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Fuel Cell Systems Program Plan

Fiscal Year 1994

MASTER

**U.S. Department of Energy
Assistant Secretary for Fossil Energy
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Washington, DC 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 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 the potential for highly efficient energy conversion, enhancement of environmental quality and stimulating creation of a major new manufacturing industry.

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 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.

Private sector participants with the Department of Energy include the Electric Power Research Institute (EPRI), the Gas Research Institute (GRI), electric and gas utilities, universities, manufacturing companies and their suppliers. The Department of Energy program is also coordinated with fuel cell development and demonstration efforts by the Department of Defense (DOD) initiated in FY 1993 and continuing in FY 1994. The DOD effort is focused on demonstration and use of early fuel cell products at defense bases and development of durable operating units.

The Department of Energy has proposed an initiative, targeted to begin in FY 1995, to accelerate commercialization of fuel cells. The initiative forms part of the President's Climate Change Action

Plan, published in October, 1993, addressing reduction of greenhouse gas emissions by the year 2000. The proposed fuel cell initiative aims to stimulate market growth of fuel cell products by using rebates to early buyers to increase manufacturing volume and reduce unit cost and through accelerated field testing of advanced products. Congressional approval for this initiative has not been given and is expected to be deliberated in the FY 1995 appropriation procedure.

Also within the Department of Energy, the Office of Energy Efficiency and Renewable Energy is participating in sponsoring development of fuel cells for transportation propulsion systems. The program for transportation applications is focused primarily on the development of polymer electrolyte or proton exchange membrane fuel cells, and also includes a demonstration program for phosphoric acid fuel cell buses and analysis of fuel cells for heavy duty transportation such as trucks and trains. DOE fuel cell research, development and demonstration efforts are part of the national fuel cell development and commercialization efforts which also involve private sector funding. This Plan describes the fuel cell activities of the DOE 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 efficiency and economic effectiveness of power generation through the development and commercialization of cost-effective, efficient and environmentally desirable 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.

The overall schedule of the fuel cell program is shown in Exhibit 1.

EXHIBIT 1 OVERALL FUEL CELL PLAN

The activities shown in Exhibit 1 include basic and applied research and development, proof-of-concept activities, precommercial demonstrations, and associated commercial scale activity. Some of the key elements of the program include:

- Development and demonstration of MCFC and SOFC technologies for electric utility, commercial and industrial applications
- Cost reduction and durability improvements to enable production of competitive market entry power plants
- Evaluation of advanced fuel cell concepts and configurations for electric utility, industrial, residential and commercial sector applications

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- **Support of advanced research needed to develop fuel cell technologies**
 - **Cooperation with commercialization activities**
 - **Coordination with fuel cell development and testing activities of the Department of Defense, DOE's Office of Energy Efficiency and Renewable Energy, the Electric Power Research Institute, the Gas Research Institute, the National Aeronautics and Space Administration, electric and gas utilities and manufacturing companies.**

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 market entry of these power plants fueled by natural gas in the late 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 1994 are \$51.8 million.

I

INTRODUCTION

Fuel cell power systems are emerging power generation technologies for the efficient, economical and environmentally acceptable production of electricity. In some applications the by-product heat can also be efficiently used in cogeneration. Fuel cells produce electricity through the electrochemical oxidation of a fuel. They can be operated on a variety of fuels, including natural gas, coal gas, land fill gas and renewable fuels. First market entry units are fueled by natural gas. Fuel cells offer the opportunity for a major new manufacturing industry.

System studies 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 are unique in that they offer high efficiency and low emissions even at part-load and in small sizes. Because of their efficiency, fuel cells will help in reducing CO₂ emissions that have been linked to "global warming."

Additional benefits are the environmentally desirable operating characteristics offered by fuel cells. 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

1 Efficiencies stated on higher heating value basis.

and populated areas and early commercial units have been installed in hotels, office buildings and similar locations. The overall program goal is to develop and commercialize cost-effective fuel cell systems which utilize these advantages.

Development of fuel cell technologies has been underway in the United States with funding support provided by both public and 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 of development and demonstration is also provided by fuel cell developers and potential users.

This document describes the fuel cell program of the DOE Office of Fossil Energy and its coordination with other fuel cell activities.

II

GOAL AND OBJECTIVES

The goal of the fuel cell program is to increase energy efficiency and economic effectiveness 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 by the late 1990s.

Activities in support of the goal and objectives include:

- Supporting development of MCFC and SOFC systems
- Expediting the application of fuel cells 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

- Coordinating with private sector and Department of Defense activities to accelerate development and use of fuel cell systems.

Development targets for system efficiency and capital cost 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 • On-Site	\$800/KW \$1000/KW	\$600/KW \$800/KW
Coal-Fueled Plant: • Electric Utility	\$1200/KW	\$1000/KW
Efficiencies (2) Natural Gas-Fueled Plant: • Electric Utility • On-Site	60% 55%	55% 50%
Coal-Fueled Plant: • Electric Utility	50%	50%

- 1) Power plant capital cost targets are in mature production, 1990 dollars and include installation costs.
- 2) Efficiency targets are for electric generation only and are 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 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, module and power plant designs by the early 1990s
- To define the economics and performance characteristics of power plant configurations by the mid 1990s
- To identify and resolve technical barriers to commercialization by the late 1990s
- To demonstrate feasibility and market entry through testing of cells, stacks and systems by the late 1990s.

The objective of the now completed PAFC development program was to reduce the cost and improve the performance of PAFC systems to enable private sector commercialization. Over fifty 200 kilowatt units have been manufactured and sold by International Fuel Cells Corporation. A remaining hurdle is the realization of lower unit costs through increased manufacturing volume. The DOE is continuing to cooperate with the private sector and a Department of Defense program for expanded use of PAFC units.

Experience from the PAFC program and other programs 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 prospective users and manufacturers to more realistically evaluate requirements concerning performance, costs, warranties and the values of "externalities" in market place decisions.

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

III

PROGRAM STRATEGY

The program 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 of fuel cells. 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. The DOE is cooperating with the private sector and a program within the Department of Defense for purchase of commercially produced fuel cell power plants for use at military bases.

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) simplifies use of natural gas as a fuel and makes the MCFC a more efficient user of coal-derived fuels in integrated systems.

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 cell operating temperature can result in good thermal integration into natural gas or coal based systems with minimum need for heat exchangers. These systems can provide high grade heat for process steam and/or various bottoming cycles, thus achieving high overall

system efficiency. R&D conducted over the last few years has advanced the SOFC technology substantially.

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

- Product improvement and cost reduction to meet market competition
- Continued funding of development and improvement needed for field verifications and prototype demonstrations
- Continued private sector commitments to addressing user requirements and obtaining production capabilities needed to reduce market entry risks and assure commercialization
- Establishment of joint ventures and teaming relationships to enhance private sector financial resources for 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 durability, cost and customer benefits
- 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 DOE program includes these strategic elements.

- Support development of MCFC and SOFC systems through the demonstration plant stage (with increasing levels of cost sharing).
- Facilitate technology transfer within the private sector by stimulating interactions between 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.**
- **Structure DOE contracts with fuel cell developers to encourage early manufacturing and commercialization.**
- **Cooperate with PAFC private sector activities to provide information for application to advanced fuel cell technologies and to accelerate fuel cell commercialization.**
- **Coordinate with Department of Defense activities in development, demonstration and utilization of fuel cell systems.**
- **Evaluate alternative fuel cell materials, components, configurations and concepts.**

IV

TECHNOLOGY DESCRIPTION

A basic fuel cell consists of two electrodes, the anode and cathode, separated by an electrolyte. Fuel cell types are typically 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., natural gas or coal) 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.

EXHIBIT 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 composed of alkali metal 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

Solid oxide fuel cells are being developed which use a ceramic electrolyte of yttria stabilized zirconia and operate 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 additional power production 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 (PEM) 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 Energy Efficiency 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.

TECHNICAL STATUS

MOLTEN CARBONATE FUEL CELL STATUS

The MCFC status has advanced to the stage of scaling up to commercial size stacks, integrating with the balance of plant and preparing for field testing of units. Developers have pilot plant manufacturing facilities with capacities of 2- to 3-megawatts (MW) per year. Subscale stack testing also continues with emphasis on testing that directly supports the pilot manufacturing and commercial-scale demonstration efforts. Private sector (i.e., utilities and manufacturing industries) and regional (state and local) interest and funding support remain strong and industry is proceeding to implement commercialization plans. Domestic MCFC developers are Energy Research Corporation (ERC), M-C Power Corporation and International Fuel Cells (IFC).

ERC has constructed a pilot manufacturing facility in Torrington, Connecticut which is manufacturing full size 120 kW test stacks with cell areas of .56 square meters each (6 square feet). Manufacturing capacity of this plant is 2 to 3 MW/year. Two full size stacks were tested in 1993 and additional testing is planned for 1994. Assembly of full size stacks is also planned in 1994 for a 2 MW field test described below.

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 16 stacks. The cost-shared power plant is scheduled to be installed and tested in 1994 and 1995 at a municipal utility site in Santa Clara, California.

Another developer, M-C Power, is developing an internally manifolded MCFC design and has tested three 20 kW stacks using full area cells of 1 square meter (11 square feet). Their full scale stack will contain approximately 250 cells and produce 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 1994 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 estimated at 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 to be tested at a site in San Diego, California in 1995.

In addition to the two continuing efforts described above, another developer, IFC, has concluded DOE funded research contracts to improve MCFC stack performance. Further development is planned under private sector sponsorship. This private sector effort is being assisted through a Cooperative Research and Development Agreement between DOE and IFC which makes certain development equipment available to IFC and keeps DOE informed on program progress.

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

Conceptual 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) 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 in Exhibit 2) are achievable.

In cooperation with an initiative by the American Public Power Association, ERC has developed a commercialization plan that aims to have, by 1977, orders for over 100 MW of early production units. A group of electric and gas utilities, known as the Fuel Cell Commercialization Group, (presently approximately 40 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 around 1998. A number of gas and electric utilities and other companies have formed a group known as the Alliance to Commercialize Carbonate Technology to facilitate commercialization of the M-C Power technology.

SOLID OXIDE FUEL CELL STATUS

Several SOFC geometric configurations are now under development or are being evaluated in the United States. These have been characterized as tubular and various monolithic or planar approaches. The tubular configuration is much farther along the development cycle than the other SOFC approaches. The planar and monolithic approaches may offer advantages in power density, efficiency and fabrication costs, but are at a very early development stage and projections have not yet been proven.

Westinghouse Electric Corporation has been the major developer of the tubular configuration. 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 an electric utility test site in California in 1994. 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 40,000 hours. In addition,

cells with self supporting electrodes (eliminating the support tube) and longer cells of up to 200 centimeters are being tested to improve performance, and reduce cost. 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 tested in 1995.

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. International Fuel Cells (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 delivered. The 200 kW power plant is currently a first of a kind cogeneration system. The cost of these units is expected to decrease from the initial market entry levels with increased production and with continued technology improvement by industry.

The Department of Defense began implementing a fuel cell demonstration and use program in FY 1993 and funding was also included in the FY 1994 Defense Appropriations. Under this program the Army, Navy and Air Force will each purchase and install commercially manufactured PAFC fuel cells. The DOE is cooperating in these activities to provide information 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. In addition, an Advanced Research category provides for fundamental research on key technology issues critical to the program. Cooperative efforts are also continuing regarding fuel cell activities of other agencies and the private sector.

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

MOLTEN CARBONATE FUEL CELLS

Multi-year contracts were negotiated in 1990 with M-C Power and ERC to develop full-size stacks for natural gas and coal-fueled system designs. Full size stack tests in 1993 and 1994 are resulting from these contracts. The first field test power plants are scheduled for installation and operation in 1994 and 1995. Multi-year cooperative agreements to develop packaged power plant modules and reduce costs are planned to begin in 1994. Supporting research is also continuing.

Stack/System Development, Scale-up and Testing

ERC: Internal Reforming, Externally Manifolder MCFC

In FY 1991, ERC completed the assembly of a pilot manufacturing facility in Torrington, Connecticut. This facility is currently manufacturing full-area, 0.56 square meter (6 square foot), components, and full size, 120-kW test stacks.

EXHIBIT 5 FUEL CELL PROGRAM ACTIVITIES

In FY 1992, ERC tested a 70-kW, 0.37 square meter (4 square foot), natural gas fueled MCFC stack at Pacific Gas and Electric in San Ramon, California. Also in FY 1992, ERC entered into a cooperative agreement with DOE for fabrication of full-size stacks for a natural gas fueled MCFC 2-MW field test demonstration. The ERC field test is to be conducted at a municipal utility site in Santa Clara, California, and is funded by DOE, EPRI, and the Santa Clara Demonstration Group.

In FY 1993 ERC began testing a 20-kW coal-fueled MCFC stack on a Destec coal gasifier slip stream in conjunction with an EPRI initiative. ERC also conducted activities in stack scale-up and tested two full-area, 0.56 square meter (6 square foot), 120-kW MCFC stacks.

In FY 1994 ERC is completing stack scale-up efforts with fabrication and test of a 3rd full area stack and is fabricating field test stacks and balance of plant. Installation of the 2-MW field test power plant is scheduled to begin in Santa Clara, California.

M-C POWER: External Reforming, Internally Manifolderd MCFC

In 1991, M-C Power completed the assembly of a pilot manufacturing facility capable of making full-area, 1 square meter (11 square foot) cell and stack components. A test facility which can accommodate full-area stacks of up to 20-kW was also completed and subscale, 0.09 square meter (1 square foot), 24-cell and 70 cell stacks were tested.

In FY 1992 M-C Power continued development, testing and scale up efforts. The first full area, 20-kW stack was fabricated and tested.

M-C Power tested two additional 20-kW stacks in FY 1993 and completed plans for full size stack testing. The company also began fabrication of components for the pressurized, full size 250-kW stack test at the UNOCAL Science and Technology Center in Brea, California, scheduled for FY 1994. Manufacturing and test

capability were also expanded at M-C Power. A fourth full area, 20-kW stack is to be fabricated and tested in FY 1994.

A test facility capable of acceptance testing 250-kW stacks is to be completed in FY 1994 at M-C Power.

M-C Power has also entered into a cooperative agreement for a full-size natural gas fueled MCFC power plant field test. The co-generation power plant will be operated at a site in San Diego, California. The field test is funded by DOE, GRI, and San Diego Gas and Electric. Installation and testing is scheduled for 1995.

Product Improvement and Cost Reduction

In 1994, cost improvement cooperative agreements are planned aimed at reducing system costs and obtaining integrated packaging of the power plants to enable competitive power plants to be introduced in the late 1990s.

Advanced Research and Technology Development - MCFC

Efforts by several contractors and laboratories provide supporting research and a technology base which is applicable to more than one of the MCFC development approaches. Activities in FY 1994 will address the following areas:

- Modified cathode fabrication and life testing
- Corrosion understanding and control
- High power density operation
- Fuel contaminants; identification, long term effects, improving cell tolerance to contaminants
- Component and materials studies applicable to a number of areas including contact resistances and component durability,
- System analyses and market studies

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 their first multi-kilowatt unit, a 20-kW generator containing 576 cells, each 50 centimeters long. This unit operated for over 3000 hours with testing on hydrogen, natural gas, and naphtha fuel.

During FY 1992 and 1993, Westinghouse operated two 25-kW generators at customer sites. Each of these generators consists of 1,152, 50-centimeter cells and were manufactured in the pre-pilot manufacturing facility using semi-automated techniques. System analysis activities were conducted to examine the effects of pressurization on cell performance and system economics. Materials issues and lower-cost fabrication techniques were also undertaken. Westinghouse continued testing of numerous single cells in scaling up to cell lengths of 100 and 200 centimeters. A cell endurance test has surpassed 40,000 hours.

In 1994, a 20-kW generator is planned for delivery to Southern California Edison and a 100-kW generator is scheduled for testing in 1995. Efforts will also continue on cost reduction, pressurized operation and layouts for a 1-MW module.

Planar and Monolithic SOFC Development

A competitive selection process was begun in FY 1993 and contracts are to be initiated in FY 1994 to proceed with proof-of-concept and development of alternative SOFC concepts and configurations.

Planar cell configurations have been under development in the private sector by several groups and DOE has been funding a contract for development of a monolithic concept by Allied-Signal

Aerospace Corporation. Argonne National Laboratory has been a major subcontractor in the monolithic concept development. Laboratory tests of 2 and 3 cell monolithic units have been performed.

Advanced Research and Technology Development - SOFC

Efforts by several contractors and laboratories provide supporting research and a technology base which are applicable to a range of SOFC concepts and development approaches. Activities in FY 1994 will address the following areas:

- Ceramic powder synthesis and processing technologies for lower cost
- Materials and application methods for thin ceramic layers and components
- Seals applicable to various SOFC concepts
- Materials studies for better understanding of phase relations in SOFC materials
- Interactions among components including areas related to expansion matching and bonding
- System analysis and evaluation of alternative concepts

PHOSPHORIC ACID FUEL CELLS

The DOE program has funded PAFC development for electric utility and on-site applications. DOE sponsored PAFC development work was completed in 1992. DOE continues to monitor PAFC private sector activities and continues cooperative efforts with the Department of Defense fuel cell demonstrations.

VII

COORDINATED FUEL CELL ACTIVITIES

The DOE fuel cell program is part of a coordinated national fuel cell development and commercialization 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. Close coordination is also maintained with fuel cell activities being funded within the Department of Defense.

Programs which are being conducted by the GRI, EPRI and the Department of Defense and other related programs are briefly summarized below.

Gas Research Institute

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 while maintaining some monitoring activity in the performance of the PAFC units.

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 GRI budget planned for fuel cells in FY 1994 is approximately \$3.5 million.

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

- Develop the stack and balance of plant for 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
- Identify and assess alternate materials and processing techniques for solid oxide fuel cell components with emphasis on reducing SOFC operating temperatures
- Assist in PAFC deployment efforts.

Electric Power Research Institute

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 EPRI budget planned for fuel cells in FY 1994 is approximately \$6 million in direct funding plus an additional \$6 million (referred to as "tailored collaboration") involving co-funding by EPRI and member utilities.

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

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- **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**

Department of Defense

The Department of Defense was active in the evaluation of fuel cell power plants in the 1980s and participated in the DOE, GRI and utility companies' field test of 40-kW phosphoric acid fuel cell units produced by International Fuel Cells Corporation.

In FY 1993 the Department of Defense initiated a program to demonstrate and use commercially produced fuel cell power plants at sites located on military bases. Also in FY 1993, DOD initiated a program to further develop fuel cell power plants for defense applications. This effort is emphasizing the need for durability and operation on logistic diesel and jet fuels. These programs are continuing in FY 1994 and close coordination between the two Departments is being maintained to insure that synergistic benefits are realized. DOD funding budgeted for these efforts in FY 1994 is \$24 million for procurement and operation of fuel cell power plants and \$11.4 million for fuel cell development within the Advanced Research Projects Agency.

Other Related Programs

Within the Office of Fossil Energy, the gas stream cleanup and coal gasification programs are supporting work which is important to the fuel cell program. 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 fuel cleanup systems. 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 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 Energy Efficiency and Renewable Energy is supporting a project to develop polymer electrolyte fuel cell power plants for transportation applications. A phosphoric acid fuel cell powered bus design is also currently being evaluated.

In addition to these development and application programs, the DOE Office of Energy Efficiency and Renewable Energy is also supporting research applicable to industrial electrochemistry and fuel cell systems.

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 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 Environmental Protection Agency has been funding a program to develop and evaluate a 200 kW class PAFC power plant fueled with landfill gas. A unit has been built and is scheduled to operate

at a landfill site in California. A second unit is being developed to operate with the output of an anaerobic digester as fuel.

The Department of Energy has proposed an initiative, targeted to begin in FY 1995, to accelerate commercialization of fuel cells. The initiative forms part of the President's Climate Change Action Plan, published in October, 1993, addressing reduction of greenhouse gas emissions by the year 2000. The proposed fuel cell initiative aims to stimulate market growth of fuel cell products by using rebates to early buyers to increase manufacturing volume and reduce unit cost and through accelerated field testing of advanced products. Congressional approval for this initiative has not been given and is expected to be deliberated in the FY 1995 appropriation procedure.

VIII

INTERNATIONAL ACTIVITIES

The high efficiency, environmental benefits and other attributes of fuel cells (including low noise, modularity, and fuel flexibility) continue to attract world-wide attention. Approximately 250 PAFC units, 35 MCFC stacks, and 12 SOFC modules have been or are being tested or used. Total capacity of these fuel cells is approximately 45 MWe. Manufacturers in the U.S. have exported approximately thirty-three PAFC 200 kW plants, at least eighteen 675 kW PAFC stacks, two SOFC 25 kW modules, and at least one MCFC system. Japan has embarked on extensive government and private programs to manufacture, install and export fuel cell power plants for environmental and economic advantages. Other countries in the Far East have taken notice and have reacted with their own programs. In Europe, fuel cell development is emphasized due to concern about the effect of emissions on the quality of life. Other regions look to the fuel cell as offering convenient electrical power and a means for improvement in the quality of life in many remote areas and villages.

The majority of fuel cell applications and tests to date outside the U.S. have been in Japan and European countries. Some of these are summarized below.

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. In addition to sponsoring numerous PAFC demonstrations (totaling 20 MWe), the government has instituted a cost sharing program where approximately one-third of the purchase cost of an on-site cogeneration PAFC power plant is available for units installed during 1992 through 1994. There is reported to be a high probability that this program will be extended into FY 1995 and FY 1996. The government has stipulated that Japan will plan to install 2,250 MWe of PAFC plants by the year 2000. By the year 2010, 10,700 MWe of PAFC and MCFC plants are planned to be installed. Manufacturers have and are building fabrication facilities to respond to this government directive.

In Europe, significant fuel cell development programs have been identified in Germany, Italy, the Netherlands, Belgium, Denmark, Norway, and Switzerland. The Commission of European Communities is conducting a program to support fuel cell R&D at European research institutions and cosponsor demonstrations in various member countries through cost sharing. The fuel cell effort in Europe is focused on applying U.S. and Japanese PAFC stacks to systems which incorporate European balance of plant; on developing MCFC for stationary use; on developing SOFC (the fuel cell technology in which the Europeans feel they hold a competitive advantage); and on developing PEFC for vehicular use. U.S. and Japanese PAFC units are currently being tested to gain insight into the technology.

Among the programs of individual European countries, Germany is developing fuel cells as an important part of effort aimed at developing a hydrogen economy. 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, and in using U.S. and Japanese PAFC stacks with European balance of plants. The Netherlands is developing MCFC stacks and has recently started a SOFC program. Belgium has developed a significant alkaline fuel cell technology and is seeking to apply it for transportation purposes. The U.K. has renewed their fuel cell development activities and is concentrating on SOFC and PEFC technology.

Other countries have reported various degrees of fuel cell activities. Noteworthy are the Canadian and Australian activities. Ballard Power Systems, Inc. of Canada has become one of the leaders in Polymer Electrolyte Fuel Cell (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 and commercialization program. Additional countries which are involved with either smaller development programs or have demonstrations are: Austria, Brazil, China, Finland, India, Korea, Norway, Spain, Sweden, Russia, and Taiwan.

The Department of Energy continues to monitor the progress being demonstrated in the development and early commercialization of fuel cells throughout the world.

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