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# FUEL CELLS FOR ELECTRIC UTILITY AND TRANSPORTATION APPLICATIONS

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## ABSTRACT

This review article presents: (i) the current status and expected progress status of the fuel cell research and development programs in the U.S.A., (ii) electrochemical problem areas, (iii) techno-economic assessments of fuel cells for electric and/or gas utilities and for transportation, and (iv) other candidate fuel cells and their applications. For electric and/or gas utility applications, the most likely candidates are phosphoric, molten carbonate, and solid electrolyte fuel cells. The first will be coupled with a reformer (to convert natural gas, petroleum-derived, or biomass fuels to hydrogen), while the second and third will be linked with a coal gasifier. A fuel cell/battery hybrid power source is an attractive option for electric vehicles with projected performance characteristics approaching those for internal combustion or diesel engine powered vehicles. For this application, with coal-derived methanol as the fuel, a fuel cell with an acid electrolyte (phosphoric, solid polymer electrolyte or "super" acid) is essential; with pure hydrogen (obtained by splitting of water using nuclear, solar or hydroelectric energy), alkaline fuel cells show promise. A fuel cell researcher's dream is the development of a high performance direct methanol-air fuel cell as a power plant for electric vehicles. For long or intermittent duty cycle load leveling, regenerative hydrogen-halogen fuel cells exhibit desirable characteristics.

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## THE RENAISSANCE OF FUEL CELLS AFTER THE ENERGY CRISIS OF 1973

The energy crisis of 1973 stimulated the renaissance of fuel cells. Fuel cells are the only energy conversion devices, which convert the chemical energy of fuels directly to electricity, without the intermediary of heat. Thus, with the main objective of prolonging the life of fossil fuels, petroleum in the near term and coal in the long term, it is necessary to develop fuel cell systems for the generation of electricity and

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efficient use of natural gas and petroleum, to shift towards the utilization of the more abundant coal reserves and eventually utilize the renewable resources (nuclear, solar, fusion).

## TYPES OF FUEL CELLS, THEIR ADVANTAGES AND POTENTIAL TERRESTRIAL APPLICATIONS

The essential requirements of a fuel cell power plant are high efficiency (higher than with conventional plants), low capital cost and long life. Fuel cells may be characterized as modular, pollution free, and highly efficient devices that offer applications over a wide range of power levels from watts to megawatts. Due to the difficulty of the direct utilization of the fossil fuels in fuel cells (1), it is necessary to produce the hydrogen by gasification reactions. Since reformed gases contain carbon dioxide, a $CO_2$ rejecting electrolyte is essential. The possible options are acid, molten carbonate or solid oxide electrolyte fuel cells (2). To maximize the efficiency of fuel cells, it is essential to utilize their waste heat for the endothermic gasifier reactions. Thus reactions of fuel cells at temperatures 200°C are desirable. To minimize electrocatalysis problems, higher temperatures are favored.

With natural gas or petroleum-derived fuels, a system composed of a steam reformer, phosphoric acid fuel cell, and power conditioner, appears best for applications such as spinning reserves or integrated energy systems. With coal gasifiers, the molten carbonate and solid electrolyte fuel cells have distinct advantages for base and intermediate load power generation from the points of view of direct utilization of CO and increasing the system efficiency. As long as petroleum-derived fuels are available, it will be difficult for fuel cell-powered vehicles to compete with internal combustion or diesel engine vehicles. With coal-derived methanol, fuel cell/battery hybrid vehicles will be more advantageous than conventional vehicles (3). In a hydrogen economy, alkaline fuel cells could play a distinct role for dispersed power generation and as power sources for electric vehicles. Solid polymer electrolyte, "super" acid and direct methanol fuel cells are long-range shots for terrestrial applications. Regenerative fuel cells (e.g., hydrogen-halogen) may find application for long or intermittent duty cycle energy storage (4).

PHOSPHORIC ACID FUEL CELLS

Single Cells - Design, Reactions, Electrode Kinetics and Electrocatalysis

The building block - the single cell - of the most advanced phosphoric acid fuel cell of the United Technologies Corporation (UTC) (5), is schematically represented in Figure 1. The Teflon-bonded porous gas diffusion electrodes consist of platinum catalyst particles, supported on a conductive carbon and held together by a Teflon binder, and backed by a porous conductive support sheet. The static electrolyte is contained in an inert inorganic or organic matrix.

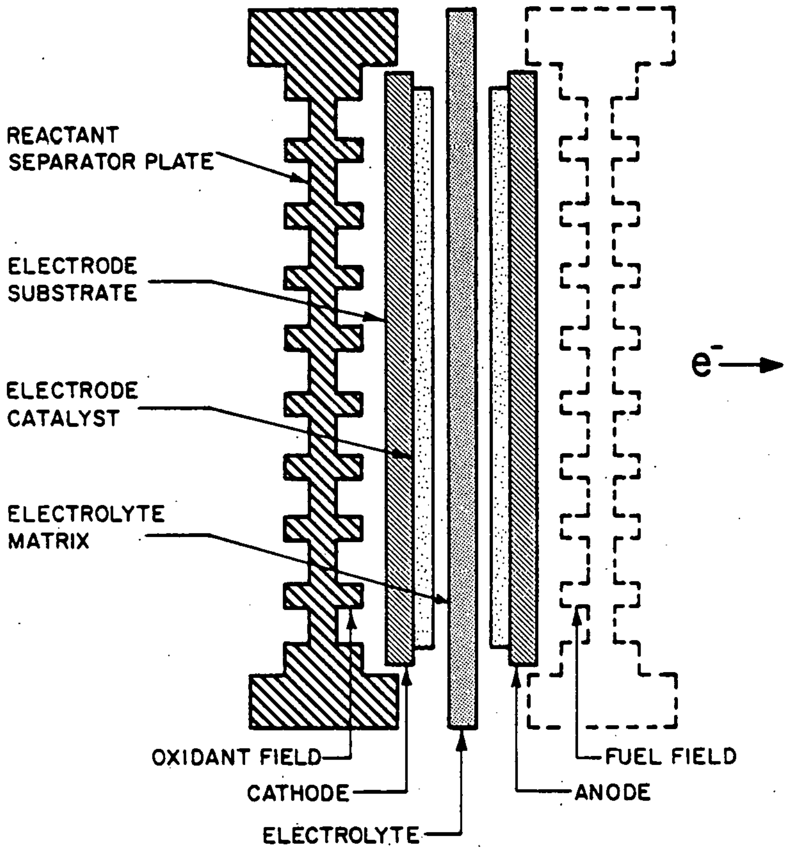


Figure 1. Single Cell in UTC Phosphoric Acid Fuel Cell.

The reactions in the cell are as follows:

| | | | |
|---|---|---|---|
| Anode | $2H_2 + 4H_2O \longrightarrow 4H_3O^+ + 4e_o^-$ | | (1) |
| Cathode | $O_2 + 4H_3O^+ + 4e_o^- \longrightarrow 6H_2O$ | | (2) |
| Cell | $2H_2 + O_2 \longrightarrow 2H_2O$ | | (3) |

The typical cell performance (6) as a function of current density is shown in Figure 2. This figure also illustrates the anode, cathode and ohmic overpotentials. It is obvious that the irreversibility of the oxygen electrode reaction is the dominant cause for the loss in electrochemical cell efficiency of about 45%.

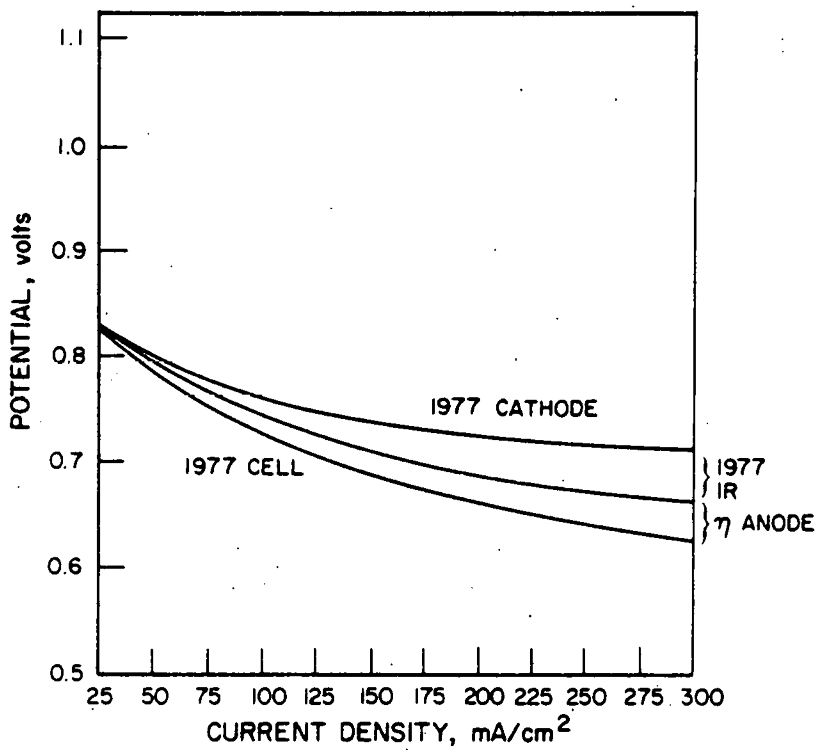


Figure 2. Single Cell Performance in UTC Phosphoric Acid Fuel Cell (6).

Platinum is the best known electrocatalyst for both the hydrogen and oxygen electrode reactions. During the last 10 years, the noble metal loading has been reduced from about 10 mg $cm^{-2}$ at each electrode, to about 0.75 mg $cm^{-2}$ on both electrodes, mainly due to the successful development of carbon supported electrodes. At a current density of 200 mA $cm^{-2}$, the development at the hydrogen electrode is only 20 mV, whereas at the oxygen electrode, it is 400 mV. A remaining problem at the hydrogen electrode is the poisoning due to impurities, such as carbon monoxide or hydrogen sulfide (with a synergistic effect of CO and $H_2S$). Finding better and more stable oxygen electrodes is a major problem area. Firstly, it is essential to reduce its overpotential by at least 100 mV. Secondly, side effects of corrosion of both the carbon and platinum at close to the open circuit potential are encountered. Thirdly, there is a slight decrease in activity with time due to sintering of the electrocatalyst particles. Possible approaches in finding solutions to these problems are by alloying, alteration of support material, pretreatment of support or change in proton activity of the electrolyte.

Multi-cells - Design, Operation and Performance

The fuel cell stack consists of a series of repeating units - anode, electrolyte matrix, cathode, and graphite bipolar plate. In the UTC fuel cells, the stacks are liquid cooled, while in the Energy Reserch Corporation (ERC) fuel cell (7), the stacks are air cooled. In the ERC cells, the same air is used for electrochemical combustion and for cooling, which simplifies heat removal from the stack and is reliable and inexpensive.

An important recent development is the ribbed substrate cell stack by UTC (8). A comparison with a conventional stack is shown in Figure 3.

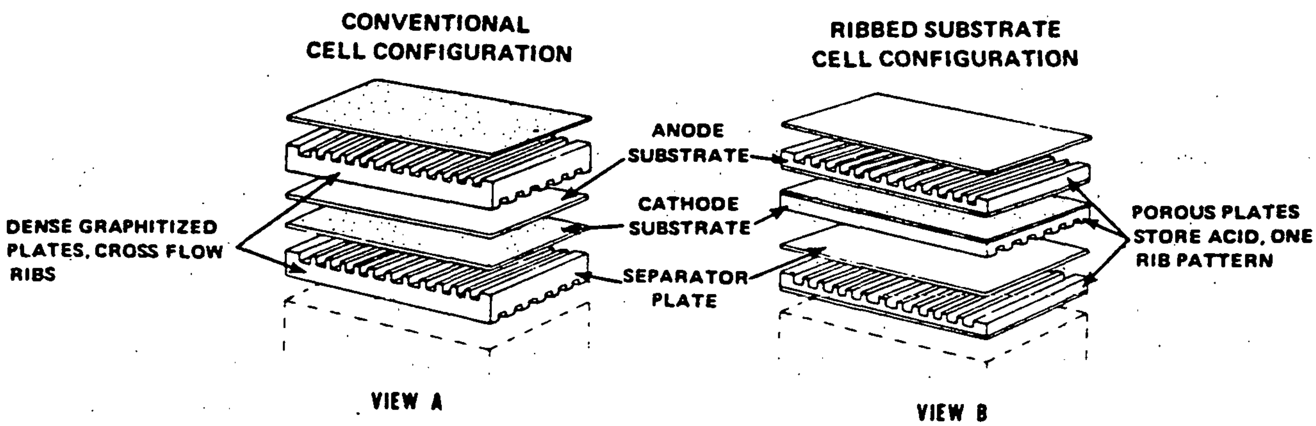


Figure 3. UTC Phosphoric Acid Fuel Cell-Improvements in Stack Configuration (8). This new configuration reduces stack cost and maintenance intervals, and improves electrochemical efficiencies.

One of the problems in the multi-cell stack is the small loss of electrolyte by evaporation, absorption in the carbon components, or corrosion of cell components. This loss may make it necessary for electrolyte replenishment or for finding methods to minimize it. Efforts are underway to improve cell performance and reduce capital costs by operating at higher temperatures (up to 225°C) and pressures (about 10 atmos.).

Power Plants - Design, Development, Applications, Performances and Economics

The most advanced fuel cell power plant is the one using phosphoric acid electrolytes.

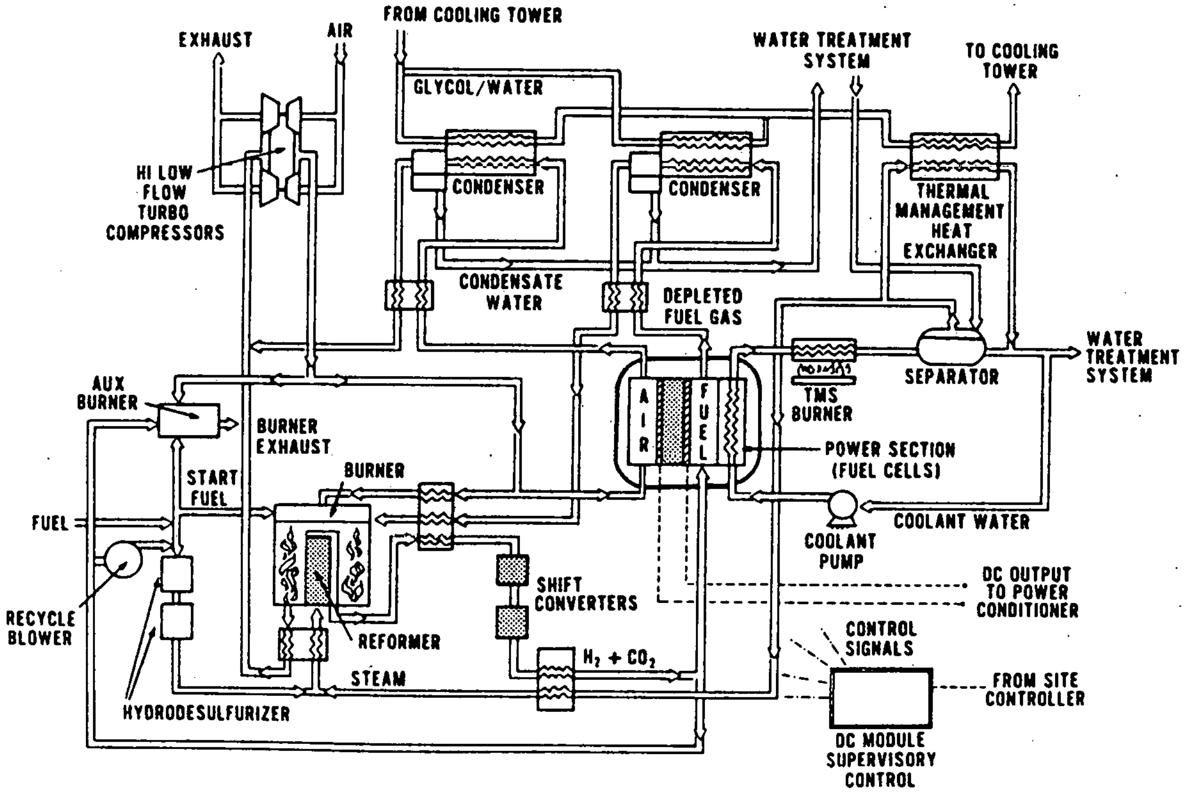


Figure 4. Schematic of UTC Phosphoric Acid Fuel Cell Power Plant. The power plant (5) consists of three major sub systems: (i) fuel processor, which converts the hydrocarbon or alcohol fuel to hydrogen, (ii) fuel cell module, which produces dc power by the electrochemical combustion of hydrogen and oxygen, and (iii) power conditioner, which converts dc to ac. A program is underway at UTC to develop, install and test a 4.8 MW fuel cell power plant in New York City (9). The fuel processor, which incorporates a hydrodesulfurizer, reformer and shift converter, is designed to operate on naphtha, with natural gas as an alternate fuel. The fuel cell module consists of two truck transportable pallets, each containing ten 240 kW fuel cell stacks. The fuel cell stacks are arranged in a series- parallel arrangement to produce 3000 volts dc. The dc power is fed to the power conditioner, which converts the 4.8 MW to three-phase 60-cycle ac at 13.8 kV and 4.5 MW. The 4.8 MW fuel cell power plant designed to operate at 25 to 100% of rated power and with any change in power level to be effected in 15 sec. Such a power plant is being considered for peaking device or a spinning reserve by an electric utility. The overall efficiency of this power plant (chemical - electrical energy) is projected to about 40%, which is a considerable improvement over the values (25-35%) for gas turbines. The capital costs of the MW size fuel cell power plants are projected to be of the order of \$350/kW. Though this is higher than that of gas turbines the cost of electricity for fuel cell power plants and gas turbines should be of the same order, when one takes into account the fuel efficiency, lifetime, and environmental factors.

A novel application of kW size phosphoric acid fuel cell power plants is for "on site integrated energy systems" (10-12). The generation of electricity and heat by fuel cells, particularly in the power range 40-500 kW, is an option with little competition for applications in industries, apartment buildings, shopping centers, hospitals, etc. The idea is to use natural gas, or synthetic gas, distributed by pipelines, reform it to hydrogen and convert its energy to electric and heat energy in a phosphoric acid fuel cell. This system is made even more efficient by coupling it with a heat pump. The overall efficiency for utilization of the primary energy source is projected to be close to 90%, which easily surpasses that of any other energy conversion device. The ongoing programs at UTC, ERC-Westinghouse Corporation, and Engelhard Industries, will soon lead to demonstrations, testing, and market assessments.

## MOLTEN CARBONATE FUEL CELL POWER PLANTS

### Single Cells - Design, Reactions, Electrode Kinetics, and Materials

The single cell in a molten carbonate fuel cell (13) consists of a porous stabilized nickel anode, an electrolyte tile and porous nickel oxide cathode (Figure 5). The electrolyte tile, 1-2 mm thick, consists of submicron particles (30% by volume), and a molten mixture of lithium and potassium carbonates (optimum composition for operating at 650°C is 40% $LiAlO_2$, 28% $K_2CO_3$, and 32% $Li_2CO_3$). It is held between two stainless steel cell housings, which form the anode and cathode cavities. The stainless steel housing ensures low contact resistance of the electrodes and provides a wet-seal for the fuel and oxidant gases. The anode is a sintered nickel structure, containing small amounts of additives, such as Cr, to prevent sintering of the micron-size nickel particles. The nickel oxide cathode is doped with 2-3% lithium to enhance its electronic conductivity. The reactions occurring in the cell are:

| | | | |
|---|---|---|---|
| Anode | $H_2 + CO_3^{2-}$ | $\longrightarrow CO_2 + H_2O + 2e_0^-$ | (4) |
| or | $CO + CO_3^{2-}$ | $\longrightarrow 2CO_2 + 2e_0^-$ | (5) |
| Cathode | $CO_2 + 1/2O_2 + 2e_0^-$ | $\longrightarrow CO_3^{2-}$ | (6) |
| Overall | $2H_2 + O_2$ | $\longrightarrow 2H_2O$ | (3) |
| or | $2CO + O_2$ | $\longrightarrow 2CO_2$ | (7) |

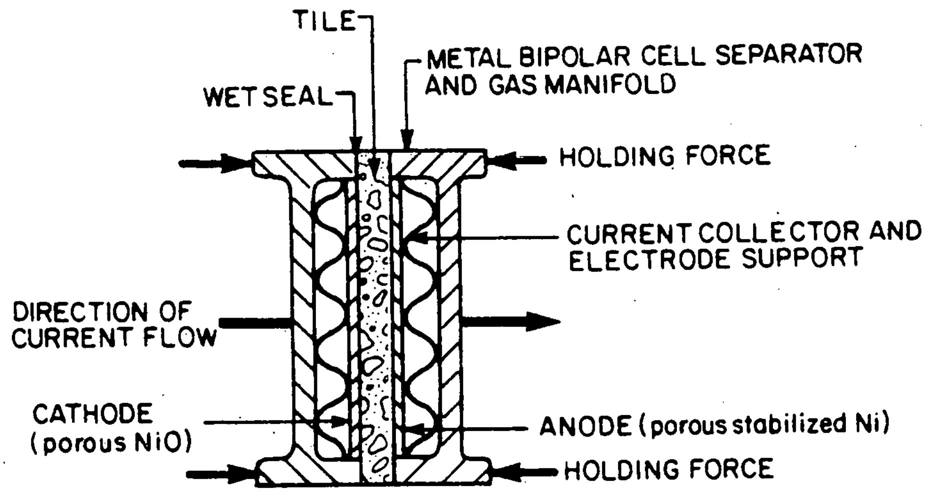


Figure 5. Single Cell in UTC-IGT Molten Carbonate Fuel Cell (13).

The optimum operating temperature of the cell is about 650$^{o}$C. A typical cell potential vs. current density plot for a single cell is shown in Figure 6. The power density at present is about 125 mW cm$^{-2}$ and is quite close to the goal of 135 mW cm$^{-2}$. At about 200 mA cm$^{-2}$, the activation and mass transfer overpotentials add up to about 250 mV, while the ohmic contribution is about 75 mV. From an electrode kinetic point of view, the advantages of this cell are that (i) carbon monoxide is not a poison but a reactant, and (ii) noble metals are not required. As seen from equations 4 to 7, $CO_2$ is produced at the anode but is a reactant at the cathode. This necessitates the supply of $CO_2$ from the anode effluent to the cathode oxidant stream. The sulfur and chlorine tolerances of the cell are only a few parts per million.

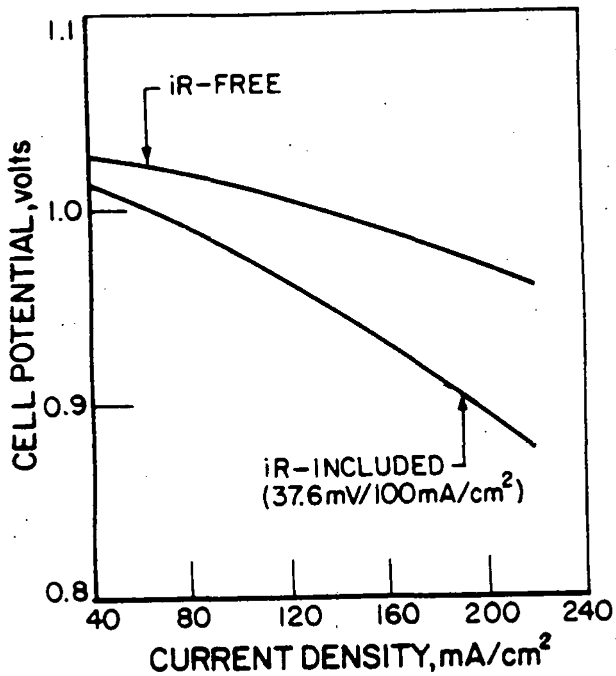


Figure 6. Single Cell Performance in UTC-IGT Molten Carbonate Fuel Cell (13).

Multi-Cells - Design, Operation and Performance

The multi-cell development activity on a molten carbonate fuel cell has been rather limited until the present time. A fuel cell stack, consisting of 20 cells, (active area of electrodes about 900 $cm^2$), was designed, developed, and tested jointly by the Institute of Gas Technology (IGT) and the UTC for about a 1000-hour period (14). The work to date has revealed the following major problem areas in molten carbonate fuel cells: (i) tolerance to sulfur and chlorine impurities is only a few parts per million, (ii) electrolyte loss due to vaporization (it can be partially overcome by having an electrolyte reservoir for sufficient replenishment to achieve the design goal of 40,000 hours), (iii) corrosion in the wet seal area (this is minimized by coating with alumina, but its lifetimes are uncertain), (iv) phase transformations in tile due to thermal cycling, and (v) mode of separating $CO_2$ from anode effluent and transfer to inlet cathode gas stream.

Power Plants - Design, Development, Applications, Performance, and Economics

The molten carbonate fuel cell power plant, for base load and intermediate load power generation, will include as its principal components, a coal gasifier, fuel cell module, bottoming cycle, and power conditioner (Figure 7). The expected goals for this system are: a current density of 150 mA $cm^2$ at a cell potential of 0.85 volts, an overall efficiency (coal to electricity) of 45-50%, lifetime of over 40,000 hours, and a capital cost of $60/kW for the electrochemical cell stack. A second application of molten carbonate fuel cell power plants is for cogeneration of electricity and heat. The high grade waste heat from molten carbonate fuel cells could be used for district heating or for industries requiring such high quality heat. The active industrial participants in the U.S.A. molten carbonate fuel cell program are UTC, GE, ERC, and IGT. The current 30-month program, supported by the U.S. Department of Energy (DOE) and the Electric Power Research Institute (EPRI), focuses on cell and stack design, development, and testing. This will be followed by the design and construction of prototype coal based molten carbonate fuel cell power plants. The results of these programs will be essential in deciding whether such types of power plants will satisfy the following requirements: (i) reliable performance, (ii) long life 40,000 hours for cell stack), and (iii) cost of electricity to be competitive with that of advanced gasification/combined cycle gas turbine power plants.

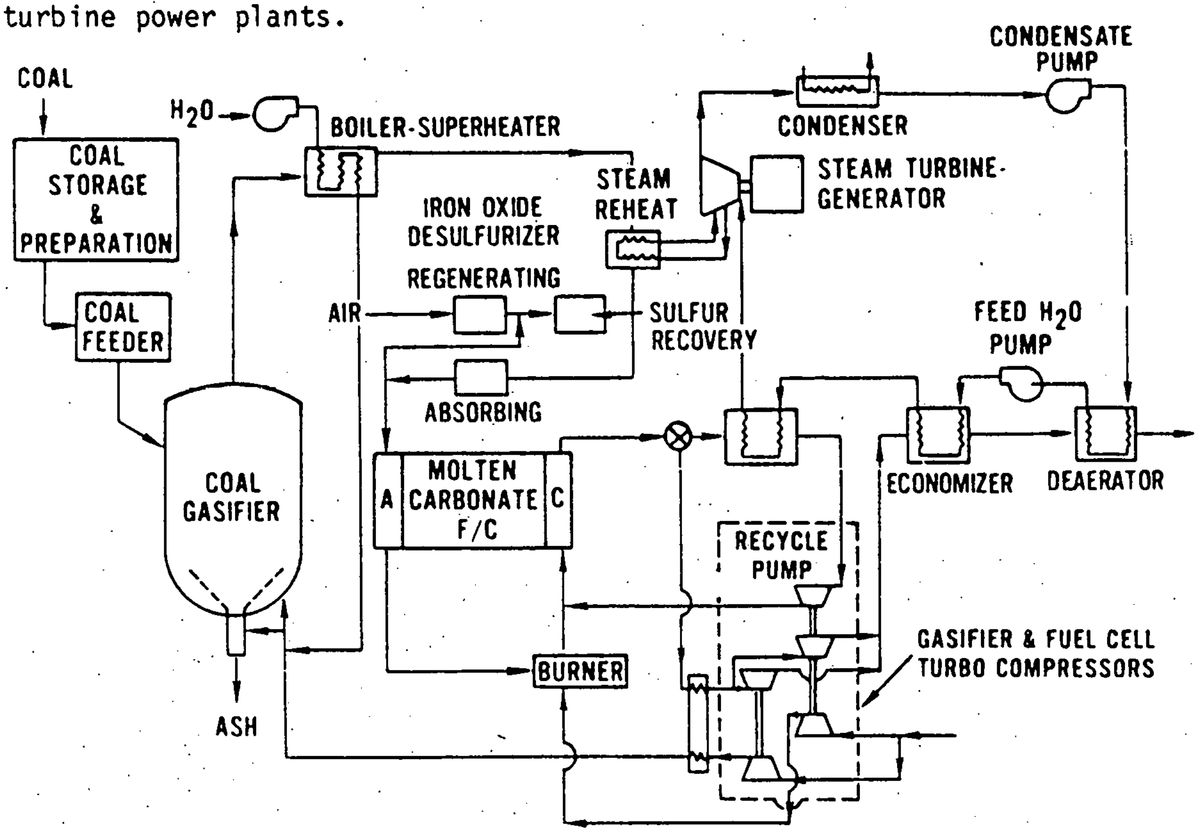


Figure 7. UTC Molten Carbonate Fuel Cell Power Plant Design (13).

## SOLID ELECTROLYTE FUEL CELL POWER PLANTS

### Single and Multi-Cells - Design, Reactions, Electrode Kinetics, and Materials

With the aim of minimizing ohmic overpotentials, the Westinghouse Research and Development Center is concentrating on the design and fabrication of thin film solid electrolyte fuel cells, using electrochemical vapor deposition methods for the electrodes, electrolytes, and interconnections (Figure 8) (15).

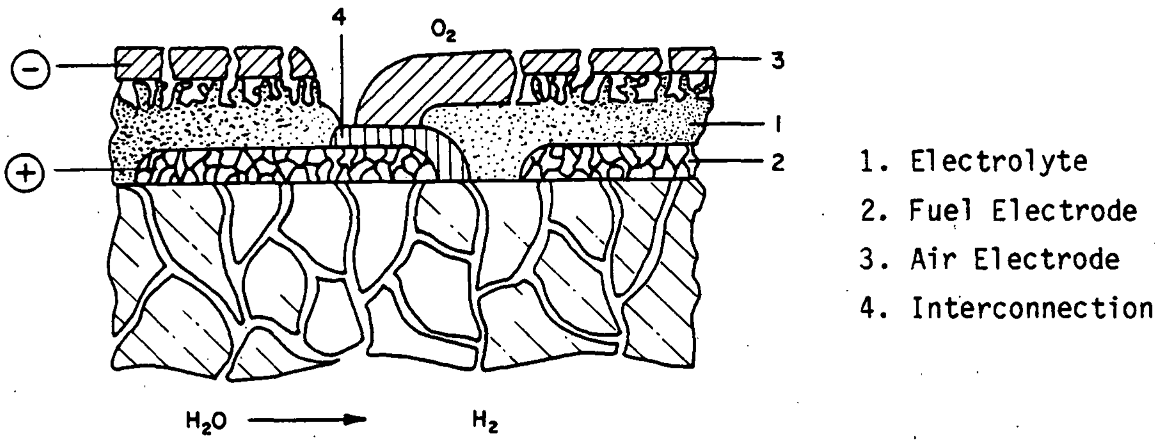


Figure 8. Bi-Cell in Westinghouse Solid Electrolyte Fuel Cell (16). The total thickness of a cell stack (i.e., electrodes, electrolytes, and interconnections), is about 100 μ. Since such a thin film fuel cell stack would be fragile, it is deposited on a porous zirconia support tube. The order and mode of deposition of the respective layers are as follows: (i) a slurry of nickel oxide and yttria-stabilized zirconia is sintered on the porous support tube. The nickel oxide is reduced with hydrogen, leaving a porous cermet, 20 μ thick. This nickel is partially dissolved electrochemically to achieve a band and ring structure for multi-cell fabrication; (ii) electrochemical vapor deposition of magnesium and aluminum doped lanthanum chromite - a gas tight interconnection layer with a thickness of approximately 20 μ. An alternate method which may be of value to attain the proper composition is RF sintering; (iii) electrochemical vapor deposition of yttria-stabilized zirconia (electrolyte layer) 20 μ thick. During this deposition, interconnections are masked; (iv) chemical vapor deposition of tin doped indium oxide, the air electrode current collector (more recently, lanthanum manganite, was found to be more stable during fuel cell operation). The porous electrolyte layer under the air electrode is then impregnated with praseodymium nitrate solution, which is thermally decomposed to the oxide. Praseodymium oxide reduces the air electrode overpotential.

The conducting species in the electrolyte is the oxide ion. Cell stacks (consisting of 5, 7 and 18 cells) have been fabricated and tested. The projected performance of 400 mA $cm^{-2}$ at 0.66 volts, necessary to meet power plant goals, was met (16). However, a performance degradation, due to flaking of the indium oxide in spots over the interconnection material, was observed. The substitution of lanthanum manganite for indium oxide appears to overcome this problem. Investigations of the electrode kinetics of the oxidation of the fuel and of reduction of oxygen, using direct current and alternating currents are in progress. Even at 1000°C (the cell operating temperature), catalytic effects of the oxygen electrode material are apparent. The slow step for oxygen reduction on some metals (eg., Pt) is the dissociative adsorption of oxygen (17).

The reactions occuring in the fuel cell may be represented as follows:

| | | | |
|---|---|---|---|
| Anode | $2H_2 + 2O^{2-}$ | $\longrightarrow H_2O + 4e_o^-$ | (8) |
| or | $2CO + 2O^{2-}$ | $\longrightarrow 2CO_2 + 4e_o^-$ | (9) |
| Cathode | $O_2 + 4e_o^-$ | $\longrightarrow 2O^{2-}$ | (10) |
| Overall | $2H_2 + O_2$ | $\longrightarrow 2H_2O$ | (3) |
| or | $2CO + O_2$ | $\longrightarrow 2CO_2$ | (7) |

A photograph of the fuel cell stack is shown in Figure 9.

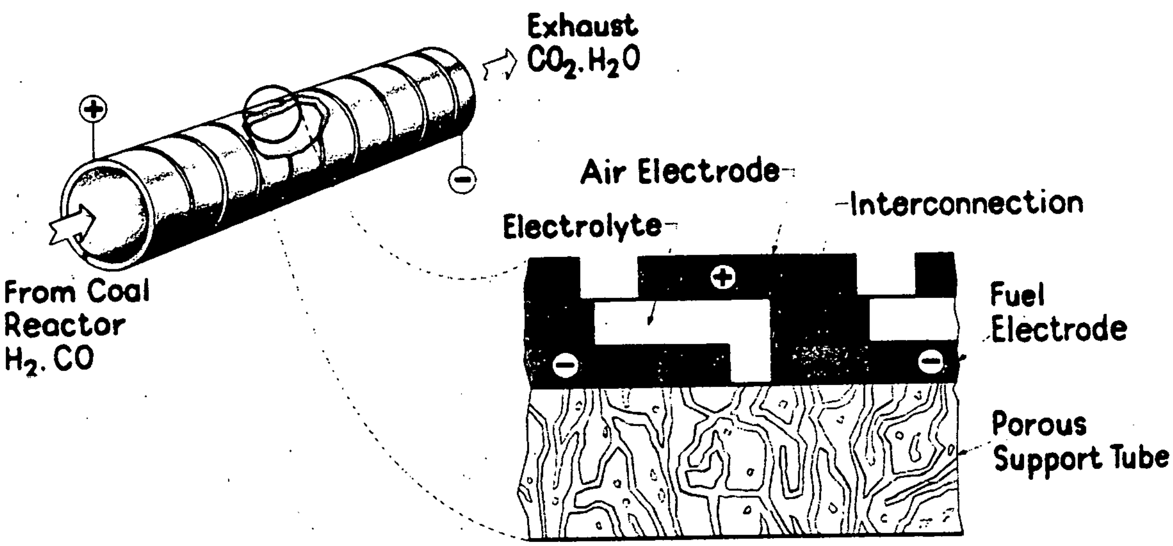


Figure 9. Multi-Cell in Westinghouse Solid Electrolyte Fuel Cell (16).

<u>Power Plants - Design, Development, Applications, Performance, and Economics</u>

Coal will play a dominant role as the primary energy source, particularly in the U.S.A., but it will still be necessary to use it most economically with the aim of extending its lifetime. Of the three fuel cell systems (phosphoric, molten carbonate, solid electrolyte), which are currently under development in the U.S.A., solid electrolyte fuel cells integrated with coal gasification plants are expected to have the highest overall efficiencies (about 50%) for the conversion of the chemical energy of coal to electrical energy (for base load power generation in an electric utility). A schematic representation of a coal gasification - solid electrolyte fuel cell power plant is found in Figure 10. The high grade heat required for the coal gasification is partially supplied by the waste heat from the electrochemical subsystem. For efficient heat transfer, it has been proposed that the fuel cells be located within the reactor. Carbon monoxide, a product of coal gasification, is a reactant and not a poison, as in phosphoric acid fuel cells. Carbon dioxide is not a cathodic reactant in the solid electrolyte fuel cell but is so in the molten carbonate fuel cell. The solid electrolyte fuel cell technology is at its infancy in comparison with the other two technologies, described in the preceding sections. It is rather premature to make any economic assessments. However, at this stage, it appears that this technology has some distinct advantages (18) - use of low cost materials, no liquids involved in electrochemical subsystem, invariant electrolyte, no cooling water required, and minimal air pollution levels. Some of the apparent problems are the fabrication techniques and the large number of small cells in megawatt size plants.

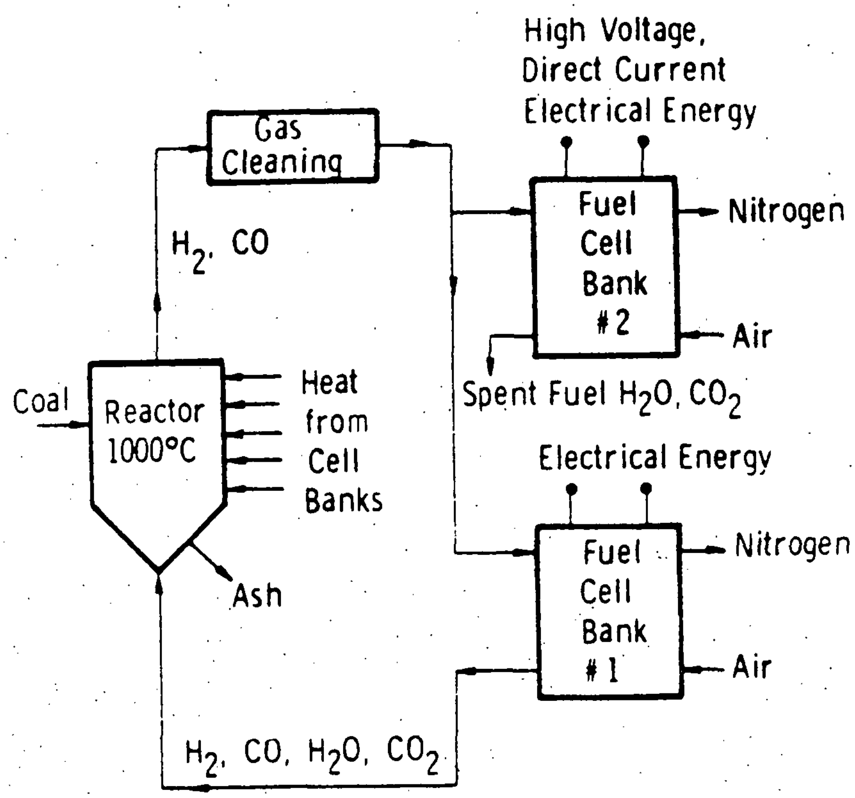


Figure 10. Westinghouse Solid Electrolyte Fuel Cell Power Plant Schematic (16).

FUEL CELLS FOR TRANSPORTATION APPLICATIONS

Rationale for Fuel Cell Powered Vehicles

As long as petroleum derived liquid fuels are available, there will be very little competition for internal combustion engine or diesel powered vehicles. In the "coal era" and the following "nuclear, solar and fusion era" with methanol or hydrogen being the synthetic fuels, the high efficiency and low pollution characteristics of a fuel cell makes this energy converter an appealing alternative as a power source for automotive propulsion.

Several conventional and advanced batteries are being considered for electric vehicles. The Ragone plot (Figure 11) is a very useful illustration for predicting performance characteristics of electric vehicles (19).

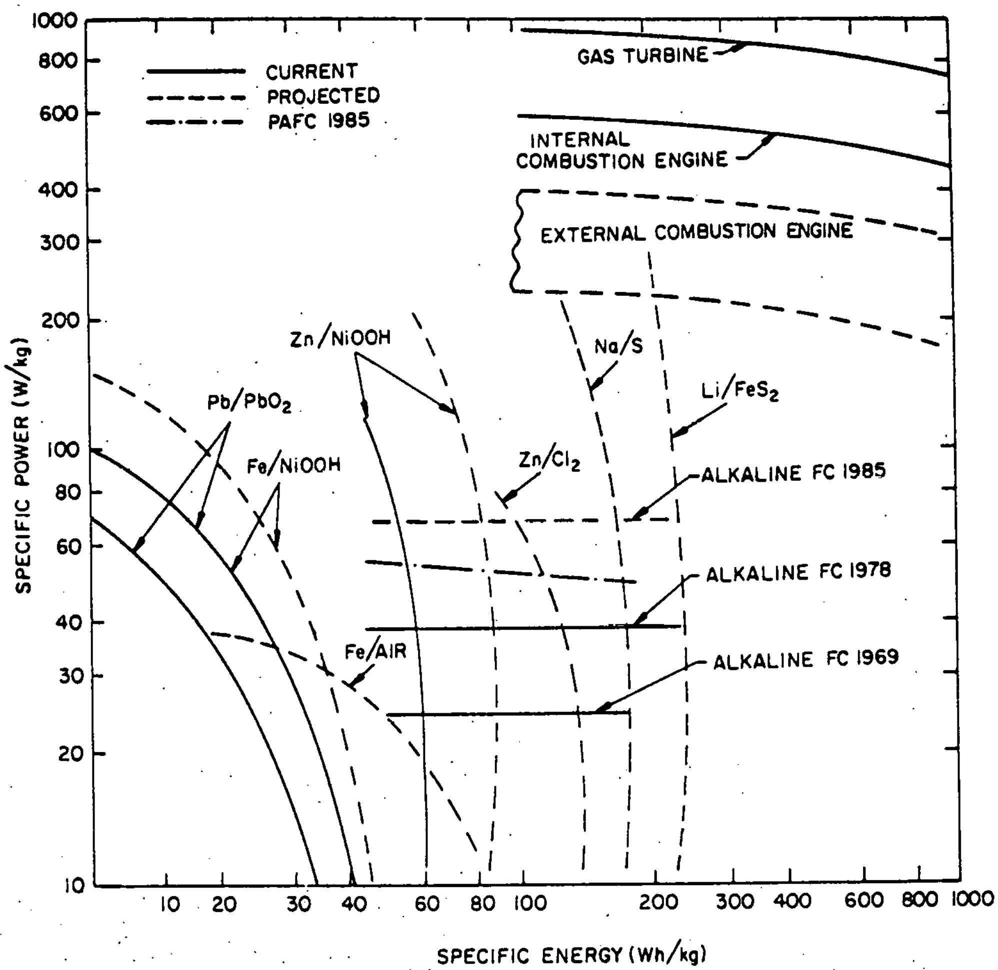


Figure 11. Ragone Plots for Batteries, Fuel Cells, and Various Heat Engines.

The specific power versus specific energy relations for internal and external combustion engines and for gas turbines are also shown in Figure 11. These plots are horizontal for the energy converters (including fuel cells) but vertical for the energy storers. The mechanical energy converters have the desirable characteristics of high power/weight (required for start-up, acceleration) and energy/weight (required for range) ratios, while the fuel cells have low power/weight ratios but can attain high energy/weight ratios (the latter, for the mechanical and electrochemical energy converters, are determined by the amount of fuel carried on board the vehicle). Batteries can attain high power/weight ratios but have relatively low energy/weight ratios.

## The Fuel Cell/Battery Hybrid Power Source

Figure 11 demonstrates that the only way in which electric vehicles can reach the performance characteristics of engine-powered vehicles is by use of a fuel cell/battery hybrid power source (Figure 12). In this type of vehicle, first demonstrated by Kordesch (20), the fuel cell provides the power required for cruising and the battery for start-up and acceleration. Batteries will have a much longer life in the shallow depths of discharge during such a fuel cell/battery hybrid operation. Deep discharges, which will occur in a battery electric vehicle, considerably shorten cycle life. The battery will be charged by the fuel cell during cruising. A fuel cell/battery hybrid vehicle offers high efficiency for fuel utilization, power requirements for start-up, cruising and acceleration, long range and fast refueling. The fuel distribution network will not be altered with this concept (as will be the case with battery powered vehicles). Furthermore, a fuel cell/battery hybrid vehicle requires no breakthrough in battery technology--presently available lead acid or nickel-zinc batteries will be more than adequate.

## Reformed Carbonaceous Fuels and Acid Fuel Cells

No single factor has inhibited the development of fuel cells as much as the fact that hydrocarbons from petroleum cannot be used directly in a fuel cell. Much of the complexity, bulk, and weight of present day fuel cells accrues from the fact that natural gas and petroleum derived fuels require a high degree of processing prior to use in the fuel cell stack. For instance, if naphtha is used as a fuel, the fuel processor requires a

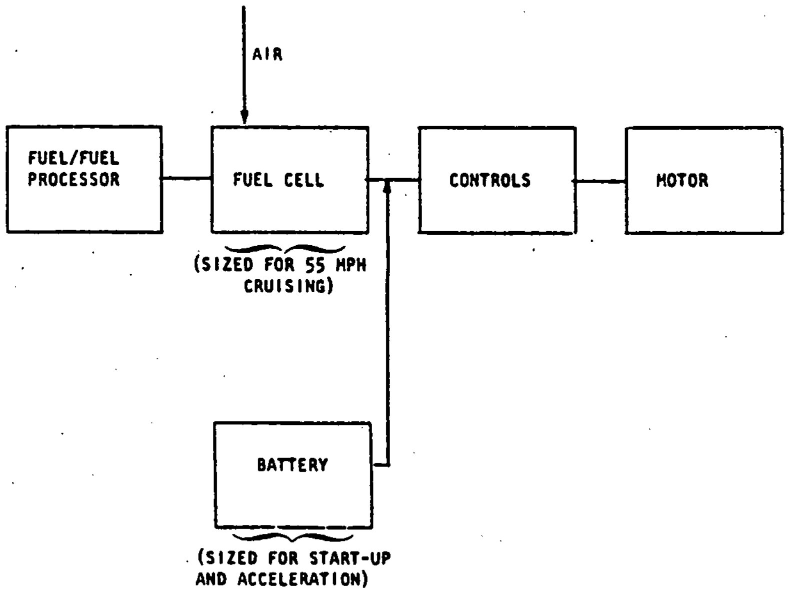


Figure 12. Fuel Cell/Battery Hybrid Power Plant for Electric Vehicles (23).

hydrodesulfurizer, a high temperature (700°C) steam reformer, a high temperature shift reactor, a low temperature shift reactor, and heat exchangers and plumbing for the fuel processor. With alcohol fuels from coal or biomass, processing becomes simpler. A 1:1 by volume mixture of methanol and water can easily be reformed at 190°C and the reformate ($H_2$ + $CO_2$ + trace CO) fed directly into a phosphoric acid fuel cell operating at 200°C. No shift converter is necessary. Such a fuel cell power plant is compact, simple, and attractive for transportation applications.

The phosphoric acid fuel cell, technologically requires platinum electrocatalysts. However, as stated in the third section, the catalyst loading has decreased to 0.75 mg $cm^{-2}$ cell area. This has been achieved in conjunction with extension of life to many thousand hours, scale-up to stacks of 400 cells (3.25 $ft^2$ being area of electrodes) and an increase of power density to 200 mW $cm^{-2}$. Undoubtedly, the platinum loading will be further reduced. More recently, other acid electrolytes such as trifluoromethanesulfonic acid (TFMSA) have been investigated (21). Cells with 6 N TFMSA exhibit a performance at 90°C superior to that of phosphoric acid fuel cells at 200°C. Other sulfonic and phosphoric acids are now being synthesized for potential use in fuel cells (22). Reduction of the platinum loading to an amount in the vicinity of 1 g/kW appears possible. At these low operating temperatures, 100°C, with these alternate electrolytes in fuel cells, it may be possible to dispense with platinum and use metal-organic complexes (e.g., porphyrins, phthalocyanins) as electrocatalysts.

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 volume and weight. For vehicular applications, it is necessary to optimize power densities and costs. This would necessitate a complete redesign of cell stacks, heat removal equipment, etc.

## Hydrogen Fuel and Alkaline Fuel Cells

If pure hydrogen were available (e.g., from renewable energy resources), the alkaline fuel cell will be quite attractive because it does not require platinum electrocatalysts and it delivers its rated power (which is about the same as the phosphoric acid fuel cell at 200°C) at low temperatures (100°C). As a result, start-up time is fast. An important aspect of the alkaline fuel cell is that nickel plated steel parts can be incorporated in the structure and rugged power plants, suitable for mobile applications, can be constructed. Pure hydrogen may also be available if advanced gas separation facilities for syngas streams are developed. Another source of hydrogen is electrolysis in conjunction with intermittent primary energy sources such as solar or wind energy. The disadvantages of this system are the $CO_2$ removal problems, hydrogen storage in the vehicle and refueling.

## APPLICATIONS SCENARIO STUDY OF FUEL CELL POWERED VEHICLES

An applications scenario study (23), which included a detailed technical and economic evaluation of potential applications of fuel cells in transportation, was recently carried out at Los Alamos Scientific Laboratory (LASL). Four vehicle types were evaluated: city bus, highway bus, delivery van, and consumer car. Typical drive cycles and economics for these vehicles were gathered and comparisons made between conventional (internal combustion engine or diesel) and fuel cell/battery hybrid vehicles. The results strongly suggest the feasibility of fuel cell vehicles in the late 1990's. It should be emphasized that no fuel cell, battery, motor, or vehicle aerodynamic performance improvements were projected in making these assessments. Technical feasibility was demonstrated for each of the four vehicles studied. Economic viability was more difficult to prove because of the scarcity of data on uniform vehicular performance, duty cycle, and costs, as well as the lack of experience with fuel cells in the vehicular environment. However, since conservative estimates were used in the analysis, first-order economic viability in the 1990's time frame was predicted. These studies suggested more design, development, and testing programs for fuel cell/battery hybrid vehicles. Since maintenance plays a strong role in assessing economic feasibility, experience with fuel cells in vehicular environments must be obtained.

## PRESENT AND PROJECTED PERFORMANCE CHARACTERISTICS OF FUEL CELL POWERED VEHICLES

In Table I are shown the demonstrated and projected performance characteristics of fuel cell powered passenger vehicles. The first case cited is that of the General Motors Electrovan with a Union Carbide Hydrogen-Oxygen Alkaline Fuel Cell as the only power plant (24). The fuel cell reactants were carried on board the vehicle as cryogenic liquids. The main drawbacks of this vehicle were the excessive weight of the power train and the long time for acceleration from 0-100 km/h.

TABLE I
Demonstrated and Projected Performance Characteristics of Fuel Cell Power Vehicles

| | GM Electrovan | Kordesch Car | LASL-BNL-ERC Projections for Subcompact Car |
|---|---|---|---|
| Power Train | $H_2/O_2$ Fuel Cell | Fuel Cell/ Battery Hybrid $H_2$-Air | Fuel Cell/ Battery Hybrid Methanol $H_2$-Air/ Lead Acid |
| Rated Power, kW | 32 | 6 | 15 |
| Peak power, kW | 160 | 22 | 35 |
| Curb weight, kg | 3550 | 910 | 1360 |
| Power train weight, kg | 1765 | 320 | 365 |
| Top speed, $kmh^{-1}$ | 110 | 90 | 120 |
| Cruising speed, $kmh^{-1}$ | --- | 65 | 90 |
| Acceleration | | | |
| 0-100 $kmh^{-1}$, sec | 30 | --- | --- |
| 0- 50 $kmh^{-1}$, sec | --- | --- | 14 |
| Start-up time, min | --- | --- | 10 |
| Fuel consumption | --- | 40 km/kg, $H_2$ | 11 km/$\ell^{-1}$, methanol |

The first fuel cell/battery hybrid vehicle was designed, developed and tested by Kordesch, while at Union Carbide Corporation (20). The power plant consisted of a hydrogen-air alkaline fuel cell and a lead acid battery. The hydrogen was stored as compressed gas in five small cylinders. The vehicle was capable of cruising at 70 km/h and the range with 1.6 kg of hydrogen was 300 km. The vehicle was tested for a period of one year and the distance covered was 24,000 km.

Assessments have been made of the expected performance of fuel cell powered vehicles by the Institute of French Petrole and Renault Automobile Company in France (25). ELENCO, a conglomerate of Bekaert, Belgian Nuclear Center and Dutch State Mines is engaged in a multi-million dollar program to develop fuel cell powered vehicles (26). The technoeconomic assessments at ELENCO reveal that the first impact of fuel cell powered vehicles will be with buses. The present program is to design, develop and test 10 kW alkaline fuel cells.

Because the phosphoric acid fuel cell is in the most advanced state of development, expected performance and cost assessments of 15 kw (for passenger vehicles) and 60 kw (for buses) systems were made at ERC (27). The results of this study were used in projecting performance characteristics of fuel cell powered vehicles (Table I). For this case, a vehicle similar in size to the Volkswagen Rabbit was considered. The expected performance of the fuel cell/battery hybrid vehicle will match that of a diesel powered vehicle. It is estimated that the electric vehicle will cost about $3000 more than the diesel one and also exceed in weight by about 200 kg. However, the efficiency of fuel utilization and maintenance costs are more favorable for the fuel cell/battery vehicle.

OTHER CANDIDATE FUEL CELLS AND THEIR POTENTIAL APPLICATIONS

There is only a low level of effort for the development of solid polymer electrolyte fuel cells, and this too is mainly for space applications (28). This system offers nearly the same characteristics as the phosphoric acid fuel cell system but suffers from the additional disadvantages of a high cost solid polymer electrolyte and a difficult water management problem.

Alkaline fuel cell development has declined in the USA, particularly because of the emphasis on utilization of fossil fuels. However, according to the views of several European and Canadian scientists, in the nuclear, solar and fusion era, alkaline fuel cells will have a distinct role in a Hydrogen Energy Scenario. Siemens A.G., in West Germany, is developing a 7 kW hydrogen-oxygen alkaline fuel cell for military applications (29). Such a system also shows value for stand-by power, say in hospitals. ELENCO is engaged in the design, development and testing of alkaline fuel cells for transportation applications (26). There is a small effort at Brookhaven National Laboratory, with the assistance of Professor K.V. Kordesch, to optimize alkaline fuel cells as power sources for electric vehicles (30).

The ideal fuel cell for transportation applications is the direct methanol-air fuel cell. Unfortunately, the power density is too low, at least by a factor of six. The second problem is the poisoning of the fuel electrode, presumable by an intermediate formed during methanol oxidation. There is a low level of effort at Shell Research Laboratories in England to investigate direct methanol-air fuel cells (31).

Practically all fuel cells, which have been developed, use oxygen (pure or from air) as the cathodic reactant. The efficiency losses, particularly in the low temperature fuel cells, are mainly due to the high overpotential at the oxygen electrode. Substitution of chlorine for oxygen greatly enhances fuel cell performance. The prospects for an energy storage system utilizing a regenerative hydrogen-halogen fuel cell were examined in detail jointly by Brookhaven National Laboratory, General Electric Company, Oronzio de Nora, Clarkson College, Energy Development Associates and Gould, Inc. (4). The general conclusions were that such a system shows promise for coupling with intermittent energy sources (e.g., solar wind) or with remote nuclear power plants.

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