Fuel Cells Feasibility Status Report

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Fuel cells are electrochemical devices that promise a more efficient use of fossil fuels. The present feasibility study describes the operation of fuel cells and shows their potential benefits to the DSN. The authors describe the current research effort in this field and point out the major technical problems which still remain. Because of these major problems and because of DOE funding uncertainties, the authors conclude that fuel cells will probably not become commercially viable until the early 1990s.

I. Introduction

As part of the Master Plan of the Energy Conservation Project for the Deep Space Network, fuel cells are forecast to play an important role in future power generation subsystems. A management directive was given to review the technical and economic status of fuel cells as of 1980 and provide an up-to-date account of where the fuel cell technology is and where it will be 5 to 10 years hence. Furthermore, preliminary answers are sought for the very practical question of whether fuel cells can be used economically at the DSN Goldstone Deep Space Communications Complex to take part of, or eventually replace, the electrical load now being generated by diesel engines.

This article summarizes the efforts and results of the fuel cell task which have been carried out by members of the technical staff at the Advanced Engineering and Energy Conservation Group of the DSN Engineering Section. The article is divided into five parts. Following the introduction, the second part begins with a short review of what a fuel cell is, how it operates, and what its outputs are. The technical problems of each of the components are analyzed next. The fourth part concentrates on the economics of fuel cell use, with emphasis on fuel costs. The last part of the article details the conclusions that have been drawn from the review and makes some predictions for the future of fuel cells.

Fuel cells can be classified by electrolyte, by temperature of operation, by oxidant, and by fuel types. Possible combinations of these factors are limited due to the constraints the electrolyte imposes on the other factors and vice versa. For various technical reasons, most of the industry's efforts have been concentrated into the development of phosphoric acid fuel cells (PAFC) so named after the electrolyte in them. These cells have reached a relatively high level of technological maturity and they will probably be the first to be commercially available.

The second generation of cells will probably be that of molten carbonate fuel cells (MCFC). Their technological development is about 5 years behind that of PAFC.

The conclusions presented at the end of this article are based on literature sources as well as on numerous personal communication with members of the fuel cell community. These conclusions can change if DOE funding will modify its direction and magnitude.

II. Technology of Fuel Cells

A. Fuel Cell Operation

The fuel cell is a device that converts chemical energy of fuels into an electric energy by electrochemical reactions. As shown in Fig. 1, a single fuel cell unit can be considered as two electrodes separated by electrolyte. The electrolyte is either a liquid or solid substance and allows free passage of ions, but not electrons. The two electrodes are connected by an external path for an electric current to occur. Fuel is supplied to the anode and oxygen or air to the cathode. The electrochemical oxidation of the fuel at the anode produces electrons. The electrons flow through the external circuit to the cathode on which oxygen is reduced. The ionic and neutral species that participate in the electrochemical reactions are different for the various types of fuel cells.

In the case of acid cells, the electrolyte is typically an aqueous solution of phosphoric acid stored in a matrix structure. The electrodes are thin, porous carbon structures catalyzed with a noble metal such as platinum. At the anode, hydrogen molecules in the fuel gas are dissociated into hydrogen ions, releasing electrons:

$$H_2 \rightarrow 2H^+ + 2e^- \qquad (1)$$

At the cathode, oxygen from the air is reduced by reaction with the hydrogen ions passing through the electrolyte and electrons flowing from the external circuit to produce water vapor:

$$\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O \qquad (2)$$

The overall cell reaction, combining Eqs. (1) and (2), is the oxidation of hydrogen to water, producing electricity and some waste heat:

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O + \text{Heat} + \text{Electricity} \qquad (3)$$

The mechanism of creating the ions and electrons at the anode using catalysts has been described elsewhere (Ref. 1). Molecular hydrogen can be dissociated into hydrogen ions when passed over a catalyst. The most often used catalyst is platinum (Pt) and the reaction also produces free electrons ($2e^-$). Typical of catalytic reactions, the electron yield will increase if the surface area of interstices over which the reaction takes place is increased. Thus, increasing the surface area of the anode will increase the efficiency of the cell. This is achieved by using porous electrodes which result in a very large contact area between the gaseous fuel and electrode interstices. Classically, the production of electrons will be speeded up as the amount of catalyst is increased. In practice, one cannot increase the catalyst loading indefinitely, otherwise polarization of the electrode will occur, which results in a loss of cell efficiency. Thus, catalyst loading represents a compromise between reaction kinetics and diffusion rates.

The choice of electrolyte is based on its tolerance to fuel gas impurities. The most widely used fuel cell electrolyte today is phosphoric acid. This limits the temperature operating range of the cell to between 150 and 200°C. Below the 150°C limit, the phosphoric acid electrolyte has a poor ionic conductivity. Above the 200°C limit, the electrode materials tend to become unstable (Ref. 2). The choice of electrolyte not only depends on the operating temperature, but also on the way that ions migrate between the electrodes. In the phosphoric acid cell, the electrolyte is an acid and the H^+ ions move from the anode section to the cathode section. In other types of fuel cells, such as the molten carbonate, the electrolyte is a carbonate salt and the ions ($CO_3^=$) migrate from the cathode to the anode.

B. Types of Fuel Cell

A number of fuel cell types offering reduced heat rate and capital costs are: molten carbonate cell, solid oxide cell, phosphoric acid cell, and alkaline cell. The electrochemical reactions for those cells are given in Table 1.

The first two fuel cells, molten carbonate and solid oxide, operate at high temperature and offer high power density at about 7913 kJ/kWh$_e$ (7500 Btu/kWh$_e$) heat rate (46 percent overall efficiency). Because carbon monoxide (CO) is shifted in molten carbonate fuel cells, a separate water-gas shift converter is not required as part of the fuel processor. Higher operating temperatures facilitate waste heat rejection and integration with other power plant functions. The development efforts for the molten carbonate cell are focused on improving cell endurance and performance and on establishing the initial scaleup needed in practice. Solid oxide cells operating at 980° to 1090° C have been under investigation. Because this temperature range imposes severe material and design requirements, the solid oxide cell development effort is focused on establishing a cell concept which operates satisfactorily at a temperature range similar to the molten carbonate cell (650° C).

The two low-temperature cells are the phosphoric acid and the alkaline cells. Alkaline cells offer higher performance than phosphoric acid cells. However, carbon oxides present in fuel and in air streams fed to the cell cause a rapid conversion of hydroxide to carbonates and loss of performance. The phosphoric acid cell performance is promising for the near-term applications. The material costs are acceptable, but the cell components require relatively expensive manufacturing processes. Development efforts are focused on both the reduction of manufacturing costs and the increase of the tolerance of the phosphoric acid cell to sulfur and other impurities in the fuel gas stream.

Fuel cells with sulfuric acid, sulfonic acid, or solid polymers as the electrolyte are limited by the vapor pressure of the water in the electrolyte. If air is used as the oxidant, these fuel cells must be operated at temperatures below 100° C. Otherwise, the electrolyte becomes unstable due to water evaporation and the associated venting of nitrogen. At temperatures below 100° C, however, high efficiency cannot be achieved. These electrolytes are, therefore, not receiving much attention for nonspace applications.

C. Fuel Cell Powerplant System

The schematic of a fuel cell power plant system is shown in Fig. 2. The full system is composed of three elements: the fuel processor, the power section, and the inverter. The fuels for the fuel cell powerplant can be of various types such as natural gas, coal-derived gases and liquids, alcohols, naphtha, and other hydrocarbon-based fuels. The fuel processor is used to break up the raw fuel into a gas rich in hydrogen (H_2).

The power section converts processed fuel and air into direct current power. At present technology levels, a single fuel cell unit generates roughly 100 to 200 watts of direct current (dc) electricity for each square foot (0.093 m^2) of electrode area at a potential on the order of 1 volt. In a fuel cell power section, a number of single cells are connected in series to permit generating hundreds of volts in a stack. Connecting a number of stacks in parallel permits power levels from kilowatts to multimegawatts.

The power conditioner (inverter) converts the direct electric current into alternating current to meet the customer requirements. Two basic types of inverter systems were considered for dispersed generation application of fuel cell powerplants; they are line-commutated inverters and self-commutated inverters. In line-commutated inverters, the kVA required to turn off the power thyristors is supplied by the ac system; in self-commutated inverters, it is supplied by energy stored within the inverter itself.

D. Operational Advantages

Direct energy conversion by fuel cells promises to be a highly efficient process. Since fuel cells do not have Carnot cycle limitations (Ref. 3), their thermodynamic efficiency is of the order of 95 percent. In contrast, a Carnot cycle operating between 150° and 200° C, the PAFC temperature limits, has an efficiency of only 11 percent. However, the efficiency η of the fuel cell stack is made up of voltage and current efficiencies in addition to the thermodynamic one (Ref. 4):

$$\eta_{\text{stack}} = \eta_{\text{thermo}} \times \eta_{\text{current}} \times \eta_{\text{voltage}} \tag{4}$$

With voltage and current efficiencies of the order of 75 percent, the stack efficiency is of the order of 42 percent for PAFC and 48 percent for MCFC.

The total fuel cell system includes the power sections, the power conditioner and the fuel processor. This system's efficiency is expressed as

$$\eta_{\text{system}} = \eta_{\text{stack}} \times \eta^{1}_{\substack{\text{power}\\ \text{converter}}} \times \eta^{2}_{\substack{\text{fuel}\\ \text{processor}}} \tag{5}$$

If the stack efficiency is taken as 42 percent, the fuel processor efficiency 85 percent, and the power conditioner efficiency 95 percent, the system efficiency is about 34 percent. This number does not take into account possible heat recovery. A comparison of the total fuel cell system efficiency with other power plants (Ref. 5) is given in Fig. 3. Figure 3 also indicates that fuel cells have a relatively constant heat rate (efficiency) versus load characteristics. Therefore, the fuel cell power plant offers greater economies than conventional power generation when utilized for load following or spinning reserve applications.

Other operational advantages of fuel cell systems include their nonpolluting quality and their dispersibility. The pollution levels from experimental fuel cell power plants are very low. Typically, nitrogen oxide emissions are of the order of 3 ppm, hydrocarbons 4 ppm, sulfur dioxide 0.1 ppm, as sketched in Fig. 4 (Refs. 6 and 7). In addition, fuel cells are noise and vibration free and require no auxiliary machinery except fuel pumps and cooling fans. Fuel cells do not offer economy of scale. Thus, one could build modular units which can be installed at distributed users' locations. This is in

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[1] Defined as the ratio of ac power/dc power since the fuel cell produces a dc voltage.

[2] Defined as the heating value of processed gaseous fuel/heating value of raw fuel.

contrast to conventional large power plants which require a central station together with electrical transmission lines. It is estimated that savings in transmission line losses are in the order of 5 to 9 percent.

III. Technical Problems of Fuel Cell Systems

The history of fuel cells dates back to 1842. Grove (Ref. 8) wrote of experiments with fuel cells in 1842, and practical devices were already sought in the 1880s (Ref. 9). Despite this early interest, and the more recent impetus given by the Apollo space program and by the increase in fossil fuel costs, fuel cells are still mostly in a "demonstration" stage. It appears that most of the work is being done by three companies: (1) United Technologies Corporation (UTC), Power Systems Division, South Windsor, Connecticut, (2) a consortium between Westinghouse Electric Corporation in Pittsburgh and Energy Research Corporation (ERC) in Danbury, Connecticut, and (3) Engelhard Minerals and Chemicals Corporation – Engelhard Industries Division in Menlo Park, New Jersey. Most of our discussion will reflect the opinions and experiences of these companies.

A. Fuels and Fuel Processing

The near-term technology of fuel processing in fuel cell systems uses petroleum-based fuels as the raw fuels to produce hydrogen-rich gas. The far-term technology will use coal or some sort of renewable resource such as biomass for H_2 generation. A schematic of the paths leading from raw fuels to processed fuels is shown in Fig. 5 (Ref. 10). Of the fuels shown in Fig. 5, the following types are discussed:

1. **Gaseous fuels.** The basic technology for steam-reforming of gaseous fuels, such as methane, is relatively mature. In the future, the important factor will be the design of fuel processors to use the stack-generated heat. For gaseous fuels, commercial catalysts (e.g., Pt) are readily available. ERC is doing exploratory studies of fuel processors for Molten Carbonate fuel cells. UTC and Westinghouse/ERC are working on the engineering development of fuel processors. The first application of UTC's fuel processor is likely to be at a 4.8 MW_e demonstrator plant being built for ConEd in New York City. A similar plant is also being built in Tokyo. Westinghouse/ERC is working on processors for dispersed systems, the so-called OS/IES (On-Site Integrated Energy System).

2. **Alcohol fuels.** The basic technology for processing alcohol-based fuels, such as methanol, is not as advanced as that for gaseous fuels. Between methanol and ethanol, it is likely that methanol processors will be built first. ERC plans to have methanol-fueled 2- to 10-kW power plants by 1982 (Ref. 11). Engelhard is also working in methanol processors initially for a 5-kW unit (Ref. 12). They base their work on the projected availability of methanol from coal by 1990.

3. **Hydrocarbon liquid fuels.** Mid-distillates and heavier hydrocarbon liquid fuels hold a promise mainly because of the availability of coal in the United States. Unfortunately, the technology for processing these liquids is not very well developed. The major problems associated with the processing of these fuels are thermal efficiency and prevention of carbon formation in the processor. Several processing schemes are being investigated at the bench scale level with support from DOE and EPRI.

Adiabatic steam reforming technology is being developed at UTC to process No. 2 fuel oil (a heavy liquid) and other coal-derived liquids (Ref. 13). In this reformer, air is added to the fuel and steam to provide, by combustion, the endothermic heat for reforming in the catalyst bed. The combustion of additional air is also necessary to raise the reactor to high temperature to compensate for deactivation of the catalyst by sulfur in the feed.

Similar reformers for processing heavy liquid fuels are being studied at Engelhard (Ref. 14). They have developed noble metal catalysts (Pt/Rh) which allow partial oxidation of the feed stock and its conversion to lower molecular weight hydrocarbons.

A high-temperature steam reforming called THR Process combined with autothermal reforming (ATR) step has been identified as one of the most promising technologies for processing of distillate fuels. The THR process is now under pilot plant development by Toyo Engineering Corporation, Japan. The ATR step, as part of the reformer train, is used to complete the reforming conversion of the fuel and, therefore, it is a key to achieving the high thermal efficiency. The processing of light hydrocarbon liquids, such as naphtha, are being developed by UTC, but limited, by their questionable availability. It is possible, however, that naptha will be tried at the 4.8 MW ConEd pilot plant.[3]

The conclusion for hydrocarbon liquids seems to be that by 1982, a decision will have to be reached whether to build a commercial demonstrator for the processing of these liquids (Ref. 10). If such a plant is going to be built, the completion or production date is envisioned to be around 1990. Until that time, natural gas based fuels, and possibly methanol, will be the feedstock of choice.

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[3] The cost of naphtha may be getting too high to run tests with it at the ConEd plant. Also, fire department mandated safety tests are making naphtha an expensive trial feedstock.

B. The Fuel Cell Power Section

1. **The electrodes and the catalyst.** Fuel cell electrodes are basically flat plates of some material throughout which catalyst crystals are dispersed. The electrode material is usually carbon, and the catalyst is usually platinum (Pt) in acid fuel cells. The role of the electrodes is to conduct and at the same time provide a solid support for the catalyst. Cathode corrosion has been, and still is, one of the operational problems. Corrosion of the catalyst support as well as recrystallization and dissolution of the high-surface-area platinum catalyst downgrade fuel cell performance. Electric Power Research Institute (EPRI) is funding contracts (the EPRI RP 1200 series) to develop new technology for better catalyst support (Ref. 15). Under one of these contracts, Stonehart Associates, Danbury, Connecticut, has found (Ref. 16) that the degree of corrosion can be correlated with lattice parameters and with the degree of graphitization. Acetylene Black, Shawinigan, and fluorinated phosphonated Vulcan show promise for good corrosion performance and manufacturability. There are very few published results that indicate the lifetime of electrodes in hours (Fig. 6) and it is difficult, therefore, to predict when commercial use electrodes will become available.

Catalyst performance depends on the dispersion and activity of the catalyst. It is desirable to have the catalyst crystallites dispersed at a certain distance from each other as this will maintain a high catalyst surface area. Furthermore, one must take into account that platinum has a certain solubility in acids depending on the electric potential and the operating temperature. Stonehart Associates (Ref. 16) has shown that catalyst crystallites initially at 100 m^2/g degrade to 20 m^2/g after 40,000 hours in phosphoric acid at 200° C and 0.7 volts. Note that the desired end-of-life surface area is taken to be 80 m^2/g.

It seems that Pt area loss depends upon initial Pt surface area and is unrelated to the surface energy of the crystallite. Tests at Engelhard (Ref. 12) show that a new catalyst (No. 11099-39) has little surface area decay after 2000 hours.[4] However, in general, attempts at solving crystallite migration in the phosphoric acid fuel cell environment have been only marginally successful (Ref. 17).

The activity of the catalyst in fuel cells is reduced by catalyst poisoning. At the anode, catalyst poisoning is due to the presence of carbon monoxide and sulfur traces in the fuel. Work at Lawrence Berkeley Laboratory indicates that Pt-V alloys have increased the activity and durability of the cathode. Similar claims for the Pt-Rh catalysts have been put forward at Engelhard (Ref. 14).

2. **The electrolyte.** Electrolyte problems are of two kinds. The electrolyte must be physically and chemically stable at the high temperatures used in fuel cells. Second, the electrolyte must not be lost during the cell's lifetime through flooding of the electrodes.

New and better electrolytes are continuously sought. In this area, ECO, Inc., Buzzards Bay, Massachusetts, has found two new very promising electrolytes: difluoromethanediphosphonic acid $[CF_2(PO_3H_2)_2]$ and difluoromethanedisulfonic acid $[DF_2(SO_3H)_2]$. Both appear to be very stable at high temperatures. The United States Army (MERADCOM, Ft. Belvoir, Virginia) is also sponsoring ERC research in aqueous solutions of trifluoromethanesulfonic acid as an electrolyte. Solid electrolyte research is being conducted at Westinghouse (Ref. 18), and at some national laboratories such as Brookhaven National Laboratory (Ref. 19) and the National Bureau of Standards (Ref. 20). All of these projects are in the early experimental stages.

Molten Carbonate fuel cells have been tested for a number of years and they appear promising as second generation fuel cells. An active research program in Molten Carbonate fuel cells is being pursued nationally with DOE funding (currently at about $12 million per year). The tasks of this program are to:

(1) Develop a reference coal-fueled power plant design.

(2) Develop fuel cell stack components and verify 10,000 hour life of single cells.

(3) Initiate development of full-scale stack testing capability.

(4) Determine tolerance to contaminates in coal-derived gas.

The bulk of this work is concentrated in two major long-term contracts with United Technologies Corporation (UTC) and General Electric Company (GE).

EPRI funding (currently at $3.5 million per year) is focused on power plant technology development at UTC (20 KW breadboard) and on advanced concepts at GE, ERC, UTC, and Institute of Gas Technology (IGT). The Gas Research Institute (GRI) funding (at $1 million per year) is directed at systems studies and experimental work in the area of cogeneration applications at UTC, IGT, and ERC. Niagara Mohawk (in New York state), ERDA, and the Tennessee Valley Authority (TVA) are supporting power plant technology development.

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[4] At the present time, about 10 percent Pt at 0.5 mg Pt/cm^2 represents the most desirable configuration.

If projected funding levels are maintained, mid-1982 appears to be a branch-point for the Molten Carbonate Fuel Cell Program. At that time, the major technology development contracts will be coming to a close. If the objectives have been accomplished and readiness to proceed with engineering development has been established, funding levels must be increased to support the more demanding tasks of full-scale stack testing and system integration. If the objectives of the current contracts are not met, the nature of the problems must then be determined and the program reevaluated and restructured as appropriate.

3. **Fuel cell stack performance.** The typical phosphoric acid fuel cell unit produces between 0.6 and 0.85 volts dc. A fuel cell stack consists of a number of unit cells arranged in series. For example, the 4.8 MW plant being built for ConEd in New York uses 20 stacks, in parallel, of about 500 cells each. The output power of such stacks is simply the sum of the outputs of the individuals. Therefore, overall stack performance can be established by looking at a single cell's performance characteristics.[5]

There are a number of indexes that show how well a cell performs. One of these indexes is a plot of cell voltage versus time. Such a graph totals all the losses that the cell suffers over a length of time. The losses appear as a decay in the cell's voltage. Figure 7 indicates the performance of cells from various manufacturers. Two observations can be drawn from this figure. First, some cells undergo a voltage decay after 5000 hours from the beginning of the test. Some published results indicate that progress is being made in limiting this voltage decay. As an example, for some UTC phosphoric acid cells the rate has been decreased from 60 mV per 1000 hours to approximately 12 mV per 1000 hours (Ref. 24). The second observation from Fig. 7 is the limited amount of time that these tests represent and the small number of cells that form the stacks. A notable exception is the ERC data where cell voltage shows practically no decay after almost 2 years of running. This improved performance is due to a new electrolyte matrix with better retention of the electrolyte. It is also possible that better data exists as manufacturers proprietary information.

An alternate way of looking at cell performance is to plot voltage versus current density. (Current density is a function of Pt loading, Ref. 25.) Such a plot gives an idea of the power that can be obtained per cell unit area. Figure 8 shows such a graph, representing tests from various manufacturers.

Cell performance can be improved by increases in both temperature and pressure. In both cases, this is due to an increased reaction rate. It is typical of the engineering problems of fuel cells that an attempt to optimize one parameter may cause an adverse effect in another. For example, while a temperature increase will improve the reaction rate, it will also cause an increase in the decay rates. Furthermore, "from the overall power plant standpoint, the optimum pressure and temperature depend not only on stack technology and development, but also on the cost and performance implications upon the balance of the system (turbocompressors, heat exchangers, piping, etc.)" (Ref. 24).

Molten Carbonate fuel cell development at ERC (Ref. 26) has focused on improving cell and stack technology in the areas of component stability, material compatibility, fabrication techniques, operating power density, sulfur tolerance, and lightweight stack design. Test results have showed no performance loss for a fuel gas containing up to 15 ppm H_2S for a total test duration of 400 hours. A significant advance has been made in stack design and performance during the past 2 years. The latest stack, assembled with four 300 cm^2 cells, was successfully operated for 1000 hours including a thermal cycle. The improvements made in the stack design are due to different stack components such as gas manifolds, seals, and bipolar plates. The stack was operated for 1000 hours with stable performance. A theoretical open circuit voltage of 1.03 volts per cell was attained, indicating no crossleaks. Efficiencies of 94 to 96 percent were achieved for anode and cathode gases, respectively; average cell potential of 0.75 volt per cell at 100 mA/cm^2 was obtained. The stack operation also included a thermal cycle at about 400 hours.

At IGT (Ref. 27), bench-scale cell testing was conducted to evaluate new materials and components for performance and endurance at 1 to 10 atm operating pressure. Performance testing at pressures about 1 atm continues to show gains twice as large as those predicted by Nernst.[6] One of the reasons for the larger gains is that the effective cell resistance decreases with increasing pressure. Two bench-scale cells attained 10,000 hours of continuous operation, the last 2,300 hours on a low-Btu coal gasification fuel. Decay rates were approximately 9 to 10 mV/1000 hours, 60 percent due to increase in measured internal resistance.

Electrolyte powders containing alkali carbonates and $LiAlO_2$ support particles are prepared by the potassium-free

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[5] This point is illustrated in Ref. 2 where a simple formula is given for the efficiency of the overall power plant (from fuel processor to AC current). This formula is $N_p = 59\ V_c$ "where N_p is the efficiency of the plant, as a percent, and V_c is the voltage of a single cell. This relation is accurate to within 5 percent and illustrates the importance of single-cell voltage in establishing the overall efficiency of a plant."

[6] The Nernst potential relates the equilibrium cell voltage to the partial pressures of the gases.

aqueous slurry process. The K_2CO_3 required in the final electrolyte composition is added after the carbonation step. The final characteristics of the $LiAlO_2$ support are established in the firing step (600° to 700°C). Electrolyte tiles hot-pressed from such powders yield high cell performance levels. Decay rates of 9 to 10 mV/1000 hours observed in bench-scale cells operated for 8,000 to 10,000 hours without carbonate additions are influenced significantly by loss of surface area and phase change in $LiAlO_2$ and electrolyte loss. Progress in tile thermal cycling response has been achieved by improving tile mechanical properties, reduction of tile thermal expansion coefficients, and fabrication and cell design modifications.

Promising results were obtained on the processing of powders by spray drying. Development of this process is continuing. The advantages of spray drying include easier and more efficient processing, high production rate, and more homogeneous powder product. Tiles fabricated from spray-dried powders have more uniform microstructures and higher strength. Preparation of $LiAlO_2$ without carbonates, adaptable to alternative tile fabrication techniques, has also been demonstrated by spray drying.

The stack tests at UTC (Ref. 28) have been with cells of 1 square foot (0.093 m^2) total area containing 8 to 20 cells per stack. The primary feature of the stack was a temperature cyclible tile configuration that had proven successful in bench-scale size cells. During the initial 2000-hour time period, the stack was subjected to five thermal cycles. The reactant gas leakage was acceptable and remained essentially unchanged through the thermal cycles. The 20-cell stack was subsequently rebuilt into a 16-cell stack, which accumulated an additional 650 hours of testing. The rebuild was undertaken to determine whether Molten Carbonate stacks could be refurbished after removing poorer performing cells. This is considered to be a significant advantage in reducing cost and minimizing time in a fuel cell stack development program. The leakage was unchanged. However, all of the cell internal resistance increased; those of the replacement cells being the highest. It was concluded that the increased IR was caused during the rebuilding by disruption of the cathode current collector contact area with the separator plate which resulted in high contact losses. Planned changes to component design may alleviate this problem.

IV. System Economics

The fuel cell powerplant system is still in the research and development stage. Many of the characteristics such as capital cost, operation and maintenance (O & M) requirements and costs, availability, etc., have not been established. A reliable economic analysis cannot be done until the power plant technology has been further demonstrated. Installed costs for the fuel cell power plant including manufacture, supplied equipment, and site ancilliaries in a range of $350 to $750 kW in 1978 dollars were suggested by DOE. Costs of annual O & M have ranges of 1.8 to 4.0 mills/kWh and 4.4 to 10.0 mills/kWh with the capacities of 88.1 and 30 percent, respectively, as estimated by UTC (Ref. 29).

To make the fuel cell power plants commercially attractive depends in a large part on the financial support that either the manufacturer and/or the government are willing to give the user. This support can take the form of either the government underwriting the cost of the initial units and/or the manufacturer taking the "risk of underwriting the learning curve" from present day prices to the target figure. Among the various uncertainties of the national fuel cell program, what stands out clearly is a price of $\$1500/kW_e$ in 1980 dollars that a potential user must be willing to spend *today* for a fuel cell power plant (Ref. 30).

Spurred by the current shortage in petroleum-based fuels, the fuel costs in the future is unpredictable. Figure 9 (Ref. 31) represents these costs in a somewhat conservative projection. Fuel cell systems available in the near future, most likely, are natural gas-fueled phosphoric acid cells. Hence, a 40 kWh_e[7] plant with a heat rate of 9918 kJ/kWh_e will consume about 255 cubic meters per day of natural gas. For an isolated site such as the Goldstone complex, the transportation and the storage of natural gas could be more complicated than that of diesel fuels.

Similarly, it is extremely difficult to establish the cost benefits of cogeneration. Most of the analyses in the literature refer to the 4.8 MW UTC-designed unit. This is similar to the one to be used by ConEd in New York City and it is to be noted that this unit was not designed with cogeneration in mind.[8] We limit ourselves to quoting from Criner and Steitz (Ref. 32):

> "Faced with a variety of uncertainties in the input parameters, an economic study must examine the sensitivity of results over the range of reasonable uncertainty in the variables. However, beyond the range of such sensitivity results, it usually is not possible to make definite conclusions regarding the economic viability of

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[7] A 40 kW unit is chosen as an example partly because there exists a national program to install demonstrator 40 kW units at different facilities throughout the country.

[8] Two types of thermal energy could be generated by such a unit: "High quality" meaning saturated steam at 241 kPa and "low quality" meaning heated water at 34° C. With natural gas as a fuel, this unit can produce 9.28 GJ/h "high-quality" heat and 110 GJ/h "low quality" heat (Ref. 29).

fuel cell cogeneration (or other types of advanced cogeneration).

It appears, then, that the ultimate question of economic viability must be resolved through installation of a significant number of cogeneration fuel cells to establish actual costs and performance. With such experience, advanced fuel cell designs potentially could achieve significant commercial penetration for industrial cogeneration applications in the pulp and paper industry."

V. Conclusions

One of the objectives of this study is to find what can be predicted about the future commercialization of fuel cells. In the literature on fuel cells, there is a considerable optimism regarding their future. This optimism emanates from manufacturers, from utility groups, and from contract monitoring agencies.[9] DOE has a "Phosphoric Acid National Fuel Cell Plan" which is currently being coordinated by other funding agencies such as EPRI, GRI, TVA, etc. This plan is as follows (Ref. 33):

Electric Utility Power Plants	Year
First power plant delivery	1984 (UTC), 1986 (W/ERC)
Design phase concluded	1984–1985
Field testing	1986–1987
OS/IES Systems	
Breadboard testing	1982 (UTC)
Field testing	1985

Figure 10 presents the "history" of predictions for fuel cell plants under this plan. The basic conclusion, from this figure, is that past predictions have been too optimistic. For example, in 1975, UTC predicted that the first commercial electrical utility plants will be delivered in 1977 to 1978. In 1980, the prediction is that these units will appear in 1987 to 1988.

Furthermore, the delay between the time of prediction and the predicted event has grown. Thus, in 1975, the event was predicted for 2 to 3 years from that time (1977 to 1978); by 1980 the delay had grown to 7 to 8 years, with predicted dates of 1987 to 1988. A similar history exists for OS/IES systems and for the 4.8 MW_e demonstrator plant of ConEd.[10]

In the previous sections we have discussed the progress being made in solving the technological problems of fuel cells. We wish to stress that all these results refer to laboratory devices only. At the present time, no demonstrator models are in operation. The first such demonstrator devices (i.e., fuel cell systems working in a real life environment) will be the ConEd and Tokyo plants. The testing programs for these demonstrators are expected to last between 4 and 5 years.

It is unlikely that industry will move into commercial production of fuel cells until the demonstrator units are proven. Furthermore, the industry is still waiting for market acceptability of fuel cells. It is at this point that the relationship among government, manufacturers, and utilities becomes a rather complicated one. Both manufacturers and DOE agree on the need for government support for the demonstrator plants; the disagreement is on the amount of this support.

Partly because of this disagreement the schedule for the demonstrator plants keeps slipping. For example, the latest schedule for the ConEd plant is a checkout of the reformer in late spring of 1981, with the plant scheduled to be operational in July 1981. For the Tokyo plant, the schedule is for the equipment to arrive in Japan before September 1981 and for the operational start to occur in February 1982 (Ref. 43).

Similar funding problems exist in the 40 kW_e demonstration program (Ref. 44). This program provides that about fifty 40 kW_e UTC units will be distributed at various sites around the country in order to monitor and better understand the performance of these units. Sites have already been selected, most of them belonging to the utilities. However, no units for this program have been built yet. This still awaits funding negotiations between DOE, GRI, and UTC.

From the open literature cited and from personal communications held with members of the fuel cell community, we estimate that commercial fuel cell systems will not be available before 1990, with a probable range 1985 to 1992. This conclusion is based on funding difficulties, on lack of market support and, last but not least, on remaining technological difficulties. We wish to stress again that at the present time no commercial or demonstrator systems are operational. All present cost estimates, e.g. \$350 to \$400 (1978)/kW (Ref. 45), are based on the future commercial availability of ConEd type systems.

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[9] NASA Lewis is the lead center for the DOE fuel cell program. The Marshall Space Center is monitoring the 40-kW program.

[10] In July 1980, the predictions for the start up of the ConEd plant were for April 1981. By September 1980, the predictions had been postponed to July 1981.

We were not able to obtain any costs per installed kW for the smaller OS/IES systems.

We close this article by suggesting the following topics for further study:

(1) Size and obtain specifications for a 40 kW system to be installed at Goldstone. This phase should include not only the design of the fuel cell stack, but also include detailed information regarding the fuel availability at Goldstone, the fuel processor, and the inverter. Potential cogeneration should also be studied.

(2) Obtain from the manufacturers 1982 cost estimates for a system such as that described above.

Both the 40 kW size and the 1982 time frame are arbitrarily set. Regardless, it would be very useful to have a thorough preliminary design and cost estimate for potential use at Goldstone.

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Table 1. Electrochemical reaction of some fuel cells

	Molten carbonate cell	Solid oxide cell	Phosphoric acid cell	Alkaline cell
Anode	$H_2 + CO_3^{=} \rightarrow H_2O + CO_2 + 2e^-$	$H_2 + O^{=} \rightarrow H_2O + 2e^-$	$H_2 \rightarrow 2H^+ + 2e^-$	$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$
Cathode	$\frac{1}{2} O_2 + CO_2 + 2e^- \rightarrow CO_3^{=}$	$\frac{1}{2} O_2 + 2e^- \rightarrow O^{=}$	$\frac{1}{2} O_2 + 2H^- + 2e^- \rightarrow H_2O$	$\frac{1}{2} O_2 + H_2O + 2e^- \rightarrow 20H^-$
Overall	$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$ + Heat + Electricity	$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$ + Heat + Electricity	$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$ + Heat + Electricity	$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$ + Heat + Electricity

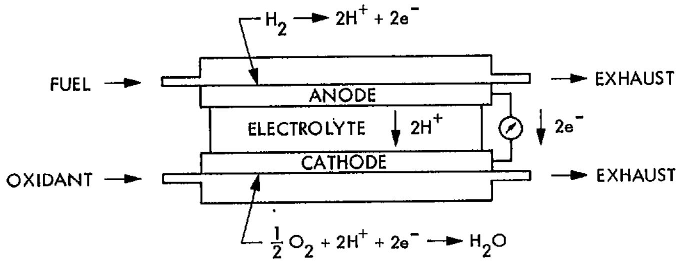

Fig. 1. Operation of acid fuel cell

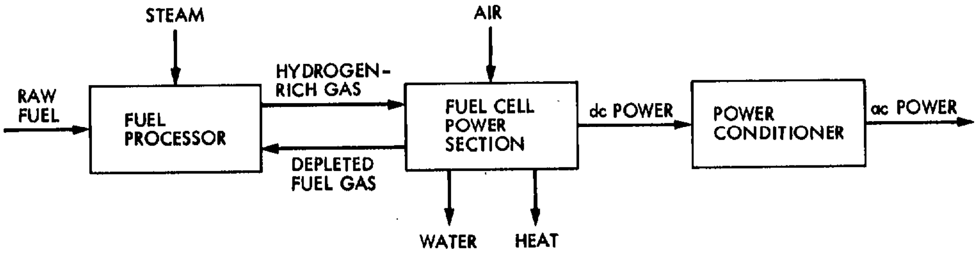

Fig. 2. Fuel cell power plant elements

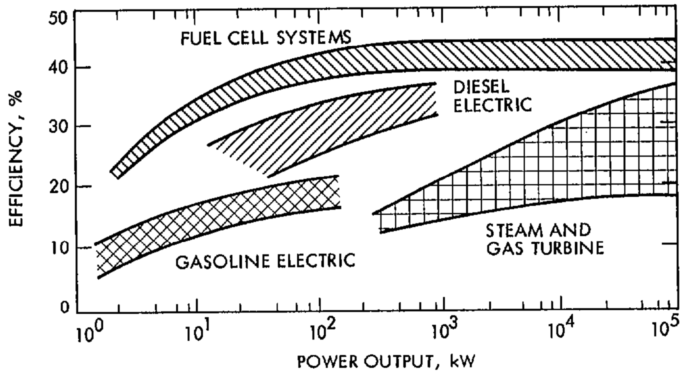

Fig. 3. Efficiency of power generation systems

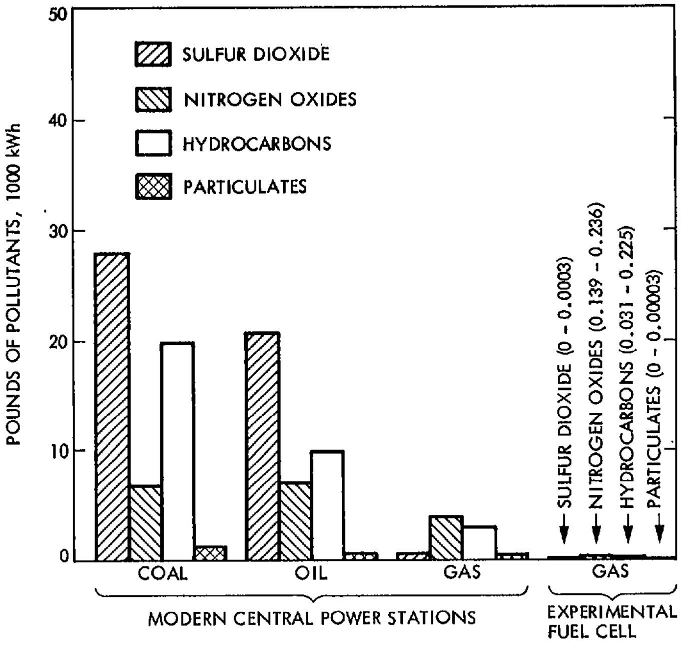

Fig. 4. Pollutants from power generation systems

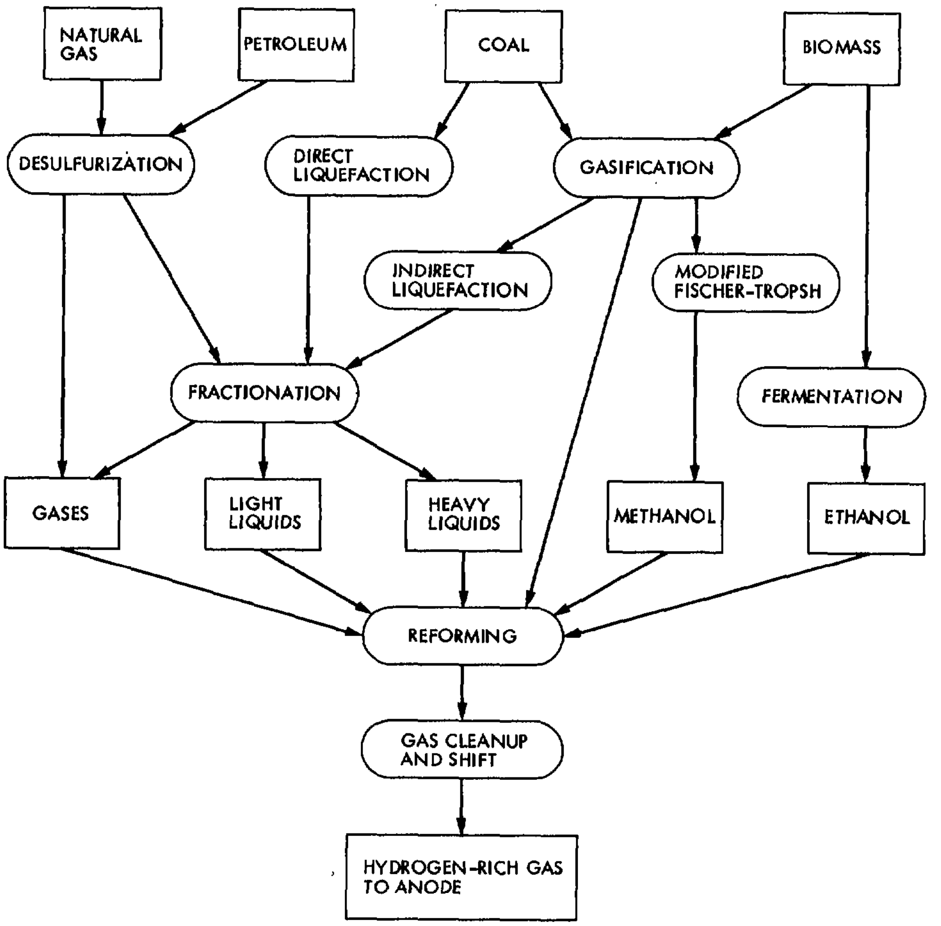

Fig. 5. Raw fuels for fuel cell application

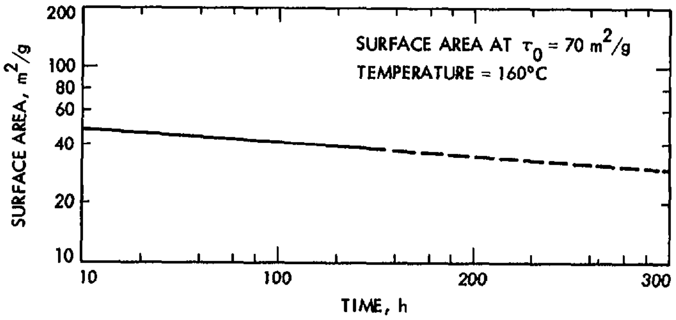

Fig. 6. Platinum surface area reduction on carbon substrate

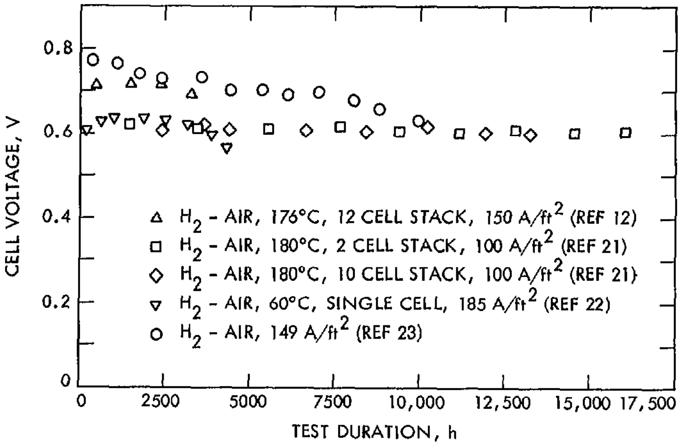

Fig. 7. Fuel cell stack endurance

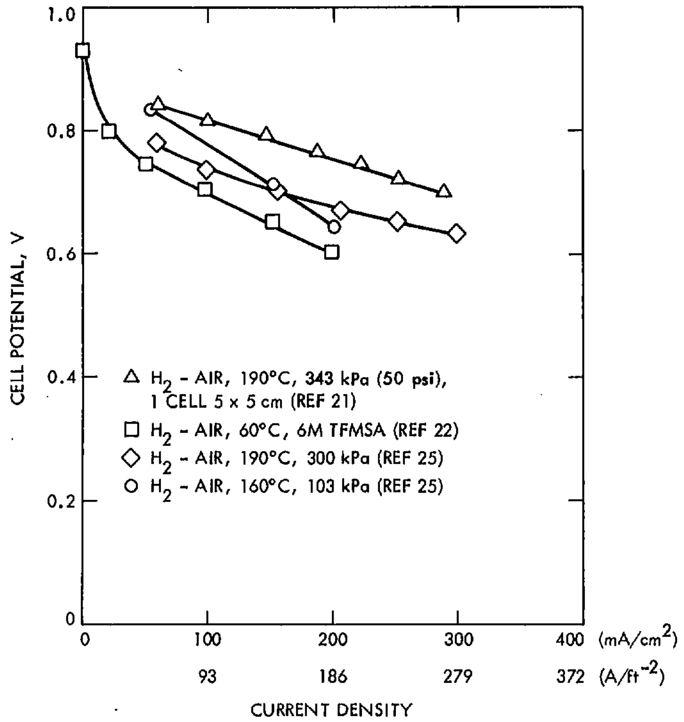

Fig. 8. Fuel cell performance

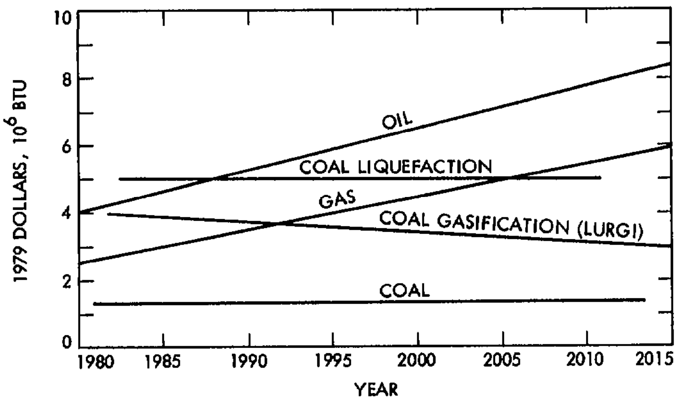

Fig. 9. Fuel costs projection

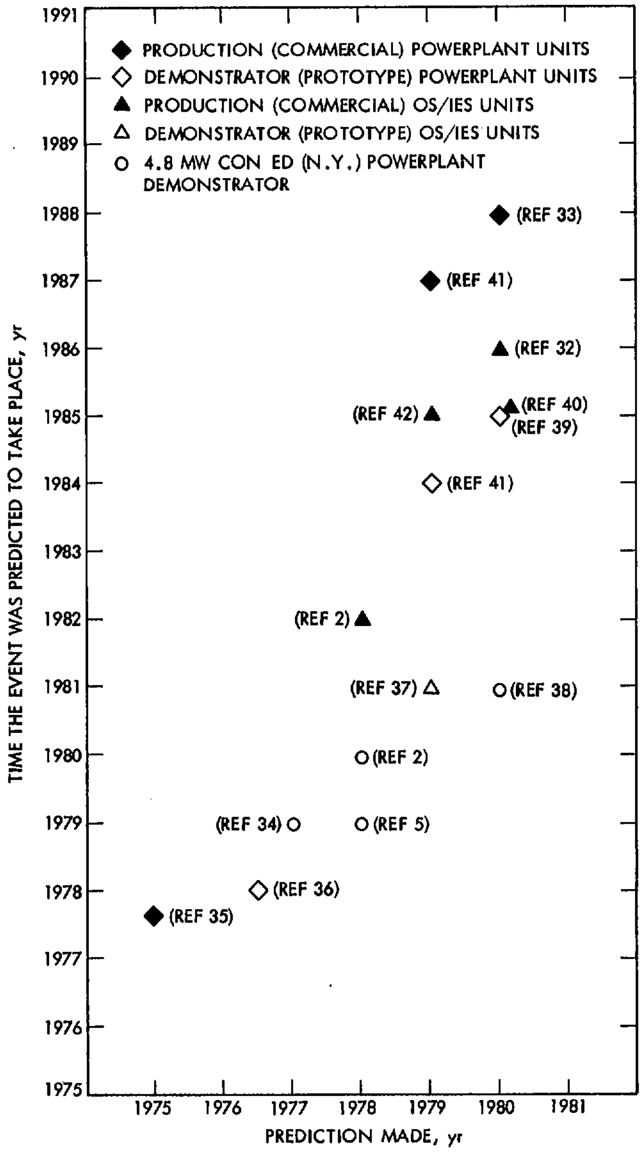

Fig. 10. Fuel cell development prediction history