have made a careful analysis of how a number of cars and trucks are used, i.e., the amount of time which they normally will travel at the different speeds each day, the amount of time they stand idling, and the amount of time between trips. A Volkswagen would require only 30 pounds, or approximately 5 gallons of fuel for a 300-mile trip. Its 3-kilowatt fuel cell would weigh approximately 105 pounds and its 20 kilowatt-hour battery would weigh approximately 135 pounds. Since its average power consumed is only about three to four kilowatts, the fuel cell would normally power

the Volkswagen during its travel, but the 20 kilowatt hours of stored energy is available in the battery for high speeds when required. Any energy removed from the battery during high speed periods could be replaced while the Volkswagen is idling or at rest waiting for the next trip. The total weight of the Volkswagen's electric battery system and fuel tank would therefore be approximately 270 pounds, which is very favorable compared to its present engine and fuel tank.

A standard 3/4-ton truck has an engine and fuel tank which combined weigh 773 pounds and it is able to consume gasoline in its engine at about 12% efficiency. If we put a battery and fuel cell hybrid system and fuel tank in this same weight, we find that we can increase the efficiency of using the fuel by a factor of three and have a total stored energy of 2-1/2 times that of the conventional gasoline engine vehicle. This means that the 3/4-ton truck can be driven 2-1/2 times as far between refuelings and likewise would cost only 1/3 as much per mile for fuel.

#### CONCLUSIONS

Through the use of a fuel cell-battery hybrid power source, all of the "battery problems" can be overcome. This power source allows an electric vehicle to have: (1) full range capability, (2) excellent acceleration characteristics, and (3) use of conventional hydrocarbon fuels. To achieve the required performance depends upon the successful development of a 150-watt-hour per pound molten electrolyte battery and

a 20-35 pound per kilowatt hydrocarbon-air fuel cell. Research progress indicates that these goals should be achieved in operational hardware within the next five to ten years.

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13. ABSTRACT  Based on extensive experience with battery and fuel cell power sources during various Army programs, the author extrapolates into the future world of the electric car and speculates on the power sources most suited as the electrical energy source. The conclusion is that both the battery and the fuel cell have their place when combined uniquely in a hybrid configuration which by proper design can provide outstanding characteristics. (Author)		

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Electric Car						
Power Source						
Battery						
Engine						
Fuel Cell						
Hybrid Electric Source						
Energy Density						
Power Density						
Energy Reserve						
Electrochemical System						
Molten Electrolyte						
Duty Cycle						
Vehicle Propulsion						