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DEVELOPMENT OF FUEL CELL TECHNOLOGY FOR VEHICULAR APPLICATIONS

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OCTOBER 1, 1977 - SEPTEMBER 30, 1978

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**ELECTROCHEMICAL TECHNOLOGY GROUP
ENERGY STORAGE AND CONVERSION DIVISION
DEPARTMENT OF ENERGY AND ENVIRONMENT**

**BROOKHAVEN NATIONAL LABORATORY
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J. MCBREEN, E.J. TAYLOR, K.V. KORDESCH,
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SUMMARY

The program entitled "Development of Fuel Cell Technology for Vehicular Applications," initiated in FY 1978, involved the collaboration of Los Alamos Scientific Laboratories (B. McCormick, et al.); Energy Systems Research Group Inc. (S. Nelson); U.S. Army Mobility R&D Command (J.R. Huff); and Brookhaven National Laboratory (J. McBreen, S. Srinivasan, et al.).

This report contains a survey of the present state-of-the-art of fuel cells and of batteries suitable for hybrid fuel cell/battery power plants. Also included are a systems study on phosphoric acid fuel cells for transportation applications and the results of an experimental study of phosphoric acid and alkaline fuel cells under conditions of intermittent operation.

Fuel cells are attractive for transportation applications because of their high efficiency and low emissions and noise levels. A unique feature of the fuel cell is that its efficiency does not decrease as rapidly as heat engines when one goes to the smaller plant sizes (10-100 kW) required for most mobile applications. Another important aspect of the fuel cell efficiency is that it does not decrease significantly at partial load (down to 25% of rated output). Hence the fuel cell has a decided efficiency advantage in the stop-go type of duty cycle that is often encountered in transportation applications.

Fuel cells are an ideal method for efficient use of synthetic fuels in the transportation sector. The results of the LASL study indicates that for identical fuels, in stop-go duty cycles, fuel cells can yield fuel economies as much as two and a half times that of the internal combustion engine. In terms of range per unit weight of fuel, a hydrogen fuel cell can yield more than 7.5 times the range of a gasoline internal combustion engine in stop-go duty cycles. Apart from the fact that fuel cells have low gaseous and no particulate emissions, they are environmentally attractive because their high efficiency minimizes primary energy source utilization with its concomitant pollutions problems.

Fuel cells, optimized for transportation, would have a specific power in the range of 50-60 W/kg. While this power level is more than adequate for cruising, an auxiliary power source such as a battery would be needed for acceleration. Several benefits accrue from such a hybrid power plant. An electric/electric hybrid is inherently much simpler than a mechanical/electric hybrid. The battery accelerates fuel cell startup and protects the fuel cells against cell reversal during startup. Batteries have a much longer life in the shallow cycling regimens in hybrid cycling. Deep discharges, which occur in a battery electric vehicle, considerably shorten battery life. A fuel cell/battery hybrid power plant offers good performance, long range and fast refueling. Long range can be achieved with rechargeable batteries; however, the cost is high. A battery that would yield a range of 200 miles would have an initial cost of about \$2800.

In the U.S., the phosphoric acid fuel cell is technologically the most advanced. It is being developed for utility applications and integrated energy systems. Emphasis has been on optimizing the system for efficiency and cost. Hence, there has been little incentive to reduce the weight or volume of the system and as a result none of these units are suitable for transportation applications. Much of the complexity, weight and bulk of present day fuel cells accrues from the fact that the fuels used (natural gas and naphtha) require a high degree of processing prior to use in the fuel cell stack.

Energy Research Corporation carried out a system study of a 60 kW and a 15 kW phosphoric acid fuel cell for transportation application. Two fuels - methanol and propane - potentially useful for this application were considered. The projected performances and conceptual designs of the various systems and estimated costs were the end results of this investigation. The 60 kW system was a pressurized unit while the 15 kW system operated at atmospheric pressure. For the 60 kW unit, the estimated system volume and weight were 0.73 ft³/kW and 22 lbs/kW respectively for the methanol system and 1.24 ft³/kW and 28 lbs/kW respectively for the propane unit. System efficiency was found to be 42% and the efficiency did not vary significantly

with the fuel used or with partial load down at 25% of rated output. The increased weight and volume of the propane system was due to the necessity for two water gas shift reactors and six extra heat exchangers. A sulfur containing fuel would require a hydrodesulfurizer and its ancillary equipment thus adding further to system volume and weight.

The most significant result of this study is that the system weight volume and complexity is very dependent on the fuel. A 15 kW fuel cell is adequate for a commuter car. A 15 kW alkaline fuel cell with hydrogen fuel has a volume of 17.8 ft³. A similar phosphoric acid fuel cell has a volume of 18.1 ft³. A 15 kW phosphoric acid fuel cell with methanol as the fuel has a volume of 22 ft³, and if propane were used, the volume would be 33.2 ft³. These figures include the volume of fuel storage. If hydrogen were available, it would be an attractive fuel. An alkaline hydrogen air fuel cell would be a compact power plant with fast startup.

Experimental work on fuel cells included construction of a phosphoric acid fuel cell test stand, assembly and testing of Energy Research Corporation phosphoric acid fuel cells (single cells) and an alkaline fuel cell, construction of a 16-cell alkaline fuel cell module and assembly of facilities for testing of two solid polymer electrolyte fuel cells (single cells) obtained from the General Electric Company.

In the case of phosphoric acid it was found that intermittent operation had no adverse effects on performance up to 1000 hours of operation. It was also found that temporary cutoff of air flow (for a few minutes) while the cell is under load increased performance (40 mV at 100 mA/cm²) over a period of several hours.

The alkaline fuel cell, which included improved electrode structures (electrodes purchased from Union Carbide Corp.) yielded a 50% improvement in cell performance over that obtained by Kordesch in the late sixties. Intermittent operation over a 50-day period had no adverse effect on performance.

For most fuel cell/battery hybrid power plants, the lead acid battery is adequate. If fast charge acceptance is needed, nickel-zinc batteries

may have to be used. It has been demonstrated that nickel-zinc batteries can accept charge at the 4C rate in simulated hybrid service whereas the charge acceptance for most lead acid batteries up to 90% state of charge is about the C/2 rate. In hybrid service, battery life is more a question of calendar life rather than cycle life. A 3 to 4 year battery life can be expected for lightweight designs.

From the results of the joint studies of LASL, MERADCOM, ESRG and BNL during the first year of this program, it can be concluded that fuel cells can meet the performance and cost requirements as power sources for electric vehicles, buses, delivery vehicles, passenger cars, etc. which will be better than the projected figures for the near term and advanced batteries.

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PUBLICATIONS

1. McBreen, J., "Batteries - An Overview of the State of the Art," Proceedings of the Fuel Cell in Transportation Applications Workshop, August 15-17, 1977, Los Alamos Scientific Laboratories, Los Alamos, New Mexico (1978), pp. 38-40.
2. Srinivasan, S., "Potential Fuel Cell Systems for Transportation Applications," *ibid.*, pp. 41-45.
3. Srinivasan, S., McBreen, J., McCormick, B., Hamilton, D. and Kerwin, W., "Fuel Cells for Transportation," Workshop on Fuel Cells in Building and Industrial Applications, Sarasota, Florida, Nov. 14-17, 1977.
4. McBreen, J., Srinivasan, S., and McCormick, B., "Fuel Cell/Battery Hybrid Vehicles," Extended Abstracts, Vol. 78-2, The Electrochemical Society, Inc., Princeton, N.J. (1978), Abstract 108, pp. 286-288.
5. Srinivasan, S., "Fuel Cells for Electric Utility and Transportation Applications," Pres. at 29th Meeting of International Society of Electrochemistry, Budapest, Hungary, August 28-September 2, 1979.

DEVELOPMENT OF FUEL CELL TECHNOLOGY FOR VEHICULAR APPLICATIONS

1. Present State of the Art of Fuel Cells

1.1 General Characteristics of Fuel Cells

1.1.1 Definition, Types, Advantages

Fuel cells are galvanic cells in which the chemical energy of a fuel is converted directly into electrical energy by means of electrochemical processes. In the narrowest definition, fuel and air or oxygen are continuously and separately supplied to two electrodes at which they undergo electrochemical reactions. The power produced corresponds to low voltage (0.6-0.8 V) and reasonably high current densities ($> 100 \text{ mW/cm}^2$). With other fuels, a fuel cell power plant consists of a fuel storage system, a fuel processor, fuel cell stacks, heat exchangers and ancillary control equipment.

Fuel cells will continue to produce electrical energy as long as they are supplied with fuel and air. In mobile applications, vehicle operation over long distances simply requires refueling in a manner similar to the present gasoline or diesel-operated vehicles.

The salient features of fuel cells are that they have high efficiency and low emissions and noise levels.

1.1.2 The Efficiency of Fuel Cells

The high efficiency stems from the fact that they are not Carnot cycle limited. Fuel cell operation avoids the random processes of combustion. The maximum amount of electrical work (W_e) that can be derived from a fuel cell is related to the Gibbs free energy (ΔG) of the overall cell reaction:

$$W_e = \Delta G = -nFE \quad (1)$$

where n is the number of electrons in the overall reaction F is the Faraday constant, and E is the reversible potential of the reaction. In the case of a hydrogen/oxygen fuel cell operating at 25°C , $\Delta G = -113.38 \text{ k cal/mole}$, $n = 4$ and $F = 23.05 \text{ k cal mole}^{-1}$. Thus E is 1.229 Volts. The total energy released by a fuel cell corresponds to the enthalpy (ΔH) of the reaction. Since the enthalpy change of a hydrogen oxygen fuel cell is more negative than the Gibbs free energy, a part of the total energy change of the reaction which cannot be converted to electrical energy is given out as heat. This part is represented by:

$$\Delta H - \Delta G = T\Delta S \quad (2)$$

Since $\Delta H = 136.6 \text{ k cal mole}^{-1}$ and $T\Delta S$ is $23.2 \text{ k cal mole}^{-1}$, the ideal thermodynamic efficiency at 25°C is 83%. In actual practice, cells operate between 0.65 V and 0.8 V, corresponding to an overall thermal efficiency of between 44% and 54%. For a hydrogen/oxygen fuel cell:

$$\frac{\Delta H}{nF} = 1.48 \text{ V} \quad (3)$$

This is referred to as the thermoneutral voltage and is essentially invariant with temperature. The heat (Q) released from a single cell in a fuel cell over an operating time period t is:

$$Q = \int_0^t (1.48 - E_t) i_t dt \quad (4)$$

where E_t is the cell voltage at any time t and i_t the cell current at any time t . In actual practice, an excess of one watt of heat is released for every watt of electricity. In small units with no heat recovery, this heat is removed by air cooling. In larger units with heat recovery, water cooling panels are often used.

Fuel cell efficiency differs in two important ways from the efficiency of heat engines. Fuel cells do not exhibit the characteristic sharp decline in efficiency that occurs when the size (power) of the unit is decreased or

when operation is throttled back to partial rated load. Figure 1 is a plot of system efficiency versus plant size for fuel cells and various heat engines(1). The efficiency of a fuel cell does not decrease as rapidly as that of a heat engine with plant sizes. The power plant sizes of interest for mobile application are in the vicinity of 10-100 kW. In this range, the fuel cell has a significant advantage. The efficiency of fuel cells and of heat engines as a function of percent rated output is shown in Figure 2 in terms of BTU/kWh(2). Here the BTU is the enthalpy of the fuel. Fuel cells have the advantage in that their efficiencies do not decrease significantly at part loads down to 25% of rated output. This is important in applications with a variable load duty cycle, such as ground transportation. It should be pointed out that the intercomparisons in Figure 1 and Figure 2 are made for similar long chain hydrocarbon fuels. In the case of simple chemical fuels, such as hydrogen or methanol, the disparity in efficiencies between fuel cells and heat engines would be even greater. These data indicate that when intercomparisons are made between the efficiencies of fuel cells and heat engines, the comparison must be made for power plants of identical size and duty cycle.

1.1.3 Fuel Cells and Fuel Economy

Fuel cells are an ideal method for efficient use of synthetic fuels in the transportation sector. This is particularly true in applications with stop-go drive cycles. Table I gives a comparison of fuel utilization in heat engines and fuel cells. These data are based mostly on the results of the LASL study(3). In applications with stop-go duty cycles, fuel cells can yield fuel economies as much as two and a half times that of internal combustion engines. In terms of range per unit weight of fuel a hydrogen fuel cell can yield more than 7.5 times the range of a gasoline internal combustion engine in stop-go duty cycles.

Figure 1. Power system efficiency comparison comparison.

Figure 2. Fuel cell efficiency as a function of power output.

TABLE I

Comparison of Fuel Utilization in a Consumer Car (3858 lb)
with Heat Engine and Fuel Cell Power Plants

Fuel	ICE	Power Plant Fuel Utilization	
		Diesel	Fuel Cell
Gasolene (Mpg)	40 (26)	---	---
(Mplb)	6.8 (4.4)	---	---
Diesel Oil (Mpg)	---	53 (40)	---
(Mplb)	---	7.8 (5.9)	---
Propane (Mpg)	31 (18)	---	38 (38)
(Mplb)	7.4 (4.3)	---	9.1 (9.1)
Methanol (Mpg)	20 (13)	---	26 (27)
(Mplb)	3.1 (1.9)	---	4.0 (4.2)
Hydrogen (Mpg)	12 (7.5)	---	17 (20)
(Mplb)	20 (12.7)	---	28 (33)

Utilizations are given for cruise at 55 mph and for the J227 Urban Cycle, in parentheses. Fuel utilization is given both in terms of Miles per gallon (Mpg) and Miles per pound (Mplb).

1.1.4 Environmental Aspects of Fuel Cells

Fuel cells are environmentally attractive for a number of reasons. If one considers coal derived fuels, the efficient operation of fuel cells minimizes the amount of coal mined and the concomitant environmental impact of such mining. Extensive tests of fuel cells for utility application by UTC indicates that the emissions of CO, NO_x, hydrocarbons

and particulate matter is minimal. Results are shown in Table II for particulates, NO_x , SO_2 and smoke(4).

TABLE II
Environmental Impact of Fuel Cells

POUNDS OF POLLUTANTS PER MILLION BTU HEAT INPUT				
	FEDERAL STANDARDS*			
	GAS-FIRED CENTRAL STATION	OIL-FIRED CENTRAL STATION	COAL-FIRED CENTRAL STATION	EXPERIMENTAL FUEL CELLS**
PARTICULATES	0.1	0.1	0.1	0.000029
NO_x	0.2	0.3	0.7	0.013-0.018
	NO			
SO_2	REQUIREMENT	0.8	1.2	0.000023
SMOKE	20% OPACITY	20% OPACITY	20% OPACITY	NEGLEGIBLE

*FEDERAL STANDARDS EFFECTIVE 8-17-71

**YORK RESEARCH CORP., Y-7309 APRIL 1970

The power requirements for a 2200 lb car cruising at 55 mph, or driving in an urban environment at an average speed of 20 mph and a top speed of 30 mph is about 15 kW. This represents an energy consumption of 0.27 - 0.75 kWh/mile. If one assumes 9000 BTU/kWh, the expected NO_x emissions are 0.013 g - 0.054 g/mile. Present federal standards are 2.0 g/mile and projected standards for 1981 are 1.0 - 1.59 g/mile. All the pollutants are generated in the reformer and not in the fuel cell stack. The fuel cell emission data are for fuel cells with hydrocarbon reformers that operate at about 750°C. The NO_x levels would be much less in the case of a methanol reformer, which operate at about 200°C. An important aspect of fuel

cells is the lack of any significant particulate emissions. At present there are no legislative limits on particulates. However, as the population of diesel vehicles increases there will be pressure to impose limits on particulate emissions. In this case the fuel cell would have a decided advantage. A hydrogen fuel cell which has no reformer would essentially have no emissions other than water vapor.

In the U.S., research and development work is being carried out on several types of fuel cells - phosphoric acid fuel cells, solid polymer electrolyte (SPE) fuel cells, molten carbonate fuel cells, solid electrolyte fuel cells, and alkaline electrolyte fuel cells. In Europe, there are several programs on alkaline electrolyte fuel cells.

1.2 Phosphoric Acid Fuel Cells

1.2.1 The Current U.S. Development Programs

Development of phosphoric acid fuel cells is being carried out in the U.S. at Energy Research Corporation (ERC), Englehard Corporation and United Technologies Corporation (UTC). ERC has developed a 2.5 kW phosphoric acid fuel cell, which uses methanol as a fuel, under a contract with the U.S. Army (MERADCOM). At present, ERC is starting development work on a 60 kW fuel cell for use in integrated energy systems. UTC has a 40 kW phosphoric acid fuel cell in an advanced state of development. This fuel cell uses reformed natural gas as a fuel and is for use in integrated energy systems. UTC is also in the final stages of construction of a 4.8 MW phosphoric acid fuel cell power plant for installation by Consolidated Edison in New York City. The fuel is reformed naphtha. The goal of this work is the development of multi-mega watt fuel cell power plants for dispersed power generation and spinning reserve within electric utility networks(5).

In the development of phosphoric acid fuel cells for integrated energy systems and utility networks, the focus has been on improving efficiency.

There has been little incentive to reduce the volume and weight of the system. For vehicular applications, it would be necessary to design a system that is optimized with respect to power density and cost.

At present, the phosphoric acid fuel cell is technologically the most advanced system. The main reason for this is that it has many attractive engineering features. It is compatible with reformed carbonaceous fuels. Thermal management and water management are simple and the temperature of operation is such (200°C) that thermal feedback from the fuel supply system is possible.

1.2.2 UTC 40 kW Phosphoric Acid Fuel Cell

The UTC 40 kW phosphoric acid fuel cell is designed for use in integrated energy systems for apartments, shopping centers and industrial complexes. The fuel is reformed natural gas and air is the oxidant. The 40 kW fuel cell consists of a fuel supply, a fuel processor, fuel cell stacks, heat exchangers, heat and water recovery systems and an inverter(6).

The fuel processor consists of a deoxidizer, a hydrodesulfurizer, a steam reformer and a shift converter. The deoxidizer removes oxygen from the incoming gas. Oxygen is sometimes added to gas to modify its heating value. The hydrodesulfurizer converts sulfur compounds to H_2S and the H_2S is adsorbed in a zinc oxide bed. This step is necessary because of the low tolerance of reformer catalyst to sulfur compounds. The steam reformer converts the mixture of steam and gas, at 870°C , to a mixture of hydrogen, carbon dioxide and carbon monoxide. The carbon monoxide content of the gas from the reformer is 11%-14%. The shift converter further reacts the carbon monoxide with steam to reduce the carbon monoxide content to tolerable levels for the fuel cell ($<1.5\%$). The shift reaction is carried out at about 200°C .

The fuel cell stacks consist of 270 cells in series. Electrode area is 2.2 ft^2 . The cells are cooled by heat exchange panels that are interspersed between every sixth cell. Eighty percent of the hydrogen in the incoming gas is used in the cells. The spent gases are used for heating

the reformer. The stacks operate at 190°C and a pressure of 5"-7" of water. When one considers the overall system, the necessity for an extensive heat exchange system is obvious. The heat and water recovery systems improve overall system efficiency.

Table III gives a weight on volume breakdown for the UTC 40 kW system. A cursory inspection of the Table indicates the added weight and volume that accrues from use of a sulfur containing fuel that has to be reformed at high temperatures. Sulfur removal is difficult in fuel cell fuel processors because of the low pressure of operation. The optimum pressure for sulfur removal is about 10 atmospheres.

TABLE III		
Weight and Volume Breakdown for the UTC 40 kW Fuel Cell		
Component	Displaced Volume (ft ³)	Weight (lbs)
Cell Stack	50	1800
Fuel Processor		
HDS/DO*	6	80
Reformer	20	500
Shift Converter	4	180
Thermal Management	11	450
Water Recovery	14	250
Heat Recovery	3	85
Reactant Supply	4	140
Plumbing	40	800
Inverter	11	520
*Hydrodesulfurizer/deoxidizer		

The 40 kW unit has a design voltage of 163 V and a design current of 287A. A typical cell stack polarization curve is given in Figure 3. A pilot version of the 40 kW unit has accumulated 14,000 hours operation. The startup time for the reformer is <0.5h and the startup time for the cell stack is 3h.

Figure 3. Polarization curve for 40 kW phosphoric acid fuel cell.

Table IV gives a projected cost breakdown for a phosphoric acid fuel cell of this type. The complexity and the added components accruing from the use of a sulfur containing fuel that is reformed at high temperature adds considerably to the costs. Regular maintenance costs are projected to be 0.1 to 0.15 ¢/k Wh. When one include major replacements, these costs increase 0.7 ¢/k Wh. This assumes replacement of the cell stack every five years and replacement of the reformer every 10 years.

TABLE IV
Projected Cost of a 40 kW Phosphoric Acid Fuel Cell Using Reformed Natural Gas

Total Costs	Costs (\$/kW)*
Manufacturer Cost	250
Installed Cost	435
Selling Cost	385
<u>Breakdown of Installed Cost</u>	
Cell Stack	148
Fuel Processor	35
Heat Exchangers	65
Auxiliary Components	83
Structure/Assembly	30
Miscellaneous	22
Inverter	52
*1977 \$	

1.2.3 ERC 2.5 kW Phosphoric Acid Fuel Cell

ERC has built a 2.5 kW phosphoric acid fuel cell under contract with the Army (MERADCOM). The fuel cell uses reformed methanol as a fuel and air as the oxidant. The methanol is steam reformed at about 200°C. No shift converter is necessary because of the low reforming temperature. The fuel feed to the reformer is a 1:1 by volume mixture of water and methanol. Table V gives a weight and volume breakdown for the system. This unit is air cooled and does not have provisions for heat recovery(7).

The cell stack consists of 80 cells with electrodes that are 5" x 15" in area. The stack operates at atmospheric pressure and a temperature in the range of 150⁰-175⁰C. A performance curve for operation in the lower temperature range is given in Figure 4. Startup time is in the range of 15-20 min.

TABLE V

Weight and Volume Breakdown for the ERC 2.5 kW Fuel Cell

Component	Volume (in ³)	Weight (lbs)
Cell Stack		
Electrode Stacks	1500	49
Stack Hardware	100	28
Manifolds	720	15
Reformer	1100	9.8
Insulation	500	7

In both of these surveys, it became apparent that no phosphoric acid fuel cell has been designed or built for mobile applications. There is a great lack of information on performance and life under vehicle operating conditions. There is very little data on the effect of variable duty cycles. The effects of thermal cycling and intermittent operation are virtually unknown. The only available data point on this is that MERADCOM have operated four Engelhard 1 kW phosphoric acid fuel cells in a fork lift truck over a period of three years without any degradation in performance(8).

1.2.4 Possible Improvements in Phosphoric Acid Fuel Cells

The present trend in phosphoric acid fuel cells is to improve efficiency and power density by operation at higher temperatures (up to 215⁰C) and pressures (up to 3 Atmospheres). The effect of temperature

Figure 4. Performance characteristics of ERC 2.5 kW phosphoric acid fuel cell.

and pressure on cell performance is shown in Figure 5(9). It is evident that significant gain can be made by pressurization. The effect of the higher operating temperatures on cell life is unknown. Platinum catalyst loading in phosphoric acid fuel cell is about 0.75 mg/cm^2 . About 20% of the platinum is utilized. Present goals are to achieve 50% platinum utilization.

An important recent development is the ribbed substrate cell stack. A comparison of this stack with a conventional cell stack is shown in Figure 6. This new configuration has the potential to reduce stack cost, reduce maintenance intervals and improve efficiency(10).

1.3 Solid Polymer Electrolyte Fuel Cells

Solid polymer electrolyte fuel cells are under development at General Electric Company. These cells are based on the use of perfluoro-sulfonic acid membranes and are an outgrowth of General Electric work on the Gemini program. Recently efforts have been made to scale up these cells to electrode sizes of 1020 cm^2 . A reformed methanol-air fuel cell is currently under development. This work, sponsored by MERADCOM, is for terrestrial mobile applications. General Electric have made a conceptual design of 4 kW reformed methanol-air fuel cell(11).

The SPE fuel cell is attractive for vehicular applications because of its fast start up time ($<5 \text{ m}$)(12). It lends itself to designs that are tolerant to shock and vibration. It can also tolerate gas pressure surges. The SPE cell is compatible with reformed carbonaceous fuels and can operate at high power densities. One difficulty is water management. Unlike inorganic electrolytes, there is little suppression of water vapor pressure and the electrolyte tends to dry out. This can be avoided by prehumidification of the reactants.

Figure 7 gives performance data for laboratory size (35 cm^2) cells with simulated reformat fuels. Significant gains have been made by increasing the pressure of operation(11). Lifetimes of 50,000 hours have been demonstrated in a four cell stack.

Figure 5. Effect of temperature and pressure on cell performance.

Figure 6. Cell configuration comparison.

Figure 7. Performance of GE 35 cm² SPE fuel cells.

In 1975 General Electric made a cost analysis of a 5 kW reformed methanol-air SPE fuel cell. The manufactured cost was \$277/kW. A cost breakdown is given in Table VI(11).

TABLE VI	
Cost Breakdown for General Electric Reformed Methanol/Air SPE Fuel Cell	
Component	Cost (\$/kW)
Cell Stack	190
Reformer	35
Auxiliary Components	35

1.4 Alkaline Electrolyte Fuel Cells

In the U.S., alkaline electrolyte fuel cells have been developed to a very sophisticated level for spacecraft applications. Power densities as high as 3.5 kW/ft² at 0.6 V have been reported. UTC has developed a 12 kW fuel cell for the space shuttle(13). The system weight, exclusive of fuel storage is only 200 lbs. Even though this system is a H₂/O₂ fuel cell with high noble metal catalyst loadings, it demonstrates potential advances in the development of mobile power plants.

If hydrogen were readily available and could be easily stored on a vehicle, the alkaline electrolyte fuel cell would be the obvious choice for vehicular applications. Alkaline fuel cells have high power densities. It is possible to construct alkaline cells without any noble metal catalysts and metallic components can be incorporated in the cell stack to yield designs that are resistant to shock and vibration. The main problem with alkaline fuel cells is that the electrolyte carbonates due to ingress of CO₂ from either the fuel or air stream. Carbonate in the electrolyte ultimately

proves deleterious to the electrode structure. Successful operation depends on removal of CO_2 from the fuel and air stream and the exclusion of any plastics that can decompose in the electrolyte. Carbon dioxide removal from the air stream is relatively simple because of its low concentration (~ 400 ppm). However, in mobile applications, no satisfactory method has been found for removal of the large amounts ($\sim 25\%$) of CO_2 from reformed fuel streams. Hence, at present alkaline fuel cell cannot be considered for use in mobile applications with reformed carbonaceous fuels.

One promising aspect of alkaline fuel cells is that programs are underway in the U.S. to develop alkaline electrolyte air electrodes for air depolarized chlorine electrolysis cells. Hopefully, the result will be large scale mass production of inexpensive long lived air electrodes that would be suitable for alkaline fuel cells. This allied developing technology could help greatly in the commercialization of alkaline electrolyte fuel cells.

In Europe, work continues on alkaline fuel cells for terrestrial applications. At the Electrochemistry Laboratory of Siemens in Erlangen, West Germany 3.5 and 7 kW alkaline hydrogen/oxygen fuel cells have been built and tested. A program is now underway to construct a 20 kW unit(14). These units are being considered for standby applications, for example, in hospitals. The 7 kW unit which was completed in May, 1978 consists of a fuel cell stack and an electrolyte regeneration for product water removal. The cell stack consists of 70 cells and it delivers 142A (420 mA/cm^2) at 53.8 V. The electrocatalysts for the anode and cathode are Raney nickel and doped silver respectively. The system weight is 85 kg and the volume 60 l. The unit reaches 45% of rated power at 20°C and reaches the desired operating temperature of 80°C in eight minutes.

In 1974, ELENCO, an organization consisting of three partners, the Study Center for Nuclear Energy (SCK/CEN), Mol, Belgium, Dutch State Mines, Geleen, Netherlands and Bekaert, Brussels, Belgium was formed with the aim of developing alkaline fuel cells particularly for transportation(15). Work to date has involved the design, fabrication and testing of a 10 kW fuel cell. The 10 kW system consists of three 36 V module stacks in series. Each

module stack consists of six 6 V modules. Each module consists of 18 cells in a series-parallel. The active electrode area in the cells is 300 cm². The present design point is 80 mA/cm² at 0.67 V per cell. ELENCO has also carried out technoeconomic assessments. The main applications considered are for use of hydrogen byproduct gas from the chloralkaline industry and as power sources for buses, fork lift trucks and special purpose vehicles.

The ELENCO program is being funded at a \$5 million dollar level for the first three years which ends in December, 1978. The program has been renewed for a second three-year term at a \$7 million dollar level. In the second period stress will be on improvements in power densities by about 50% and continuation of the systems studies to explore further applications.

2. Fuels and Fuel Processing

2.1 Fuel Options

No single factor has inhibited the development of fuel cells as much as the fact that readily available fuels such as coal and petroleum derivatives cannot be used directly in fuel cells. In our survey of the present state of the art, it quickly became apparent that much of the complexity, bulk, and weight of fuel cells accrued from the fact that the fuels used required a high degree of processing prior to use in the fuel cell stack. In mobile applications where weight and volume are a consideration, it is desirable that the fuel require the minimum amount of pre-processing before use in the fuel cell.

The fuel cell options are outlined below and are:

Hydrogen

Alcohol Fuels

- Methanol
- Ethanol

Hydrocarbon Fuels

- Propane
- Sulfur Containing Hydrocarbons

Hydronitrogen Fuels

- Hydrazine
- Ammonia

2.2 Hydrogen

Hydrogen is the ideal fuel cell and can be used directly, without processing, in any type of fuel cell. Unfortunately, it is not yet readily available and it is difficult to distribute and store. Methods of hydrogen storage that have been considered are metal hydrides, liquid hydrogen and compressed gas. A comparison of the various storage media is given in Table VII(16). Cryogenic hydrogen storage is not attractive because of the

TABLE VII
Comparison of Hydrogen Storage Media

Medium	Hydrogen Content Wt %	Storage Capacity g/ml of vol	Energy Density Heat of Combustion** (higher)	
			cal/g	cal/ml of vol
MgH ₂ *	7.0	0.101	2373	3423
Mg ₂ NiH ₄	3.16	0.081	1071	2745
VH ₂	2.07		701	
FeTiH _{1.95}	1.75	0.096	593	3245
TiFe _{0.7} Mn _{0.7} H _{1.9}	1.72	~0.09	583	~3050
LaNi ₅ H _{7.0}	1.37	0.089	464	3051
R.E.Ni ₅ H _{8.5}	1.35	~0.09	458	~3050
Liquid H ₂	100	0.07	33900	2373
Gaseous H ₂	100	0.007	33900	244
N-Octane			11400	8020

*Starting alloy 94% Mg 6% Ni

**Refers to H only in metal hydrides

enormous energy penalty involved in conversion of ortho to para hydrogen prior to liquefaction. This quantum transition occurs in the cryogenic region and the heat of conversion is 703 j/g as opposed to the latent heat which is only 444 j/g. If this conversion is not carried out, excessive

boiloff can occur (about 18%) after one day and about 50% after one week(17). Metal hydrides are attractive from the point of view of volume and safety and have been demonstrated in vehicles with internal combustion engines. Table VIII lists the characteristics and costs of some metal hydrides(18). The temperature of decomposition of FeTiH_2 is very compatible with alkaline fuel cells. The costs are reasonable, particularly when one considers that Kordesch got a range of 200 miles with less than 4 lbs of hydrogen.

TABLE VIII
Characteristics of Some Metal Hydride Alloys

Alloy	Nominal, wt %	Raw Materials Cost, \$/lb	Raw Materials Cost, \$/lb H_2 Storage Capacity	Dissociation Temp. ($^{\circ}\text{C}$) for 10 atm Plateau Pressure
Mg	7.60	1.00	12.20	375
Mg (6 wt % Ni)	~7.0	1.10	14.60	375
Mg_2Ni	3.30	1.90	55.70	350
Mg_2Cu	2.60	0.98	36.70	319
$\text{TiFe}_{0.85}\text{Mn}_{0.15}$	1.7	1.45	84.00	63
FeTi	1.5	1.40	92.50	50*
CaNi_5	1.40	2.10	148.00	>100
LaNi_5 (present)	1.35	7.85	573.60	65
LaNi_5 (future)	1.35	4.30	314.20	65

*Lower plateau

Kordesch used lightweight high pressure (2000 lbs) tanks in his fuel cell battery hybrid car. The six tanks he used weighed only 180 lbs and contained 660 ft³ (3.861 lb) of hydrogen(19). Thus the hydrogen content was 2% of the storage weight. More recently Plenard has reported on the development of composite storage tanks where the hydrogen content is 4% of the storage weight(20). This demonstrates what could be done if a source of hydrogen were available. Lack of availability of hydrogen will preclude its use in vehicular application in the near term.

2.3 Alcohol Fuels

Alcohol fuels are currently being proposed as possible extenders or even replacements for petroleum fuels. Brazil has considered an economy based on ethanol. Alcohol fuels are attractive for fuel cells because they are clean and are easily steam reformed at moderate temperatures. Methanol is the most promising fuel since it is seriously being considered by many to be an energy source of significant magnitude(21,22). Furthermore it can be synthesized from coal. The general process steps for the synthesis of methanol from coal are shown in Figure 8. If the heating value of the concomitant methane is included the overall efficiency for methanol production is as high as 70%(21,22).

Methanol has the advantage of being a liquid fuel. The advantages of easy mobility is likely to favor the continued use of liquid fuels as energy storers for the transportation sector. However, some materials changes, such as elastomer parts, in the present gasoline distribution infrastructure would have to be made if methanol were the fuel of choice. The great advantage of methanol, in the case of fuel cells, is that it can be easily reformed at about 200°C without the use of a separate shift converter(23). Reforming methanol comprises of 75% H₂ and 25% CO₂. No practical method is available for removal of massive amounts of CO₂ in a mobile fuel cell(24,25). Reforming carbonaceous fuels have to be used either in conjunction with phosphoric acid fuel cells or with solid polymer electrolyte fuel cells. Further details of the impact of methanol on fuel cell design and performance are given in Section 3 and Appendix B of this report.

2.4 Hydrocarbon Fuels

Hydrocarbons require much higher reforming temperatures ($\sim 800\text{--}900^{\circ}\text{C}$) than methanol and as a result a considerable amount of CO (26) is produced in the reformer. This requires the use of a high temperature and low temperature shift converter prior to introduction of the fuel into the cell stack.

At present the most available clean hydrocarbon is propane. Further details of the impact of propane on fuel cell design and performance are given in Section 3 and Appendix B of this report.

Since conventional liquid hydrocarbons contain sulfur a hydrodesulfurizer has to be incorporated in the fuel cell system. The added complexity weight and volume (see Section 1.2.2) precludes use of such a fuel cell in practically all transportation applications.

2.5 Hydronitrogen Fuels

Like hydrogen hydrazine can be used directly in fuel cells and several operating hydrazine/air fuel cells have been demonstrated(27-29). The main problems are cost, availability and toxicity of hydrazine.

Since ammonia cannot be used directly, it has to be cracked ($\sim 1100^{\circ}\text{C}$) prior to use in a fuel cell. It can be used in an alkaline fuel cell or in a phosphoric acid fuel cell provided no ammonia is carried out in the cracked gases(30). Once again it is a question of availability and toxicity. Figure 9 shows an intercomparison of the hazard index of various fuels(31). Here the hazard index is defined as the vapor pressure divided by the threshold limit value (TLV) for the substance. Since hydronitrogen fuels have a considerably higher hazard index than other fuels it is doubtful if they would gain acceptance in the transportation sector.

Figure 8. General process steps to manufacture methanol from coal.

Figure 9. Hazardous index of some fuels and related chemicals.

2.6 System Complexity and Fuel Option

The impact of the fuel option on system complexity is shown in Table IX. As fuels become more chemically complex, fuel processing adds considerably to system complexity. This is reflected in the number of heat exchangers required and the added volume of the system. Sulfur containing fuels are out of the question since hydrodesulfurizers would further add to the system volume weight and cost. Even with iron-titanium hydride storage the hydrogen option looks very attractive from the point of view of weight and volume. There is the additional advantage that hydrogen can be used with alkaline fuel cells. This reduces the operating temperature and decreases the startup time of the system.

TABLE IX				
System Weight and Volume for a 15 kW Low Pressure Fuel Cell - Projected Values for 1985				
Parameter	Alkaline Fuel Cell	Phosphoric Acid Fuel Cell		
Fuel	Hydrogen	Hydrogen	Methanol	Propane
Cell Stack Temperature ($^{\circ}\text{C}$)	80	200	200	200
Number of Heat Exchangers	2	2	2	8
Reformer Temperature ($^{\circ}\text{C}$)	--		190	760
Component Weight (kg)				
Cell Stacks	68	187	187	187
Reformer	--	--	45	96
Accessories	23	5.5	5.5	32
Fuel Supply	273	273	63	70
TOTAL WEIGHT	364	465.5	300.5	385
Component Volume (ℓ)				
Cell Stacks	100	181	181	181
Reformer	--	--	68	218
Assessories	30	3	3	11
Fuel Supply	73	73	60	60
Packing Density	50	50	50	50
TOTAL VOLUME (ℓ)	506	514	624	940

3. Fuel Cell Optimization for Vehicular Applications

In surveying the present state of the art of fuel cells a number of issues became evident:

1. If carbonaceous fuels are considered then acid electrolyte fuel cells have to be used.
2. No acid electrolyte fuel cell system has been optimized for vehicular propulsion.
3. The chemical nature of the fuel has a major impact on system complexity volume and weight.
4. There is practically no data available on the impact of intermittent operation on fuel cell system life and performance.

To resolve some of these issues, a system study of phosphoric acid fuel cells for transportation applications was carried out by ERC. The ERC Final Report is incorporated as Appendix B of this report. Only a summary of their work will be given here.

ERC carried out a system study of the 60 kW and 15 kW phosphoric acid fuel cells. The former is representative of a power plant for a bus while the latter is representative of that for a passenger car. Two different fuels - methanol and propane - were considered. Fuel cell performance was projected using the ERC analytical model and a conceptual design of the various systems was made. The assumptions were:

1. A catalyst loading of $0.5 \text{ m}^2/\text{g}$ at the cathode and $0.25 \text{ mg}/\text{cm}^2$ at the anode.
2. A fuel (H_2) utilization of 80% and an oxidant (O_2) utilization of 59%.
3. In the case of methanol the composition of the gas feed to the anode is the water gas shift equilibrium at 450°F and in the case of propane the water gas equilibrium at 520°F .

In the case of the 60 kW system, pressurization (at 50 psia) was considered worthwhile because of the improvements in performance volume, weight and cost whereas in the case of small units (15 kW) pressurization was not deemed worthwhile. Accordingly, the 60 kW unit employed liquid cooling and the 15 kW had an air cooled stack.

The analysis included material and energy balances, weight and volume estimates for the various components and determinations of overall system efficiency as a function of load.

For the 60 kW unit, the estimated system volume and weight was 0.73 ft³/kW and 22 lbs/kW respectively for the methanol system and 1.24 ft³/kW and 28 lbs/kW respectively for the propane system. For the 15 kW unit the estimates were 1.19 ft³/kW and 35 lbs/kW for the methanol system and 1.93 ft³/kW and 46 lbs/kW for the propane system. System efficiencies for the 60 kW size were found to be 42% whereas in the 15 kW unit it was approximately 34%. System efficiencies did not vary significantly in the load range from 25% to 100% and efficiencies did not depend significantly on whether propane or methanol was used as the fuel.

The estimated cost of the fuel cell stack was \$83/kW for the 60 kW unit and \$156/kW for the 15 kW unit.

The results of this study indicate how dependent system volume weight are on the fuel. In going from methanol to propane, one has to add two water gas shift reactors and six heat exchangers.

4. Experimental Studies on Fuel Cells Under Simulated Vehicle Operating Conditions

4.1 Types of Studies

Fuel cell testing at BNL in FY1978 involved the testing of single cells of various types under intermittent operation. Fuel cell in transportation applications would not be operated continuously. However in most other applications continuous operation is the norm. Because of this there are no published data on the effects of intermittent operation on fuel cell performance and life.

Three types of fuel cells were considered, namely phosphoric acid, alkaline and solid polymer electrolyte fuel cells. The phosphoric acid fuel cells (PAFC) were obtained from ERC. The alkaline electrolyte fuel cells

were constructed at BNL using electrodes obtained from Union Carbide Corp., Solid polymer electrolyte fuel cells were obtained from General Electric Company.

4.2 Phosphoric Acid Fuel Cell Test Station

A test station was constructed for the experimental studies on phosphoric acid fuel cells. The station has the capability of testing four cells or four modules simultaneously and is shown in Figure 10. Figures 11-13 are diagrams of the DC circuitry, the AC circuitry and the gas plumbing respectively.

4.3 Phosphoric Acid Fuel Cells

The phosphoric acid fuel cells were small cells with electrode areas of 25 cm^2 . Catalyst loading were approximately 0.75 mg/cm^2 . Cell components are shown in Figure 14 and the completed cell in Figure 15. The cell electrolyte was 97% H_3PO_4 which is prepared by mixing 333 ml of reagent grade 85% H_3PO_4 with 167 ml of 30% stabilized H_2O_2 . The two components were mixed in an ultrasonic bath for 30 minutes and then heated for 16h at 100°C . The mixture was then heated for a further 15h at 150°C . Concentration determinations were made from density measurements.

The testing conditions for the phosphoric acid fuel cells were:

Temperature	175°C
H_2 flow	1.25 X^*
Air flow	5 X^*
Current density	100 mA/cm^2

*X indicates the stoichmetric amount of reactant.

Cell #1 was run continuously while cell #2 and cell #3 were run only during working hours (40 hours/week). The remainder of the time the cell was on open circuit. On open circuit the cell was maintained at temperature and gases were passed through the cell continuously.

Figure 10. H_3PO_4 Test Stand.

Figure 11. DC Circuitry.

Figure 12. AC Circuitry.

Figure 13. Gas delivery system.

Figure 14. H_3PO_4 cell components.

Figure 15. H_3PO_4 single cell.

The performance of H_3PO_4 cells tested at BNL was somewhat lower than that reported by ERC (Figure 16). This was probably due to an added resistance in the BNL cells and may be due to some detail in the assembly method. Because of time constraints it was decided to proceed with tests of fuel cells under intermittent operation conditions rather than devote time to resolving this problem. The goal of the work was not cell optimization but rather to determine if intermittent operation introduced an unknown failure mode.

Sintering of Pt catalysts particles occurs during long term operation of H_3PO_4 fuel cells and causes degradation of performance(32). The effect of open circuit operation on this phenomenon has not been reported but it was surmized that this would accelerate electrode degradation.

Performance variation of cell #1 is shown in Figure 17 contrary to expectations intermittent operation did not decrease performance. Rather, when a load was applied after an overnight at open circuit the voltage would drop about 40 mV below the steady state operation level and the voltage would recover to normal after about 10-15 minutes. The cell performance is shown in Figure 18. Cells #2 and #3 failed after 900 and 1000 hours respectively. Cell failure in both instances was caused by mechanical difficulties and resulted from plugging of the electrolyte replenishment parts. The matrix dried out.

In a later test a cell (cell #4) was operated under intermittent operation. The cathode was purged with N_2 prior to shutdown and during open circuit operation the cathode compartment was blanketed with nitrogen. However, this mode of operation resulted in rapid and drastic degradation of performance. On switching to load the performance was about 200 mV lower than the previous day and performance increased very slowly throughout the day. Testing was terminated after five days. This phenomena is as yet unexplained.

Early in FY 1979 all the electrodes tested will be examined by TEM. It is hoped that these investigations will shed more light on any electrocatalyst changes that may have occurred.

One interesting feature of H_3PO_4 cell performance is that performance can be temporarily improved by shutting off the air supply while the cell

Figure 16. ERC single cell polarization.

Figure 17. Potential vs. time.

Figure 18. Potential vs. time.

is under load. This causes the cell potential to decrease rapidly to zero on resumption of air flow cell performance is improved (by about 40 mV at 100 mA/cm²). This added performance slowly decays over an eight hour period.

Two possible explanations for this effect are:

1. During operation the catalyst particles become coated with an oxide. During the starvation the oxide is burned off the catalyst. In this way the catalyst particles are "rejuvenated."
2. The carbon support may be cleared of inert blocking gases during the starvation period.

Several conclusions may be drawn from the experiments on H₃PO₄ single cells; 1) intermittent operation seems to have no adverse effects on cell performance up to 1000 hours. However, drawing absolute conclusions from single cell studies may be risky. A need to test a larger 4-7 kW H₃PO₄ module is evident; 2) temporary cut-off of air flow while the cell is under load increases performance over a period of several hours. The practicality of such a procedure in multi-kilowatt units should be investigated.

4.4 Alkaline Fuel Cells

4.4.1 Design, Fabrication and Testing of Single Cells

At present, there is no vendor for alkaline fuel cells in the U.S. and no testing of multicell units has been carried out recently. Therefore, it was decided to construct both single cell alkaline fuel cells and multicell units at BNL. This work was initiated by Professor K.V. Kordesch of the Technical Univerisyt, Graz, Austria while he was a visiting scientist at BNL in the summer of 1978.

Electrodes for construction of alkaline cells were obtained from Union Carbide Corporation. A flow sheet for electrode manufacture is shown in Figure 19(33). The present Union Carbide air cathode differs from those by Kordesch in the late sixties. Improvements in cathode performance have been achieved by reversing the cathode structure. Formerly the electrode structure consisted of a PTFE bonded catalyst layer on a wetproofed porous

Figure 19. Electrode manufacture.

nickel sheet. During cell operation the catalyst layer faces the electrolyte. In the present structure the porous nickel sheet is not wetproofed. The catalyst layer is coated with a thin film of PTFE and faces the air plenum. This structure accelerates back diffusion of nitrogen and mitigates the sloughing of carbon particles from the catalyst layer. The design point for this structure is 100 mA/cm^2 at 0.7 V as opposed to 50 mA/cm^2 at 0.7 V for the old structure(34). In the past the hydrogen electrode has not been a limiting factor in performance so the old structures with the electrocatalyst layer facing the electrolyte was maintained.

The components for the alkaline test cell are shown in Figure 20. The cell comprised of two electrodes with an electrolyte plenum $0.050''$ thick and two gas plenums $0.125''$ thick. Uniform spacing was achieved by the use of neoprene rubber gaskets and plastic screens. Gasket surfaces were roughened by treatment with sulfuric acid and were epoxy bonded to the electrodes. Edge areas were sealed with epoxy and provisions were made for electrolyte circulation and gas flows. An assembled cell is shown in Figure 21.

The cell was tested under the following conditions. The electrolyte was 50% KOH and the temperature was 65°C . Temperature was maintained by external heating of the circulating electrolyte. Carbon dioxide was removed from the air stream using a caustic scrubber. The anode was operated with pure tank hydrogen. The test setup is shown in Figure 22. The cell was tested for 50 days as follows. During working hours the cell was maintained at 65°C and discharged at a current 100 mA/cm^2 . At night and on weekends there was no electrolyte in the cell and the cell was allowed to return to room temperature.

Figure 23 is a polarization curve for the alkaline cell that was obtained on startup. Performance data for Union Carbide alkaline cells from the late sixties(34) is shown in Figure 24 for comparison. Figure 25 depicts a family of polarization curves that were obtained at weekly periods during the tests. Figure 26 illustrates the effect of temperature on polarization and Figure 27 shows cell performance when pure oxygen is used as the oxidant. During the 50 day period, there was some decay in performance; however,

Figure 20. Alkaline components.

Figure 21. Alkaline single cell.

Figure 22. Alkaline test station.

Figure 23. Alkaline polarization.

Figure 24. Old alkaline polarization.

Figure 25. Alkaline polarization.

Figure 26. Alkaline polarization.

Figure 27. Alkaline polarization.

washing the cell with water resulted in a recovery of performance as indicated in Figure 28. This recovery was most probably due to carbonate removal from the electrodes.

These tests indicate that intermittent operation had no major effects on performance. The major factor in cell performance appears to be carbonate buildup.

4.4.2 Design, Fabrication and Testing of 0.5 kW Fuel Cell Module

A nominal 0.5 kW alkaline fuel cell module was constructed using electrodes obtained from Union Carbide Corporation. Because of time constraints and the large number of electrodes involved, the first module was built with the older type of electrodes. In the case of the first module, the aim was to develop construction techniques. The module consisted of eight bicells connected in series.

Figure 29 depicts a bicell which consists of two cells connected in parallel. The cells are reversed so that the two anodes face one another to form the fuel plenum. The exterior surfaces of the bicell are the anodes. As with the single cell spacing was maintained using neoprene rubber gaskets and plastic mesh screens. Module assembly is achieved by stacking the bicells in a fixture shown in Figure 30. The stack was compressed to the appropriate thickness and the assembly was potted with epoxy. Gas and electrolyte ports were introduced by inserting removable PTFE plugs prior to potting. Intercell parasitic current losses were minimized by use of tubular manifolds for the electrolyte inlet and tubular overflow system for the electrolyte exits. Finally the eight bicells were connected in series by welding the nickel tabs together. The completed module is shown in Figure 31. Time did not permit testing of the module prior to the end of FY 1978. Apart from the fact that subsequent modules will contain the new Union Carbide cathodes that have demonstrated superior performance in single cells, the present module design incorporates several design improvements. These are the exclusive use of polysulfone as a manifold material, provisions to minimize parasitic currents and gas plenum designs that improve gas distribution and eliminate blockage due to water droplet accumulation in the gas plenums.

Figure 28. Alkaline polarization.

Figure 29. Alkaline bicell.

Figure 30. Alkaline construction jig.

Figure 31. Alkaline module.

4.5 Solid Polymer Electrolyte Fuel Cells

Toward the end of FY 1978 two solid polymer electrolyte fuel cells were provided by the General Electric Company. One of the cells is shown in Figure 32. The cell is an integrated unit consisting of a membrane electrode assembly, temperature control plates for coupling with a circulating oil system, and a system for prehumidification of reactants. The latter permits cell operation up to 220°F without dryout of the membranes. No tests were carried out on these cells before the end of FY 1978 because of late delivery and the necessity of construction of a test facility. A design for such a facility is shown in Figures 33 and 34.

5. Candidate Batteries for Hybrid Fuel Cell/Battery Power Plants

Because of the present interest in electric vehicles and in batteries for utility load leveling many new batteries are under development. Commercial batteries and those under development are classified in Table VII. The general characteristics of the most promising candidates for vehicle propulsion are given in Table X. Figure 35 are plots of specific energy versus specific power for these batteries. Times of discharge at various power levels are indicated by the diagonal cross/hatched lines. Also, indicated in Figure 35 is the specific power required for a vehicle with a 200 kg test weight and a 340 kg battery weight. Cruise speed is assumed to be 55 mph. The intersection of the cruise specific power line and the discharge rate lines indicates vehicle range. For instance, a zinc-chlorine battery would give a range of 3 h or 165 miles. The cost data in Table XI and the data in Figure 35 were used to calculate initial battery cost for such a vehicle. The results are shown in Figure 36. This would indicate that in the case of battery vehicles there is going to have to be a trade off between battery cost and range. The likely outcome is a vehicle with a range of about 100 miles.

In a fuel cell-battery hybrid car, a battery with high specific power is needed. There are several possibilities but at present, the most likely

Figure 32. SPE fuel cell.

Figure 33. Test facility.

Figure 34. Test facility

Figure 35. Specific power versus specific energy for various batteries. The specific power required for acceleration and cruise at 55 mph is indicated for a vehicle with 1000 kg test weight and 340 kg battery weight.

Figure 36. Vehicle range and initial battery cost.

TABLE X
Classification of Secondary Batteries

<u>Current Battery Technology</u>	
(a) Lead-Acid Battery	
(b) Alkaline Electrolyte Batteries	
Iron/Nickel Oxide	
Cadmium/Nickel Oxide	
Zinc/Silver Oxide	
Cadmium/Silver Oxide	
<u>Emerging Battery Technology</u>	
Aqueous Electrolyte Batteries	Non-Aqueous Electrolyte Batteries
(1) Zinc Batteries	(1) Organic Electrolyte Batteries
(a) Alkaline Electrolyte Batteries	(a) Lithium/Bromine Batteries
Zinc/Nickel Oxide	(b) Lithium/Metal Chalcogenide Batteries
Zinc/Manganese Dioxide	Lithium/Titanium Disulfide
(b) Zinc/Halogen Batteries	Lithium/Niobium Diselenide
Zinc/Chlorine	
Zinc/Bromine	
(2) Batteries with one Gaseous Reactant	(2) High Temperature Batteries
(a) Metal/Air (Oxygen) Batteries	(a) Sodium Batteries
Zinc/Air (Oxygen)	Sodium/Sulfur
Iron/Air (Oxygen)	Sodium Chloroaluminate Batteries
Cadmium/Air (Oxygen)	(b) Lithium Batteries
(b) Hydrogen/Metal Oxide Batteries	Lithium/Iron Disulfide
Hydrogen/Nickel Oxide	Lithium/Chloride
Hydrogen/Silver Oxide	Lithium Charge Storage Batteries
(3) Batteries with Fluid Reactants	
(a) Hydrogen/Oxygen	
(b) Hydrogen/Halogen Batteries	
Hydrogen/Chlorine	
Hydrogen/Bromine	
(c) Redox Batteries	
Titanium/Iron	
Chromium/Iron	

TABLE XI
Performance Summary for Batteries for Vehicle Propulsion

Battery System	Cell Voltage (V)	Specific Energy (Theoretical) (wh/kg)	Operating Temperature (°C)	Energy Efficiency	Cycle Life (Cycles)	Cost(Projected) \$/kWh
Pb/H ₂ SO ₄ /PbO ₂	2.1	175	-35 -70	60	500	60
Fe/KOH/NiOOH	1.37	267	-40 -80	50	>1000	120
Zn/KOH/NiOOH	1.7	326	-40 -65	75	300	50
Zn/ZnCl ₂ /Cl ₂ ·6H ₂ O	2.1	460	15-60	70	100	50
Zn/ZnBr ₂ /Br ₂	1.8	431	0-50	75	300	70
Zn/KOH/Air	1.6	1310	25-65	<50	500	60
Fe/KOH/Air	1.2	720	26-60	<30	>1000	60
Li/PC/TiS ₂	2.15	485	0-70	N/A	N/A	40
Li/LiCl-KCl/FeS ₂	2.1, 1.6	650-1342	400-450	70	700	40
Na/BAI ₂ O ₃ /S	2.08-1.75	308- 763	300-400	70	100	40

candidate batteries for fuel cell battery hybrids power plants are the Pb-acid and Zn-NiOOH batteries. Recent performance data for these two systems are given in Figure 37(35-37). These plots are based on complete discharges and do not reflect the high power levels that can be achieved for short (e.g., 10 sec) discharges that would occur in a fuel cell/hybrid power plant during acceleration. An example of the high power levels that can be achieved for short periods of time in a Zn-NiOOH battery is shown in Figure 38(38). Indications are that improved lead acid batteries can deliver 374 W/kg in hybrid service.

In some hybrid service, fast charge acceptance may be needed. Lead acid batteries can accept charge at half the rate of the previous charge if the state of charge is 90% or lower(39). The expected overall energy efficiency in a well designed battery would be about 85%. Indications are that maintenance free lead acid batteries can accept charge at a faster rate than conventional batteries(40). Data are presented in Figure 39. It has been demonstrated that zinc-nickel oxide batteries can accept charge at the 4C rate in simulated hybrid service(38). Efficiencies in the order of 85% can be expected.

In hybrid service, battery life is more a question of calendar life than cycle life. In the case of lead acid batteries life would be limited by grid corrosion and in the case of zinc-nickel oxide batteries by deterioration of the separator. In either case a 3-4 year battery life can be expected for lightweight designs.

Figure 37. Specific energy versus specific power characteristics for Pb-acid and Zn-NiOOH Batteries

Figure 38. Voltage-current characteristics for a 35 Ah Form Cell Zn-NiOOH Battery. The voltage is the minimum voltage for a 10.8 sec pulse. Battery charged at 7.4 for 50.2 sec between pulses. Battery weight = 4.12 kg power levels and state of charge are indicated on the figure.

Figure 39. Deviations from the ampere-hour rule (416). Lead-calcium system, 1.210 sp gr electrolyte, discharge at 8-H rate, recharge to 2.17 V/Cell.

REFERENCES

1. "National Benefits Associated with Commercial Application of Fuel Cell Power Plants, Report to U.S. ERDA, United Technologies Corp., February 27, 1976, p. 5.
2. Ibid, p. 6.
3. McCormick, B., Huff, J., Srinivasan, S. and Bobbett, R., "Applications Scenario for Fuel Cells in Transportation," Informal Report LA-7634-MS, Los Alamos Scientific Laboratories, Los Alamos, New Mexico (1979).
4. Op cit, p. 7.
5. Handley, L. M., Extended Abstracts, Vol. 78-2, Abstract No. 301, The Electrochemical Society Inc., Princeton, New Jersey (1978), pp. 809-10.
6. Brown, J., Clausi, J. and Falcinelli, R., private communication, March 22, 1978.
7. Baker, B. S., private communication, May 3, 1978.
8. Huff, J. R., private communication, July 10, 1978.
9. Baker, B. S., private communication, March 21, 1978.
10. Johnson, W. H., National Fuel Cell Seminar Abstracts, Courtesy Associates (1978), pp. 62-5.
11. McElroy, J. F., private communication, March 14, 1978.
12. McElroy, J. F., Proceedings of the Fuel Cell in Transportation Applications Workshop, August 15-17, 1977, Los Alamos Scientific Laboratories, Los Alamos, New Mexico (1978), pp. 53-7.
13. Bolan, P. and Gitlow, B., National Fuel Cell Seminar Abstracts, Dynatrend Inc. (1977), pp. 115-6.
14. Richter, J., Mund, K. and Rao, J. R., private communication, September 4-5, 1978.
15. Alfenaar, M. and Hovestreydt, J., private communication, September 7, 1978.
16. Reilly, J., "Metal Hydrides as Hydrogen Storage Media and Their Application," BNL Report 21648, Brookhaven National Laboratory, Upton, New York (1977).

17. Baker, C. R., Society of Automotive Engineers, Paper No. 751094.
18. Strickland, G., private communication, December 5, 1978.
19. Kordesch, K. V., Batteries, Vol. 2, K. V. Kordesch, Ed., Marcel Dekker, Inc., New York (1977), pp. 201-414.
20. Plenard, F. J., Paper presented at 2nd World Hydrogen Energy Conference, Zurich, Switzerland, August 21-24, 1978.
21. Reed, T. B., Paper presented at 171st Meeting of the Division of Fuel Chemistry, American Chemical Society Symposium on Net Energetics of Integrated Synfuel Systems, April 5-9, 1976.
22. Conner, D. A. and Plock, J., "Methanol Production from Coal," Speed Scientific School, University of Louisville, Louisville, Kentucky, June 1975.
23. Kurpit, S. S., Proceedings 10th IECEC Conference, Paper No. 759036, Institute of Electric and Electronic Engineers, New York (1975), pp. 222-8.
24. Giner, J. and Swette, L., Final Report to EPRI on "Evaluation of Feasibility of Low-Cost Carbon Dioxide Removal/Transfer Methods for Fuel Cell Application."
25. Giner, J., Proceedings of the Fuel Cell in Transportation Applications Workshop, August 15-17, 1977, Los Alamos Scientific Laboratories, Los Alamos, New Mexico (1978), pp. 49-52.
26. Khan, A. R., Meek, J. and Baker, B. S., Chemical Eng. Progress 62, 74 (1966).
27. Terry, P., Gallagher, J., Salathe, R. and Smith, J. O., Proceedings 20th Ann. Power Sources Conference, Atlantic City, 1966, p. 49.
28. Gillis, E. A., *ibid*, p. 41.
29. Williams, K. R., An Introduction to Fuel Cells, Elsevier Publishing Co., Amsterdam (1966), pp. 147 and 298.
30. Szymanski, S. T., Grover, J. A., Katz, J. and Kunz, H. R., Extended Abstracts, Vol. 78-2, Abstract No. 316, The Electrochemical Society, Inc. Princeton, New Jersey (1978), pp. 850-2.
31. Schmidt, E. W., Future Automotive Fuels, J. M. Colucci and N. E. Gallopoulos, Eds., Plenum Press, New York (1977), pp. 320-41.
32. Stonehart, P. and Zucks, P. A., *Electrochim. Acta* 17, 2333 (1972).

33. Kordes, K. V., "Hydrogen Air/Lead Battery Hybrid System for Vehicular Propulsion," Union Carbide Report CRM-244, Union Carbide Corp., Parma, Ohio, August 11, 1970.
34. Kordes, K. V., J. Electrochem. Soc. 118, 5 (1971).
35. Cairns, E. J. and McBreen, J., Ind. Res. 17 (6), 56 (1975).
36. Sheridan, D. C., Bush, J. J. and Kuziak, W. R., Trans. SAE, Paper No. 760119, 1976.
37. Mao, K. W. and Hwang, G. J., Proceedings 11th IECEC Conference, Paper No. 769059, 1976.
38. Sulkes, M. J., Second Quarterly Report for EPA, Obligation Code 690 403, U.S. Army Electronics Command, Fort Monmouth, New Jersey, March 1972.
39. Biddick, R. E., Mueller, J. A., Sayano, R. R. and Silverman, H. P., Proceedings Symp. on Batteries for Traction and Propulsion, R. L. Kerr, J. McCallum and D. E. Semones, Eds., The Electrochemical Society, Inc., Princeton, New Jersey, 1972.
40. Willihnganz, E., Extended Abstracts, Vol. 71-2, The Electrochemical Society, Inc., Princeton, New Jersey (1971).

APPENDIX A

Fuel Cell Data

A. Fuel Cells

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3. Oxidant
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5. Volume
 - a. Cell Stack
 - b. Reformer
 - c. Water Management Systems
 - d. Heat Management Systems
 - e. Auxiliary Hardware
6. Packaging Factor
7. Weight
 - a. Cell Stack
 - b. Reformer
 - c. Water Management Systems
 - d. Heat Management Systems
 - e. Auxiliary Hardware
8. Operating Conditions
 - a. Temperature
 - b. Pressure
9. Operating Characteristics
 - a. Electrode Area
 - b. Design Voltage
 - c. Design Current
 - d. Current-Voltage Characteristics
 - e. Efficiency-Power Characteristics
 - f. Startup Time
 - g. Life
 - i. Continuous Operation
 - ii. Intermittent Operation

Fuel Cell Data (Continued)
Page 2

10. Effect of Operating Conditions
 - a. Impurity Effects
 - b. Environmental Effects
11. Costs
 - a. Initial Costs (Optimistic/Pessimistic)
 - b. Maintenance Costs
12. Emissions
13. Time Between Major Overhauls
- B. Fuel Processing
 1. Fuel
 2. Processing Conditions
 - a. Temperature
 - b. Pressure
 - c. Fuel to Water Ratio
 - d. Catalyst
 - e. Tolerance to Impurities
 - f. By-Products
 - g. Space Velocity (h^{-1})
 - i. Projected Maximum Space Velocity (h^{-1})
 3. Volume
 4. Weight
 5. Packaging Factor
 6. Life
 7. Costs
 - a. Initial Costs (Optimistic/Pessimistic)
 - b. Maintenance Costs
 8. Efficiency
 9. Startup Time

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APPENDIX B

Draft of

FINAL REPORT FOR CONTRACT NO. 450177-S

SYSTEM STUDY OF PHOSPHORIC ACID FUEL CELLS FOR TRANSPORTATION APPLICATION

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SUMMARY

Two reformed fuel-air phosphoric acid fuel cell (PAFC) systems were studied for transportation application - a 60 kW system for a bus and a 15 kW system for a car. For the 60 kW system pressurized operation (at 50 psia) was considered to take advantage of high fuel cell performance and reduced system volume, weight and cost. Liquid cooling of the stack for the 60 kW system and gas cooling for the 15 kW system were employed.

Fuel cell performance characteristics were estimated using the available analytical model and conceptual design of both the systems was carried out. Two different fuels - methanol and propane - were considered for this study. The methanol system is fairly simple whereas the propane system is somewhat complex. The high reforming temperature in the propane system requires water gas shift reactors to reduce CO levels in the reformed gas and number of heat exchangers for heat recovery, to be incorporated in the system. Material and energy balances were computed. Weight and volume estimates for the major system components were carried out. In 60 kW size, system volume and weight of 0.73 ft³/kW and 22 lbs/kW respectively for the methanol system and 1.24 ft³/kW and 28 lbs/kW respectively for the propane system were estimated. Whereas for the 15 kW size system volume and weight of 1.19 ft³/kW and 35 lb/kW for the methanol system and 1.93 ft³/kW and 46 lb/kW for the propane system were estimated. The estimates did not include the fuel

tank. Inclusion of the fuel tank would reduce the differences between the two systems and make them more competitive. Overall system efficiency as a function of load was derived. As would be expected, fuel cell system efficiencies in the load range from 25% to 100%, do not vary significantly. This makes fuel cell systems attractive for transportation application. The propane system has slightly higher efficiency than the methanol system. System efficiency in the 60 kW size is approximately 42%, whereas that in the 15 kW size is approximately 34%. Efficiencies are higher in the 60 kW size because of the pressurized operation.

1.0 INTRODUCTION

Fuel cells are being considered for transportation application. Some of the fuel cell benefits associated with this application are -

- High efficiency - especially at part load
- Low chemical and noise pollution
- Low maintenance
- High reliability

Since phosphoric acid fuel cell (PAFC) is technologically the most advanced fuel cell today, it is considered for this application. An analytical study was conducted to help preliminary assessment of the expected performance of a fuel cell system for the application in consideration. Two different size systems were studied - 60 kW and 15 kW. The following sections describe the efforts made in this direction.

2.0 60 kW REFORMED FUEL-AIR PHOSPHORIC ACID FUEL CELL (PAFC) SYSTEM

A 60 kW reformed gas-air PAFC System is being considered for transportation application to a bus. An analytical study was carried out in conjunction with this application. Two different fuels - methanol and propane - were considered. Fuel cell performance characteristics were projected and a conceptual design of the system was performed. Material and energy balances were carried out. Overall efficiency of the system was computed as a function of load. The above points are discussed in detail in the following sections.

2.1 Fuel Cell Performance Characteristics

Fuel cell performance was estimated for the operating conditions of 50 psia pressure and 375°F temperature, with the available analytical model.⁽¹⁾ The following assumptions were made in the estimation -

1. A catalyst loading of 0.5 mg/cm² at cathode and 0.25 mg/cm² at anode was assumed.
2. Fuel (H₂) utilization of 80% and oxidant (O₂) utilization of 59% was assumed.
3. Compositions of reformed methanol in water gas shift equilibrium at 450°F temperature and reformed propane in water gas shift equilibrium at 520°F were considered as fuel compositions to the fuel cell.

The estimated performance data for both the fuels are summarized in Table 1. Performance curves for the methanol system are

TABLE 1.
Cell Performance at 50 psia
and 375°F for 60 kW System
(Phosporic Acid Fuel Cell)

Current Density, i <u>Amps/Ft²</u>	Cell Potential V <u>Volts</u>	
	<u>Methanol System</u>	<u>Propane System</u>
10	0.880	0.874
25	_____	0.834
33.3	0.828	_____
50	_____	0.802
66.7	0.793	_____
100	0.767	0.764
150	0.741	0.738
200	0.720	0.716
250	0.701	0.697
300	0.683	0.680
350	0.667	0.664
400	0.652	0.649

plotted in Figure 1 and for the propane system in Figure 2. It can be observed that cell performance is 3 to 4 mV higher in the case of methanol than in the case of propane because of higher H_2 concentration in the former. As a result, fuel cell stack efficiency is slightly higher for the methanol system than for the propane system.

2.2 Conceptual Design

Conceptual design was carried out for both the systems - methanol and propane. For both the cases, pressurized operation was considered to take advantage of higher fuel cell performance and reduced volume and weight of the system. System cost will also be reduced because of high power density. Also, system components required for pressurized operation, such as compressor, turbocompressor, etc. can be obtained for the power-plant size in consideration. Two-phase water cooling of the fuel cell stack was chosen to avoid handling of large volumes of coolant gases and also to take advantage of uniform stack operating temperature. The process design was carried out in each case, which is described in detail in the following subsections.

2.2.1 Methanol System

The final system configuration is shown in Figure 3. A fuel mixture of methanol and water in the molar ratio of 1:1.3 is used.

The excess of water ensures practically complete conversion of methanol and helps reduce CO concentration in the reformer

Figure 1. Estimated performance curve for 60 kW reformed methanol-air PAFC system.

Figure 2. Estimated performance curve for 60 kW reformed propane-air PAFC system

Figure 3. Schematic of 60 kW reformed methanol-air PAFC system

product gas. The fuel mixture is pumped to 50 psia pressure and then vaporized and superheated to 325°F using a part of the waste heat from the fuel cell, in heat exchanger HE-1. In the reformer it is further heated to 450°F. The reforming reaction is carried at 450°F and elevated pressure. Sensible heat of burner flue gas supplies the necessary superheat and endothermic heat of reaction. The reformer product gas is cooled down to 375°F (the operating temperature of the fuel cell) in the air cooled heat exchanger HE-3. Unspent fuel from the fuel cell is combusted in the reformer burner using compressed air. Atmospheric air is compressed to 50 psia pressure. Part of it is supplied to the reformer burner. The rest is preheated to 325°F using a part of the waste heat from the fuel cell in heat exchanger HE-2. It is then supplied to the cathode of the fuel cell as oxidant. In the fuel cell H_2 , supplied at the anode, reacts with O_2 electrochemically, generating D.C. electricity and water. Water produced at the cathode is removed from the fuel cell by oxidant gases. Burner flue gas from the reformer is mixed with cathode exhaust. The effluent stream is at a high temp. (486°F) and high pressure (50 psia). The waste energy in this stream is recovered by passing it through a turbocompressor. The energy recovered is sufficient to compress the required air in the system. Overall efficiency of 56% was assumed for the turbocompressor. The unutilized waste heat from the fuel cell cooling loop is removed by an air cooled

exchanger, HE-4.

Material and energy balances were carried out for 100% load conditions. Fuel cell operating characteristics of 0.7 volt and 253 ASF were selected. The cell area of 1.25 ft² was chosen and parasitic power of 5% was assumed. The flow rates and enthalpies of various streams are presented in Table 2.

Volumes and weights of the major equipment were projected using the available data for a 2 kW system. The fuel tank was not included in the estimates because of a lack of power profile data. The results are presented in Table 3. A packaging factor of 0.5 gives system volume of 0.73 ft³/kW. Whereas system weight was computed to be 22 lbs/kW.

2.2.2 Propane System

The process flow diagram is shown in Figure 4. Liquid propane at 150 psia and 70°F was considered as fuel. It is throttled down to 50 psia pressure and then preheated in the exchanger HE-2 using sensible heat of the reformer product stream. Part of the fuel is supplied to the reformer burner. The rest is mixed with superheated steam at 700°F and 50 psia and further preheated to 1350°F in the reformer feed preheater HE-1, using sensible heat of reformer product stream. The reforming reaction is carried out at 1400°F and elevated pressure. The product gas from the reformer is at 1400°F and is cooled down to 660°F. CO in the product gas is water gas shift converted to produce H₂ rich gas for the fuel cell. To take

TABLE 2

Material & Energy Balance for 60 kW
Reformed Methanol-Air PAFC System

Stream No.	Temp. °F	Pressure psia	Enthalpy BTU/hr.	CH ₃ OH	H ₂ O	H ₂	CO ₂	CO	O ₂	N ₂	Total lbmole/hr.
				lbmole/hrs.							
1	60	14.7	-389918	1.5765	2.0494	--	--	--	--	--	3.6259
2	325	50.0	-314366	1.5765	2.0494	--	--	--	--	--	3.6259
3	450	--	-268367	--	0.5694	4.6300	1.4778	0.1017	--	--	6.7789
4	375	--	-272376	--	0.5694	4.6300	1.4778	0.1017	--	--	6.7789
5	375	--	-293550	--	0.5694	0.9260	1.4778	0.1017	--	--	3.0749
6	193	--	74247	--	0.2687	--	--	--	4.6347	17.4866	22.3900
7	800	--	-219310	--	1.7641	--	1.5795	--	4.1208	17.4866	24.9510
8	561	--	-265309	--	1.7641	--	1.5795	--	4.1208	17.4866	24.9510
9	60	14.7	89623	--	0.4512	--	--	--	7.7831	29.3654	37.5997
10	193	50.0	124684	--	0.4512	--	--	--	7.7831	29.3654	37.5997
11	193	50.0	50437	--	0.1825	--	--	--	3.1484	11.8787	15.2097
12	325	--	64564	--	0.1825	--	--	--	3.1484	11.8787	15.2097
13	375	--	-296839	--	3.8865	--	--	--	1.2964	11.8787	17.0616
14	486	--	-562148	--	5.6506	--	1.5795	--	5.4172	29.3653	42.0126
15	308	14.7	-617502	--	5.6506	--	1.5795	--	5.4172	29.3653	42.0126

Girdler Enthalpy Base (O⁰R) Electricity Generated: gross - 63.2 kW, net - 60 kW

TABLE 3
ERC DATA
FOR 60 kW SYSTEM

1. Name of Company	ERC		
2. Fuel Cell Type	Reformed Methanol/Air (H ₃ PO ₄)	Reformed Propane/Air	
3. Size (kW)	2	60 kW	60 kW
4. Status	Demonstrated Hardware	Conceptual Design	
5. Volume(displaced ft ³)			
a. Cell Stack	1.86	12.9	12.9
b. Fuel Processing (Reformer, HTSR, LTSR)	15" (h) x 10" (d) x 7" (w)	8.8	23.1 (3.9 + 8.1 + 11.1)
c. Thermal Management	Start up HEX 0.043	0.15	1.1
d. Water Recovery	None	None	None
e. Heat Recovery	_____	_____	_____
f. Reactant Supply	0.018		
g. Inverter	_____	_____	_____
h. Plumbing	_____	_____	_____
6. Packaging Factor	0.3-0.5	_____	_____
7. Weight(lbs.)			
a. Cell Stack	96	811.4	812
b. Fuel Processing (Reformer, HTSR, LTSR)	49.0	481.1	636 (108.3 + 223.6 + 304)
c. Thermal Management	Start up HEX 12.5	30.1	231
d. Water Recovery	None	None	None
e. Heat Recovery	_____	_____	_____
f. Reactant Supply	8.5		
g. Inverter	_____	_____	_____
h. Plumbing	_____	_____	_____
8. Operating Conditions			
a. Temperature	350°F	375°F	375°F
b. Pressure	1 atm	50 psia	50 psia

... continued

TABLE 3 (continued) - ERC DATA FOR 60 kW SYSTEM

9. Operating Characteristics				
a.	Electrode Area (ft ² /cell)	0.404	1.25	1.25
b.	Design Voltage	48V	200 V	200 V
c.	Design Current	40 A	316 A	316 A
d.	V-i Characteristics		Figure 1	Figure 2
e.	η -Load Characteristics		Figure 5	Figure 5
f.	Start-up Time	15-30 min. (stack) 15 min. (reformer)	10-15 min.	10-15 min.
g. Life				
i.	Cont. Operation	5,000 hrs. (stack) 10,000 hrs. (reformer)	5,000 hrs.	5,000 hrs.
ii.	Intermittent Operation	N.A.	N.A.	N.A.
10. Maintenance Cost With Major Replacement				
11. Time Between Major Overhauls				
			Stack 5 yrs. N.A. Reformer 10 yrs.	Stack 5 yrs. Reformer 20 yrs.
12. Capital Cost [Stack (\$/kW)]				
			82.00	83.00

Figure 4. Schematic of 60 kW reformed propane-air PAFC system

advantage of the high reaction rate at high temp. and high CO conversion at low temp. the water gas shift reaction is carried out in two steps in two different reactors - high temp. shift reactor (HTSR) and low temp. shift reactor (LTSR). The shifted gas from HTSR is cooled down to 450°F in heat exchanger HE-5 and HE-6. The heat recovered is utilized in the superheating steam for the reformer.

The shifted gas from LTSR is at 520°F and is cooled down to 375°F in an air cooled exchanger, HE-9. Unspent fuel from the fuel cell is preheated to 1200°F using waste heat of burner flue gases. Atmospheric air is compressed to 50 psia. Part of it is preheated to 1000°F using waste heat of burner flue gas in heat exchanger HE-3 and then supplied to the reformer burner for combustion of supplemental fuel (propane) and unspent fuel from the fuel cell. The rest of the air is preheated to 325°F using the waste heat of the cathode exhaust in heat exchanger HE-8 and then supplied to the cathode of the fuel cell. In the fuel cell H_2 , supplied to the anode, reacts electrochemically with O_2 at the cathode, generating DC electricity and producing water which is removed by oxidant gases. Cathode exhaust after preheating cathode air is mixed with burner flue gas. The effluent stream is at a high temp. (509°F) and high pressure (50 psia). The waste energy in this stream is recovered in the same way as the methanol system. Waste heat removed from the fuel cell by the coolant loop is utilized to generate steam for the reforming reaction. The excess is thrown to atmosphere by air cooled exchanger HE-10.

Material and energy balances for 100% load conditions are presented in Table 4. Fuel cell operating characteristics of 0.696 volt and 253 ASF were used. The cell area and parasitic power were assumed the same as the methanol system.

Volume and weight estimates for major equipment are presented in Table 3. System volume of 1.24 ft³/kW and system weight of 28 lb/kW was obtained in this case.

2.3 System Efficiency as a Function of Load

Fuel consumptions were estimated for various load conditions in the range of hot idle to 100% load. They are summarized in Table 5. Overall efficiency of the system was computed based on the high heating value (HHV) of the fuel. Plots of efficiency vs load were prepared for both the methanol and propane systems. They are shown in Figure 5. The efficiencies are summarized in Table 6. It can be observed that efficiency increases at part load up to 75 or 50% load and then decreases for both the systems. Efficiency curves are almost flat in the load range of 25 to 100%. Efficiency of the propane system is lower at low load (25-50% load).

Table 4

Material & Energy Balance for 60.kW Reformed Propane-air PAFC System

Stream No.	Temp. °F	Pressure psia	O ₂	CO ₂	H ₂	CO lbmol/hr.	N ₂	H ₂ O	C ₃ H ₈	Total Flow	Enthalpy BTU/Hr.
1	70	14.7	4.1423				15.6286	0.2402		20.0111	49086
2	193	50	0.9718				3.6668	0.0564		4.6950	15561
3	1000		0.9718				3.6668	0.0564		4.6950	43243
4	375			1.3500	0.9325	0.0697		1.4893		3.8413	-359801
5	1200			1.3500	0.9325	0.0697		1.4893		3.8413	-329892
6	70	150							0.5225	0.5225	-15307
7	44	50							0.5225	0.5225	-15307
8	800								0.5225	0.5225	-4984
9a	800								0.0493	0.0493	-471
9b	800								.4732	0.4732	-4513
10	700							4.2588		4.2588	-397427
11	1350							4.2588	.4732	4.7320	-366100
12	1400			0.5830	3.8954	0.8366		2.2555		7.5705	-262215
13	831			0.5830	3.8954	0.8366		2.2555		7.5705	-298056
14	660			0.5830	3.8954	0.8366		2.2555		7.5705	-308379
15	800			0.9880	4.3004	0.4316		1.8505		7.5705	-308379
16				0.9880	4.3004	0.4316		1.8505		7.5705	-321388
17	475			0.9880	4.3004	0.4316		1.8505		7.5705	-325424
18	520			1.3500	4.6624	0.0697		1.4893		7.5712	-327880
19	375			1.3500	4.6624	0.0697		1.4893		7.5712	-338478
20	193	50	3.1704				11.9618	0.1838		15.3150	50748
21	325		3.1704				11.9618	0.1838		15.3150	65019
22	375		1.3055				11.9618	3.9137		17.1810	-298916
23	262		1.3055				11.9618	3.9137		17.1810	-313187
24	950		0.2243	1.5676			3.6672	2.6754		8.1345	-448593
25	1320		0.2243	1.5676			3.6672	2.6754		8.1345	-420909
26	1700		0.2243	1.5676			3.6672	2.6754		8.1345	-390996
27	70	50						4.2588		4.2588	-419860
28	159							4.2588		4.2588	9734
29	325							4.2588		4.2588	91039
30	350	135						10.8180		10.8180	232445
31	350							10.8180		10.8180	151140
32	350							10.8180		10.8180	62727
33	509		1.5297	1.5676			15.6286	6.5891		25.3150	-761735
34	326	14.7	1.5297	1.5676			15.6286	6.5891		25.3150	-797087

Girdler Enthalpy Base (O^oR), Electricity Generated: Gross-63.2 kW, Net-60 kW

TABLE 5
Fuel Consumption as a
Function of Load for 60 kW System

% Load	Fuel Consumption lb Mole/Hr	
	<u>CH₃OH</u>	<u>C₃H₈</u>
100	1.5765	.5225
75	1.1631	.3810
50	0.7685	.2548
25	0.3946	.1343
Hot Idle	0.0623	.0208

Figure 5. Efficiency (based on HHV) as a function of load
for 60 kW PAFC system

TABLE 6
Powerplant Efficiency as a
Function of Load for 60 kW System

% Load	% Efficiency η Based on HHV	
	<u>CH₃OH System</u>	<u>C₃H₈ System</u>
100	41.6	41.3
75	42.3	42.5
50	42.7	42.4
25	41.5	40.2

2.4 System Operation

Since the design fuel cell operating point is in the upper portion of cell performance curve (0.7 volt), the fuel cell stack has the flexibility of meeting the peak loads during acceleration. It can still operate with reasonable fuel cell thermal efficiency. Because of pressurized operation, the reformer has a large inventory of reformed fuel. As a result, it can also be overloaded during acceleration. This eliminates the need for a battery during acceleration. Also since the 60 kW system is considered for application to a bus, it was assumed that no battery is required for start-up. The fuel cell stack can be brought to operating temperature during start-up while the bus is in the terminal itself.

During operation at hot idle condition, the fuel cell will be operating at very high cell voltage (close to 0.9 volts) because of pressurized operation. This might lead to severe material problems like carbon corrosion and platinum dissolution at cathode. This can be avoided by running fuel cells with cathode gas lean in O_2 . This would be the same thing as starving the fuel cell of oxygen.

3.0 15 kW REFORMED FUEL-AIR PAFC SYSTEM

Two 15 kW reformed gas-air phosphoric acid fuel cell (PAFC) systems were studied in conjunction with transportation application for a car - one with methanol fuel and one with propane fuel. Analysis similar to 60 kW system was performed in this case too. Results of the analysis are discussed in the following subsections.

3.1 Fuel Cell Performance Characteristics

Using the available analytical model⁽¹⁾, the fuel cell performance was estimated for the operating conditions of 350°F and 14.7 psia. Because of the recycle stream at the cathode, the performance is projected in an iterative manner using a computer program that incorporates material and energy balances around fuel cell stacks. Catalyst loading and fuel and oxidant utilizations were assumed the same as 60 kW system. The fuel compositions to the fuel cell were considered to be reformed propane in water gas shift equilibrium at 520°F in the case of the propane system and reformed methanol in water gas shift equilibrium at 450°F in the case of the methanol system. Steam to fuel ratio in the reformer feed was determined on the basis that reformed and shifted gas going into the fuel cell has approximately 1% CO to avoid catalyst poisoning. The performance data for both the fuels is summarized in Table 7. The performance curve for the methanol system is plotted in Figure 6 and for the propane system in Figure 7. In this case too, cell

TABLE 7
ESTIMATED PERFORMANCE CHARACTERISTICS
FOR 15 kW PAFC SYSTEM

Current Density i , ASF	Cell Potential V , Volts	
	Methanol System	Propane System
10	0.734	0.731
25	0.696	0.693
50	0.664	0.661
100	0.626	0.623
150	0.601	0.597
200	0.580	0.576
250	0.560	0.556
300	0.543	0.540
350	0.526	0.523
400	0.512	0.508
450	0.497	0.493

Figure 6. Estimated performance curves for 15 kW reformed methanol-air PAFC system

Figure 7. Estimated performance curves for 15 kW reformed propane-air PAFC system

performance for methanol is 3-4 millivolts higher than for propane because of higher hydrogen content of the former.

3.2 Conceptual Design

Process design was performed for both the systems - methanol and propane. Atmospheric pressure operation was considered because of the small size of the system. Also gas flow rates being low, gas cooling of the stack was chosen to have a simple system.

3.2.1 Methanol System

The final system configuration is shown in Figure 8. The system differs from the 60 kW reformed methanol-air PAFC system in few aspects. Since the system operates at atmospheric pressure the turbocompressor is eliminated. Instead of liquid cooling, gas cooling of the stack is applied. Heat generated in the stack is removed by passing reactant gas flows much higher than stoichiometric. Part of the cathode exhaust is recycled after cooling it by heat exchange with fuel mixture in heat exchanger HE-1. It is further cooled in an air cooled heat exchanger HE-2. Fresh atmospheric air is added to the cathode recycle stream to make up for oxygen consumed in the fuel cell. Fuel mixture is vaporized and superheated to 325°F in HE-1.

Material and energy balances for 100% load condition are presented in Table 8. Fuel cell operating conditions of 0.603 volts and 145 ASF are chosen. The cell electrode area

Figure 8. Schematic of 15 kW reformed methanol-air PAFC system

TABLE 8 MATERIAL AND ENERGY BALANCE FOR 15 kW
REFORMED METHANOL-AIR PAFC SYSTEM

Stream	Temp °F	Pressure PSIA	O ₂	H ₂ O	N ₂	H ₂	CO ₂	CO	CH ₃ OH	Total Flow (lb mole/hr)	Total Enthalpy (Btu/hr)
			-----		-----	lb moles/hr	-----	-----	-----		
1	60	14.7		0.5976					0.4597	1.0573	- 113699
2	325	14.7		0.5976					0.4597	1.0573	- 91668
3	450	14.7		0.1660		1.3500	0.4309	0.0297		1.9766	- 78251
4	350	14.7		0.1660		1.3500	0.4309	0.0297		1.9766	- 79805
5	350	14.7		0.1660		0.2700	0.4309	0.0297		0.8966	- 85791
6	60	14.7	1.1068	0.0642	4.1760					5.347	12745
7	800	14.7	0.9569	0.5002	4.1760		0.4606			6.0937	- 73046
8	514	14.7	0.9569	0.5002	4.1760		0.4606			6.0937	- 86463
9	60	14.7	0.9485	0.0550	3.5785					4.5820	10922
10	350	14.7	0.3912	1.1736	3.5827					5.1475	- 90606
11	350	14.7	6.028	18.084	55.203					79.315	-1396167
12	312	14.7	6.028	18.084	55.203					79.315	-1418198
13	302	14.7	6.028	18.084	55.203					79.315	-1423976
14	250	14.7	6.963	18.122	58.812					83.897	-1413130
15	350	14.7	6.4192	19.2575	58.7859					84.4625	-1486763

Girdler Enthalpy Base(0°R), Electricity generated: gross - 15.79kW, net - 15 kW

is 1.25 ft². Parasitic power consumption is 5% of the total power production at 100% load and is assumed constant with change in load. Volumes and weights of the major system components were projected using the available data for a 2 kW system, and are presented in Table 9. A H₂ space velocity of 800 hr⁻¹ was assumed in the reformer. Again the fuel tank was not included in the analyses. System volume of 1.19 ft³/kW using a packaging factor of 0.5 and system weight of 35 lbs/kW were computed.

3.2.2 Propane System

The process flow diagram is illustrated in Figure 9. The system is similar to the 60 kW reformed propane-air PAFC system except for a few modifications. Since the system is operated at atmospheric pressure, the turbocompressor is eliminated. Also the stack is gas cooled instead of liquid cooling. The waste heat of the fuel cell is recovered from the recycle stream and utilized in generating steam for the reformer.

Material and energy balances for the propane system are presented for 100% load in Table 10. Fuel cell operating conditions at 100% load are 0.599 volts and 145 ASF. Volumes and weights of major components for this system are summarized in Table 9. System volume of 1.93 ft³/kW and system weight of 46 lbs/kW were estimated.

TABLE 9
ERC DATA FOR 15 kW SYSTEM

1. Name of Company	ERC	
2. Fuel Cell Type	Reformed Methanol/Air (H ₃ PO ₄)	Reformed Propane/Air
3. Size (kW)	15	15
4. Status	Conceptual Design	Conceptual Design
5. Volume (displaced ft ³)		
a. Cell Stack	6.4	6.4
b. Fuel Processing (Reformer, HTSR, LTSR)	2.4	7.7 (1.2 + 3.5 + 3.0)
c. Thermal Management & Heat Recovery	0.1	0.4
d. Water Recovery	None	None
e. Reactant Supply		
f. Inverter	None	None
g. Plumbing	—	—
6. Packaging Factor	0.5	0.5
7. Weight (lbs.)		
a. Cell Stack	414.7	414.7
b. Fuel Processing (Reformer, HTSR, LTSR)	97	210.6 (31.4 + 97 + 82.2)
c. Thermal Management & Heat Recovery	11.7	70.7
d. Water Recovery	None	None
e. Reactant Supply		
f. Inverter	None	None
g. Plumbing	—	—
8. Operating Conditions		
a. Temperature	350°F	350°F
b. Pressure	14.7 PSIA	14.7 PSIA

TABLE 9 (continued) - ERC DATA FOR 15 kW SYSTEM

9. Operating Characteristics		
a. Electrode Area (ft ² /cell)	1.25	1.25
b. Design Voltage, V	87	87
c. Design Current, A	181	181
d. V-i Characteristics	Figure 6	Figure 7
e. η -Load Characteristics	Figure 10	Figure 10
f. Start-up Time		
g. Life		
i. Cont. Operation	5000 hrs	5000 hrs
ii. Intermittent Operation	N.A.	N.A.
10. Maintenance Cost With Major Replacement		
11. Time Between Major Overhauls	Stack 5 yrs Reformer 10 yrs	Stack 5 yrs Reformer 10 yrs
12. Capital Cost [Stack (\$/kW)]	156	156

Figure 9. Schematic of 15 kW reformed propane-air PAFC system

TABLE 10 MATERIAL AND ENERGY BALANCE FOR 15 kW
REFORMED PROPANE-AIR PAFC SYSTEM

Stream	Temp °F	Pressure PSIA	O ₂ -----	CO ₂ -----	H ₂ -----	CO lb mole/hr-----	N ₂ -----	H ₂ O -----	C ₃ H ₈ -----	Total Flow lb mole/hr	Enthalpy Btu/hr
1	60	14.7	0.2555				0.9641	0.0148		1.2344	2943.6
2	1250		0.2555				0.9641	0.0148		1.2344	13985.6
3	350			0.3904	0.2697	0.0202		0.4307		1.1110	-104311.7
4	1200			0.3904	0.2697	0.0202		0.4307		1.1110	- 95402.5
5	60	150							0.1472	0.1472	- 4322.3
6	40	14.7							0.1472	0.1472	- 4322.3
7	800								0.1472	0.1472	- 1404.0
8	800								0.0103	0.0103	- 98.2
9	800								0.1369	0.1369	- 1305.8
10	700	14.7						1.2317		1.2317	-114941.0
11	1350							1.2317	0.1369	1.3686	-105880.2
12	1400			0.1684	1.1264	0.2422		0.6528		2.1898	- 75857.3
13	831			0.1684	1.1264	0.2422		0.6528		2.1898	- 86223.9
14	662			0.1684	1.1264	0.2422		0.6528		2.1898	- 89142.2
15	810			0.3187	1.2767	0.0919		0.5025		2.1898	- 89142.2
16	607			0.3187	1.2767	0.0919		0.5025		2.1898	- 90648.2
17	475			0.3187	1.2767	0.0919		0.5025		2.1898	- 91190.0

TABLE 10 (Cont.)

MATERIAL AND ENERGY BALANCE FOR 15 kW
REFORMED PROPANE-AIR PAFC SYSTEM

Stream	Temp °F	Pressure PSIA	O ₂	CO ₂	H ₂	CO lb mole/hr	N ₂	H ₂ O	C ₃ H ₈	Total Flow lb mole/hr	Enthalpy Btu/hr
18	520			0.3904	1.3485	0.0202		0.4307		2.1898	- 95082.0
19	350			0.3904	1.3485	0.0202		0.4307		2.1898	- 98333.0
20	60	14.7	0.9616				3.6279	0.0557		4.6450	11076.7
22	250		0.9614				8.1201	2.5021		11.5836	-198180.7
23	350		0.4012				8.1208	3.6349		12.1569	-302003.7
25	350		6.1446				56.2422	18.4044		80.7912	-1420503.2
26	348		6.1446				56.2422	18.4044		80.7912	-1421698.8
27	262		6.1446				56.2422	18.4044		80.7912	-1472476.3
28	207							1.2317		1.2317	- 120070
29	325							1.2317		1.2317	- 118874.4
30	350		0.3966				3.6321	1.1898		5.2185	- 91857.2
31	1700		0.0590	0.4416			0.9641	0.7565		2.2212	-111538.8
32	1288		0.0590	0.4416			0.9641	0.7565		2.2212	-120447.5
33	743		0.0590	0.4416			0.9641	0.7565		2.2212	-131489.6

Girdler Enthalpy Base (0°R), Electricity Generated: gross - 15.79kW, net - 15kW

3.3 System Efficiency as a Function of Load

Fuel consumptions are estimated for load conditions in the range of hot idle (0% load) to 200% load, and are presented in Table 11. Overall efficiency was based on the higher heating value of the fuels. Plots of efficiency versus load for propane and methanol are shown in Figure 10 and numerically tabulated in Table 12. For all loading conditions, the propane system has higher efficiency than methanol. However, the propane system is more complex than methanol. Propane has two shift reactors for reducing carbon monoxide, and has three times as many heat exchangers as the methanol system. The numerous heat exchangers are applied practicably due to the enhanced driving force of high temperatures.

In both cases, parasitic power requirement was assumed to be 5% of gross power production at 100% load. It was further assumed that parasitic power is independent of load conditions though parasitic power for the methanol system will be somewhat lower than that for the propane system and that will further bring the efficiencies of the two systems together.

3.4 System Operation

Power necessary during start up can be supplied by a battery. Ni-Zn battery with a power density of 35 watt-hr/lb was considered. The size of the battery was estimated using a start up time of 15 minutes. The total wt. of the battery was estimated to be 107 lbs. and the volume approximately 1 ft³. During

Figure 10. Efficiency as a function of load for 15 kW PAFC system

TABLE 11

FUEL CONSUMPTION AS A FUNCTION OF LOAD FOR 15 kW PAFC SYSTEM

% Load	Fuel Consumption lb mole/hr.	
	Methanol System	Propane System
200	1.0176	0.3168
150	—	0.2269
125	0.5065	—
117	—	0.1718
100	0.4597	0.1472
75	0.3455	0.1083
50	0.2251	0.0715
25	0.1189	0.0379
Hot Idle	0.0190	0.0060

TABLE 12

EFFICIENCY AS A FUNCTION OF LOAD FOR 15 kW PAFC SYSTEM

% Load	% Efficiency (based on HHV)	
	Methanol System	Propane System
25	34.5	35.6
50	36.4	37.7
75	35.6	37.4
100	35.7	36.7
117	—	36.7
125	34.9	—
150	—	35.7
200	32.2	34.1

acceleration, additional power can be obtained by overloading the fuel cell stack. But the reformer can not be overloaded because it does not have the large inventory of reformed gas as it had in the pressurized 60 kW system. So either the reformer should be over designed or an additional battery should be provided to meet the load during acceleration. An acceleration time of 20 seconds in the power cycle and overloading of 100% might require a battery of approximately 300-400 lbs in weight. The trade-off between reformer size and battery size is required for this purpose. Though it was not performed in this study because of the short time available, it is recommended for future work.

4.0 CONCLUSIONS

The efficiency vs load curve for the fuel cell system is almost flat in the range of 25% to 100% load. This makes it attractive for the transportation application. The system efficiency integrated over the whole power cycle will depend upon the ratio -

$$R = \frac{(\text{acceleration time} + \text{cruise time})}{(\text{deceleration time} + \text{stop time})}.$$

Lower the ratio, higher the efficiency will be. In the case of diesel internal combustion engine, the efficiency drops considerably as the load drops from 100%. So efficiency integrated over the power cycle will be considerably less than that for the fuel cell system.

Although reformed methanol-air fuel cell performance is 3 to 4 mV higher than reformed propane-air fuel cell performance, the propane system efficiency is competitive with, or greater than, that of the methanol system. Higher propane efficiency is offset by the increased system complexity introduced by more heat exchangers and water gas shift reactors.

The weight and volume of the propane system are higher than those of the methanol system in both the sizes. Volume and weight estimates for the fuel tank are not included in the analysis, since a well-defined power cycle was not available. Fuel consumption and hence, fuel tank size will depend upon the ratio R. Higher the ratio, lower the fuel consumption and fuel tank size will be. It was estimated that fuel tank volume would be 40%

larger for the methanol system than that for the propane system. Also fuel weight for the methanol system would be 120% larger than that for the propane system. This will reduce the differences in weight and volume of the two systems and make both the fuels competitive for the transportation application.

Fuel cell stack efficiency and hence, overall system efficiency increases because of pressurized operation, resulting in higher system efficiency of the 60 kW system compared to the 15 kW system.

5.0 REFERENCES CITED

1. Baker B., Maru H., Patel D., "Fuel Cell Power Configurations", Final Report to Science Applications, Inc., LaJolla, CA, Contract No. 04-117-01, to be published.
2. Abens S., Lambrech M., Marchetti P., Michalko, I., Patel D., "1.5 kW Methanol Fuel Cell Powerplant", Final Technical Report submitted to the U. S. Army Mobility Equipment Research and Development Command, Fort Belvoir, VA, Contract No. DAAG53-76-C-0118, April, 1978.