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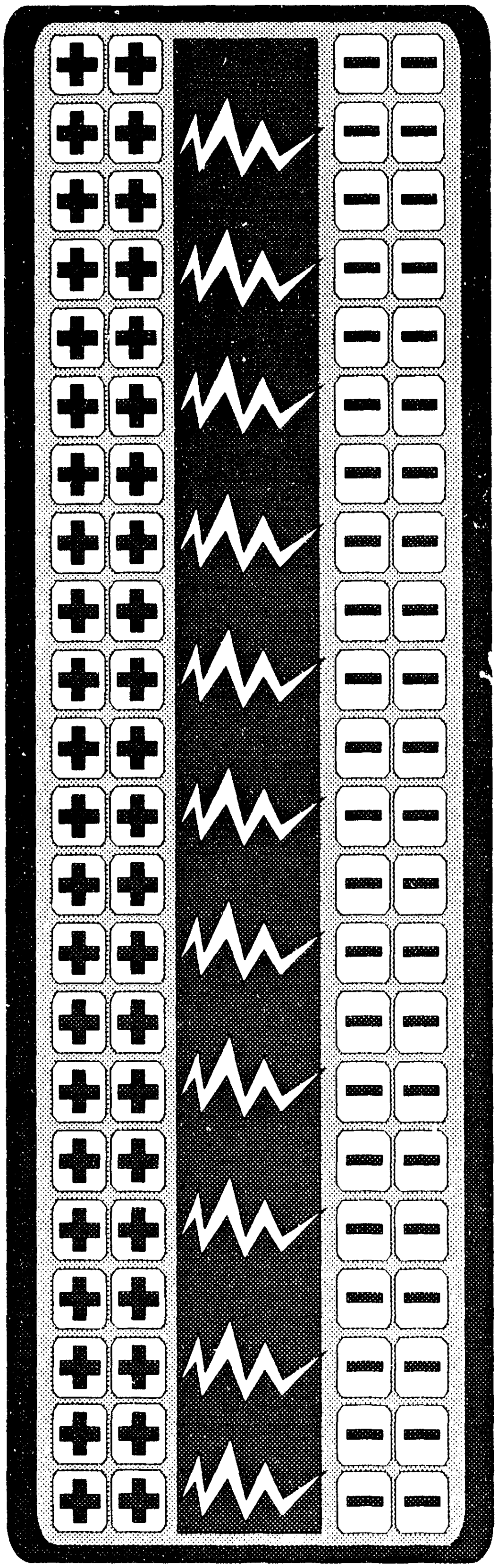

Fuel Cell Systems Program Plan

Fiscal Year 1993

U.S. Department of Energy

Assistant Secretary for Fossil Energy
Deputy Assistant Secretary for Advanced
Research and Special Technologies
Washington, D.C. 20585

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EXECUTIVE SUMMARY

Securing future energy supplies and enhancing environmental quality are among the major goals of national energy policy. The National Energy Policy Act of 1992 lays the foundation for a more efficient, less vulnerable and environmentally sustainable energy future. Several advanced energy conversion technologies under development by the Department of Energy can help achieve these objectives. Fuel cell systems are among those technologies having both the potential for ultra-high efficient energy conversion and enhancement of environmental quality.

The Department of Energy (DOE), Office of Fossil Energy, is participating with the private sector in sponsoring the development of molten carbonate fuel cell (MCFC), and advanced concepts including solid oxide fuel cell (SOFC) technologies for application in the utility, commercial and industrial sectors. Phosphoric acid fuel cell (PAFC) development was sponsored by the Office of Fossil Energy in past years and is now being commercialized by the private sector. In 1993 the Department of Defense is undertaking a coordinated program to utilize and demonstrate phosphoric acid and other fuel cell systems. In addition, the DOE Office of Conservation and Renewable Energy is participating in sponsoring development of fuel cells for transportation propulsion systems. The Office of Conservation program is focused primarily on the development of polymer electrolyte or proton exchange membrane fuel cells, although they also are implementing a congressionally mandated demonstration program for phosphoric acid fuel cell buses. DOE fuel cell research, development and demonstration efforts are also supported by private sector funding. This Plan describes the fuel cell activities of the Office of Fossil Energy.

Fuel cell systems are emerging power generation technologies which are expected to have significant worldwide impacts. PAFC power plants have begun to enter the marketplace and MCFC and SOFC power plants are expected to enter the marketplace in the mid to late 1990s.

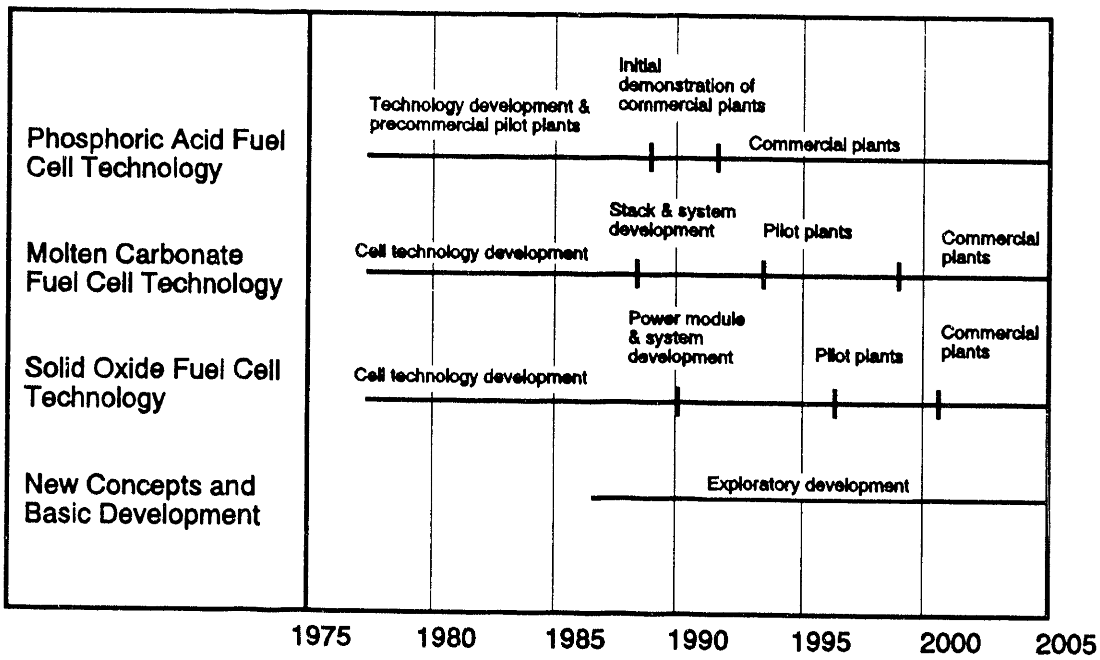
The goal of the fuel cell program is to increase energy and economic efficiency of power generation through the development and commercialization of cost-effective, efficient and environmentally benign fuel cell systems which will operate on fossil fuels in multiple end use sectors.

The program objectives are to develop and demonstrate cost effective fuel cell power generation which can be successfully commercialized in the 1990s.

To achieve the program goal and objectives, a series of steps must take place, some sponsored largely by DOE and some largely by the private sector. The activities include basic and applied research and development, proof-of-concept activities, precommercial demonstrations, and associated commercial scale activity. Key elements of the fuel cell systems program are shown in Exhibit 1 and include:

- Development and demonstration of MCFC technology for electric utility, commercial and industrial applications
- Development and demonstration of SOFC technology for electric utility and industrial applications
- Evaluation of potentially promising advanced fuel cell concepts or configurations for electric utility, industrial, residential and commercial sector applications
- Support of advanced research needed to develop fuel cell technologies
- Monitoring of PAFC commercial activities in the private sector following completion in 1992 of DOE participation in funding the development of this technology.
- Coordination with Department of Defense, DOE's Office of Conservation and Renewable Energy, the Electric Power Research Institute and the Gas Research Institute activities in utilization and demonstration of PAFC and other fuel cell technologies.

EXHIBIT 1
OVERALL FUEL CELL PLAN



The program strategy is to assist the private sector in developing molten carbonate and solid oxide fuel cell technologies and to participate in field tests which improve prospects for commercialization by the private sector. Commercialization plans have been formulated by the private sector for introduction of these power plants fueled by natural gas in the mid-1990s. Introduction of larger power plants with integrated coal gasifiers is anticipated prior to 2010.

Advanced research is also supported to provide solutions in critical areas and to identify concepts which offer opportunities for significant improvements.

Congressional appropriations for this program in fiscal year 1993 are $51.1 million.

I

INTRODUCTION

Fuel cell power systems are emerging power generation technologies for the efficient, economical and environmentally acceptable production of electricity. In some configurations the by-product heat can also be efficiently used in cogeneration applications. Fuel cells produce electricity through the electrochemical oxidization of a fuel. They can be operated on a variety of fuels, including coal gas, natural gas, land fill gas and renewable fuels. First market entry units are fueled by natural gas. Systems studied have shown that fuel cell power plants can be designed with overall system efficiencies in the 50 to 60 percent range.[1] Fuel cell power plants, because of their efficiency, will help in reducing CO_2 emissions that have been linked to "global warming." Additional benefits are the environmentally attractive operating characteristics offered by the fuel cell. Because electricity is produced through an electrochemical reaction rather than by combustion, fuel cells generate very low amounts of NO_X and are extremely quiet. These systems have also been designed so that they emit very little SO_X into the atmosphere. This combination of operating characteristics and high efficiency make fuel cells attractive for future electric utility applications. On-site industrial and commercial applications where the waste heat can be utilized are also attractive. Fuel cells can be sited in environmentally sensitive and populated areas and early commercial units have been installed in hotels, office buildings and similar locations.

Development of fuel cell technologies has been underway in the United States with funding support provided by both public and

[1] Efficiencies stated on higher heating value basis.

private sectors. The DOE Office of Fossil Energy, the Gas Research Institute (GRI), and the Electric Power Research Institute (EPRI) are cooperatively sponsoring the development of fuel cell systems for applications in the utility, commercial and industrial sectors. Funding support for development and application is also provided by fuel cell developers and potential users. This plan describes the DOE Office of Fossil Energy program goal and objectives, program strategy, technology status, implementation plan, and other related fuel cell activities.

II

GOAL AND OBJECTIVES

The goal of the fuel cell program is to increase energy and economic efficiency through the development and commercialization of cost-effective, efficient and environmentally benign fuel cell systems which operate on fossil fuels in multiple end use sectors.

The program objectives are to develop and demonstrate cost effective fuel cell power generation which can be successfully commercialized in the 1990s.

In support of the goal and objectives, DOE Office of Fossil Energy overall activities include:

- Supporting development of MCFC and SOFC systems
- Expediting the application of these technologies by assisting the private sector and other government organizations in activities related to the commercialization of fuel cell systems
- Funding basic and applied research to provide the technology foundation for the development of fuel cell systems
- Supporting the development of potentially promising advanced fuel cell concepts or configurations that may offer improved performance and cost.

- Monitoring of PAFC private sector and Department of Defense activities to provide information for application to advanced fuel cell technologies.

The fuel cell system efficiency and capital cost objectives, represented as development targets, for MCFC and SOFC are shown in Exhibit 2.

EXHIBIT 2
DEVELOPMENT TARGETS FOR FUEL CELL SYSTEMS

	TYPES OF FUEL CELL SYSTEMS BEING DEVELOPED	
	Molten Carbonate	Solid Oxide
Capital Cost (1)		
Natural Gas-Fueled Plant:		
•Electric Utility	$800/KW	$600/KW
•On-Site	$1000/KW	$800/KW
Coal-Fueled Plant:		
•Electric Utility	$1200/KW	$1000/KW
Efficiencies (2)		
Natural Gas-Fueled Plant:		
•Electric Utility	60%	55%
•On-Site	55%	50%
Coal-Fueled Plant:		
•Electric Utility	50%	50%

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1) Power plant capital cost targets are in mature production, 1990 dollars and include installation costs.

2) Efficiency targets are for electric generation only based on higher heating value of fuels (overall efficiencies for onsite cogeneration applications are expected in the 75-80% range).

The specific objectives of the MCFC and Advanced Concepts - SOFC programs are to develop and demonstrate systems that are technically superior and economically competitive with alternative systems. The following sub-objectives have been established:

- To develop cost effective, long-life stack and module designs capable of operating on dual fuel (coal gas or natural gas)
- To define the economics and performance of plant configurations
- To identify and resolve technical barriers to commercialization of the technology
- To demonstrate feasibility through testing of cells, stacks and systems.

The objective of the now completed PAFC program was to reduce the cost and improve the performance of PAFC systems to enable private sector commercialization. Technology advancements were verified with long-term testing of full area stacks. The government is continuing activities to assist in realizing successful commercialization of PAFC through a demonstration and fuel cell utilization program in the Department of Defense with DOE coordination.

Experience from the PAFC program and other programs which are aimed at development and commercialization of products for utility power generation underscore the importance of multiple tests and demonstrations in user environments. These multiple demonstrations will enable more realistic evaluations by prospective users and manufacturers of the market requirements concerning performance, costs and warranties and the values of "externalities" in market place decision making.

Approaches and progress in achieving current program objectives are described in the following sections of this report.

III

PROGRAM STRATEGY

The DOE strategy is to aid in the development and demonstration of the necessary technologies to ensure that national benefits are realized through commercial production and use. The strategy supports commercial introduction on natural gas during the 1990s and with integrated coal gasifiers before 2010.

The PAFC power plant technology is the furthest developed fuel cell technology and is in early commercial production. In 1992 DOE concluded sponsored development addressing cost reduction and performance improvement of PAFC. The Congress, in FY 1993 appropriations, directed that the Department of Defense conduct a PAFC demonstration and utilization program to facilitate successful commercialization of this technology. The DOE is cooperating in this program to ensure maximum benefits are realized.

DOE is developing MCFC technology because it offers potential advantages over other energy conversion technologies. Studies have shown that 50 to 60 percent efficient MCFC systems are possible. Carbon monoxide, which was removed to avoid poisoning the lower temperature PAFC, is indirectly utilized as a fuel in the MCFC. The higher operating temperature of approximately 650 °C (1,200 °F) makes the MCFC a more efficient user of coal-derived fuels in integrated systems.

The SOFC has, in the past, been termed a third generation technology behind PAFC and MCFC. Significant R&D conducted over the last few years has advanced the commercial development of SOFC technology substantially. The SOFC offers the added benefits of solid state construction for reliability and high-grade thermal energy due to its higher operating temperature of approximately 1000 °C (1,800 °F). The high SOFC temperature results in good thermal integration into high temperature, coal based systems minimizing the need for heat exchangers and providing high grade heat to be used for process steam and/or various bottoming cycles, thus achieving high overall system efficiency.

To achieve success in establishing a strong U.S. fuel cell industry, the following needs are identified.

- Continued funding of cell, stack and system level technology development and improvement to establish the technology needed for field verifications and prototype demonstrations

- Continued private sector funding addressing user requirements, manufacturing processes and developmental production capabilities to reduce market entry risks and assure commercialization

- Product improvement and cost reduction to meet market competition

- Establishment of joint ventures and teaming relationships (which may include international teams) to enhance private sector financial resources fcr demonstration activities and for the transition to commercial products

- Multiple demonstrations in user environments to assure market success

- Market acceptance of fuel cell products based on performance, functionality, reliability, durability, cost and customer benefits to sustain continued sales and profit levels

- Multiple and competitive suppliers of fuel cell products to ensure product improvements, customer service and attention to cost control

In support of these needs, the strategic elements of the DOE program include:

- Support development of MCFC and SOFC systems through the demonstration plant stage (with increasing levels of cost sharing)

- Facilitate technology transfer to the private sector by stimulating interactions between U.S. fuel cell manufacturers and potential users

- Continue activities for basic and applied research on materials, processes and components applicable to fuel cell systems to provide the understanding needed to achieve steady progress in improving these technologies. This effort provides supporting technology as well as evaluation of improvements

- Structure DOE contracts with fuel cell developers to encourage early commercialization and manufacturing in the U.S.

- Monitor PAFC private sector activities to provide information for application to advanced fuel cell technologies

- Coordination with Department of Defense activities in utilization and demonstration of fuel cell systems

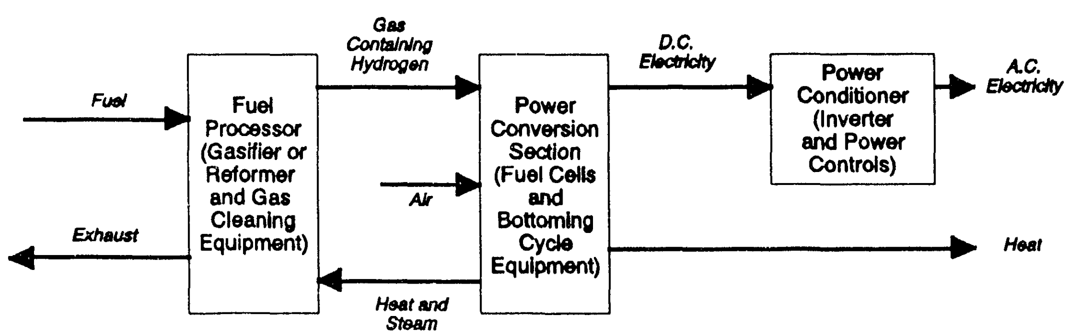
- Evaluation of alternative solid oxide electrolyte fuel cell concepts and configurations.

IV

TECHNOLOGY DESCRIPTION

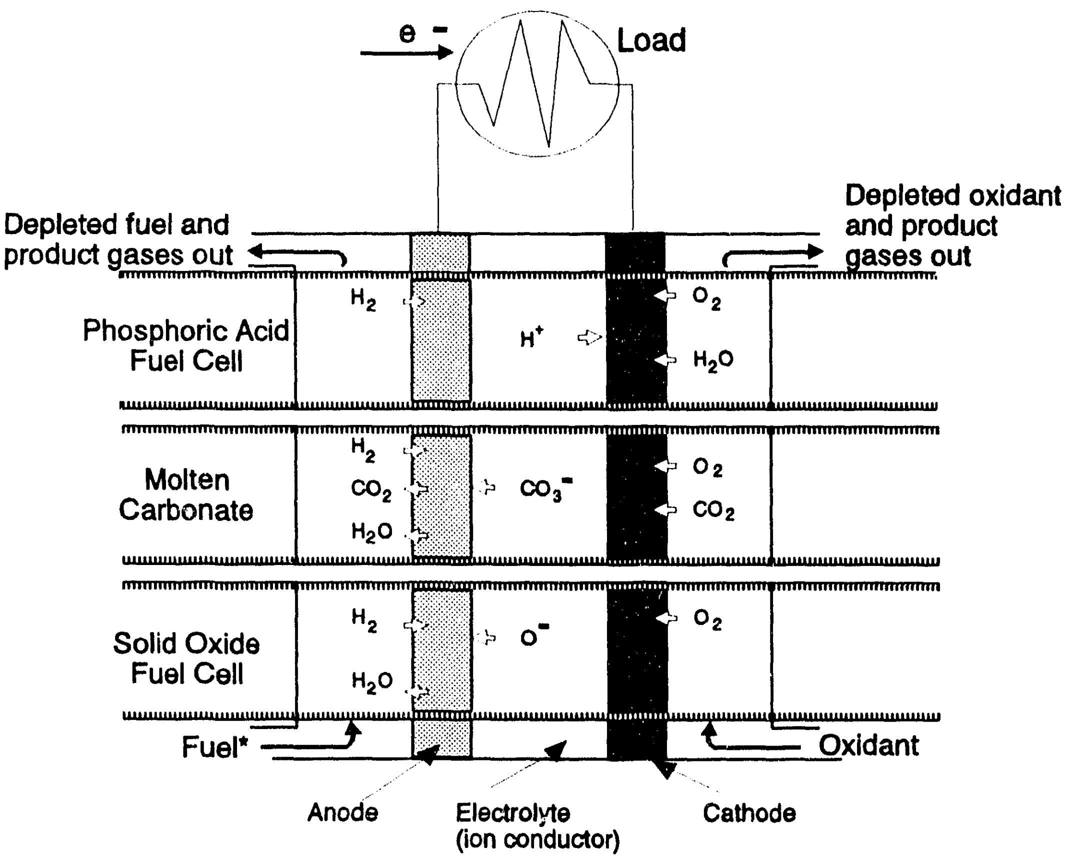
A basic fuel cell consists of two electrodes, the anode and cathode, separated by an electrolyte. Fuel cell types are characterized by their electrolyte. For example, phosphoric acid fuel cells utilize a phosphoric acid electrolyte in a matrix between anode and cathode electrodes. A fuel cell power plant as shown schematically in Exhibit 3 has three main components: the power conversion section which contains the series of fuel cells (referred to as the fuel cell stacks), the fuel processor, and the power conditioner. The fuel processor converts a hydrocarbon fuel (e.g., coal or natural gas) to a hydrogen-rich gas that is fed to the fuel cell stacks. The fuel cell stacks combine oxygen from the air with the hydrogen from the fuel processor to generate direct current electricity and heat. The heat may either be used directly as a co-product or applied in a bottoming cycle to produce additional electricity. The power conditioning section changes the direct current from the fuel cells to alternating current.

EXHIBIT 3
FUEL CELL POWER PLANT



Fuel cell technologies under development in the U.S. include phosphoric acid, molten carbonate, solid oxide, polymer, and alkaline. A schematic representation of the three fuel cell technologies addressed by DOE's Office of Fossil Energy is shown in Exhibit 4. The figure shows the hydrogen and oxygen reacting with the electric charge carrying ion of the electrolyte. These reactions produce an electric current which powers the external load. Water and heat are also produced by these reactions and must be controlled by the overall system. In the case of molten carbonate systems carbon dioxide is also used at the air electrode and formed at the fuel electrode, requiring a CO_2 supply or recycle in these systems. In the solid oxide and molten carbonate fuel cells, carbon monoxide in the fuel stream is also typically utilized as fuel.

FIGURE 4
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.

Phosphoric Acid Fuel Cell

The phosphoric acid fuel cell uses an electrolyte of phosphoric acid in a matrix and operates at approximately 200 °C (400 °F). Development since the late 1960s has brought the technology to market introduction in the electric utility and commercial on-site sectors with natural gas as the fuel. Commercial deliveries of 200 kW on-site units began in 1992 and an electric utility 11 MW power plant has been demonstrated in the private sector.

Molten Carbonate Fuel Cell

The molten carbonate fuel cell uses an electrolyte of lithium and potassium carbonates and operates at approximately 650 °C (1200 °F). The high operating temperature is needed to achieve sufficient conductivity of the electrolyte. An effect associated with this higher temperature is that noble metal catalysts are not required for the cell electrochemical oxidation and reduction processes. Molten carbonate fuel cells are being developed for natural gas and coal based power plants for the industrial and electric utility sectors.

Solid Oxide Fuel Cell

The solid oxide fuel cell using a ceramic electrolyte of yttria stabilized zirconia operates at about 1000 °C (1800 °F). The attractiveness of this cell relates principally to its solid state nature, its potential to reform gaseous fuel within the cells and its high operating temperature which can provide high quality heat for energy conversion or other uses. The solid electrolyte eliminates problems of electrolyte containment and allows designs which utilize the electrolyte as part of the structural members of cells.

Polymer Fuel Cell

The polymer fuel cell uses a class of fluorinated sulfonic acid polymer electrolytes. The electrolyte is a solid membrane which is currently operated between 40 °C and 90 °C (100 °F and 200 °F). The polymer fuel cell has demonstrated the potential for specific power approximately ten times higher than is being achieved with phosphoric acid fuel cells. Polymer fuel cells are being considered for applications where high specific power together with high efficiency are important. Examples are space power and transportation system applications. Polymer fuel cells currently being developed are also sometimes referred to as proton exchange membrane fuel cells. Polymer fuel cells development is not being funded by the DOE Office of Fossil Energy but is being funded by the DOE Office of Conservation and Renewable Energy for transportation applications.

Alkaline Fuel Cell

Alkaline fuel cells have been used since the mid 1960s in the U.S. space program. Future space system applications are expected. Alkaline fuel cells are not economically attractive for commercial terrestrial applications at present because they require the use of reactants free of carbon dioxide. The carbon dioxide contained in reformed fuels and air forms insoluble carbonates in the alkaline electrolyte. These carbonates hinder operation of the cell. Removal of the carbon dioxide from the fuel and air has not been economical. Alkaline fuel cell development is not being funded by the Department of Energy.

V

TECHNICAL STATUS

MOLTEN CARBONATE FUEL CELL STATUS

The MCFC effort is focused on scaling up to commercial scale stacks and demonstrations. It is supported by pilot plant manufacturing operations with capacities of 2- to 3-megawatts (MW) per year. Subscale stack testing also continues with primary emphasis on testing that directly supports the pilot manufacturing and commercial-scale demonstration efforts. GRI and the Electric Power Research Institute (EPRI) continue to provide integrated support to MCFC development. Private sector (i.e., utility and industry) and regional (state and local) interest and funding support are increasing and industry has developed commercialization plans. Domestic MCFC developers are Energy Research Corporation (ERC), M-C Power Corporation and International Fuel Cells (IFC).

ERC's MCFC development has progressed to testing of their internal reforming, externally manifolded cells in stacks of up to 70 kW on natural gas and simulated coal gas. The first 70 kW full height stack successfully completed testing in 1992. ERC also has a cost shared program with the Pacific Gas and Electric Company and EPRI. Continued testing of a 70 kW class stack is scheduled at the utility's San Ramon Research Center in 1993. The scope of the ERC program includes testing of stacks on simulated and actual coal gas.

ERC has constructed a pilot manufacturing facility in Torrington, Connecticut which is manufacturing full size components for 100 to 125 kW stacks. Manufacturing capacity of this plant is 2 to

3 MW/year. Assembly of a full size stack began in 1992 and testing is planned for 1993. Assembly of a second full size stack is planned for 1993.

ERC has received an endorsement by the American Public Power Association and a buyers group to support a utility demonstration and efforts to commercialize a fuel cell power plant matched to the needs of publicly owned municipal utilities. ERC has offered 2 MW internal reforming MCFC plants for the demonstration and commercial entry units.

An ERC subsidiary, Fuel Cell Engineering Corp. (FCE), signed an agreement with DOE in 1992 for a 2-megawatt field test demonstration. The 2 MW unit will include 18 stacks. The cost-shared power plant will be tested beginning in 1994 at a facility to be built in Santa Clara, California.

M-C Power is developing an internally manifolded MCFC design approach and has tested stacks of up to 20 kW composed of full area cells of 1 square meter (11 square feet). The first full area 20 kW stack successfully completed testing in 1992. The second was assembled in 1992 and is scheduled to complete testing in 1993. A pressurized 50 kW stack is also scheduled to be assembled and tested in 1993. Their full scale stack will contain approximately 220 to 250 cells and is designed to yield approximately 250 kW of electric power plus cogeneration heat. The first 250 kW stack is scheduled to be assembled in a cogeneration system and tested in late 1993 at a site in Brea, California.

M-C Power produces full size stack components in their pilot manufacturing facility in Burr Ridge, Illinois. Manufacturing capacity is 2 to 3 MW/year.

M-C Power signed an agreement with DOE in 1992 for a 250-kilowatt field test demonstration of a cogeneration unit. The cost-shared power plant is scheduled be tested at a hospital site in San Diego, California beginning in late 1994.

IFC has concluded research to improve MCFC stack performance under DOE sponsorship. IFC has tested externally manifolded stacks of up to 20 kW. Further development is planned under private sector sponsorship.

Although significant progress has been made in the development of MCFC, it is recognized that further cell and stack technology advances aimed at product improvement will be required to achieve the cost targets, performance and durability necessary for prototype MCFC power plants.

Conceptual power plant designs have been prepared by the developers for typically 100 to 300 kW on-site plants and 2-3 MW dispersed generators (both using natural gas as primary fuel) and 100-500 MW plants integrated with coal gasifiers. Design studies predict 50-60 percent efficiency with small scale units on natural gas and for plants integrated with coal gasifiers. Manufacturing cost estimates indicate that stack selling prices of less than $300/kW may be feasible at modest production rates (200 MW per year). This increases confidence that overall system cost targets (shown on page 8) are achievable.

As a result of an initiative by the American Public Power Association, ERC has developed a commercialization plan that aims to have orders for over 100 MW of early production units by 1997. A group of electric and gas utilities, known as the Fuel Cell Commercialization Group, (presently 37 members) has endorsed this plan and is helping ERC secure the orders for 50 (or more) 2 MW power plants.

M-C Power has developed plans for commercial market entry in 1997-1998. A group of gas utilities, combination gas and electric utility and a petroleum company, known as the Alliance to Commercialize Carbonate Technology has formed to facilitate commercialization of the M-C Power technology.

SOLID OXIDE FUEL CELL STATUS

SOFCs are currently being developed for use in a wide variety of commercial, industrial, and utility applications. The SOFC concept and the materials contained therein have been under development by Westinghouse, and others for over twenty years. SOFCs operating at 1000 °C (1800 °F) are capable of utilizing methane directly, without extensive fuel processing and are being developed for integration with coal gasifiers.

Three geometric configurations are now under development in the United States. These are the tubular (Westinghouse), the monolithic (Allied Signal), and the planar (Ceramatec, Ztek, Interscience and others). The planar and monolithic approaches may offer higher power density, higher efficiency and reduced fabrication costs, but are at a very early development stage and have not been proven.

The Westinghouse design packages tubular cells in bundles of three by six. Groups of bundles are then mounted in a thermally integrated system which make up a module. A module, consisting of 32 bundles of 50 centimeter long cells, can produce 20 kW. Westinghouse has built and tested systems ranging in size from 500 W to 25 kW (40 kW peak). Two 25 kW generators have been built and are being tested by gas utilities. A third generator (20 kW) is scheduled to be delivered to a gas utility test site in California in early 1993. Westinghouse has a pre-pilot manufacturing facility in operation which is capable of producing approximately 300 kW of cells per year.

Testing at Westinghouse has progressed to the point where groups of cells have been operated for over 30,000 hours. In addition, longer cells of up to 100 centimeters and self supporting electrodes (eliminating the support tube) are being tested to promote scale-up, improve performance, and reduce cost. Plans call for eventually increasing the tube length to 2 meters for large electric utility applications. Conceptual design of a 300 MW integrated gasifier/fuel cell power plant has been completed. Several 100 kW tests are planned. The first 100 kW generator is scheduled to be delivered to a gas utility test site in early 1993.

Monolithic and planar cells have not yet been operated above the small module, laboratory test scale. Expanded development efforts focused on material selection and stack fabrication will be required to realize the potential of these alternative SOFC concepts. Under DOE sponsorship, Allied Signal teamed with Argonne National Laboratory has fabricated stacks of several monolithic cells by techniques which roll thin uniform layers of the materials used to form the ceramic structure.

PHOSPHORIC ACID FUEL CELL STATUS

PAFC systems were developed for megawatt-scale applications in the electric utility sector and kilowatt-scale applications in the commercial and industrial sectors. Two firms, Westinghouse and International Fuel Cells (IFC), have developed technology applicable to systems in the 1-11 MW size for the utility and industrial sectors, and IFC is marketing a 200 kW system for on-site cogeneration use in the commercial sector.

Over 50 of the 200 kW on-site power plants have been ordered. The 200 kW power plant is currently a first of a kind cogeneration system. Learning curve and production cost reductions are expected to reduce the price in a few years with further reductions anticipated through continued technology improvement by industry.

Westinghouse completed development of an air-cooled 375 to 400 kW PAFC module with the fabrication and test of this module at the Westinghouse site in 1992. The module forms a building block for larger systems.

The Department of Defense is implementing a Congressionally directed PAFC demonstration and use program in FY 1993. Under this program the Army, Navy and Air Force will each purchase and install up to $6 million of PAFC fuel cells commercially manufactured in the U.S. The DOE is cooperating in these activities to provide whatever information is needed and to obtain maximum benefits from these demonstrations.

VI

PROGRAM DESCRIPTION AND IMPLEMENTATION

The DOE program in the Office of Fossil Energy is continuing development and testing of MCFC and SOFC systems following completion of PAFC development funding in 1992. In addition, an Advanced Research category provides for fundamental research on key technology issues critical to the program.

The activities and development schedule are shown in Exhibit 5 and discussed below.

MOLTEN CARBONATE FUEL CELLS

In 1990 three multi-year contracts were negotiated for the commercial-scale stack R&D. M-C Power and ERC were funded to develop full-size stacks for natural gas and coal-fueled generation system designs and IFC was funded to perform stack improvement research. Argonne National Laboratory is continuing supporting research.

Stack/System Development Contracts

ERC: Internal Reforming, Externally Manifolded MCFC Development

In ERC's internal reforming concept, methane in the fuel is directly converted to hydrogen in the MCFC stack. In 1987, ERC was awarded its first major MCFC DOE contract. By 1989, ERC successfully completed a 60-cell, 0.09 square meter (1 square foot), stack test which incorporated the internal reforming concept. Since then, many 2- to 25-kW, 0.37 square meter (4 square foot), internal reforming stack tests have been completed using natural gas and simulated coal gas fuels. In 1990, ERC completed system studies for coal gas and natural gas fueled MCFC systems.

In FY 1991, ERC completed building a new pilot manufacturing facility in Torrington, Connecticut. This facility is currently manufacturing full-area, 0.56 square meter (6 square foot), components, and full size, 100 to 125-kW stacks.

In FY 1992, ERC tested a 70-kW, 0.37 square meter (4 square foot), natural gas fueled MCFC stack and testing of this stack is being continued in FY 1993 at Pacific Gas and Electric in San Ramon, California. Testing of a 20-kW stack with a slip stream from a Destec coal gasifier is also scheduled for 1992-1993. Activities in stack cost reduction will be accelerated in order to achieve testing of two full-area, 0.56 square meter (6 square foot), 100-kW to 125 kW MCFC power plants during 1993.

M-C POWER: External Reforming, Internally Manifolded MCFC Development

In 1990, M-C Power transitioned from a supporting role to that as the primary IMHEX technology developer, a role previously held by the Institute of Gas Technology (IGT). IGT continues sub-scale, stack testing in support of the full-area stack testing and manufacturing program at M-C Power. M-C Power has completed system studies for coal gas and natural gas fueled MCFC systems.

In 1991, the M-C Power completed its manufacturing facility which makes full-area, 1.02 square meter (11 square foot) cell and stack components. A 20-kW test facility which can accommodate full-area stacks was also completed in 1991. Subscale, 0.09 square meter (1 square foot), 24-cell and 70 cell stacks were tested in this facility in 1991. By 1993, a second "breadboard" 20-kW test facility is planned to be designed and constructed at M-C Power to test stacks with a reformed natural gas feed stock.

In FY 1992, M-C Power completed testing of a full-area, natural gas fueled, 20-kW stack and will complete testing of a second 20 kW stack in 1993. Also in 1993, a pressurized 50 kW stack is planned to be tested. Efforts at M-C Power under the current contract will culminate in a 220 to 250-cell, 250-kW, full size test to begin in FY 1993 at an oil company site in Brea, California.

IFC: Stack Research

In 1979, IFC was awarded its first major contract to investigate improvements in MCFC component and system design. In 1990, IFC completed system studies for coal gas and natural gas fueled MCFC systems.

IFC conducted full-size, 0.74 square meter (8 square foot), 20-kW stack tests in 1986 and 1990. By 1991, IFC had successfully addressed the electrolyte migration problem and continued to address performance improvement, increased life, and component cost reduction. In 1992, IFC concluded the DOE funded stack research. Further development is planned under a private sector program. Government property for development and test of fuel cells continues to be available to IFC for use in these efforts under a Cooperative Research and Development Agreement.

Field Test Demonstration and Product Improvement

In late 1992, two highly cost-shared cooperative agreements were signed for field test demonstrations of molten carbonate fuel cell systems at user sites. Fuel Cell Engineering Corporation, a subsidiary of ERC, will build and test a 2 megawatt system in 1994 at a site in Santa Clara, California. M-C Power will build and test a 250 kilowatt system in late-1994 at a hospital site in San Diego, California.

In 1993, product improvement contracts are planned aimed at reducing system costs and increasing performance to enable successful competitive power plants to be introduced in the late 1990s.

Technology Base Contracts

Development of Alternative Cathodes

In FY 1993, ANL will continue their efforts on MCFC anode and cathode fabrication procedures development to improve cell life and reduce costs. This will involve investigations of appropriate cathode microstructures, electrode surface area effects, electrode thickness effects, in-cell testing, effects of cell operational variables, and comparison of performance with existing MCFC data and models. ANL will also provide sample cathode materials to MCFC developers for testing.

Work will continue on evaluating effects of contaminants on fuel cells and improving cell tolerance to contaminants. Work will also continue on other modifications to improve cell life.

ADVANCED CONCEPTS – SOLID OXIDE FUEL CELLS

The SOFC program includes cell, stack and module development and technology base R&D activities.

Stack/Systems Development Contracts

Tubular SOFC Development

During FY 1991, Westinghouse completed fabrication and test of a 20-kW generator. This 20-kW generator consisted of 576, 50-centimeter cells. This unit operated for a total of 3,335 hours with testing on hydrogen, natural gas, and naphtha fuel.

During FY 1992, Westinghouse field tested two 25-kW generators. Each of these generators consists of 1,152, 50-centimeter cells and were manufactured in the pre-pilot manufacturing facility using semi-automated techniques. These units will be field tested off site for approximately 8,000 hours. System analysis activities were conducted to examine the effects of pressurization on cell performance and system economics. Activities to evaluate/develop alternate lower-cost fabrication technologies were also undertaken. Westinghouse continued testing on single cells to study cell scale-up and process cost reduction techniques. Cell endurance has surpassed 30,000 hours in a continuing test.

In 1993, a 20-kW generator is planned to be delivered to an electric utility in California for field testing. It will also contain 50-centimeter cells. Also, in 1993, the first 100-kW generator is scheduled to be delivered to a gas utility in California. Fabrication of the 1-meter long cells for the unit began in 1992.

Monolithic SOFC Development

A technology advancement and development effort for monolithic SOFC at Allied-Signal Aerospace was initiated in September 1989. ANL is a major subcontractor in this development. The most significant progress in FY 1991 was the development of a dense and relatively low sintering temperature interconnect, the development of a stress analysis model, and significant reduction of cell resistance. Intra-cell bonding materials are being investigated. Activities in FY 1992 included scale-up, cell performance improvement, stack performance evaluation, manifolding, quality control and systems analysis. A two-cell stack was successfully fabricated and tested. In 1993, the above work will be continued with the goal of fabricating and testing a larger multi-cell stack of up to 100 watts.

Planar SOFC Development

Development of SOFC employing a planar geometry is planned to begin in 1993 following a competitive selection.

A comprehensive review of the monolithic and planar concepts will be undertaken to evaluate the merits of each approach.

Technology Base Contracts

Alternative Electrolyte Development

In FY 1989, an effort was initiated with Argonne to evaluate/develop alternate materials for a solid state fuel cell which would operate in the 500 to 800 degrees C (900 to 1,500 degrees F) range. Several candidate electrolytes have been screened. Methods for increasing the conductivity were identified. This effort will be redirected in FY 1993 to emphasize SOFC thin film electrolytes.

Interconnect Development

In FY 1988, DOE initiated a project at Pacific Northwest Laboratories (PNL) to develop an alternative process to fabricate solid oxide interconnections via direct sintering. PNL developed a process to fabricate a more highly sinterable interconnect powder. In FY 1990, this process was extended to other alternative interconnection materials for evaluation. This work will continue in FY 1993.

Coal Gas Contaminant Evaluation

A contract was awarded at the end of FY 1989 to Westinghouse to examine the effects of coal-gas contaminants on the performance and life of SOFC's. Various contaminants such as sulfur, ammonia, and hydrochloric acid are being tested for their effect on state-of-the-art SOFC's. Contaminant testing will continue in FY 1993.

SOFC Seal Development

An effort was initiated in FY 1991 with Argonne to evaluate/develop seal materials for solid state fuel cells. Several commercially available cements were evaluated. Seals made from glasses, polycrystalline ceramics, and glass-polycrystalline composites will continue to be evaluated in FY 1993.

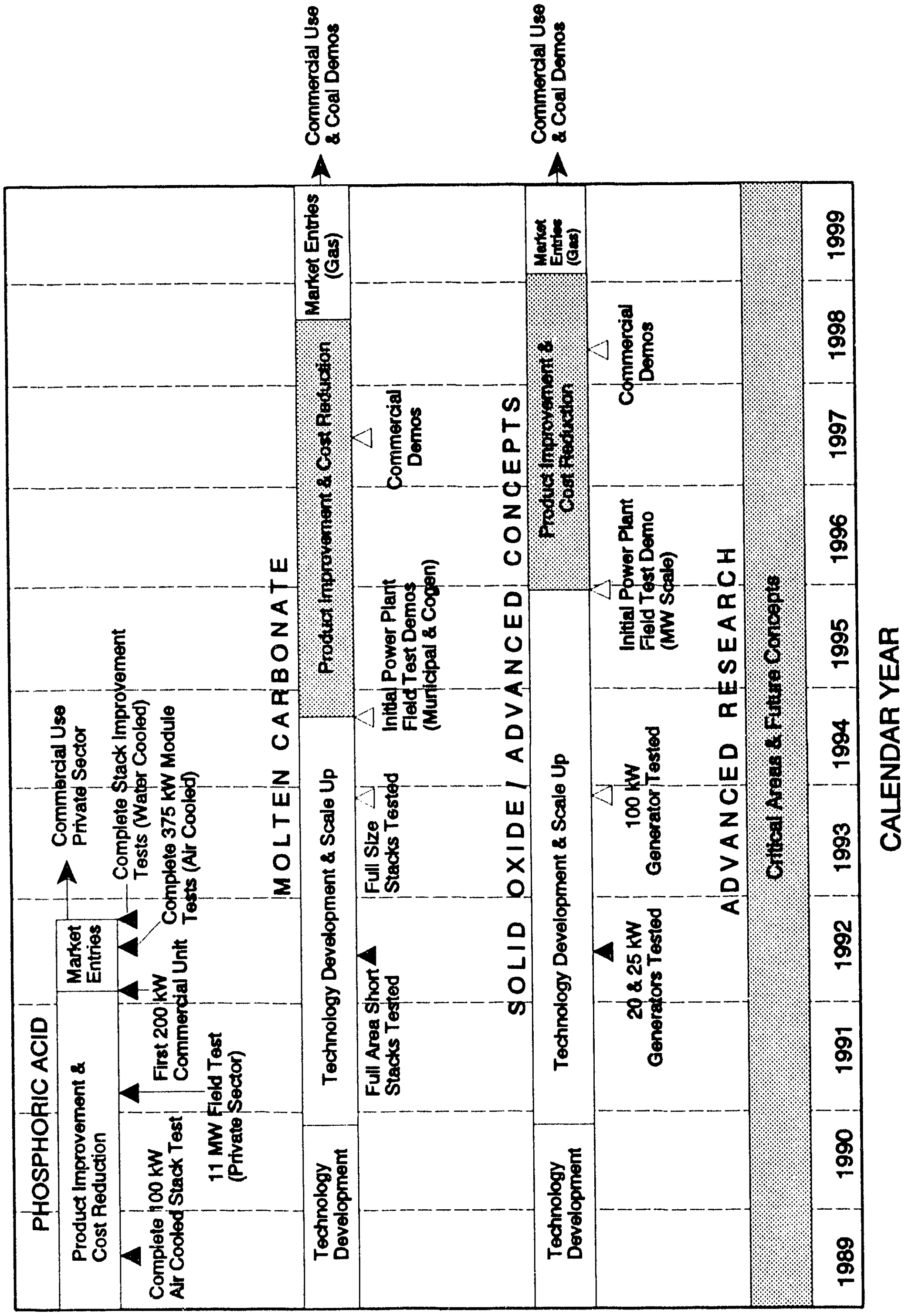
System Analysis

Work will continue at the Morgantown Energy Technology Center to develop a model that will simulate SOFC performance. Various gasification/SOFC system configurations will be assessed to determine the impact of parametric changes on system cost and performance.

PHOSPHORIC ACID FUEL CELLS

The DOE program has funded PAFC development for electric utility and on-site applications. In 1992, funding of development activity for utility applications was concluded. One contract, at IFC, developed the advanced configuration "B" water-cooled cell and stack technology. The other contract, at Westinghouse, developed the gas-cooled cell and stack technology. All DOE sponsored PAFC work was completed in 1992. In 1993, DOE will monitor PAFC private sector activities to provide information for application to advanced fuel cell technologies and will continue cooperative efforts with the DOD fuel cell demonstrations.

EXHIBIT 5
FUEL CELL PROGRAM ACTIVITIES



Water-Cooled Stack Development with IFC

The objective of the IFC contract was to develop water-cooled cell and stack technology required to meet specific performance and cost criteria suitable for a prototype commercial 11 MW to 25 MW PAFC power plant and provide advancements to the 200 kW power plants. The work involved the advanced cell and stack technology whose design is known as configuration "B". The project increased performance and decreased manufacturing cost with respect to configuration "A". The technology was verified through building and testing short stacks. This work was completed in 1992.

Westinghouse Gas-Cooled Stack Development

The objective of the Westinghouse contract was to provide the basic cell and stack technology to establish the gas-cooled PAFC's performance, endurance, and manufacturability. The basic building block module (375-400 kW) was used to demonstrate the performance characteristics for startup, various steady state, transient, and shutdown conditions. This module also verified design, manufacturing, assembly, test, quality, and servicing aspects of the PAFC technology. In 1992, the major effort focused on testing of a 375-400 kW module. This work was concluded in 1992.

VII

OTHER FUEL CELL ACTIVITIES

The DOE fuel cell program is part of a coordinated national fuel cell development effort. The U.S. fuel cell projects are cost shared or co-funded by the GRI, EPRI, electric and gas utility companies, and potential fuel cell manufacturers. Multiple development approaches are being supported in critical development areas to enhance prospects for success and to enable the private sector to establish a viable industry.

Several private sector programs which are being conducted by the GRI and EPRI are summarized below.

GRI

The focus of the GRI fuel cell program is on-site cogeneration and electric utility dispersed power generation equipment fueled with natural gas. These systems can provide cost savings to the gas consumer, distributed generation benefits to electric utilities, and environmental benefits to the nation as a whole. They can also open new business opportunities for the gas industry and enhance the revenues and profits of individual utilities which opt to provide energy service to their customers. Over the past ten years, GRI's primary effort in fuel cells has been to develop the PAFC technology for application in the commercial sector. With the introduction of a 200 kW power plant in 1992, GRI's program emphasis has shifted to supporting the development of more advanced MCFC and SOFC technologies.

GRI's interest in fuel cell technology spans the marketplace from small commercial to industrial to electric utility applications. In energy service applications the power plants are located at the site of the end-user, providing both electrical and thermal energy to the building. The commercial sector requires power plants with ratings from about 30 kW to 1000 kW to serve applications such as offices, restaurants, retail stores, hotels, apartment buildings, and hospitals. The industrial marketplace requires units with capacities from 500 kW to about 40 MW, the availability of high quality heat, and a high degree of flexibility in varying the ratio of electrical and thermal energy products. Electric utility dispersed power generation systems will likely be sized in the 1 MW to 20 MW range, with a strong emphasis on system availability and reliability.

The objectives of the GRI program over the next 5 years are to:

- Develop the stack and balance of plant of early market entry, natural gas fueled MCFC power plants with ratings applicable to commercial, industrial and dispersed utility applications

- Initiate on-site cogeneration MCFC system tests at the 250 kW scale as a smooth transition to market entry product designs in the 500 kW to 2 MW scale

- Integrate and scale up planar solid oxide fuel cell components into small systems that will establish the feasibility of direct utilization of natural gas in planar SOFC and define full-scale component performance

- Initiate on-site cogeneration planar SOFC system tests of the 50-100 kW scale

- Identify and assess alternate materials and processing techniques for solid oxide fuel cell components with emphasis on reducing SOFC operating temperatures

EPRI

The focus of the EPRI fuel cell program is to develop and commercialize electric power plants with the highest possible efficiency and least environmental intrusion. Two general applications are envisioned for the electric utility industry.

- Small modular dispersed generators are envisioned in the near term with efficiency of 50% to 57% and other characteristics suitable for siting in urban areas. In the 1 to 10 MW size and using natural gas or other clean fuel, these plants can be located near the utilities' customers and help alleviate power delivery constraints. In the mid-term as fuel cell plant capital costs decrease, larger scale plants are expected to be used to repower obsolete urban power stations.

- Central station power plants, integrated with coal gasifiers, are envisioned in the long term. These power plants will produce electricity with the highest efficiency and lowest environmental intrusion of any coal-fueled technology known.

Towards these goals, the near-term EPRI projects are aimed at assisting utilities considering the deployment of fuel cells by documenting fuel cell demonstrations, and where necessary, by developing lower-cost components and resolving systems integration problems. The demonstration projects are being conducted in collaboration with utility companies. Projects to develop lower cost plants or to resolve problems are generally conducted in collaboration with DOE or GRI sponsored R&D.

The major technology transfer projects involve helping identify high value early applications for fuel cells. Methods to quantify the values of dispersed generation on a site specific basis have been developed and are in use by many utility organizations. Other high value applications such as use of biogas, and other by-product low energy fuels are being evaluated.

The major objectives of the next five year period are to:

- Complete technical and economic evaluation of the 1 and 11 MW PAFC power plants being demonstrated overseas
- Initiate utility demonstrations of 250 kW and 2 MW MCFC power plants in dispersed generation applications
- Stimulate fuel cell commercialization programs with member utilities
- Define approaches and risks to the development of yet more efficient (49 to 57 percent) (7,000 - 6,000 Btu/kW) fuel cell power plants
- Demonstrate MCFC on coal-derived medium-Btu synthesis gas
- Develop MCFC and SOFC technology applicable for central station utility power plants in the late 1990s

Other related government programs are described in the next section of this report.

VIII

OTHER GOVERNMENT PROGRAMS RELATED TO FUEL CELLS

Within the Office of Fossil Energy, the coal gasification and gas stream cleanup programs are supporting work which is important to the fuel cell program. The gasification program provides a technology base and an analytical and assessment data base for the future use of coal gasifiers with fuel cell systems. The gas stream cleanup program is providing research data on contaminants relevant to molten carbonate and solid oxide fuel cell systems and will provide instrumentation for measuring contaminants as well as technical and economic assessment of gas stream cleanup systems. The DOE Office of Fossil Energy also supports basic research in fuel cell materials and the understanding of fundamental fuel cell processes through the Advanced Research and Technology Development Program.

The DOE Office of Conservation and Renewable Energy is supporting a project to develop fuel cell power plants for transportation applications. A phosphoric acid fuel cell powered bus design is currently being evaluated and development of polymer electrolyte fuel cell components has been underway since 1985. A polymer electrolyte fuel cell powered vehicle program was initiated in 1989.

In addition to these development and application programs, electrochemistry research is also supported by the DOE Office of Conservation and Renewable Energy.

The DOE Office of Energy Research sponsors the Small Business Innovation Research Program. Many researchers, including those developing fuel cells, respond to the yearly solicitations. A number of small businesses who have expertise in MCFC, SOFC, PAFC, and other types of fuel cell technologies have been selected to participate in this program.

NASA has been involved in fuel cell development for space applications since 1960 and has funded the development of alkaline fuel cells presently used on board the space shuttles. Currently, the NASA program is directed towards:

- Low temperature hydrogen-oxygen cells for regenerative and primary space power applications
- Advanced concepts for future space applications

The Department of Defense has been supporting the development of phosphoric acid fuel cells and has participated in the DOE, GRI and utility companies' field test of 40 kW phosphoric acid fuel cell units produced by International Fuel Cells Co.

In FY 1993, DOD is supporting a program to demonstrate and use production units of PAFC power plants by the Army, Air Force, and the Navy. A number of power plants will be operated at sites located on military bases. In FY 1993, DOD is also supporting a program to develop and demonstrate other fuel cell systems. This program will be coordinated with the DOE program and provides opportunities for valuable test results in actual user applications.

In 1990, the Environmental Protection Agency began a program to develop and evaluate a 200 kW class PAFC power plant fueled with landfill gas. A unit is scheduled to operate at a landfill site in California in 1993. A second unit is being developed to operate with the output of an anaerobic digester as fuel. This project was begun in late 1992 and will result in a 200 kW unit being run at a water treatment plant site in Baltimore MD.

IX

INTERNATIONAL ACTIVITIES

The high efficiency, environmental benefits and other attributes of fuel cells (including low noise, modularity and fuel flexibility) have attracted world-wide attention. Japan has embarked on extensive government and private programs to manufacturer and install power plants in that country and abroad. Other countries in the Far East have taken notice and have reacted with their own programs. In Europe, there is grave concern about the effect of emissions on the quality of life. Other areas look to the fuel cell as offering remote power to bring villages out of an intensive manual labor era.

Exhibit 6 shows listings of stationary fuel cell power plants throughout the world which are being operated (or are scheduled to startup in 1993 or 1994) by users who have either purchased or cost shared the units. Units which are being operated by the developers themselves are not included. This information is taken from a paper presented at the 1992 Fuel Cell Seminar (held in Tucson, Arizona); "Fuel Cell Demonstrations World-Wide" by T. Sugimoto, NEDO; L. Sjunnesson, Sydkraft; and E. Gillis, EPRI.

Exhibit 6. FUEL CELL POWER PLANTS THROUGHOUT THE WORLD

Type of Fuel Cell	Country of Location	User	Manufacturer	Capacity kW	Number of Units
PAFC	Austria	Austrian Ferngas	ONSI	200	1
	Denmark	Naturgas Syd Sonderjyllands	ONSI	200	1
	Finland	Imatran Voima	ONSI	200	1
	Germany	Ruhrgas	ONSI	200	1
		HEAG	ONSI	200	1
		Thyssengas	ONSI	200	1

Type of Fuel Cell	Country of Location	User	Manufacturer	Capacity kW	Number of Units
PAFC	Italy	Aem	Ansaldo/IFC/ Haldor Topsoe	1300	1
		Ansaldo/CLC	ONSI	200	1
		SNAM Eniricerche	Fuji	50	1
	Japan	Kansai Electric Power Co.	Fuji	5,000	1
		Kansai Electric Power Co.	Fuji, Mitsubishi	50 & 200	15
		Kansai Electric Power Co.	Fuji, Mitsubishi	50 & 200	6
		Tokyo Gas Company	Toshiba	1,000	1
		Tokyo Gas Company	Fuji	50 & 100	10
		Tokyo Gas Company	ONSI	200	10
		Tokyo Electric Power Co.	IFC/Toshiba	11,000	1
		Tokyo Electric Power Co.	Fuji, Mitsubishi	50 & 200	2
		Hokkaido Elec. Power Co.	Fuji	200	1
		Tohoku Elec. Power Co.	Fuji	50	2
		Chubu Elec. Power Co.	Fuji, Mitsubishi	50 & 200	3
		Hokuriku Elec. Power Co.	Fuji	50	1
		Chugoku Elect. Power Co.	Fuji, Mitsubishi	50, 100, 200	4
		Sikoku Elec. Power Co.	Fuji, Mitsubishi	50	1
		Kyusyu Elec. Power Co.	Fuji, Mitsubishi	50, 200	2
		Electric Power Dev. Co		100	1
		Toho Gas	Fuji	50 or 100	2
		Toho Gas	ONSI	200	1
		Osaka Gas	Fuji	50, 100	15
		Osaka Gas	Fuji	500	1
		Osaka Gas	ONSI	200	10
		Saibu Gas	Fuji	50	1
		Various End Users	Fuji, Mitsubishi	50, 100, 200, 500	30
		Petroleum Energy Center	Fuji, Mitsubishi	50, 200	3
	Spain	Enagas	Fuji	50	1
	Sweden	Sydkraft	Fuji	50	1
		Sydkraft	ONSI	200	1
		Vattenfall	Fuji	50	1

Type of Fuel Cell	Country of Location	User	Manufacturer	Capacity kW	Number of Units
PAFC	Switzerland	SIG	ONSI	200	1
	United States	Atlanta Gas Light	ONSI	200	1
		Brooklyn Union Gas	ONSI	200	1
		Consolidated Natural Gas	ONSI	200	1
		Equitable Gas	ONSI	200	1
		National Fuel Gas	ONSI	200	1
		People's Gas, Light & Coke	ONSI	200	1
		Southern California Gas	ONSI	200	10
		Others	ONSI	200	3
MCFC	United States	Pacific Gas & Electric	Energy Research Corp.	20, 70 & 120	3
		City of Santa Clara, CA	Energy Research Corp.	1800	1
		UNOCAL	M-C Power	250 kW	1
		San Diego Gas & Electric	M-C Power	250 kW	1
SOFC	Japan	Kansai Electric Power Co.	Westinghouse	25	1
		Osaka Gas	Westinghouse	25	1
	United States	So. California Edison	Westinghouse	25	1
		So. California Gas	Westinghouse	100	1

In Japan, the government, the gas and electric utilities industries, universities, and other institutions have put together cooperative, synergistic programs. The New Energy and Industrial Development Organization is the focal point for the government to coordinate the development of PAFC, MCFC, SOFC, and Polymer Electrolyte Fuel Cell (PEFC) technology, feeding the results into the manufacturer/user sectors. Companies sponsor the development of specific power plants, some with cooperative government/industry cost shared programs to demonstrate the technology. These activities have now culminated in the installation and operation of approximately 30 MWe of fuel cell power plants. The government has stipulated that Japan will plan to install 2,250 MWe of PAFC plants in Japan by the year 2000.

In addition to sponsoring numerous PAFC demonstrations (totaling over 20 MW), NEDO has instituted a plan to cost share approximately one third of the purchase cost of on-site co-generation PAFC power plants during 1992 through 1994. By the year 2010, 10,700 MWe of PAFC and MCFC plants are planned to be installed. Manufacturers have built and are building fabrication facilities to respond to this government directive.

In Europe there are significant fuel cell development programs in Germany, Italy, and the Netherlands. Other European countries with fuel cell development programs are the United Kingdom, Spain, and Belgium. The Commission of European Communities has organized a program to support fuel cell R&D at European research institutions and cosponsor demonstration in various member countries. The fuel cell effort in Europe is concentrated on applying U.S. and Japanese PAFC stacks incorporated with European balance of plant, on developing MCFC for stationary use, on SOFC in which the Europeans feel they hold a competitive advantage, and on PEFC for vehicular use. U.S. and Japanese PAFC units are being tested to gain insight into the technology.

Germany is expending serious effort on developing a hydrogen economy. Fuel cell development is an important part of this effort. Individual companies in Germany also have development programs on MCFC, SOFC and PEFC. Italy has a large program demonstrating PAFC plants, sized up to 1 MWe, using U.S. and Japanese PAFC stacks with European balance of plants. The Netherlands is developing their own MCFC stacks and Belgium is developing alkaline fuel cell systems for transportation purposes. The U.K. had renewed their fuel cell developments concentrating on PEFC technology.

Other countries have reported various degrees of fuel cell activities. Noteworthy are the Australian and Canadian activities. Ballard Power Systems, Inc. of Canada has become one of the leaders of PEFC development. Companies in other countries, including the U.S. and U.K., are using Ballard fuel cell stacks in various PEFC demonstration programs. Australia has recently announced a SOFC development program. Additional countries which are involved with either smaller development programs or have demonstrations are: Austria, Brazil, China, Denmark, Finland, India, Korea, Norway, Spain, Sweden, Switzerland, Russia, and Taiwan.

The Department of Energy continues to monitor progress of worldwide fuel cell activities.

END

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