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THE STATUS OF FUEL CELL TECHNOLOGY

by
John B. O'Sullivan

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Innovations in Natural Gas Technology**

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**INSTITUTE OF GAS TECHNOLOGY
3424 South State Street Chicago Illinois 60616**

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THE STATUS OF FUEL CELL TECHNOLOGY

by

John B. O'Sullivan
Institute of Gas Technology

During the late 50's and early 60's, many of the major U.S. industrial companies invested heavily in fuel cell technology. The potential of this direct, non-Carnot-limited energy conversion process to provide efficient, inexpensive electricity encouraged research in many fuel cell systems. These efforts emphasized systems based on alkaline, phosphoric acid, solid polymer, solid oxide, and molten carbonate electrolytes. Operating temperatures for these systems range from 100° to 1000°C. An extremely large investment by the military and NASA permitted the accelerated and successful development and utilization of the polymer- and alkaline-based power systems for use in space exploration. These successful space power developments, however, were not suitable for most terrestrial applications using hydrocarbon fuels.

During the early 70's a reduction in government funding coupled with economic pressure on the research budgets of industrial firms caused most companies to withdraw from the area. Military funding, primarily by the Army, and funding by the electric and gas industries permitted the slow but continued growth of phosphoric acid technology. Molten carbonate and solid oxide technology were funded at only a subsistence level. With the formation in the mid-70's of the Energy Research and Development Administration -- eventually the Department of Energy (DOE) -- a major infusion of funding resulted in a broader range of technology development.

The combination of DOE, Gas Research Institute (GRI), and Electric Power Research Institute (EPRI) funding enabled the field demonstration of phosphoric acid systems at the 40-kW and 4.8-MW sizes. It also permitted accelerated research in the solutions of problems associated with the molten carbonate and solid oxide electrolyte-based systems. These systems, operating at 650° and 1000°C, respectively, have the further advantage of providing for cogeneration. The temperature level of the waste heat stream permits its use to either generate more electricity by a bottoming cycle, increase efficiency, or raise high-quality process steam.

Phosphoric acid fuel cell technology has now become commercial via the initial purchase of approximately 50 200-kW onsite power systems by the gas industry worldwide. The current emphasis of DOE, GRI, and EPRI is to bring about the demonstration and commercialization of molten carbonate and solid oxide technology. To this end, contracts for the production and operation of fuel cell stacks are under way to validate technical performance and the economics of manufacture.

Research efforts are continuing, but at a much lower funding level, to examine alternative fuel cell systems, such as proton conducting and other oxide ion conducting electrolytes. There has also been a renewed interest in polymer electrolyte membrane systems, especially for electric vehicle applications.

As a result of the recent technical successes shown by these programs, the fuel cell research programs of Europe and, especially, Japan have been renewed after being essentially dormant for almost 20 years. Although this presentation emphasizes the ongoing efforts in the United States, to provide a proper perspective the national programs of Japan and the active European countries will be addressed briefly.

THE STATUS OF FUEL CELL TECHNOLOGY

Introduction

This brief status report provides an introduction to what fuel cells are, why they are important, what uses have been made of them to date, the goals and timetables of current programs, and who the players are in this vital technology. Copies of most of the slides presented and additional diagrams are appended to this paper. Further details can be obtained from the comprehensive texts cited in the bibliography.

Fuel cells are a means of converting chemical energy directly into electrical energy without going through the typical combustion engine-rotating generator steps. They are electrochemical devices, similar to batteries, except that the fuel and oxidant are provided externally; thus they are not dependent, for capacity, on the stored chemical energy as are batteries. Fuel cells were invented initially by Sir William Grove in 1839, and the period of current development was started by Francis T. Bacon in England in 1932. Bacon's early fuel cells used a concentrated aqueous alkali hydroxide (200°C) as the electrolyte.

Fuel cells are typically classified based on the nature of electrolyte utilized and the temperature of operation. Common electrolytes used in developmental systems over the last 35 years are alkaline, acidic (phosphoric acid and polymer exchange membranes), molten carbonate, and oxide ion-conducting materials. Some electrolytes are liquid and some are solid at the operating temperature. These temperatures range from about 100°C to as high as 1000°C, depending on the system.

Conceptually, fuel cells have no moving parts and thus do not "wear out" or create noise. In reality, some moving parts -- fans, compressors, pumps, etc. -- are required for an operating system, and each fuel cell type has its own unique failure modes. Fuel cells are low-voltage, high-current devices; therefore, many cells must be aligned in series to produce useful d-c voltages that must in turn be converted to a-c power for most applications. Being electrochemical devices, their major inefficiencies, resistive and polarization losses, occur at higher current densities, and thus their efficiency at

partial load is typically greater than at full load. This is the exact opposite of engine-driven systems whose efficiency drops sharply at reduced load.

Since practical systems are based on the assemblage of cells into cell stacks to yield practical voltages, these stacks may be configured into various series-parallel combinations to attain a final installed system voltage and power output. It is this inherent modularity that also serves as an attractive feature. One can install an initial system to satisfy the electrical capacity needs at that time and may then "grow" the system according to future demands without concern for efficiency of scale and premature commitment of capital. Typically, a utility or industrial firm will procure a larger generating capacity than needed because it will be more efficient than a smaller unit. However, the additional capital invested will not provide a return until some uncertain time in the future when the demand eventually reaches the installed capacity. This commitment to excess capacity is becoming more and more difficult for industry to make in the face of a rapidly changing, and thus uncertain, marketplace.

Fuel cell systems have one unfortunate characteristic, which is not inherent but is a practical reality in all present developmental systems: They cannot utilize hydrocarbon fuels directly. The dominant electrochemically active fuel species is hydrogen. Thus the fuel must be converted, usually by an external reformer, into hydrogen and carbon monoxide prior to conversion in the fuel cell. Higher temperature fuel cells can utilize carbon monoxide directly but slowly, so, in reality, the carbon monoxide is converted internally to hydrogen by the rapid water-gas shift reaction and thus is utilized indirectly through the hydrogen intermediate. Extensive research has been devoted to the direct utilization of fuels such as methanol, methane, and the lighter hydrocarbons, but the rates of conversion have been too low for the practical production of useful power levels.

Early developmental efforts focused on the lower temperature systems because it was believed that the problems concerning catalysis and materials of construction were more tractable than those inherent in the high-temperature systems. Currently, major emphasis is on the higher temperature systems

because the waste heat is rejected at temperatures sufficient for use either in a combined cycle or for cogeneration. Each of these nets out a much higher overall efficiency of fuel utilization. The materials of construction and other life-limiting problems and methods for economic fabrication are now felt to be resolvable, yielding an economically viable alternative to combustion-driven systems such as gas turbines, steam turbines, and combined cycles.

The remainder of this paper briefly details past efforts but concentrates on current developmental systems, their characteristics and advantages, and their likely entrance into the marketplace.

Space and Defense Programs

Although early fuel cell developments were concerned with the efficient production of power in general, the major funding efforts focused this development on systems targeted for space and defense applications. These applications had their own unique needs and system and economic constraints that permitted the development of systems that were not directly translatable into terrestrial systems. Thus, although these development efforts provided great insight into general fuel cell system problems and places to look for possible limitations in other systems, only part of that effort has been useful in the successful development of systems for economically practical terrestrial applications.

NASA programs for manned spacecraft required power and energy levels that were not attainable with either batteries or combustion engines using stored reactants. The Gemini series utilized a system based on a polymer electrolyte membrane (duPont-Nafion) fueled by hydrogen and oxygen, which were stored cryogenically. The materials of construction were expensive, and the electrodes needed high-platinum loadings for the optimal system power levels. Overall weight efficiency and reliability were the dominant constraints, and costs were only a minor consideration. In the competition for the Apollo Program power modules, General Electric, which built Gemini, lost out to United Technologies Corp. (UTC). The UTC system was based on the higher temperature alkaline electrolyte demonstrated by Bacon in England. This fuel cell's higher power density yielded a lighter overall system that was appropriate for the high energy needs of an eventual lunar landing. A backup

contract was also awarded to Allis-Chalmers to develop a system based on the use of a lower temperature aqueous alkali hydroxide. Both of these systems required hydrogen as fuel and utilized oxygen, both stored cryogenically. As a footnote for understanding later system emphasis, alkaline electrolytes will be neutralized by reaction with the carbon dioxide in air and especially in the product of a hydrocarbon reformer. Therefore, most terrestrial applications would require, at a minimum, the separation or removal of the carbon dioxide during the use of hydrocarbon fuels, a major cost and system complication that has prevented terrestrial use of alkaline systems for other than special (military) applications. Alkaline systems, with evolutionary development, have remained dominant in both NASA and military space applications and are in use in the Shuttle Program.

Early military programs, attempting to piggyback on the NASA developments, utilized alkaline electrolytes as well. Since cryogenic fuel/oxidant storage was cumbersome, military applications, such as submarines, torpedoes, undersea vehicles, and terrestrial mobile power sources, used either pressurized hydrogen or special fuels such as hydrazine (N_2H_4) with either pressurized oxygen or atmospheric air, as appropriate. The bulk of European developments followed a similar path at that time. Later developments for land-based -- not undersea -- power sources recognized the need to utilize common hydrocarbon fuels for any major penetration into military usage. These fuel cell developments, of necessity, shifted to CO_2 -rejecting electrolytes: solid polymers, sulfuric acid, phosphoric acid, molten carbonate, and others. Of these, the major emphasis finally settled on phosphoric acid fuel cells (PAFC), which by that time had been selected as the fuel cell system for early market implementation by the U.S. utilities. This program is covered in more detail in a following section.

The U.S. Army funded the building of developmental prototypes of the phosphoric acid system (3 kW and 5 kW) by Energy Research Corp. (ERC) and pre-production prototypes (1.5 kW) by UTC. These were complete systems and included reformers and inverters for a-c power. As a result of the complexity of fuel processors designed to handle sulfur-containing military fuels (for example, diesel and JP-4) methanol was selected as the fuel for a silent lightweight electric power source. The Army program terminated in about 1984

as a result of the Army's unwillingness to handle in quantity, logistically, a special fuel such as methanol. This extremely cursory overview does not cover the many experimental systems built and tested by the military over a 25-year period and is only used to illustrate the status of the program at its termination.

Utility Programs

In the early 60's the U.S. gas utility industry became concerned and threatened by the projected inexpensive electricity ("too cheap to meter") from nuclear reactors and the all-electric home. As a result, a major commercialization program was funded by the American Gas Association (A.G.A.) at UTC with supporting work at the Institute of Gas Technology (IGT). This program, TARGET (Team to Advance Research on Gas Energy Transformation), selected phosphoric acid-based technology for the design and construction of 12.5-kW d-c (10-kW a-c) demonstration units. These were to serve as the power generation module in an all-gas home, single or multifamily. While UTC emphasized the initial market entry unit, IGT continued R&D on molten carbonate-based systems for later and/or other applications. The TARGET program produced a field demonstration of 60 experimental units from 1971 to 1974. These were installed in commercial and residential sites across the U.S. The resulting economic evaluation indicated that those units were too small and technologically immature to yield the necessary production base and to permit a cost-effective market entry.

Shortly after the gas industry started its program, the electric utilities became concerned with their future as a result of increased emphasis on, and expense for, control of emissions from coal-based plants and the rise in cost, complexity of siting requirements, and extensive procedural delays in nuclear installations. Fuel cells, operating on reformed natural gas or naphtha, were viewed as having the greatest potential for providing future generating capacity. The electric utility program funded by the industry, and eventually the Electric Power Research Institute (EPRI), was also awarded to UTC. This program similarly emphasized phosphoric acid as the market entry technology. Molten carbonate systems combined with coal gasifiers were viewed as a longer term solution.

Following the successful demonstration of a 4.5-MW a-c unit (20 stacks) at Tokyo Electric Power and the aborted test of a similar unit at Consolidated Edison in New York, the electric industry was solicited for a commercialization venture to buy a number of 11-MW units (18 stacks). The aborted test in New York had nothing to do with the technology and a lot to do with both bad luck and the unreasonable regulatory procedures of the New York Fire Department. Because the widespread implementation of cogeneration and independent power production, along with conservation, had sapped much of the projected industry growth, the high cost of the market entry units was deemed excessive for the immediate market in the U.S. One 11-MW unit was purchased by TEPCO and some smaller units were purchased in Europe so that some countries could become familiar with the technology. Italy, for example, purchased a 1-MW demonstration unit.

The second phase of the gas industry program emphasized scale-up to 40-kW a-c to broaden application to commercial/industrial sites that could utilize some cogeneration in the form of hot water. This phase was funded by the industry and the Gas Research Institute (GRI) and resulted in a field demonstration of 46 units from 1984 through 1986. Following this successful demonstration, the gas industry was solicited by the International Fuel Cell Corp. (joint venture of UTC and Toshiba) to join in commercialization through the purchase of 200-kW units. Commitments were made, worldwide, for over 50 units; the initial units will be delivered and installed in late 1991 or early 1992. The market entry price is around \$2500/kW, with the price dropping as the production base increases in the future.

When these utility programs were initiated, the utilities were the sole funding source. After the creation of the Energy Research and Development Administration (ERDA) and subsequently the Department of Energy (DOE), the government played a major role in funding the development and demonstration of the utility units. The DOE is also funding a competitive electric utility program at Westinghouse, which is planned to eventually commercialize a 3 to 13-MW a-c, air-cooled, phosphoric acid system. This program is proceeding at this time and has demonstrated its current technologic maturity with a 100-kW single-module stack. Fabrication of a 375 to 400-kW four-stack engineering module has begun.

DOE, GRI, and EPRI have also been increasing their funding of advanced systems, both molten carbonate and solid oxide, during the last 10 years; these programs are discussed in a later section.

Current Programs -- Vehicular

Numerous prototype fuel cell-powered vehicles -- vans, trucks, forklifts, and others -- have been built by many developers and potential users. However, the first serious, and therefore significant, attempt to commercialize a vehicle, a forklift truck, was the effort initially of Engelhard Minerals and Chemicals and later in a joint venture with Fuji Electric. This vehicle utilized phosphoric acid technology and comprised a 5-kW fuel cell in a hybrid configuration with lead-acid batteries. Fuel cells have a high energy density, whereas batteries have a high power density; thus batteries will supply the additional power required above some average demand, and the fuel cells will supply excess energy to recharge the batteries at lower loads. The lift truck can also operate, although not as effectively, on the batteries while the fuel cells are being brought up to temperature during startup. Engelhard has recently gone out of fuel cell development, and Fuji is focused on transit buses as the vehicle of choice.

DOE has two transit bus programs: one with Booz-Allen and Fuji and the other with ERC. Both of these use phosphoric acid fuel cells and are designed in a hybrid configuration with batteries. Each program has built and operated a fuel cell system at about the 30-kW level. The test bed bus, which will have a 50-kW fuel cell power plant fueled by reformed methanol, will lead to eventual commercial prototypes. Recently, DOE awarded a multimillion dollar, multiyear contract to General Motors (GM) to develop a fuel cell-powered vehicle. The development team includes Los Alamos National Lab (methanol reformer), Ballard Power Systems, Inc. (polymer electrolyte membrane fuel cell), and Dow Chemical (advanced polymer membranes). The selection of the prototype vehicle(s) and its design variations is under way.

The thrust of all of these programs is an efficient, low-emissions urban vehicle to reduce the air-quality problems endemic to the major cities. Ballard Power Systems, Inc., a Canadian firm, also has a fuel cell bus program funded by its government. This vehicle's power source is not a hybrid and

relies solely on the fuel cell to provide the high current demands of the start-stop transit duty cycle.

Current Programs -- Power Generation

High-temperature fuel cells (>500°C) are viewed as the technical successors to phosphoric acid technology (<200°C) for power production and cogeneration. These applications can efficiently utilize the high-temperature exhaust streams for fuel processing, high-pressure steam generation, or bottoming cycles. The leading candidates are fuel cells based on solid oxide (1000°C) or molten carbonate (650°C) electrolytes.

Molten Carbonate Technology

The three major developers of molten carbonate fuel cell (MCFC) technology in the United States are the M-C Power Corp./Institute of Gas Technology (MCP/IGT) team, ERC, and IFC. The latter two are emphasizing externally manifolded cell stacks, whereas the MCP/IGT team has a unique internally manifolded design based, conceptually, on plate frame heat exchangers (IMHEX®). This "manifolding" refers to the means by which cell reactants, fuel and oxidant, are introduced into and exhausted from the cell stack. All three developers have DOE-funded programs, with the emphasis on commercialization at MCP/IGT and ERC and on technology development at IFC. Both MCP/IGT and ERC also have coordinated programs with EPRI, GRI, and various gas and electric utility participants. All three developers utilize flat-plate cell designs and metallic bipolar separator plates. Tape casting is the manufacturing method of choice for electrodes and electrolyte cell components. Other approaches, calendaring, hot pressing, and electrophoretic deposition, have been examined by the developers and found wanting. All three developers have assembled and tested cell stacks with varying cell areas and number of cells in series. The largest stack of each developer to date has been 1 ft², 24 cells, 2.5 kW (MCP/IGT); 4 ft², 20 cells, 8 kW (ERC); and 8 ft², 20 cells, ~15 kW (IFC).

Stacks planned for the near-term are a 60-cell, 20-kW stack at ERC and a 60-cell, 6-kW stack at MCP. All developers plan for commercial cell sizes in the range of 6 to 10 ft² in 250 to 500-cell stack modules. EPC has the endorse-

ment of the American Public Power Association for a 2-MW demonstration at the city of Santa Clara, California, and will build a 2 ft by 3 ft, 200+-cell stack module as part of this program. A 100-kW stack is also planned by ERC for testing by Pacific Gas and Electric. Both ERC and MCP/IGT will eventually build 250-kW commercial prototype stacks as part of the DOE program. MCP will be producing about eight small (1 ft²) and about six large (10 ft²) stacks for DOE, EPRI, GRI, and the utility partners during 1991 and 1992. These will include at least three complete systems at the 20 to 50-kW size. This testing will culminate in the 250-kW DOE power plant, cited previously, in late 1993, followed by a more advanced 250-kW power plant for San Diego Gas and Electric in late 1994. Following field tests of pre-production prototypes, market entry commercial production is planned for mid-1997. The market entry systems will be based on natural gas (cogeneration and dispersed power) with later, mature-production systems using the product of coal gasification (central station power).

The major design departure is based on external (ERC and IFC) versus internal (MCP/IGT) manifolding. Both of these designs have advantages and disadvantages; The MCP/IGT team believes that the advantages of co-flow or counter-current reactant flow and the self-adjustment to dimensional tolerances and vertical changes in the stack with time outweigh the additional complexity of separator plate design. External manifolds provide for cross-flow only, and the insulating gasket required to electrically isolate the manifold serves as a path for the electro-osmotic pumping of electrolyte that floods the cells at one end of the stack at the expense of drying the cells at the other end.

The major developmental issues that need to be resolved are cathode dissolution during operation at pressure; electrolyte management to control loss through evaporation; management of reactant gas crossover from anode to cathode, or vice-versa; methods of thermal management; efficiency of seals; long-term changes in cell components (physically and/or chemically); and tolerance to contaminants (primarily with coal-derived fuels).

There are three approaches to processing natural gas for molten carbonate fuel cells: an external reformer, a thermally integrated reformer, and internal reforming of the fuel in the anode passages. The first requires the use of

supplementary fuel to supply the endothermic reaction needs. The second utilizes the waste heat of the stack and thus eliminates the need for added fuel while reducing the amount of cooling required. This approach would position a reformer package between every 5 to 6 cells in the stack. The third approach, direct internal reforming, is the most efficient and the most difficult. It places the heat-absorbing reaction where it is needed within each cell. The electrochemical utilization of the hydrogen, produced by reforming, and the associated generation of water vapor, one of the reactants, drives the reaction rapidly and efficiently. However, it is difficult to maintain the long-term activity of the reforming catalyst in the presence of the reactive electrolyte, which wets all surfaces within the cell. All of the developers are examining all three approaches. MCP will utilize, initially, an economic and efficient flat-plate reformer in early systems, and ERC is planning to use direct internal reforming in its prototype stacks.

Analyses performed for EPRI have reached similar conclusions regarding coal gasification and its process integration into the MCFC system. The more the waste heat can be utilized directly within the fuel cell system and the less to drive bottoming cycles, the higher the overall net system efficiency.

Solid Oxide Technology

Like molten carbonate technology, solid oxide fuel cells (SOFC) have been under development for more than 25 years. However, it has been only in recent years, since the DOE shifted its emphasis from near-term phosphoric acid to longer term higher temperature systems, that adequate and continuous funding has been available to provide for rapid technologic advances. Westinghouse has maintained a continuous program, as the major developer, and has emphasized a tubular cell configuration as its basic design. This design has undergone evolutionary changes to accommodate new approaches to manufacturing techniques and series parallel cell stack configurations. Other developers, with other cell design concepts, have recently entered the competition. Ceramtec, ZTEK, and IGT have planar configurations, and Allied-Signal Aerospace is developing the monolithic design concept of Argonne National Laboratories.

All of these designs require utilization of very thin components because electrolyte resistance is relatively high, even at 1000°C. Problems involving the need for stable and compatible materials would be simpler to solve at lower temperatures, but adequately conductive alternative electrolytes have not been discovered. Obtaining an electronically conductive material, stable in both oxidizing and reducing conditions, for use as a cell interconnect has been a particularly challenging problem. Present developers use magnesium-doped lanthanum chromite as an interconnect, strontium-doped lanthanum manganite for the cathode, and yttria-stabilized zirconia for the electrolyte. These utilize expensive constituents, and thus the amount should be minimized. Appropriate manufacturing methods that satisfy these constraints are flame/plasma spraying, slurry coating, and various vapor deposition techniques. Westinghouse has built and tested series/parallel cell stacks (144 cells) at the 3 kW-output level. Emphasis has been on producing longer, and therefore higher output, cells. Most work has been with 14-inch-long cells, but progress through 20-inch to 1-meter cells has proceeded with 2-meter cells as the target. A 20-kW unit with 20-inch cells was put on test by Westinghouse for DOE in November 1990, and a 25-kW unit, with appropriate modifications, is scheduled for a Kansai Electric field test in the third quarter of 1991. A 100-kW unit, planned for delivery to DOE in 1992, will incorporate 1-meter-long cells. This should increase the output from around 20 watts/cell to about 100 watts/cell. This is in contrast to molten carbonate technology, which is designing cells exceeding 1000 watts.

Monolithic technology, if successful, should provide for higher output in a more compact design. Problems in matching coefficients of expansion, manifold and sealing designs, etc., are much further from resolution in the less mature planar and monolithic designs. Thus, SOFC technology holds the promise of trading off the problems of MCFC for a different set, which those developers hope will be more solvable.

Economic production of either SOFC or MCFC systems will depend heavily on the establishment of manufacturing techniques that provide reproducibility, quality control, and adequately low reject rates. These values will be established only through the production of a sufficient quantity of cells in semi-works facilities. This problem may be more severe for SOFCs, in the tubular

design, because of the greater number of cells required. Both planar and monolithic designs are at too early a development stage for any realistic comment on manufacturability.

Other Electrolytes

Research is continuing, at the basic level, to find solid electrolytes that will adequately conduct either oxide ions or protons at temperatures lower than 600°C. This would allow use of metallic components and reduce problems of compatibility and stability while still rejecting heat at an appropriate level to attain high overall system efficiencies. Recent literature, both U.S. and foreign, cites the results of many experimental efforts in this area. It is beyond the scope of this review to detail these ongoing developments; two references are in the Bibliography.

International Developments

Twenty years ago there were major fuel cell efforts in Europe. Most of these focused on alkaline technology for mainly military applications. As the U.S. emphasis shifted to phosphoric acid for terrestrial applications, the European program all but evaporated. Some efforts continued at the academic level in universities and industrial labs, but few system developments continued. Japan also had relatively little research under way. This has since changed dramatically.

Japan

With the oil shocks of 1974 and 1979, the Japanese government began intensive energy research programs, projects Sunshine and Moonlight, which had fuel cell components. As a result, over the last decade the Japanese have rapidly assimilated the current status of the U.S. technology and, with major government funding, forged ahead on their own. Japan is now the major funder of fuel cell technology with an annual budget of about \$120 million dollars. This is in contrast to the U.S. effort of around \$40 million dollars. All the technologies emphasized in the U.S. -- PAFC, MCFC, and SOFC -- have system developers in Japan. Many of these Japanese industrial firms have either joint or cooperative ventures with U.S. firms or are equity partners. They

are not only developers but also major purchasers of field test units and market entry commercial units from U.S. firms.

Europe

Along with this emphasis in the Pacific Rim has come a major, widespread renewed interest in Europe. Although their developmental budgets are small in comparison to the U.S. and Japan, most of the major industrial countries have ongoing research and evaluation programs. To accelerate their knowledge and understanding of the state-of-the-art in fuel cell technology, they are investing in technology transfer efforts and procuring prototype units for testing and evaluation. It is expected that the funding levels will increase rapidly as these countries become more comfortable with the technologies and their national programs are structured, with priorities, and put in place. Goals and schedules drive the level of funding required.

The Bibliography cites a particularly good survey (item 6) of the status and interrelationships of the foreign efforts in Japan, Europe, and other countries.

BIBLIOGRAPHY

1. Appleby, A. J. and Foulkes, F. R., Fuel Cell Handbook. New York: Van Nostrand Reinhold, 1989.
2. Kinoshita, K. et al., Fuel Cells: A Handbook. DOE/METC Contract: DE-AC03-76SF00098, (1988) May.
3. George, T. J. and Mayfield, M. J., "Fuel Cells Technology," Status Report to the United States Department of Energy, DOE/METC 90/0268 (1990) November.
4. Romano, S., "The DOE/DOT Fuel Cell Bus Program and Its Application to Transit Missions," in Proceedings of the 25th IECEC, 3, 293, 1990.
5. Swarr, T. E. et al., "Enhanced Ceria -- A Low Temperature SOFC Electrolyte," in Proceedings of the 25th IECEC, 3, 256, 1990.
6. Hirschenhofer, J. H., "Latest International Activities in Fuel Cells," in Proceedings of the 25th IECEC, 3, 176, 1990.
7. Hagey, G., "The National Fuel Cell R&D Program and U.S. Markets for Fuel Cell Systems," in Proceedings of the 25th IECEC, 3, 159, 1990.
8. Goldstein, R. H., "Electric Power Research Institute 1990 Fuel Cell Status," in Proceedings of the 25th IECEC 3, 170, 1990.
9. Benjamin, T. G. et al., "Handbook of Fuel Cell Performance," prepared by the Institute of Gas Technology for the United States Department of Energy under Contract No. EC-77-C-03-1545, May 1980.
10. Jewulski, J. J. et al., "Solid-State Proton Conductors," prepared by the Institute of Gas Technology for the United States Department of Energy under Contract No. DE-AC21-88MC24218, December 1990.
11. "Fuel Cells: A Bibliography," United States Department of Energy/Morgantown Energy Technology Center and Office of Scientific and Technical Information, Compilers, DOE/METC 88-6091 (1988) May.

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APPENDIX. Slides Presented and Other Illustrations

THE STATUS OF FUEL CELL TECHNOLOGY

by

John B. O'Sullivan

Institute of Gas Technology

Chicago, Illinois

WHAT ARE FUEL CELLS?

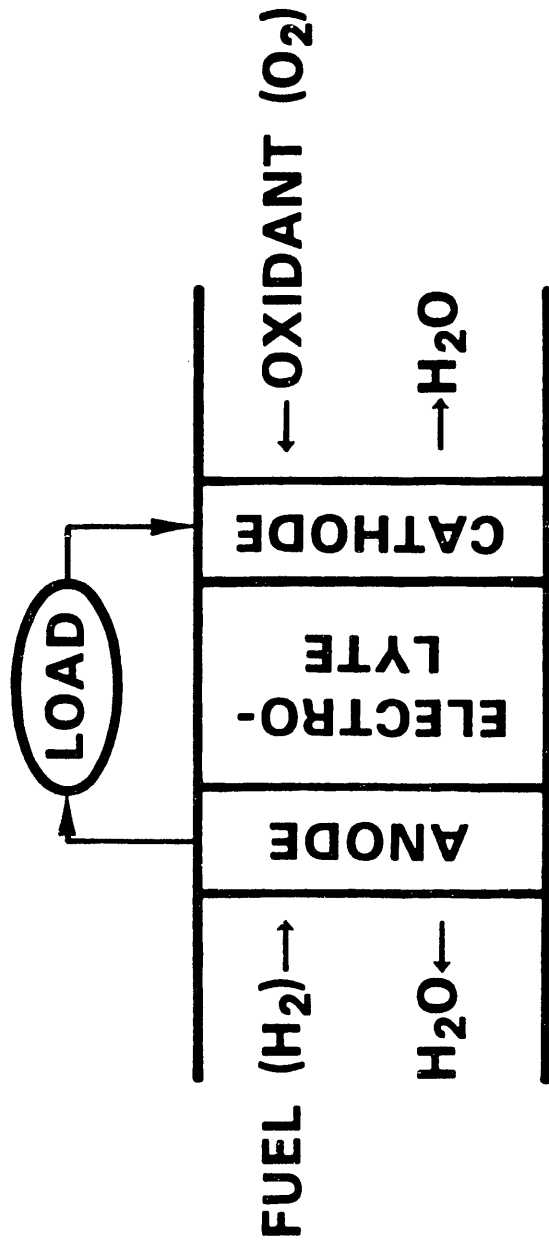
- **THEY ARE DIRECT ENERGY CONVERSION DEVICES.**
- **THEY CONVERT CHEMICAL ENERGY TO ELECTRICITY.**
- **THEY ARE CAPABLE OF CONTINUOUS OPERATION.**
- **THEY ARE NOT CARNOT-CYCLE LIMITED.**
(Efficiency is not related to operating temperature.)

HOW DO FUEL CELLS WORK?

ELECTROLYSIS:



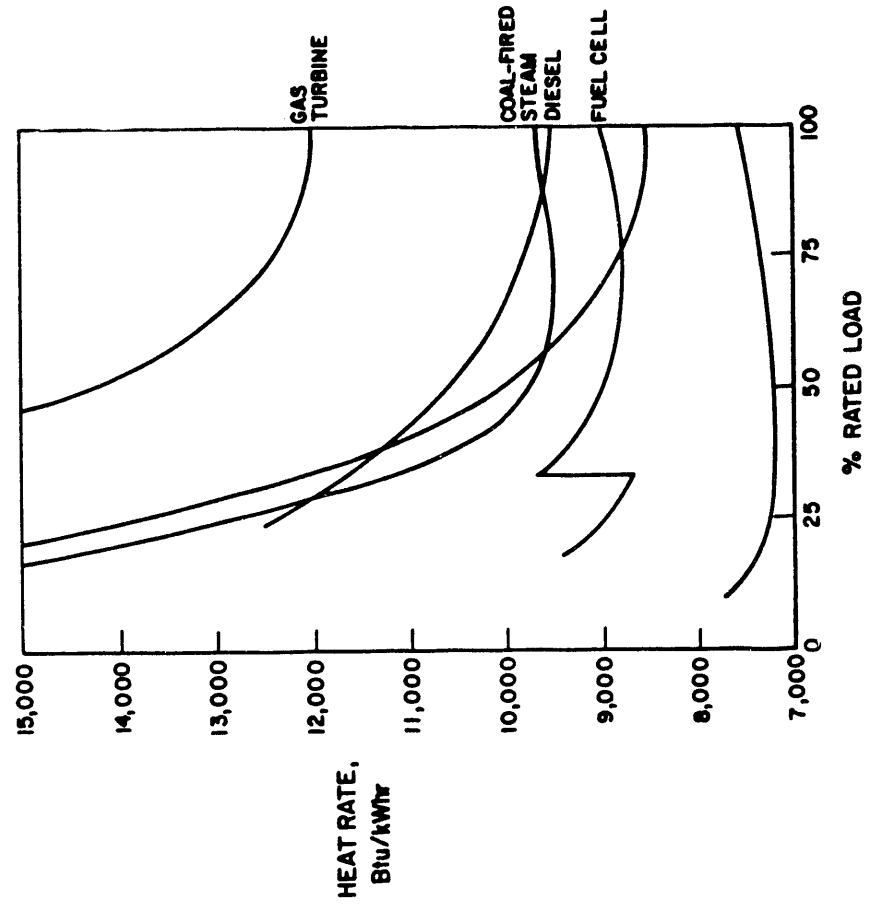
FUEL CELL:



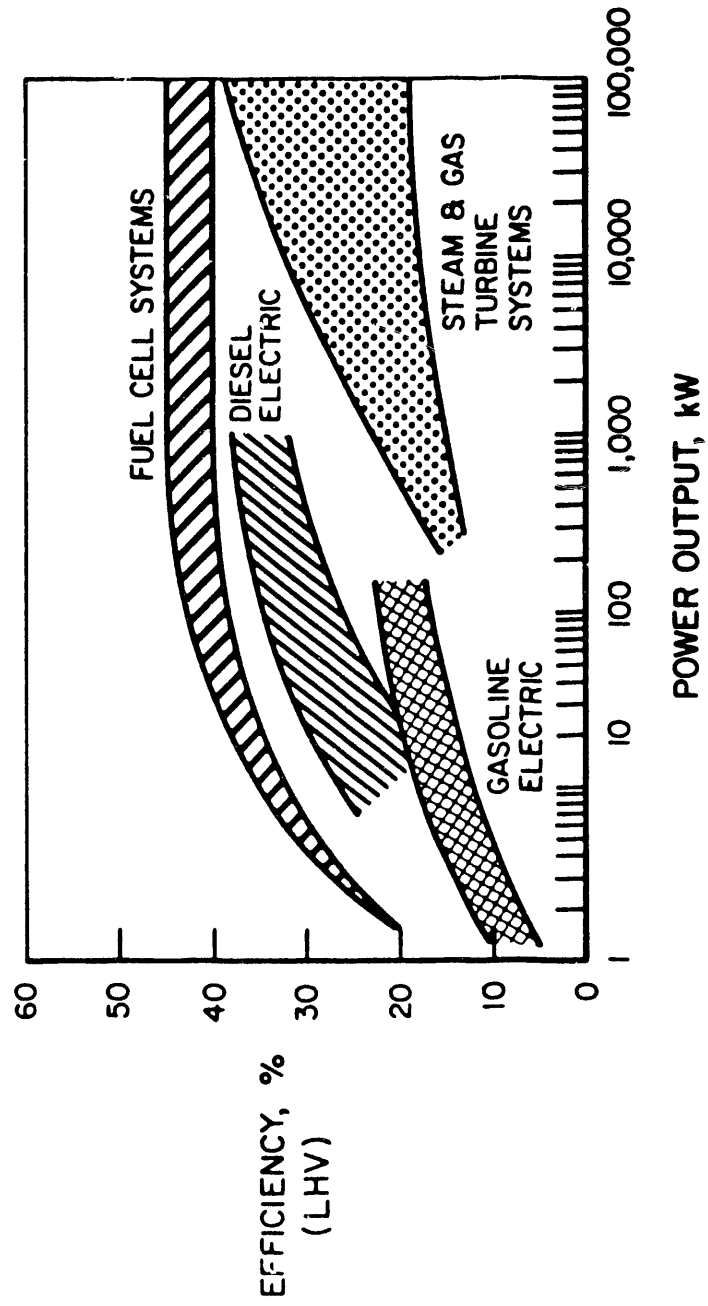
WHY FUEL CELLS?

- **HIGH EFFICIENCY**
- **HIGHER EFFICIENCY AT PART LOAD**
- **“NO MOVING PARTS”**
 - **QUIET**
 - **LONG LIFE**
- **MODULAR BUILDING BLOCKS**
- **SITING FLEXIBILITY**
- **ENVIRONMENTALLY CLEAN**

COMPARISON OF POWER SYSTEM EFFICIENCIES
(From "Fuel-Cell Power Plants" by A.P. Fickett.
Copyright December 1978, by Scientific American, inc. All Rights Reserved.)



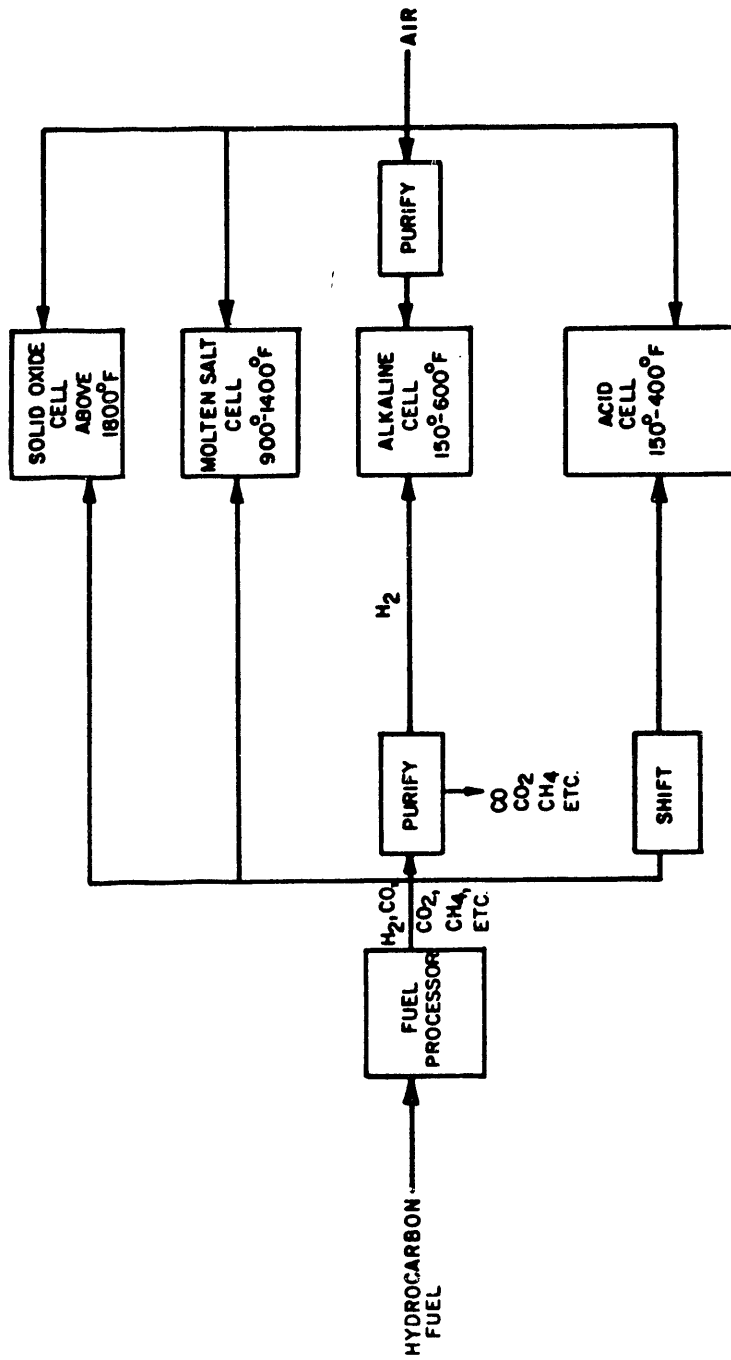
POWER SYSTEM EFFICIENCY COMPARISON AS A FUNCTION OF SIZE



FUEL CELL APPLICATIONS

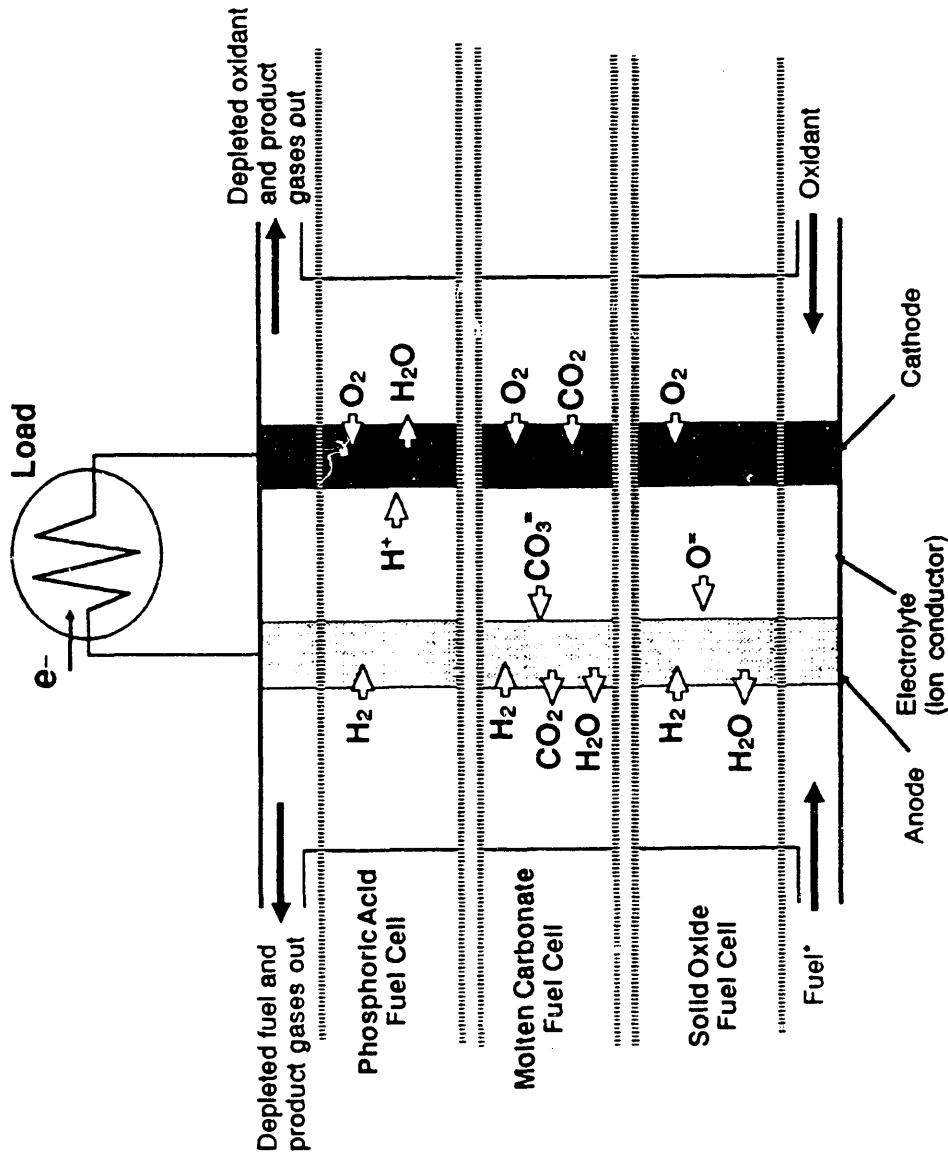
- **Multifamily Dwellings**
- **Commercial Buildings**
- **Single-Family Homes**
- **Electric Utility**
 - **Central**
 - **Dispersed**
- **Vehicles**
 - **Space Flight**
 - **Ground Transportation**
- **Military Uses**
- **Energy Storage Systems**

FUEL CELL TYPES



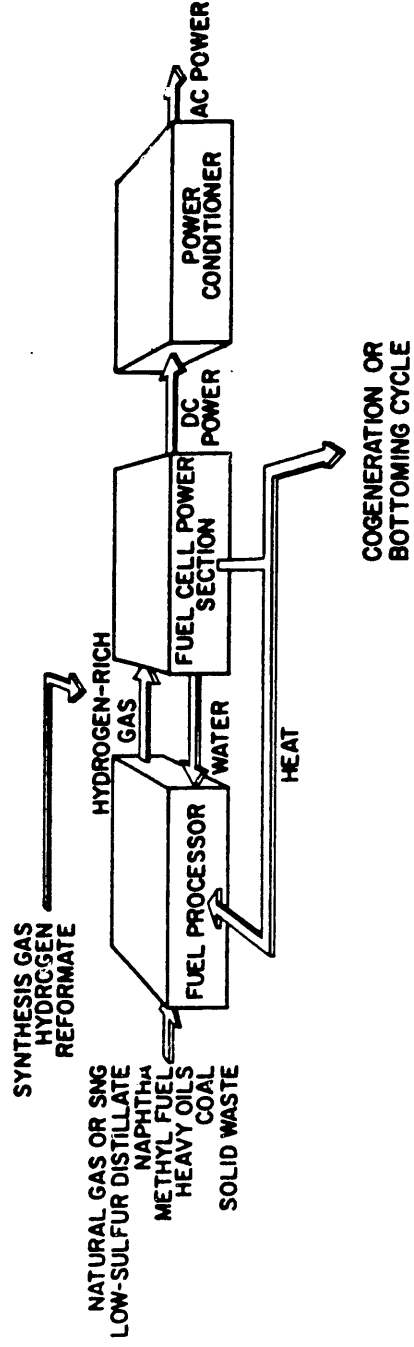
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REPRESENTATIONS OF THREE TYPES OF FUEL CELLS



- In the solid oxide and molten carbonate fuel cells, carbon monoxide in the fuel stream is also typically utilized as fuel.

COMPLETE FUEL CELL POWER PLANT

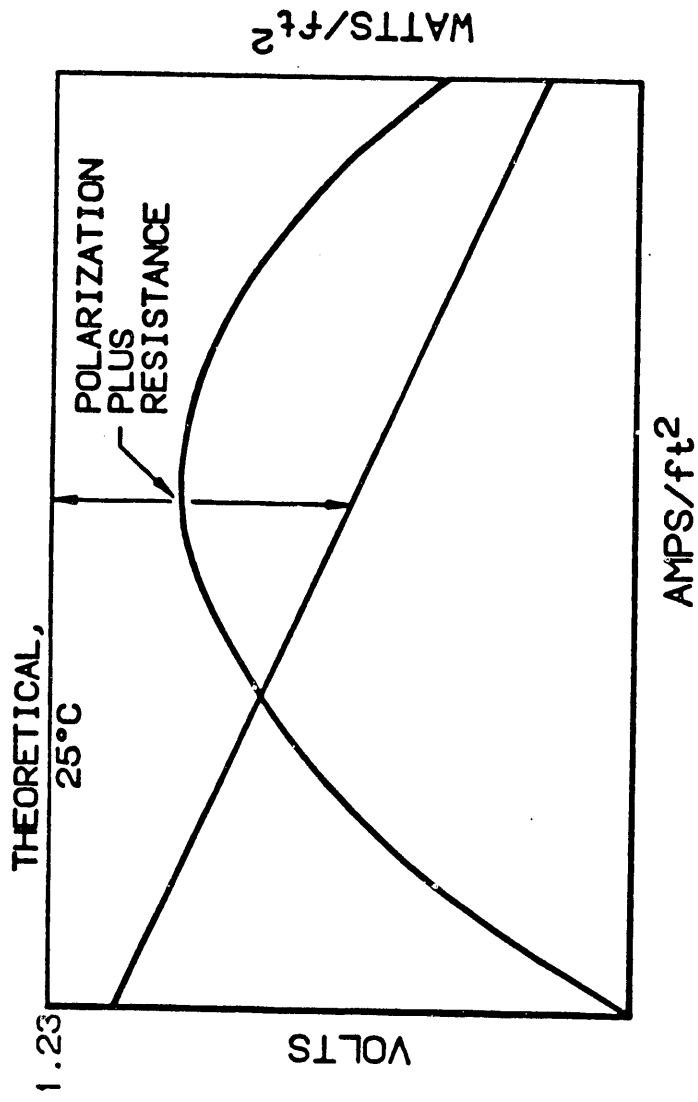


A79051244

PROBLEMS: NOT COMMON TO ALL

- **NEED FOR EXPENSIVE CATALYSTS**
- **MATERIAL CHANGES IN CHEMICAL ENVIRONMENT**
- **CORROSION OF MATERIALS**
- **MATERIAL LOSSES**
- **REQUIRE "PURE" FUELS**
- **PRODUCE d-c ELECTRICITY**

PERFORMANCE OPTIMIZATION:



OPTIMIZING VARIABLES:

- PRESSURE
- TEMPERATURE
- CURRENT DENSITY
- FUEL/AIR UTILIZATION

BRIEF FUEL CELL HISTORY

- **Space Program**
 - **Solid Polymer Electrolyte: 1965-1985**
 - **Alkaline Electrolyte: 1968-Present**
- **Terrestrial**
 - **Phosphoric Acid: 1971-Present**
 - Power Generation: 12.5 kW, 40 kW, 4.5 MW**
 - Portable Power: 1.5, 3, and 5-kW systems**
 - Vehicular: 1-5 kW**

PHOSPHORIC ACID

PLANAR DESIGN, EXTERNAL MANIFOLD

	<u>Cooling</u>
International Fuel Cells	Phase Change (H₂O)
200 kW	
11 MW	
Westinghouse	Air
7.5 MW	

VEHICULAR FUEL CELL SYSTEMS

TRANSIT BUS; 60 kW

Phosphoric Acid

Energy Research Corporation

Fuji Electric

GENERAL APPLICATIONS

**Polymer Electrolyte
Membrane**

General Motors/Ballard Corporation

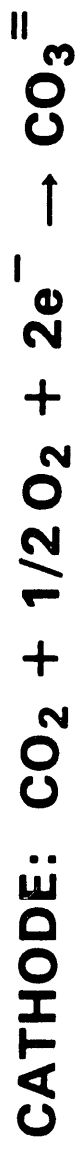
MCFC – ADVANTAGES

- **High Cell Efficiency**
- **CO Utilized (indirect)**
- **No Precious Metal Catalysts**
- **Waste Heat at Useful Temperature**
- **Capable of Scale-Up to Large Sizes**
- **Demonstrated Manufacturing Techniques**

MCFC – DISADVANTAGES

- **Chemically Active Electrolyte**
- **Liquid Electrolyte**
- **Must Be ≥ 25 Kilowatts**
- **Large Thermal Inertia**
- **Intolerant of H₂S and CO**
- **Shock/Vibration Sensitive**
- **Thermal Cycle Sensitive**

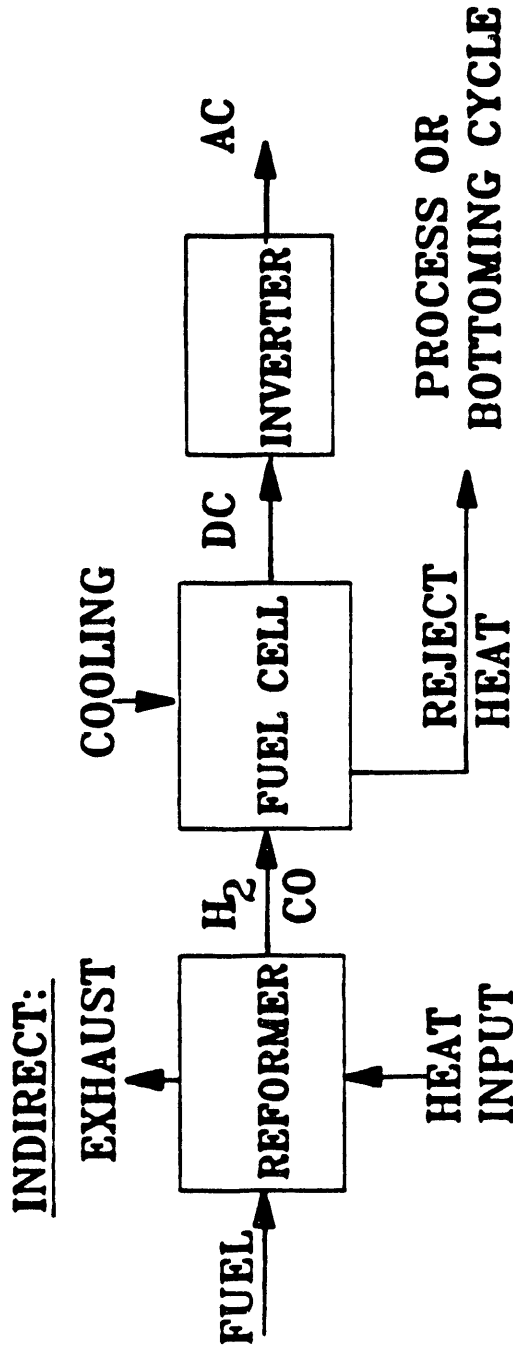
**MOLTEN CARBONATE FUEL
CELL REACTIONS**



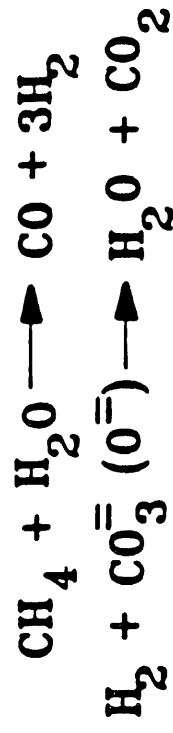
AND



FUEL PROCESSING



DIRECT:



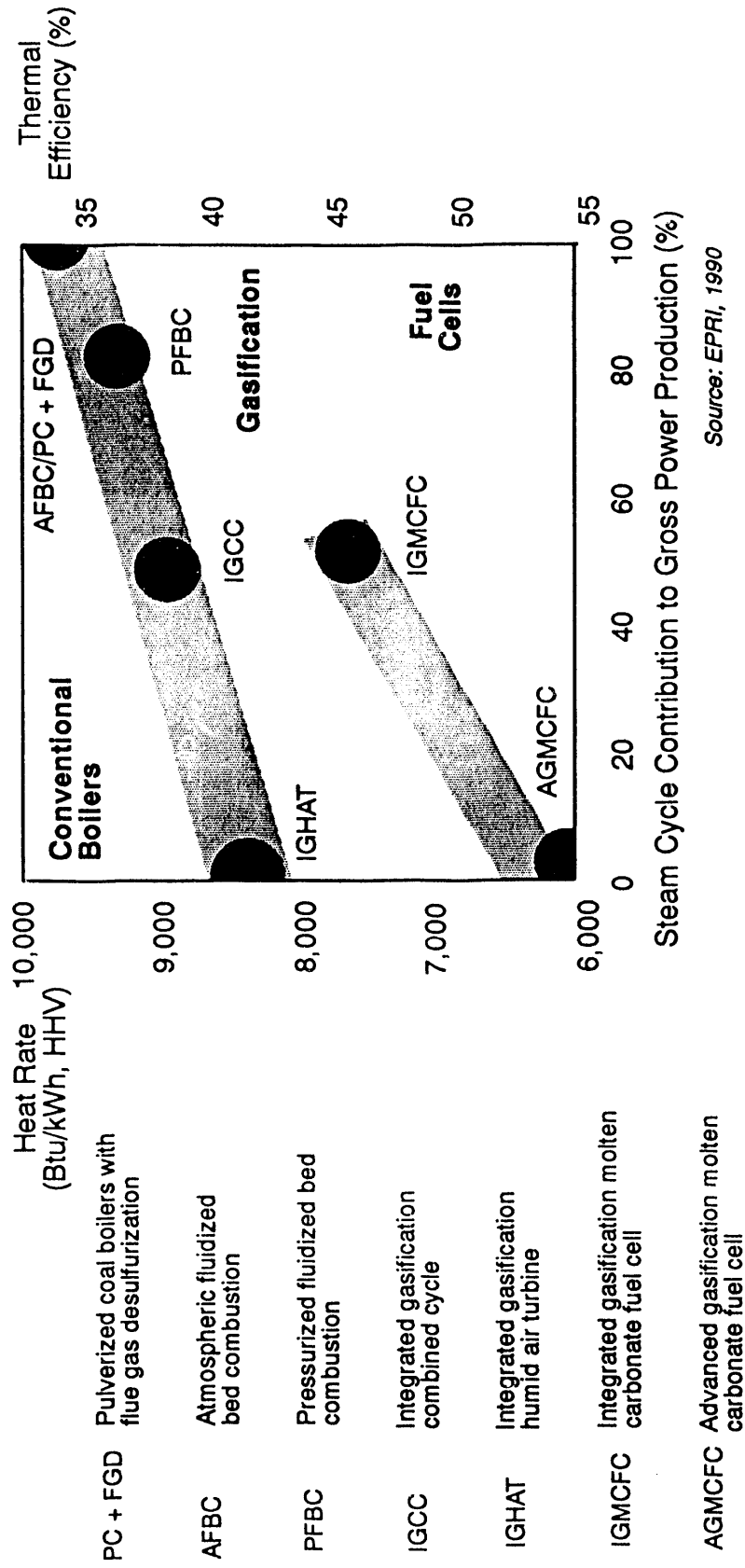
- Eliminate Reformer
- Increase Efficiency
- Reduce Cooling Load

**CARBONATE FUEL CELL
PLANT EFFICIENCY**

<u>FUEL</u>	<u>CYCLE</u>	<u>EFFICIENCY</u>
COAL*	NO	37%
NATURAL GAS	NO	45%
COAL*	YES	47%
NATURAL GAS	YES	60%
NATURAL GAS (Internal Reforming)	NO	60+%

*** COAL CONVERSION EFFICIENCY = 78%.**

COAL-FIRED POWER CYCLES



Heat Rate 10,000
(Btu/kWh, HHV)

- PC + FGD Pulverized coal boilers with flue gas desulfurization
- AFBC Atmospheric fluidized bed combustion
- PFBC Pressurized fluidized bed combustion
- IGCC Integrated gasification combined cycle
- IGHAT Integrated gasification humid air turbine
- IGMFC Integrated gasification molten carbonate fuel cell
- AGMFC Advanced gasification molten carbonate fuel cell

MOLTEN CARBONATE PLANAR DESIGN

Internal Manifold: M-C Power Inc./Institute of Gas Technology

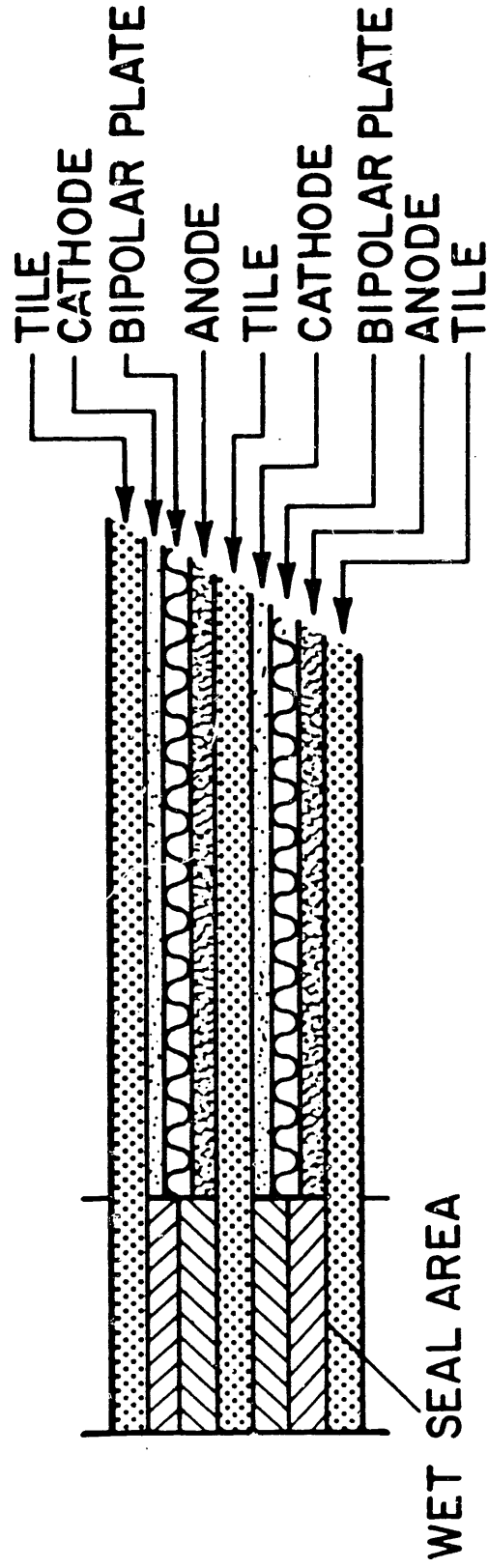
**External Manifold: Energy Research Corporation
International Fuel Cell Corporation**

*** * * * ***

Waste heat removal by —

- anode recycle ● cathode recycle ● separate cooling plates**

BIPOLAR PLATE APPROACH TO CELL DESIGN



ELECTROLYTE TILE = $\text{LiAlO}_2 + (\text{Li, K})_2 \text{CO}_3$

ANODE = Ni (Cr)

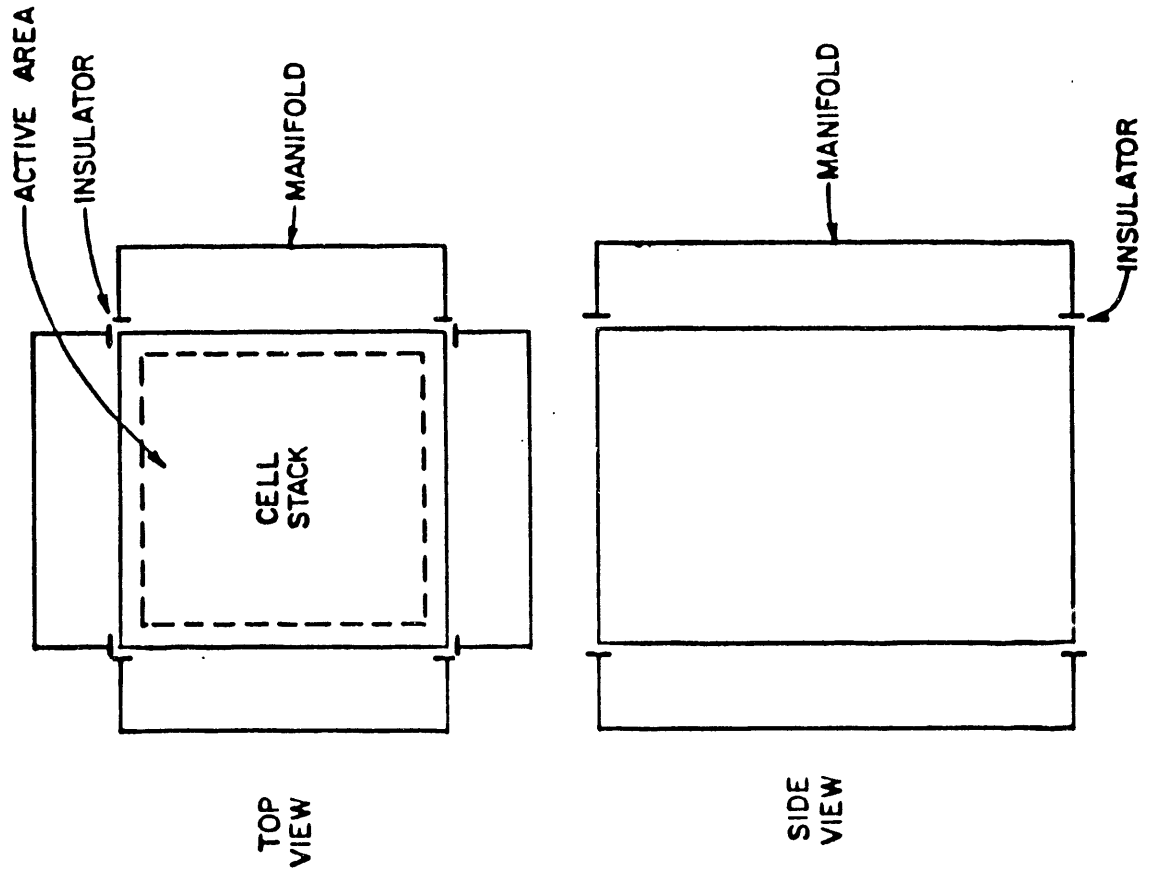
CATHODE = NiO (Li_2O)

BIPOLAR PLATE = 10 MIL SS OR Ni Clad SS

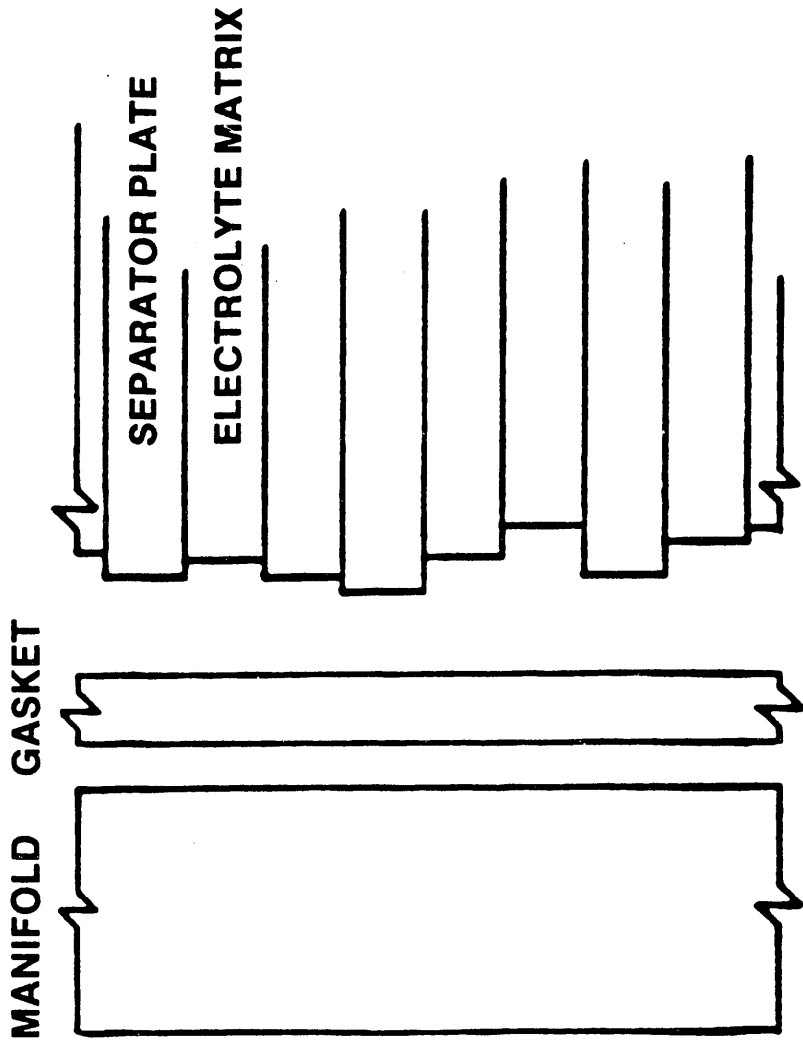
IGT PHILOSOPHY

- **Keep It Simple**
- **Minimize Components**
- **Utilize Existing Manufacturing Techniques**
- **Design for Direct Scale-Up**
- **Consider Costs in All Areas**
 - **Components**
 - **Manufacturing**
 - **Assembly**

EXTERNAL MANIFOLD SCHEMATIC,
CROSS-FLOW CONFIGURATION



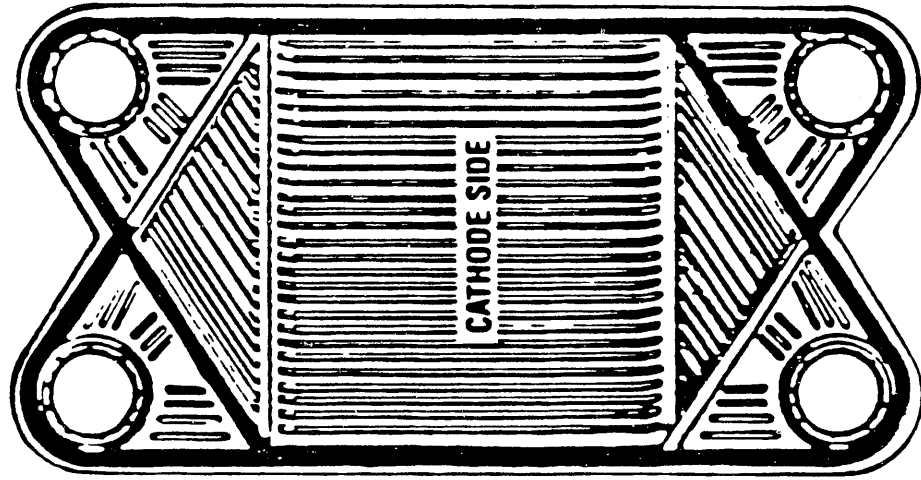
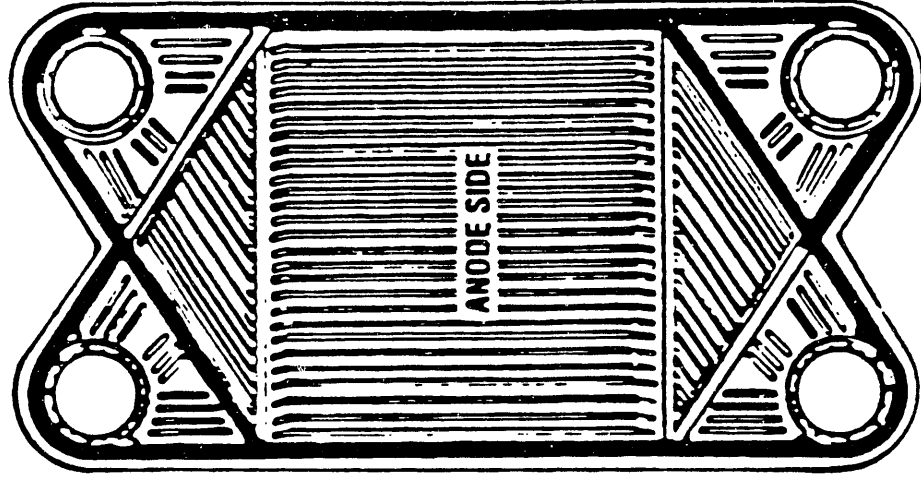
**SKETCH (Not to Scale) OF INTERNAL MANIFOLD-
GASKET-CELL STACK INTERFACE**



IMHEX™ MCFC STACK CONCEPT

- **INTERNAL MANIFOLDING**
- **PENETRATED MATRIX**
- **ANALOGOUS TO PLATE-TYPE HEAT EXCHANGER**
- **SINGLE-PIECE SEPARATOR PLATE/CURRENT COLLECTOR**
- **COMPLIANT WET SEALS**
- **TAPE CAST, FLAT CELL COMPONENTS**
- **SCALABLE TECHNOLOGY**

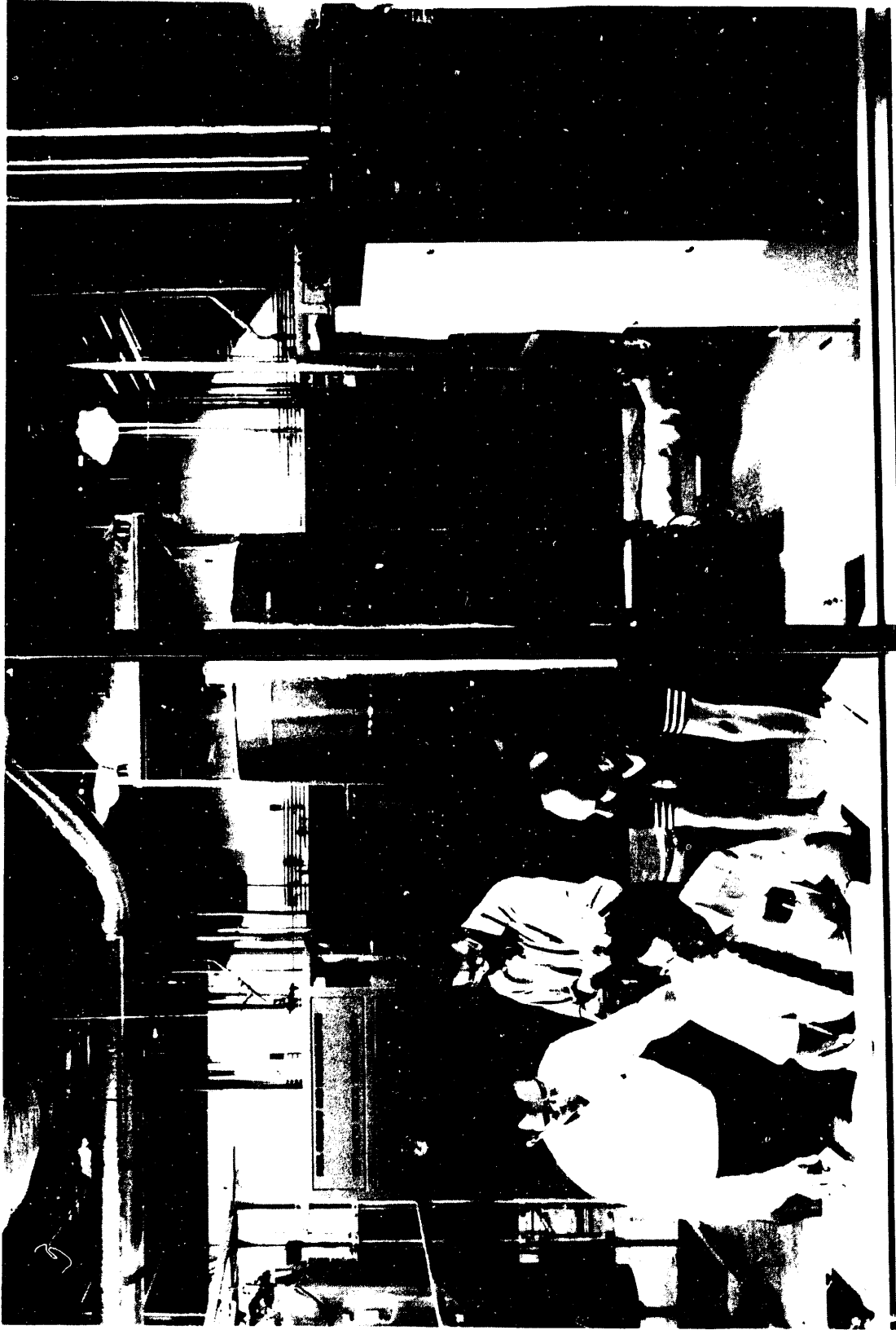
SCHEMATIC REPRESENTATION OF IMHEX™ PLATES

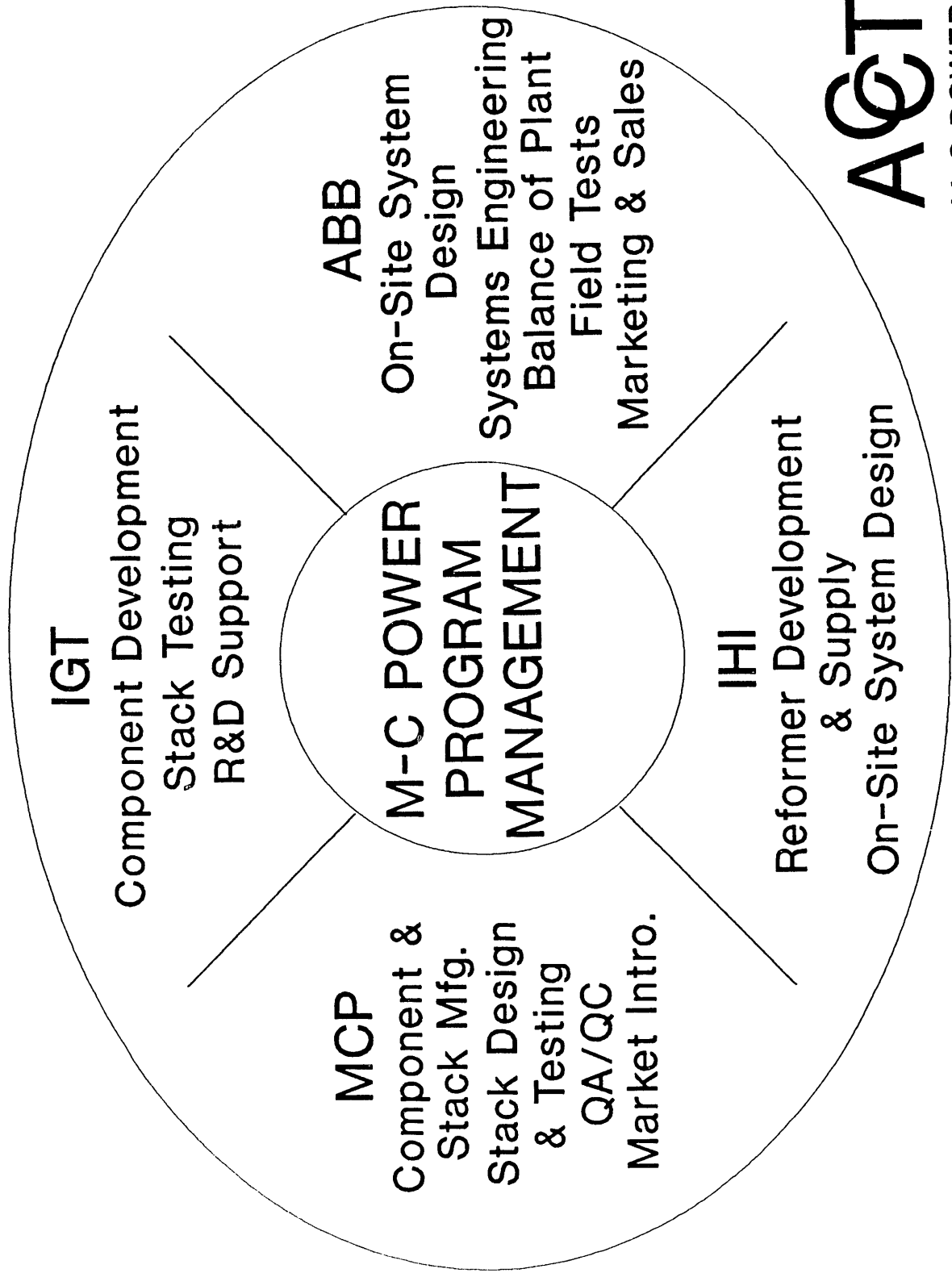


TAPE CASTING AT IGT



**3-KW PRESSURE FACILITY FOR TESTING
MCFC STACKS**





A&T
M-C POWER

PROGRAM SUPPORT ...

- DOE
- EPRI
- GRI
- SCAQMD
- SDG&E
- SoCalGas
- State of Illinois
- UNOCAL



CFC ON-SITE COGENERATION SYSTEM

MARKET ENTRY CHARACTERISTICS

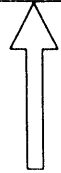
- SIMPLE
- RELIABLE
- LOW COST (<\$1000/kWE)
- FUEL TO a.c. Eff. \approx 45 - 47% (HHV)
- Eff. WITH HEAT RECOVERY \approx 80 - 82%
- P_{in} - 2 atm.

MARKETS OF INTEREST

<u>APPLICATIONS</u>	<u>SIZE RANGE</u>	<u>FUEL(S)</u>
ON-SITE, MULTI-RESIDENTIAL	UP TO 1000 kW	NATURAL GAS
ON-SITE, COMMERCIAL	0.5 - 2.0 MW	NATURAL GAS
INDUSTRIAL COGENERATION	2.0 - 20.0 MW	NATURAL GAS BY-PRODUCT GASES
ELECTRIC UTILITY, DISPERSED	20.0 - 50.0 MW	NATURAL GAS COAL-DERIVED GASES
ELECTRIC UTILITY, BASE LOAD	> 100 MW	COAL-DERIVED GASES NATURAL GAS

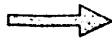
OVERALL STACK TESTING SCHEDULE

	FY 90			FY 91			FY 92			FY 93															
	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J
1 FT. ²																									
1 GRI 1																									
1 "TALL STACK" EPRI																									
1 STACK 6 DOE																									
1 SDG&E-1 SDG&E																									
1 STACK 7 DOE																									
1 SDG&E-2 SDG&E																									
1 STACK 8 DOE																									
1 STACK 9 DOE																									
1 SDG&E-3 SDG&E																									
1 STACK 10 (O) DOE																									
1 STACK 11 (O) DOE																									
20 kW SYSTEM SIMULATOR																									
10 10 kW STACK GRI																									
10 20 kW STACK DOE																									
10 20 kW STACK DOE																									
10 50 kW SYSTEM DOE																									
10 250 kW DEMO DOE																									
10 20 kW SYSTEM GRI																									
10 20 kW SYSTEM GRI																									



COMMERCIAL DEVELOPMENT PROGRAM

- System/Stack Design & Development
- Manufacturing Processes
- Field Verification
- Market Development and Commercial Support



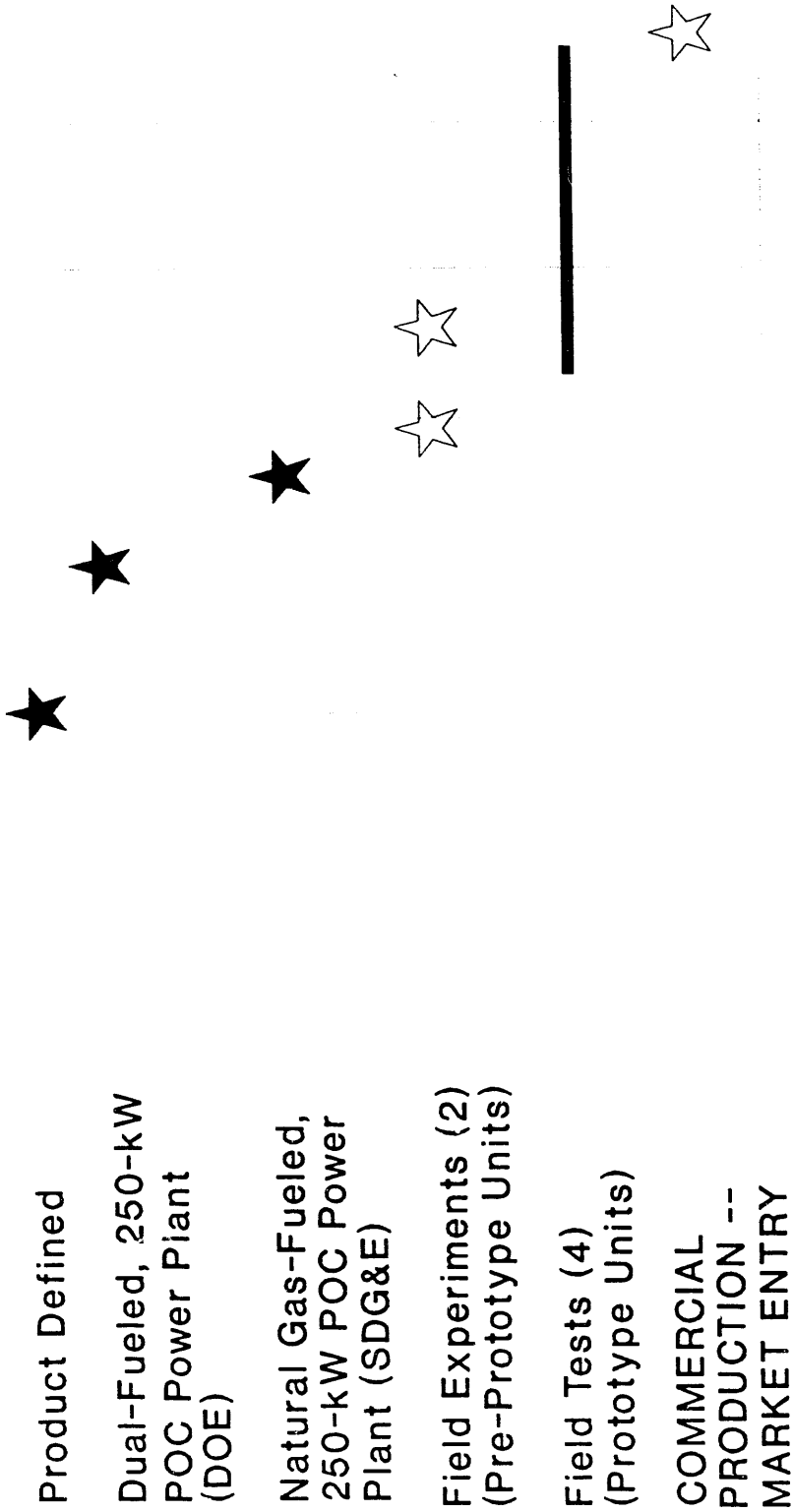
Contingent Orders
(1994-1995)



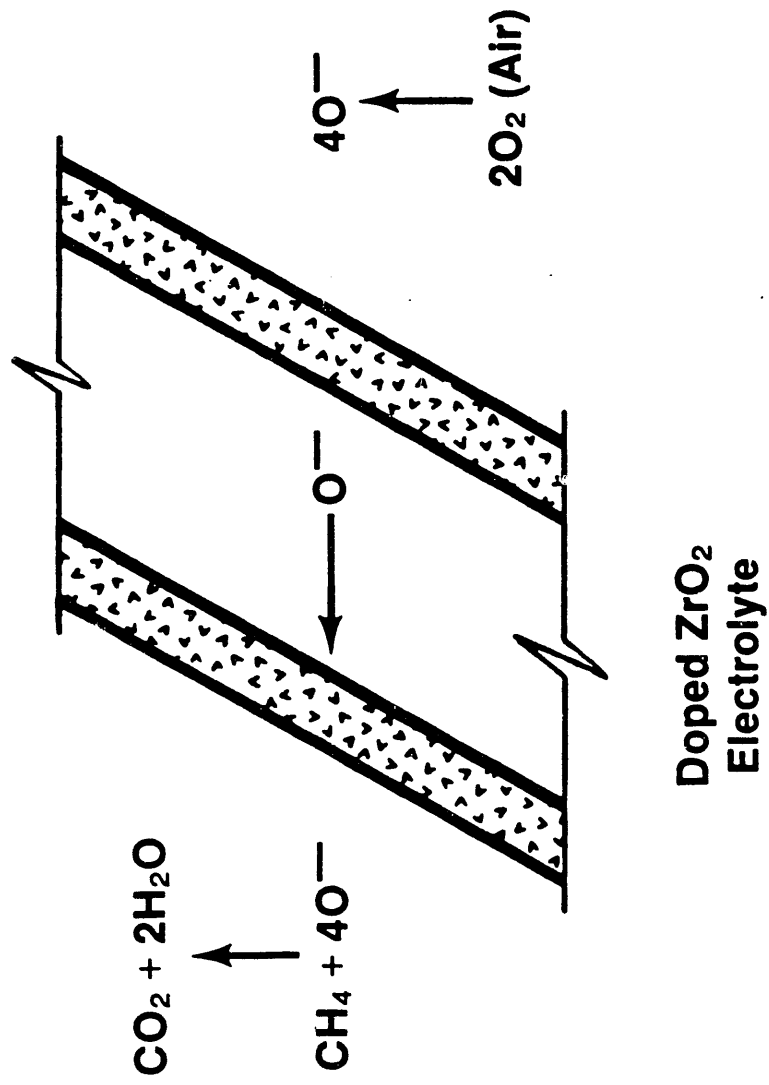
Commercial Production
(1997)

COMMERCIAL PROGRAM SCHEDULE

1991	1992	1993	1994	1995	1996	1997
------	------	------	------	------	------	------



SOLID OXIDE FUEL CELL



SOLID OXIDE FUEL CELL

Operation: 1000°C (1800°F)

Anode: Ni/ZrO₂ cermet



Electrolyte: (Y₂O₃)ZrO₂

Cathode: La(Sr)MnO₃

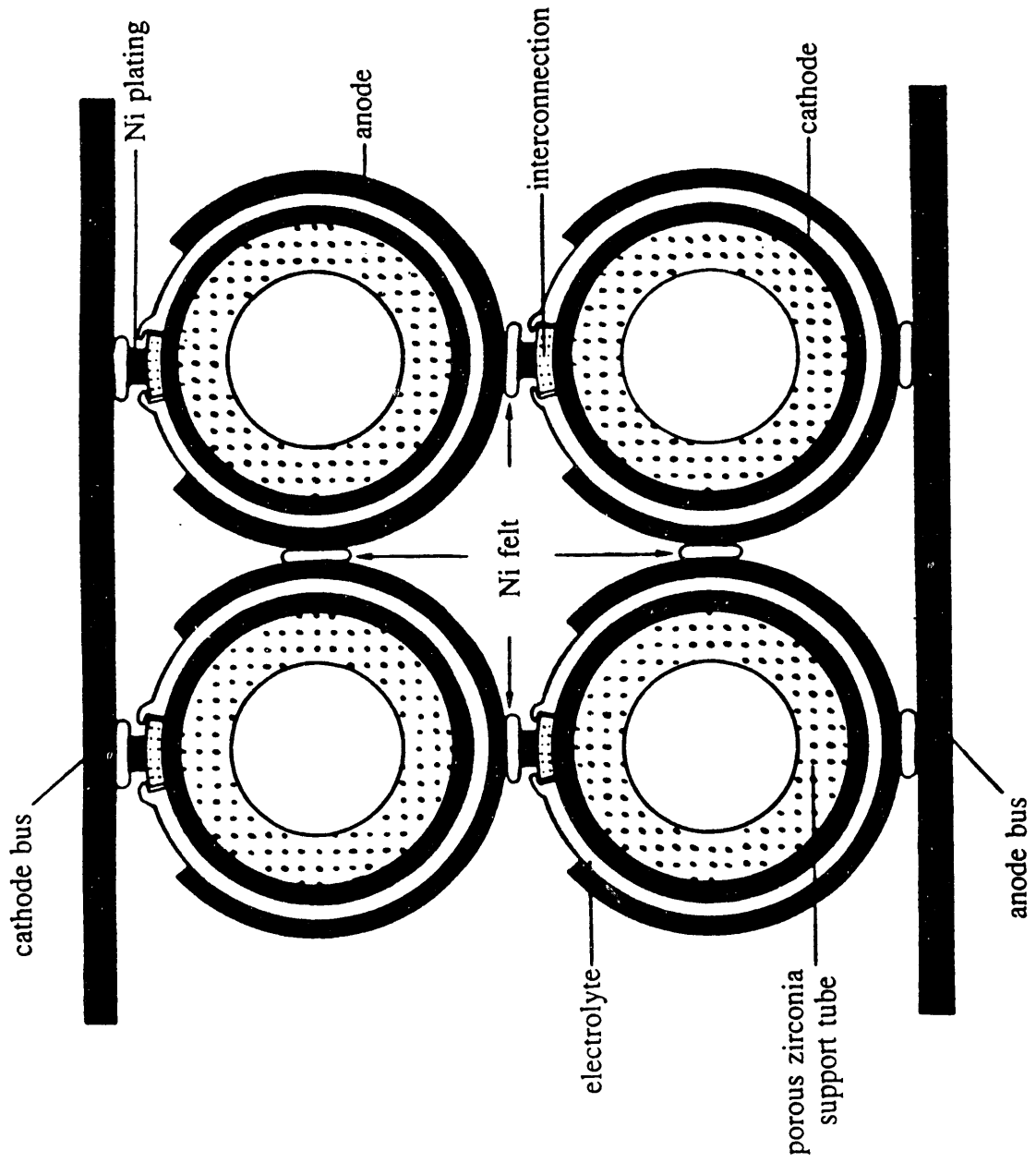


Interconnect: La(Mg)CrO₃

SOLID OXIDE CELL DESIGNS

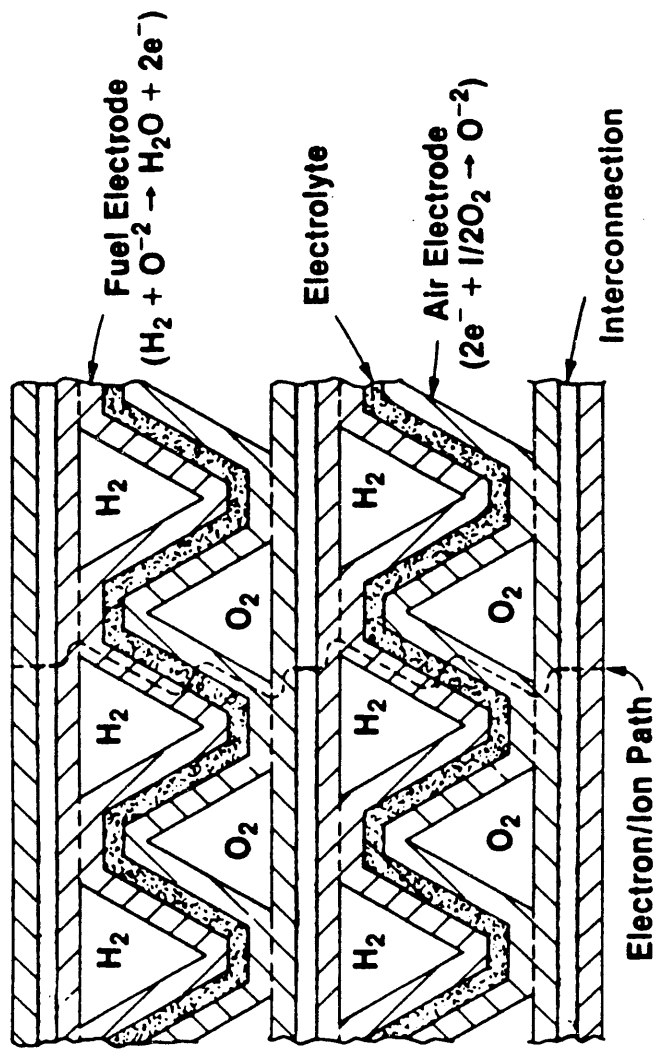
Tubular	Westinghouse
Planar	Ceramatec ZTEK Corp. Institute of Gas Technology
Monolithic	AiResearch/Argonne National Lab.

SOLID OXIDE FUEL CELL Tubular Cell/Stack Design

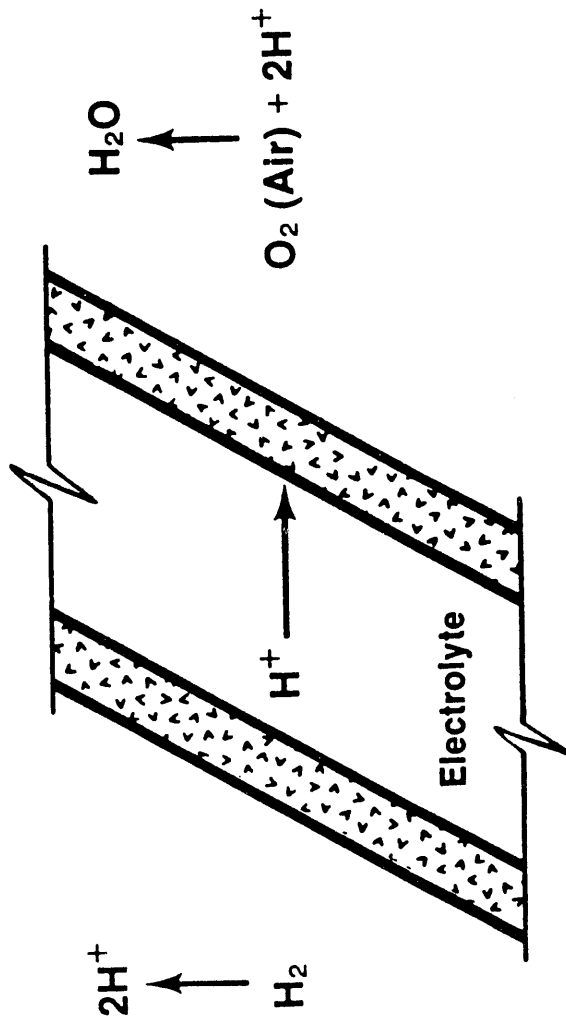


SOLID OXIDE FUEL CELL

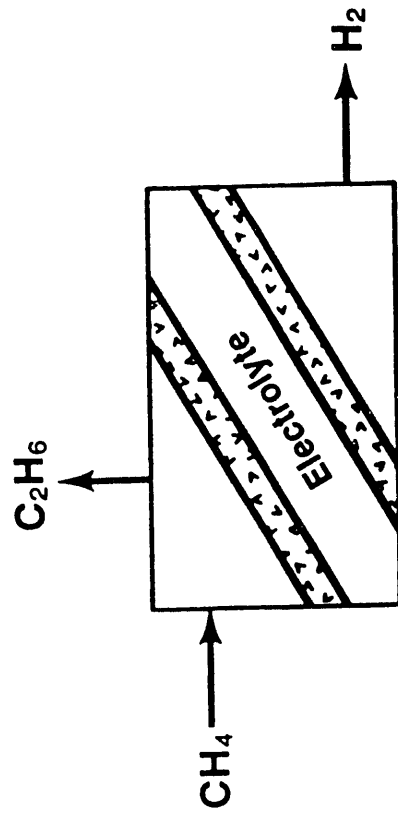
Monolithic Design



PROTON CONDUCTIVE DEVICES



FUEL CELL



ELECTROCHEMICAL REACTOR

**INTERNATIONAL
FUEL CELL
PROGRAMS**

JAPAN (AND ASIA)

Phosphoric Acid

- **Fuji Electric**
- **Hitachi**
- **Toshiba**
- **MELCO**
- **Sanyo**
- **Consortium (Korea)**

Molten Carbonate

- **Hitachi**
- **IHI**
- **MELCO**
- **Fuji Electric**

Solid Oxide

- **Nat. Chem. Lab for Ind.**
- **Fuji Electric**

EUROPE*

Molten Carbonate

- ECN (Netherlands)
- Ansaldo, ENEA (Italy)
- Hydro Electrica (Spain)

Phosphoric Acid

- TAE, Messina (Italy)

Solid Oxide

- Asea Brown Boveri (Switzerland)
- Cent. Ind. Res./Oslo Univ. (Norway)
- Various (Italy)

Polymer Electrolyte

- DeNorda (Italy)

Alkaline

- Elenco (Belgium)

* Development efforts only. Testing of foreign technology not included.

END

**DATE
FILMED**

01 / 23 / 92

