U.S. Fuel Cell Research and Applications: 1960 to 1989

**B. R. Kinzey
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ABSTRACT

This paper provides an overview of the major fuel cell research and development (R&D) programs funded by the U.S. government and the private sector, with a particular focus on terrestrial applications. Included in this overview is information on funding levels, project descriptions and goals, and selected accomplishments. Brief assessments as to the proximity of commercialization for each of the primary types of fuel cells are also furnished.

EXECUTIVE SUMMARY

Fuel cells offer a clean, potentially low-cost, high-efficiency means of producing electricity from fossil fuels. Furthermore, it is believed that this technology can be adapted to virtually any application, from large-scale power generation to electric vehicle propulsion. The United States, as well as numerous other countries, has made considerable investments in fuel cell technology for these reasons.

PURPOSE AND SCOPE

This paper provides an overview of the major fuel cell research and development (R&D) programs funded by the U.S. government and the private sector, with a particular focus on terrestrial applications. Included in this overview is information on funding levels, project descriptions and goals, and selected accomplishments. Brief assessments as to the proximity of commercialization for each of the primary types of fuel cells are also furnished.

CURRENT STATUS

Five major types of fuel cells have been included in this report:

- alkaline fuel cells (AFCs)
- phosphoric acid fuel cells (PAFCs)
- molten carbonate fuel cells (MCFCs)
- proton exchange membrane fuel cells (PEMs)
- solid oxide fuel cells (SOFCs).

Phosphoric acid fuel cells (PAFCs) are the furthest along in development towards commercial terrestrial applications. There are demonstration programs ongoing both in the U.S. and other countries (e.g., Japan and Italy). Both U.S. and Japanese companies have actually quoted prices for commercial PAFC installations in onsite power generation applications, but neither has yet publicly announced the sale of any of these units.

NASA has been employing alkaline fuel cells (AFCs) in space applications since the Apollo program in the 1960s. Current state-of-the-art systems require pure feed streams of hydrogen and oxygen, however, which makes them impractical for more conventional terrestrial applications. Development of an economical fuel reformer (fossil fuel to hydrogen gas) could alter this situation. There are no current U.S. efforts examining AFCs for terrestrial applications.

The remaining three fuel cell technologies have significant technical hurdles to overcome before they can be commercially feasible. Commercialization targets for molten carbonate fuel cells (MCFCs) and solid oxide fuel cells (SOFCs) are currently focused around the year 2000 (DOE 1988), with targets for proton exchange membrane fuel cells (PEMs) sometime after that. All of the technologies are discussed in further detail in Section 2.

HISTORICAL FUNDING

Table S.1 shows historical funding for fuel cell R&D by the federal government. The primary source of data for the Department of Defense (DOD) and the National Aeronautics and Space Administration (NASA) were project briefs (summary sheets) submitted to the Interagency Advanced Power Group (IAPG). These submissions are voluntary, and therefore this funding information is likely incomplete and probably underestimates real expenditures for fuel cell R&D by these agencies. Funding information for the Department of Energy (DOE) and the Energy Research and Development Administration (ERDA) was obtained from Congressional Appropriations Hearings documents and is believed to be more comprehensive.

As can be seen from Table S.1, DOE has been the principle source of federal funding (providing 66%) for fuel cell research in the U.S. Research conducted by DOE on PAFC technology comprises over \$200 million of the \$359 million shown in Table S.1. This funding was primarily directed at developing economical units for the large-scale conversion of coal or coal-derived fuels into electricity.

ERDA is second in terms of overall expenditures for fuel cell research. Since ERDA was a predecessor of DOE, it is not surprising that ERDA efforts have also revolved primarily around PAFC technology for coal conversion.

TABLE S.1. U.S. Federal Funding for Fuel Cell RD&D, 1960-1988
(current dollars, in thousands)

Year	Agency							Total	1988\$
	(a)	(a)	(a)	(a)	(a)	(a)	(b,c)		
	DARPA	Army	Navy	USAF	NASA	ERDA	DOE	(d)	(e)
1960	148	326	361					836	3,289
1961	144	213	566	96			1,019		3,982
1962	1,290	750	370	397	4,455			7,261	27,714
1963	2,780	1,007	59	432	4,448			8,725	32,800
1964	2,495	844	146	380	8,727			12,592	46,638
1965	2,322	665	50	341	9,117			12,496	44,948
1966	4,500	1,354	50	872	12,803			19,579	67,982
1967		1,264		1,239	1,577			4,080	13,831
1968		1,030		629	724			2,382	7,685
1969		501	850	969	377			2,697	8,248
1970		1,180	760	276	641			2,857	8,281
1971		1,752	658	335	1,308			4,053	11,104
1972		288	394	661	2,652			3,995	10,458
1973		339	136	325	1,267			2,068	5,080
1974		119		307	407	1,100		1,933	4,355
1975		268	878 ^(f)	170	675	750		2,741	5,628
1976		361	878 ^(f)		544	3,674		5,457	10,514
1977		1,444	878 ^(f)		276	17,800 ^(g)		20,398	36,886
1978		400	878 ^(f)	59	386	33,000 ^(g)		34,723	58,555
1979		551	878 ^(f)	112	100		41,452	43,093	65,691
1980		4,178			200		26,500	30,878	43,861
1981		2,892		287	70		32,012	35,261	45,675
1982		2,760		4,100	375		35,264	42,499	51,701
1983	300	1,832		560	220		30,738	33,650	39,403
1984	65	1,106		2,928	215		43,400	47,714	53,914
1985		300		2,724	480		41,272	44,776	49,151
1986	2,807	221	67	1,850	40		34,857	39,842	42,567
1987		250	82	2,219	40		33,734	36,325	37,565
1988							39,700	39,700	39,700
Total	16,852	28,194	8,939	22,171	52,222	56,324	358,729	543,629 ^(h)	877,203

(a) Source: Interagency Advanced Power Group, Electrochemistry Division, Project Briefs, Power Information Center, CSR Inc., Washington, D.C.

(b) Source: U.S. House of Representatives, Hearings Before a Subcommittee of the Committee on Appropriations, 1975-1989.

(c) Source: Personal communication with DOE staff.

(d) Totals may not sum due to rounding.

(e) Calculated using converted market GNP deflators (Source: Energy Information Administration, Annual Energy Review 1987).

(f) Total project funding from 1975 to 1979 of \$4.39 million, assumed to be distributed evenly among years. Source: Defense Technical Information Center, Work Units Database Agency Accession No. DN790557.

(g) Source: U.S. Library of Congress, Congressional Research Service. Fuel Cells for Electric Power Production: Future Potential, Federal Role and Policy Options, LTR85-26, January 17, 1985.

(h) Does not include approximately \$5.0 million of DOT funding.

Since at least 1961, NASA has been funding fuel cell research. As indicated in Table S.1, NASA has spent over \$52 million since 1961 for aerospace applications. NASA is unique among all participants in fuel cell research in that several applications have resulted from this research (e.g., power supplies for Gemini and Apollo spacecraft, the space shuttle). However, since the focus of this paper is terrestrial applications, aerospace uses are not discussed in detail.

Fuel cell research programs sponsored by the DOD total over \$75 million since 1960. The Army represents the bulk of these expenditures, with research primarily targeted towards development of small, dependable power supplies. The Air Force has examined several aerospace applications but has mainly concentrated on development of power plants for remote terrestrial applications. The Navy effort has primarily examined power supplies for underwater vehicles. The Defense Advanced Research Projects Agency (DARPA) funds research of a more exploratory nature, generally without a specific application in mind.

For purposes of comparison, a column is provided in Table S.1 that lists annual totals converted to constant 1988 dollars using the GNP deflator.

The converted 1988 dollar totals are also shown graphically in Figure S.1. The large drop in 1967 is apparently due to NASA's research entering the application phase. Also, no DARPA funding was reported for 1967 to 1982. The increased funding in 1977 reflects the interest in fuel cells generated first at ERDA, then DOE. A general downward trend in federal expenditures through the 1980s is indicated in the figure.

The private sector has also made a substantial investment in fuel cell research. Because of the proprietary nature of this information, comprehensive data on year-by-year funding and research programs have not generally been available. Still, it has been possible to gather some information from various sources. Estimated totals of private-sector research are included in Tables S.2 and S.3, where funding levels have been categorized by application and by fuel cell type for both the public and private sectors. These tables are further discussed in Section 3.5.

Total private sector funding for fuel cell R&D since 1960 exceeds \$360 million. Once again, this estimate is believed to be conservative. A partial listing of private firms known to have conducted fuel cell research at one time or another (many for whom funding information was not obtained) is included in Section 3.4.

FIGURE S.1. U.S. Federal Funding in Fuel Cell Technologies (1988 Constant Dollars)

Sources: 1) Interagency Advanced Power Group, Electrochemistry Division, Project Briefs, Power Information Center CSR Inc., Washington, D.C. 2) U.S. House of Representatives, Hearings Before a Subcommittee of the Committee on Appropriations, 1975-1989. 3) Energy Information Administration, Annual Energy Review 1987. 4) Defense Technical Information Center, Work Units Database Agency Accession No. DN790557. 5) U.S. Library of Congress, Congressional Research Service. Fuel Cells for Electric Power Production: Future Potential, Federal Role and Policy Options, LTR85-26, January 17, 1985. 6) Personal communication with DOE staff.

CONCLUSIONS

Records obtained indicate that at least \$540 million of federal money has been spent for fuel cell R&D since 1960. The great bulk of that amount has been spent by DOE and its predecessor, ERDA. In addition, the private sector has contributed over \$360 million to fuel cell research, bringing total U.S. expenditures to nearly \$1 billion. Thus far, no commercial

TABLE S.2. U.S. Public and Private Funding in Fuel Cells by Application, 1960-1988 (current dollars, in thousands)

<u>Application</u>	<u>Public</u>	<u>Private</u>	<u>Total</u> ^(a)
Stationary	409,581	360,622	770,203
Aerospace	55,373		55,373
Remote	36,652		36,652
Transportation	18,400	2,500	20,900
Aircraft	962		962
Other	2,948		2,948
Cross-Cutting	<u>19,702</u>	<u> </u>	<u>19,702</u>
Total	543,618	363,122	906,740

(a) Totals may not sum due to rounding.

Sources: 1) Interagency Advanced Power Group, Electrochemistry Division, Project Briefs, Power Information Center, CSR Inc., Washington, D.C.
 2) U.S. House of Representatives, Hearings Before a Subcommittee of the Committee on Appropriations, 1975-1989, 3) Personal communication with DOE staff.

TABLE S.3. U.S. Public and Private Funding in Fuel Cells by Fuel Cell Type 1960-1988 (current dollars, in thousands)

<u>Application</u>	<u>Public</u>	<u>Private</u>	<u>Total</u> ^(a)
PAFC	224,276	327,615	551,891
MCFC	101,953	26,376	128,329
SOFC	22,760	6,631	29,392
PEM	7,881	2,500	
Generic	5,841		5,841
Other	91,427		91,427
Unassignable	<u>89,080</u>	<u> </u>	<u>89,080</u>
Total	543,618	363,122	906,740

(a) Totals may not sum due to rounding.

Sources: 1) Interagency Advanced Power Group, Electrochemistry Division, Project Briefs, Power Information Center, CSR Inc., Washington, D.C.
 2) U.S. House of Representatives, Hearings Before a Subcommittee of the Committee on Appropriations, 1975-1989, 3) Personal communication with DOE staff.

installations of any fuel cell systems have been realized. Fuel cells have found limited applications in the space program and in certain specialized military applications.

The fuel cell type that is nearest to commercialization is PAFC. Manufacturers have offered two sizes of units for sale: natural gas-fueled onsite power plants in either a 200-kW size for localized power generation and an 11-MW size for use by electric utilities in dispersed power generation. However, no units have been installed to date. The earliest possible commercial installation date achievable for these units is currently 1991.

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1.0 INTRODUCTION

1.1 BACKGROUND

Since their inception in the early 1950s, fuel cells have held the attention of the technical community because of their potential for high efficiency in converting fossil energy into electricity. However, apart from a few specialized space and military applications, this potential has not yet been realized. In short, fuel cell technology has not achieved commercial reality for any terrestrial applications. Both technological and market-related issues have contributed to this delay in commercialization.

1.2 PURPOSE AND SCOPE

It is the objective of this report to provide a summary of both the current status of fuel cells and of historical fuel cell research. Major research programs and funding levels are discussed, as well as potential applications. Although this report is intended to be an overview, it is believed that it represents the most comprehensive attempt to date to document historical fuel cell research and development (R&D) in the U.S.

The treatment of particular research activities or applications may be somewhat uneven, because information on private-sector research is confidential by nature and therefore largely unavailable. Information on government-funded programs has been easier to obtain, and therefore more detail is provided on these programs. Fortunately, a number of larger known R&D programs represented a combined effort of both the public and private sectors, and some information on the private-sector activities can be extracted from these sources. Data on research performed by the Electric Power Research Institute (EPRI) and the Gas Research Institute (GRI) was also obtained.

This report focuses on fuel cell research specifically related to terrestrial applications. It is not intended to be a technical document. However, brief technical descriptions of the various fuel cell technologies are presented.

Section 2 describes the primary fuel cell types considered of interest. A brief history of research and applications for each fuel cell type is provided, along with the current status of the technology. Section 3 details the fuel cell research programs of each federal agency and touches on private-sector organizations.

2.0 DESCRIPTION AND STATUS OF FUEL CELL TECHNOLOGIES

The term "fuel cell" refers to a family of devices used to generate electricity through electrochemical means. Fuel cells range in capacity from a few watts to hundreds of megawatts. Most fuel cells operate on the same principle: hydrogen, either in pure form or contained in a reformat from fossil fuels (e.g., natural gas, coal gas), is electrochemically combined with oxygen to form water, releasing electrical energy in the process. Individual types of fuel cells may require additional inputs (e.g., carbon monoxide or carbon dioxide) in order to complete the full electrochemical reactions.

The fuel cell system includes a cathode where oxygen is reduced (gains electrons), an anode where hydrogen is oxidized (releases electrons), an electrolyte medium, and a circuit connected to an external load. Unlike a conventional battery, fuel cells use a continuous flow of reactants and can sustain operation as long as the reactants continue to flow and the cell components remain intact. By contrast, the fuel and oxidant are contained within a battery, and when power in those reactants has been exhausted, the battery must be recharged or replaced.

Fuel cells use either gaseous or liquid fuels that include hydrogen (in a pure state), hydrazine, hydrocarbons, or coal gas. Because the anode reaction involves only hydrogen, converting the fuel to a hydrogen-rich form from the other fuel constituents is required. Reforming the fuel is carried out via a fuel reformer. A conventional fuel reformer combines carbonaceous fuel with medium-temperature (350-400°F) steam in the presence of a copper oxide catalyst, which converts the fuel to hydrogen, carbon monoxide (CO), and carbon dioxide (CO₂) through a shift reaction. The CO and CO₂ are then used or discarded, depending on the fuel cell type.

In addition to the fuel reformer, a fuel cell system generally contains "stacks" and the electrolyte medium in a "power section," and a power conditioner. The stacks contain individual anode/cathode sets and are where the electrochemical reactions take place. The power conditioner regulates and

conditions the power to meet the requirements of the individual application. Additional system components may also be required for specific applications.

2.1 FUEL CELL TYPES

Fuel cells are generally categorized by the type of electrolyte used in the system. Phosphoric acid fuel cells, for example, use a phosphoric acid electrolyte of concentration 95% by weight. The following fuel cell technologies are discussed in this report:

- alkaline fuel cells (AFCs)
- phosphoric acid fuel cells (PAFCs)
- molten carbonate fuel cells (MCFCs)
- proton exchange membrane fuel cells (PEMs)
- solid oxide fuel cells (SOFCs).

These five are the principal fuel cell technologies that have been considered for widespread terrestrial applications. Other systems, such as hydrogen/bromine and hydrazine/air systems, have been researched for very specialized and limited military applications. For example, development of a hydrazine/air system was supported during the Vietnam war and successfully field tested as a mobile modular power source. The extreme toxicity of hydrazine, however, has prevented further use of this device. Similarly, some support from the National Aeronautics and Space Administration (NASA) goes toward hydrogen/halogen and regenerative hydrogen/oxygen systems for low-orbit long-term space station power source applications. However, these systems are very expensive and fuel limited, so no terrestrial applications are under examination. A third example is the ammonia/air fuel cell under investigation by the military. Complications associated with the handling and distribution of ammonia limit applications of this technology.

None of these more exotic systems are discussed explicitly in this report. However, funds devoted to development of these systems are included in summary tables in Section 3.

2.2 ALKALINE FUEL CELLS

The first practical fuel cell system ever constructed (in the late 1950s) consisted of an alkaline system. This system has been the workhorse of the U.S. space program. A large percentage of fuel cell development supported by the Department of Defense (DOD) and NASA has been devoted to various alkaline designs. Terrestrial applications under examination have been composed primarily of either portable power supplies or small-scale onsite power plants for military operations (e.g., remote radar stations).

Alkaline fuel cells (AFCs) use a 35 to 50 percent by weight potassium hydroxide (KOH) electrolyte and operate at about 120°C. The overall reaction involves oxidation of pure hydrogen at the anode and reduction of pure oxygen at the cathode. A primary advantage offered by alkaline systems is that the cathode performance is much better than in acid fuel cells (e.g., PAFCs) and AFCs employ low-cost materials in construction. A major drawback to AFC systems is that the KOH electrolyte reacts with carbon dioxide (CO₂) from either the fuel or air during operation to form carbonates, which degrades the electrolyte over time. For this reason, pure hydrogen and oxygen feed streams are required by the AFC. This problem currently precludes the use of AFCs with carbonaceous (fossil) fuels and thus severely limits terrestrial use.

The evolution of technology permitting economical generation of liquid hydrogen as a primary fuel will be necessary for this system to be feasible for terrestrial applications. Under this scenario, the AFC will be ideally suited for land-based power generation. There is no current U.S. effort to promote AFCs in terrestrial applications. However, the European Economic Community (EEC) is supporting a small effort to develop an alkaline system for application in transportation systems. The primary developer is ELENCO in Belgium. International Fuel Cells Corporation is the lead developer in the U.S. for AFCs, primarily in conjunction with the Air Force and NASA.

2.3 PHOSPHORIC ACID FUEL CELLS

Phosphoric acid fuel cells (PAFCs) use phosphoric acid as the electrolyte medium. PAFC technology is nearing commercialization, and several units are in the demonstration phase in the U.S. and around the world.

Development of the PAFC has always been targeted towards terrestrial applications. The electrolyte does not react with CO₂, and thus this system can be effectively used with fossil fuels. During the 1970s, the major fuel cell development activities were focused on PAFCs for electric utilities and onsite (small-scale power generation) applications.

Total U.S. expenditures in fuel cell technologies are difficult to obtain, because information about private-sector funding is not always available and estimates of these values vary. We estimate total public and private U.S. expenditures for development and demonstration of PAFC technologies to be approximately \$550 million (see Table 11 in Section 3.5). A 1985 Department of Energy (DOE) document gave a then-cumulative breakdown of PAFC funding as follows: \$100M from electric and gas utilities; \$100M from United Technologies Corporation (UTC, parent company of International Fuel Cells Corporation); \$150M from organizations such as EPRI and GRI; and approximately \$150M from DOE (DOE 1985). It should be noted that this estimate includes no DOD funding.

From 1967 to 1977, a consortium of gas and electric utilities and United Technologies formed the Team to Advance Research on Gas Energy Transformation (TARGET). The purpose of TARGET was to develop and demonstrate the PAFC for onsite residential and commercial applications. Sixty 12.5-kW fuel cell power plants were constructed and demonstrated at 35 sites in the U.S., Japan, and Canada. The performance of these fuel cells was adequate, but lifetimes were not acceptable for commercial application.

DOE and GRI continued to support this effort (no longer called TARGET) in 1978 with the goal of improving both performance and lifetime. As a result of these efforts, a 40-kW design was demonstrated at nearly 50 sites nationwide from 1982 to 1986. This second demonstration program proved more successful than the first. After approximately three to four years of operation (300,000 total hours), the relevant operating economics of the

systems were firmly established. Fourteen of the units operated over 8,000 hours, with one unit exceeding 11,000 hours (National Fuel Cell Coordinating Group 1986a). Records on this program indicate total public and private funding of at least \$75 million (Interagency Advanced Power Group [DATE]; DOE 1985).

A spinoff program funded by the DOE was to use results of the demonstration to further develop high-risk components. This effort emphasized developing components that were less costly and higher in performance and endurance than those already attained. The program was funded at \$15.5 million between FY 1982 and 1985 (Interagency Advanced Power Group [DATE]).

The development of PAFC units followed a natural evolution of increasing size. The search was for an optimally-sized module that could stand alone or be connected with other modules to produce the capacity desired. Investigations eventually led to a 200-kW design.

The On-Site Multikilowatt Power Plant Technology-Development Project was begun in 1985 as a cooperative effort between DOE, GRI, and International Fuel Cells (IFC, a joint venture between United Technologies and Toshiba). The focus of the effort was to produce a verification "test article," which included a 200-kW stack, a matched fuel reformer, and an integrated water treatment and cooling system. This system would be used primarily in onsite applications for load leveling and auxiliary power generation. DOE is to have completed testing related to endurance verification and system operational problems during FY 1988.

IFC is soliciting a minimum of 100 orders for these units, at which point the design will become feasible for commercial prototype production. Commitments for more than 60 plants are reported to have been received or under negotiation, the majority (35) of these being in the U.S. IFC intends to form a subsidiary to produce the units, on the condition that \$100 million is obtained from outside investors. These units could be delivered starting in 1991 if IFC's requirements are met (DOE 1988).

A second focus of the U.S. effort in PAFC research was to develop and demonstrate a 10- to 100-MW power plant for electric utility applications. This effort was initiated in 1971 when nine utilities combined with United

Technologies Corporation (UTC) to initiate the Fuel Cell Generator (FCG-1) program. The ultimate objective of this program was to demonstrate a 26-MW power plant by 1980. As an interim step, the program demonstrated a 1-MW pilot plant in 1976, which operated for more than 1000 hours. As a result of this success, EPRI and Energy Research and Development Administration (ERDA) became involved in the program in 1976. The technical feasibility of large-scale PAFC technology was soon established, but a need for considerable progress in performance and cost was identified. It became evident that significant effort would be required to advance the technology to a commercial state.

The program goals were modified to designing, building, and testing a 4.8-MW module of the FCG-1 power plant in a utility system. UTC remained the primary developer of the system, and the Consolidated Edison Company (ConEd) of New York was chosen as the host utility for the demonstration. A site in Manhattan was selected, site preparation activities were initiated, and a 4.8-MW module was constructed.

A change in federal administration in 1981 resulted in a concomitant change in DOE philosophy regarding demonstration projects. As a result, DOE withdrew from participation in the demonstration project, and the 4.8-MW unit remained idle for a time exceeding the design lifetime of the cells. An attempt was later made to operate the unit, but acid had migrated through the stacks and the effort was abandoned after only about 100 hours of operation. A total of \$85 million was spent on the demonstration plant in New York, including \$48 million contributed by DOE, \$17 million by EPRI, \$14 million by UTC, and \$6 million by ConEd (Library of Congress 1985).

Tokyo Electric Power subsequently purchased an identical 4.8-MW unit from UTC and operated the system successfully for approximately 2500 hours. The test resulted in a redesign of the system by Japanese companies. The redesigned system has since been offered for commercial sale in Japan.

Currently, the market for fuel cells in large-scale utility applications in the U.S. appears to be limited. EPRI has attempted to organize a consortium of utilities, in partnership with IFC and with DOE funding, to demonstrate the PAFC multi-megawatt technology, but with little success. An

11-MW system was designed as a result of the program. Though the technology was verified and IFC and EPRI have offered 11-MW gas-operated plants for commercial sale, no domestic units have been sold. Sales of components for systems in Japan and Italy have been reported, however. Total funding of the 11-MW effort of the multi-megawatt program has been in excess of \$30 million, including public and private expenditures (U.S. House of Representatives 1986-89).

A separate 1.5-MW natural gas-operated unit (leading up to eventual development of a 7.5-MW unit) is also under development with DOE funding at Westinghouse. Long-term durability has not yet been demonstrated. The DOE has contributed approximately \$60 million through FY 1988 to this program. Westinghouse's contribution is not known. (U.S. House of Representatives 1985-89).

The lack of interest on the part of U.S. utilities is primarily due to the fact that advanced gas turbines are currently more cost effective than PAFCs and are already proven for peak-demand applications. The current capital cost of an installed 200-kW fuel cell unit (for initial premium-priced units) is approximately \$500,000. The Fuel Cell User's Group (FCUG, a consortium of the electric utility industry) estimates that this cost will have to be reduced by more than half to meet utility requirements (DOE 1988). Capital costs (ranging from approximately \$2000 to \$3600 per kW of capacity, depending on system size and other factors) are too high for commercial acceptance of PAFC systems. However, cost savings could be realized through mass production. IFC believes that orders for approximately 500 units would justify mass production techniques. Although such a volume of orders has not yet materialized, IFC is evaluating construction of a pilot-scale production line to manufacture these units.

Current DOE capital cost targets for PAFC systems in electric utility and onsite applications are as follows:

- Natural gas systems: \$800/kW of installed capacity for electric utility, \$1300/kW for onsite applications
- Coal systems: \$1400/kW of installed capacity for electric utility applications.

Economies of scale are responsible for generally lower costs of larger units. Units sized for onsite generation would generally be smaller than those intended for use by electric utilities.

2.4 MOLTEN CARBONATE FUEL CELLS

Molten carbonate fuel cells (MCFCs) use an alkali metal carbonate for the electrolyte, which is heated to 600-700°C in order to allow its use as a liquid. Molten carbonate systems are best suited for applications that employ some sort of carbonaceous fuel processor (e.g., a coal gasifier), because a source of CO₂ is required to complete the anode reaction. (Oxygen and carbon dioxide form carbonate ions at the cathode, which in turn react with hydrogen ions at the anode to form carbon dioxide and water). This implies use primarily in large-scale power generation in conjunction with fossil fuel supplies.

During the 1960s, extensive work was carried out in the U.S., primarily at the Institute of Gas Technology (IGT). From 1967, the TARGET program supported MCFC development at IGT as a backup to the PAFC system. In 1976, encouraged by the promising results of assessment studies, the DOE (then ERDA) initiated a major program with EPRI and UTC to develop MCFC technology. The program began with exploratory development to determine the effects of pressure, temperature, current density, fuel utilization, and sulfur contaminants on cell life and performance. The prevailing idea was that MCFC would be the second-generation fuel cell technology, after the PAFC system. Although considerable progress has been made in MCFC technology, it is still regarded as being five to ten years behind that of PAFC.

The Office of Fossil Energy (FE) within DOE has sponsored the largest amount of federal research in MCFC technology, totaling more than \$100 million through 1988 (U.S. House of Representatives 1982-89). This effort has been closely coordinated with EPRI to avoid duplicating research and to promote manufacturing competition. Since 1979, the DOE has awarded several contracts to develop MCFC stack technology. The initial application under examination has been large-scale (multi-megawatt) coal-fueled systems.

In FY 1987, DOE issued a competitive solicitation for the development and testing of a coal-based MCFC system. It was assumed that a viable technology had been achieved, but the proposals received indicated that this was not the case. In January 1988, three two-year contracts were awarded to correct the technical weaknesses identified in the proposals. The contracts allow the proposers time to develop sufficient technology so as to have viable concepts for a future solicitation in mid-FY 1990. The contracts were awarded to IFC, IGT, and Energy Research Corporation (DOE 1988).

The thrust of the DOE MCFC program remains the development of a large-scale central station power plant composed of a coal gasifier, a gas clean-up system, the MCFC (topping cycle) plant, and a waste-heat gas or steam turbine (bottoming cycle). This system is thought to be the most efficient and cost effective of all coal-fueled electric power generating alternatives. However, the stack life of the fuel cell has not yet surpassed 10,000 hours, whereas the target is 40,000 hours. The MCFC system must overcome problems of corrosion, stability of the nickel oxide cathode, and sintering and creep problems of the anode before there is any expectation of achieving the targeted stack life. Consequently, commercialization plans remain fairly distant until the technical hurdles can be overcome.

Current DOE program goals are to establish proof-of-concept before the end of the decade, construction and demonstration of prototype units in the 1990s, and commercial plant feasibility by the year 2000. Future efforts will emphasize material stability and performance. This includes development of new materials, improved operating conditions, cell operation on lower quality fuels, and scaling-up of prototype modules to full-sized systems.

Current capital cost targets for MCFC technology are as follows (DOE 1988):

- Natural gas systems: \$600/kW for electric utility, \$1100/kW for onsite applications
- Coal systems: \$1200/kW for electric utility applications.

Economies of scale are responsible for generally lower costs of larger units. Units sized for onsite generation would generally be smaller than

those intended for use by electric utilities. The present developers of the technology appear to be confident that recent technical progress makes these targets achievable.

After approximately ten years of effort, the General Electric Company (GE) abandoned its program in MCFC technology in 1982, which had a considerably negative impact on U.S. progress. In addition, with the recent accelerated progress of the solid oxide fuel cell (SOFC) technology, there is some question as to whether the MCFC systems will ever be commercially viable. Interest in the MCFC technology still remains strong in Japan, however, and the New Energy Development Organization (NEDO) plans call for demonstration of 100-kW stacks within the next few years.

2.5 PROTON EXCHANGE MEMBRANE FUEL CELLS

A second type of acid fuel cell is the proton exchange membrane (PEM) fuel cell. The PEM uses a hydrated (water-saturated) ion exchange membrane as the electrolyte. The PEM is constrained to operation between about 0°C and 120°C (the latter at elevated pressures) so that by-product water does not freeze or vaporize faster than it is produced by the electrochemical reactions.

PEM systems have found important uses in the space program and in certain military situations and appear to be the most feasible technology for use in transportation systems. Commercialization of PEM technology is estimated to be at least ten years behind that of PAFC technology (DOE 1985).

The PEM fuel cell was first designed by GE as a very compact, low-power fuel cell for space and military applications. A PEM design was actually the first fuel cell system to find practical application when it was used as the electric power plant for the Gemini missions during 1963 to 1965. The PEM fuel cell utilizes an acid electrolyte and is therefore CO₂ rejecting (does not react with CO₂) and compatible for use with carbonaceous fuels.

Recent progress in the PEM fuel cell technology has made it an attractive candidate for electric vehicle (EV) applications. PEM fuel cells already meet a key requirement of EVs, being compact in design. In addition, the recent development of new membrane technologies and catalysts has

increased the power density to a level where it is more than suitable for vehicular application. Research on PEM fuel cells has been conducted at Los Alamos National Laboratory (LANL) and by industrial developers such as IFC and General Motors (GM).

The EV system envisioned would use methanol as the liquid fuel. Methanol would be reformed in an on-board reformer into hydrogen, which would then be oxidized on the PEM fuel cell anode to produce a stream of protons. The anode utilizes a platinum catalyst deposited on the membrane itself. The protons are transported through an ion-exchange membrane (such as Dupont's NAFION) to the cathode and react with the product of oxygen reduction to produce water. The water balance in the membrane, particularly at high current density operation, becomes a key technical issue.

Research on this concept has been ongoing only for the past five years, mostly in laboratory studies of the basic components of the fuel cell. Only recently has emphasis shifted to fabrication and testing of complete laboratory-sized systems. The Office of Energy Storage and Distribution Systems (OESD) and the Office of Energy Conservation in DOE, the Department of Transportation, and the Defense Advanced Research Projects Agency (DARPA) have contributed approximately \$1 million annually since the early 1980s to LANL for developing PEM transportation systems.

Progress made in development of these systems appears very promising. Preliminary cost estimates made by LANL indicate that a PEM fuel cell/battery hybrid vehicle could provide excellent performance at an acceptable cost. In addition, private efforts at GM and at IFC have had significant internal funding (on the order of a \$2 million to \$2.5 million combined total annually), indicating corporate commitment to this technology.^(a) Because research is still primarily of an exploratory nature, performance targets have not yet been indicated.

(a) Private communications with IFC and GM.

2.6 SOLID OXIDE FUEL CELLS

Solid oxide fuel cells (SOFCs) employ a solid, nonporous metal oxide electrolyte that allows ionic conductivity by the migration of oxygen ions through the lattice of the crystal. SOFC technology was developed in the 1960s by Westinghouse and offers the advantages of potential low cost, high power density, and very high power-plant efficiency when integrated with a coal gasification system. However, interest in this system waned by the early 1970s, primarily because of materials compatibility problems at the very high operating temperatures (on the order of 1000°C).

Interest in the system was renewed in the mid 1970s, when durable zirconia-based electrolytes were discovered. Since that time, the SOFC systems have competed very well technically with MCFC systems. Consequently, it is likely that SOFC systems will be ready for commercialization at about the same time as MCFC power plants.

Westinghouse has remained the primary developer of the SOFC. The SOFC utilizes a tubular design instead of the filter press (flat plate) configuration of other fuel cell types. This design avoids sealing problems encountered at high temperatures with filter press designs. The Westinghouse design has continued to progress at a sufficient rate so that in 1986 the company predicted competitive commercial offerings of SOFCs by the early 1990s. Much remains to be done, both technically and programmatically, for an early 1990s commercialization target to be realistic.

Accomplishments in SOFC technology include the following:

- stable cell performance at high current densities due to development of advanced materials and processing technologies
- fabrication and successful operation of a 5-kW system with good performance and reliability by Westinghouse
- development of an unique SOFC monolithic design concept, which allows for extremely high power and energy density at reasonable cost, and proof of technical feasibility in the laboratory by Argonne National Laboratory (ANL).

These accomplishments have encouraged DOE to increase funding from approximately \$2 million in 1984 to \$5 million in 1987 (Warshay 1987). DOE

funding in FY 1988 and the request for FY 1989 are \$6.9 million and \$1.6 million, respectively (included under "Advanced Concepts" in the Congressional Budget Request). Total funding from DOE between 1980 and 1989 for the Westinghouse SOFC program will have exceeded \$22 million, with Westinghouse contributing an additional \$6 million as direct cost share (NFCG 1986b). Development targets are \$500/kW of installed capacity for electric utility gas-fired plants and \$1000/kW of installed capacity for electric utility coal-fueled plants. The Gas Research Institute (GRI) has also begun supporting the Westinghouse effort at an annual level of about \$1 million, addressing onsite gas-fired applications (Warshay 1987). In addition, the ANL monolithic design is being explored through a contract with DARPA.

Future efforts will address reducing costs for materials needed to support acceptable system lifetimes. In addition, system designs and fabrication techniques must be developed that allow consistent module quality, leading to acceptable manufacturing costs. Further requirements for system operation on coal-based fuels are also to be examined.

2.7 CURRENT ASSESSMENT OF FUEL CELL TECHNOLOGIES

In conclusion, it appears that increased funding for the SOFC system will give that technology a needed push. However, it will take time to overcome the technical challenges presented, and commercialization cannot be expected before the year 2000. Thus for the near term (i.e., the next ten years), it appears that the PAFC system will be the only commercially available fuel cell system, with the primary application being dispersed 200-kW to 11-MW power plants.

3.0 FUEL CELL RESEARCH PROGRAMS

This section highlights research program activities and funding levels. Most of this section is devoted to federal government programs for which information is available through various sources in the public domain. Some information is also provided for private-sector efforts, primarily those of EPRI and GRI.

3.1 DEPARTMENT OF ENERGY

Non-defense related federal support for research on terrestrial applications of fuel cells began with the Environmental Protection Agency (EPA) in the early 1970s. The rationale was that fuel cells offered the potential for an electric energy generation source with less pollution than conventional sources. This initial effort was quite small and could be classified as exploratory research.

In 1972, under an Office of Management and Budget (OMB) directive, all fuel cell research for terrestrial application was transferred to the Atomic Energy Commission (AEC). Likewise, when ERDA was formed, the AEC research program became a part of ERDA and was concentrated within the Division of Energy Utilization and Storage Technologies, Office of Conservation and Renewable Energy (CE). The Office of Buildings and Community Systems (BCS) within CE had a small (\$200,000) effort in FY 1978 and FY 1979 to perform assessments of the potential for fuel cell installations in the buildings sector. Ultimately, however, from FY 1979, almost all fuel cell research and development activities were handled through DOE's Office of Fossil Energy (FE).

3.1.1 Office of Fossil Energy

The Office of Fossil Energy (FE) funds a considerable amount of fuel cell research through the Coal Research Division; expenditures totaled \$34.2 million in FY 1988 (U.S. House of Representatives 1987). The principal program goals are to develop cost-effective, efficient, and environmentally benign fuel cell systems that operate on coal-based fuel. The primary technologies funded by FE have been PAFC, MCFC, and SOFC. Potential fuel cell

applications of interest to FE include electric utility and onsite multi-megawatt power plants, transportation systems, and defense installations.

The emphasis in the PAFC program has been to reduce costs and increase power density and system endurance while providing demonstration plants in onsite and electric utility applications. The emphasis in research on the second-generation MCFC power plant has been more basic in nature, involving areas such as external and internal methods of fuel reforming, development of cell components and corrosion-resistant materials, and component testing. Planned MCFC applications are primarily electric utility and industrial cogeneration systems using coal or coal-derived fuels. SOFC research is more recent and, again, is very basic and entails demonstration of technical feasibility. Intended applications of SOFC are similar to those of MCFC. Distillate fuel and natural gas systems have recently come under development.

Tables 3.1 and 3.2 show annual funding for ERDA and FE, respectively. Funding data was obtained from Congressional Hearings on Appropriations documents. DOE appropriations were better chronicled than those of ERDA, providing a breakdown by fuel cell type.

The category, "Advanced Research," in Table 3.2 refers to basic research that is applicable to any fuel cell type (e.g., anode and cathode

TABLE 3.1. ERDA Funding in Fuel Cells (current dollars, in thousands), 1974-1978

Item	Year					Total
	1974	1975	1976	1977(a)	1978(a)	
Budget Authority	400	500	3,674	17,800	33,000	55,374
Supporting Activities	700	250				950
Total	1,100	750	3,674	17,800	33,000	56,324

(a) Obtained from Library of Congress, Congressional Research Service, Fuel cells for Electric Power Production: Future Potential, Federal Role and Policy Options, January 17, 1985.

Source: U.S. House of Representatives, Hearings Before a Subcommittee of the Committee on Appropriations, 1975-1979.

TABLE 3.2. Office of Fossil Energy, U.S. DOE Funding in Fuel Cells (current dollars, in thousands), 1979-1988

<u>Fuel Cell (year)</u>	<u>PAFC</u>	<u>MCFC</u>	<u>Advanced Concepts</u>	<u>Advanced Research</u>	<u>Capital Equipment</u>	<u>Total</u>
1979	19,500	17,000	4,000		552	41,052
1980	14,000	12,000			500	26,500
1981	21,012	9,000	2,000			32,012
1982	20,640	9,600	4,224			34,464
1983	17,438	7,500	5,000			29,938
1984	28,800	9,200	4,600			42,600
1985	28,573	8,851	3,048			40,472
1986	20,355	9,932	3,770			34,057
1987	15,500	7,621	4,963	1,350		29,434
1988	<u>13,200</u>	<u>11,100</u>	<u>8,353</u>	<u>1,547</u>		<u>34,200</u>
Total	199,018	101,804	39,958	2,897	1,052	344,729

Source: U.S. House of Representatives, Hearings Before a Subcommittee of the Committee on Appropriations, 1979-1989.

electrochemistry, catalysts, etc.), whereas "Advanced Concepts" refers to more applied research (e.g., "Continue development of a solid oxide multi-kW generator module," etc.).

3.1.2 Office of Conservation and Renewable Energy

Although the Office of Conservation and Renewable Energy (CE) had overall authority for fuel cell research when DOE was formed, that authority was transferred to FE within two years. Since then, there has been comparatively little activity in CE on fuel cells. In 1979, however, a joint issue paper was produced by the Office of Energy Storage and Distribution (OESD) and the Electric & Hybrid Vehicle Division of Office of Transportation Systems (OTS) within CE discussing the potential of fuel cells in electric vehicle (EV) applications. CE and FE then developed a memorandum of understanding which acknowledged that PEM fuel cells would be developed by CE for transportation applications.

Fuel cell research programs for transportation applications were initiated through OESD in FY 1982. Los Alamos National Laboratory (LANL) performed the research, and the technology chosen was the PEM technology. OESD initially supported this effort at a level of approximately \$800,000 per year. OTS and the Department of Transportation (DOT) also began funding LANL in FY 1984 for various types of assessment at a combined total of between \$100,000 and \$200,000. In FY 1988, Congress mandated that OESD expenditures be increased to \$1.5 million per year (U.S. House of Representatives 1989). In addition, \$0.5 million was contributed by OTS towards development of the PEM technology.

The other fuel cell project CE is currently funding is for development of a fuel cell system for a passenger bus, through OTS. This program is also jointly funded by the DOT and is a Congressionally-mandated program. The program began in FY 1987 with the goal of developing and demonstrating a passenger bus operating on a hybrid electric propulsion system at Georgetown University. Work in this program has been related solely to PAFC technology. The effort is to continue through demonstration and commercialization under a DOT lead. The fuel cell bus program receives annual funding of about \$5.8 million, with OTS contributing 60% and DOT providing the remaining 40% of the funds.^(a)

OESD does conduct a large amount of basic research related to various battery and other energy storage and distribution technologies. Some applied research related to electrochemical phenomena, electrocatalysis and modelling of electrochemical systems is applicable to battery technologies, as well as fuel cells. Because it is difficult to assign these research costs precisely, these programs and funding levels are not further discussed.

3.2 DEPARTMENT OF DEFENSE

The Army, Air Force, and Navy have all had research programs related to the development of fuel cell technologies for various applications. Information on levels of funding and project descriptions, however, are more

(a) Private communication with OTS.

difficult to obtain than for agencies such as DOE, both because of the size and dispersion of DOD research and the classified nature of much of that research. In addition, a significant amount of the research is performed in-house, and the level of effort is expressed in man-years. Translation of these units into dollars is difficult and has not been attempted.

The best source of information for DOD is the project briefs (summary sheets) submitted to the Interagency Advanced Power Group (IAPG). This group acts as an information clearinghouse between government agencies. Participation in the IAPG is voluntary, however, so that information from this source is almost certainly incomplete and therefore produces a conservative estimate of efforts related to fuel cell research.

Table 3.3 contains a summary by year of fuel cell expenditures by each of the three branches of the armed services. Table 3.3 also contains information for DARPA. Research programs at each of the branches and DARPA are discussed in the following subsections. Aside from aerospace applications, the only operating installations found are in remote site demonstrations.

3.2.1 Army

The Army appears to have the largest overall effort of the three DOD branches (37% of funding shown in Table 3.3), based on information obtained from the IAPG. The Army appears to be primarily interested in small, portable power generators between 0.5 and 5-kW capacities suitable for silent, forward-area power supplies. Fuel cells are desirable for forward-area military operations partly because they possess low infrared and noise "signatures" and are not as readily detected by enemy forces. Some of the effort outlined in the IAPG sheets is related to development of various alkaline fuel cells, including specialized types (e.g., hydrazine-fueled), intended for this application. PAFC systems, especially methanol-fueled, have also been investigated for power units in the 0.5- to 5-kW size range.

To a lesser extent, the Army has also investigated development and demonstration of 40-kW and larger-sized PAFC units for remote installations. The Army participated (under direction of the Air Force) in the joint DOE/GRI 40-kW demonstration, supplying one installation site at Fort Belvoir, Virginia.

TABLE 3.3. Department of Defense Funding in Fuel Cells (current dollars, in thousands), 1960-1987

<u>Year</u>	<u>DARPA</u>	<u>Army</u>	<u>Navy</u>	<u>USAF</u>	<u>Total (a)</u>
1960	148	326	361		836
1961	144	213	566		923
1962	1,290	750	370	397	2,806
1963	2,780	1,007	59	432	4,277
1964	2,495	844	146	380	3,865
1965	2,322	665	50	341	3,378
1966	4,500	1,354	50	872	6,776
1967		1,264		1,239	2,503
1968		1,030		629	1,658
1969		501	850	969	2,320
1970		1,180	760	276	2,216
1971		1,752	658	335	2,745
1972		288	394	661	1,343
1973		339	136	325	801
1974		119		307	426
1975		268	878(b)	170	1,991
1976		361	878(b)		1,783
1977		1,444	878(b)		2,598
1978		400	878(b)	59	1,723
1979		551	878(b)	112	1,641
1980		4,178			4,178
1981		2,892		287	3,179
1982		2,760		4,100	6,860
1983	300	1,832		560	2,692
1984	65	1,106		2,928	4,099
1985		300		2,724	3,024
1986	2,807	221	67	1,850	4,945
1987		250	82	2,219	2,551
Total	16,852	28,194	8,939	22,171	76,154

(a) Totals may not sum due to rounding.

(b) Total funding for one Navy project covering five years was found through a Defense Technical Information Center (DTIC) database search. Amount shown assumes funding was divided equally among project years.

Source: Interagency Advanced Power Group, Electrochemistry Division, Project Briefs, Power Information Center, CSR Inc., Washington D.C.

3.2.2 Air Force

Applications investigated by the U.S. Air Force (USAF) include power sources for both aerospace uses and for remote terrestrial installations. Aerospace applications investigated include satellite power systems and aircraft systems. As noted above, the USAF participated (with the Army) in the DOE/GRI 40-kW demonstration program. In addition to the Fort Belvoir installation, three Air Force bases (AFBs) were also included: Elmendorf AFB in Alaska, Sheppard AFB in Texas, and Wright-Patterson AFB in Ohio. DOD participation in this program was a result of the Congressionally-mandated Air Force Remote Site Fuel Cell Development Program, which has the objective of demonstrating a strategically-fueled fuel cell power plant at a remote Minimally Attended Radar (MAR) site in Alaska in the early 1990s (NFCG 1986c). Performance goals are 40% electrical efficiency, 20-year life, and 30% life-cycle cost savings over existing diesel-engine generators. Primary objectives of the program are as follows (NFCG 1986d):

- field test a 40-kW power plant at Elmendorf AFB, Alaska
- demonstrate processes capable of converting diesel fuel to fuel cell-quality hydrogen
- establish requirements for remote site fuel cell power plants and determine performance and life-cycle cost baseline of the competition
- conduct the Remote Site Fuel Cell Development activities
- demonstrate power plant(s) at a USAF site in Alaska in the early 1990s.

The USAF has also investigated numerous specialized designs. Some of the USAF effort, for example, has examined high-power, short-duration (e.g., with a life time of a few hours) system designs. As has been previously mentioned, commercial applications of these types of systems is unlikely.

3.2.3 Navy

The Navy effort appears to have been relatively small in comparison with the other branches of the DOD. In fact, the Navy is not currently funding any work in fuel cells. The primary application investigated has been for underwater power sources, with the largest portion of research related to

deep-submergence vehicles (DSVs). The Navy also has an interest in potential facility applications where uninterruptible power is required.

3.2.4 Defense Advanced Research Projects Agency

The Defense Advanced Research Projects Agency (DARPA) investigates technologies in their early stages of development that have potential for the nation's defense capabilities. Most of the effort conducted by DARPA tends toward basic research of technologies that are in their early stages of development. Specific applications are generally left to the individual branches of the DOD to investigate. As shown in Table 3.3, most of DARPA's effort in fuel cell development occurred in the early 1960s. More recently (since 1983), DARPA has investigated and developed a monolithic SOFC design at Argonne National Laboratory, aimed at very high specific power and power density. These units are being developed for initial applications in aircraft.

3.3 NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

The National Aeronautics and Space Administration (NASA) has been involved in fuel cell development for space applications since 1961. In addition, NASA's Lewis Science Research Center has directed a significant portion of research funded by other federal agencies. This includes some of the work by FE and DOD.

The applications investigated with internal funds at NASA, of course, focus on aerospace applications, which are outside the scope of this paper. The only NASA-funded research uncovered that was not explicitly directed towards aerospace applications fell under the category of "basic research," for which particular applications are not readily identified. NASA has been responsible for conducting most of the work related to alkaline fuel cells, and thus far is the only agency which has widely employed fuel cells in useful applications. Table 3.4 contains data for NASA funding. This data may be incomplete; because the focus of this paper was terrestrial applications, more emphasis was placed on non-NASA sources of information.

TABLE 3.4. NASA Funding in Fuel Cells (current dollars, in thousands), 1960-1987

<u>Year</u>	<u>Funding</u>	<u>Year</u>	<u>Funding</u>
1961	96	1975	675
1962	4,455	1976	544
1963	4,448	1977	276
1964	8,727	1978	386
1965	9,117	1979	100
1966	12,803	1980	200
1967	1,577	1981	70
1968	724	1982	375
1969	377	1983	220
1970	641	1984	215
1971	1,308	1985	480
1972	2,652	1986	40
1973	1,267	1987	<u>40</u>
1974	407	Total	52,222

Source: Interagency Advanced Power Group, Electrochemistry Division, Project Briefs, Power Information Center, CSR Inc., Washington, D.C.

3.4 PRIVATE RESEARCH EFFORTS

The Electric Power Research Institute (EPRI) and the Gas Research Institute (GRI) are research consortiums of electric and gas utilities companies. These organizations conduct research into various energy technologies, including fuel cells. The focus of research in these organizations is to accelerate commercialization of nascent technologies and to improve the state-of-the-art of existing commercial technologies. Both of these institutes conduct research in partnership with other agencies, including foreign agencies, as well as being sole sponsors of research at other institutions.

3.4.1 Electric Power Research Institute

EPRI has had a major contributing role in development and demonstration of fuel cell systems. EPRI has funded research in PAFC, MCFC, SOFC, and

advanced design technologies. The applications of interest to EPRI consist primarily of onsite and large-scale power generation plants. Information obtained from communication with EPRI staff indicates cumulative funding levels of approximately \$50 million for PAFC technology, \$25 million for MCFC technology, and \$1 million for SOFC technology.^(a) EPRI funding has included funds for basic research, technology assessment and other paper studies, and demonstration projects (largely in cooperation with DOE).

Funding continues at EPRI, as new programs are under negotiation. However, major organizational changes have recently occurred at EPRI, and funding has dropped significantly (on the order of 60%) for research programs. EPRI is now much more interested in near-term demonstrations as opposed to advanced R&D programs. Given this current environment, future large EPRI R&D programs are unlikely.

3.4.2 Gas Research Institute

GRI focuses on fuel cell technologies that use natural gas as the source fuel. Like EPRI, applications targeted are onsite and large-scale power generation. GRI has funded basic research, as well as supporting various demonstration projects. GRI funding, which has been very significant, is shown in Table 3.5.

The "PAFC" category shown in Table 3.5 includes technical R&D work, while "PAFC-Support" includes data analysis and related activities. The totals shown in the table are accurate through 1986 but may not be entirely comprehensive for later years.

SOFC research is to receive increased attention in the upcoming research budgets, due to the recent advances achieved in the technology. SOFC issues to be addressed include improved fundamental understanding of electrochemical, surface chemistry, and solid-state phenomena involved at high temperatures and improved construction materials.

Another promising concept to be investigated involves use of solid electrolyte systems at low temperatures to produce both energy and a useful

(a) Personal communication with Ed Gillis, EPRI Program Manager, December, 1988.

TABLE 3.5. GRI Funding in Fuel Cells (current dollars, in thousands), 1979-1988

Technology (year)	PAFC	PAFC- Support	MCFC	SOFC	Total Annual ^(a)
1979	1,474	50	100		1,624
1980	3,453		251		3,704
1981	4,322	768	876		5,968
1982	11,073	1,309			12,381
1983	18,477	1,571			20,048
1984	18,264	1,935			20,199
1985	3,359	1,383			4,742
1986	4,289	213		998	5,500
1987	5,673			2,550	8,223
1988			149	2,084	2,234
Total	70,386	7,228	1,376	5,631	84,622

(a) Totals may not sum due to rounding.

Source: Personal communication with R. Woods, GRI, January 18, 1989.

chemical byproduct. For example, such a system might produce ethylene, as well as useful heat and electricity, from methane. Basic research is the intended focus.

3.4.3 Other Private-Sector Involvement

Table 3.6 contains an incomplete listing of private-sector firms known to have participated in fuel cell research at one time or another. It is possible that one or more of these firms has performed research only under contract to a federal agency without contributing any internal funds. Funding levels from each firm are at best only partially known, so no attempt has been made to estimate totals here. The following section contains the known private-sector information.

3.5 SUMMARY TABLES OF PUBLIC AND PRIVATE FUNDING

Tables 3.7 and 3.8 show a breakdown of U.S. funding in fuel cell technologies by application and fuel cell type. These tables were constructed

TABLE 3.6. U.S. Private-Sector Firms that have Performed Fuel Cell Research

Westinghouse	Union Carbide
General Electric	American Cyanamid
Engelhard	EIC, Inc.
International Fuel Cells	MC Power
United Technologies Corp.	Treadwell Corp.
Energy Research Corp.	Giner, Inc.
General Motors Corp.	Analytic Power Corp.
AiResearch	

TABLE 3.7. U.S. Public and Private Funding in Fuel Cells by Application, 1960-1988 (current dollars, in thousands)

<u>Application</u>	<u>Public</u>	<u>Private</u>	<u>Total (a)</u>
Stationary	409,581	360,622	770,203
Aerospace	55,373		55,373
Remote	36,652		36,652
Transportation	18,400	2,500	20,900
Aircraft	962		962
Other	2,948		2,948
Cross-Cutting	<u>19,702</u>		<u>19,702</u>
Total	543,618	363,122	906,740

(a) Totals may not sum due to rounding.

Sources: 1) Interagency Advanced Power Group, Electrochemistry Division, Project Briefs, Power Information Center, CSR Inc., Washington, D.C. 2) U.S. House of Representatives, Hearings Before a Subcommittee of the Committee on Appropriations, 1975-1989. 3) Personal communication with DOE staff.

from various sources mentioned earlier in the report. Hence, they are subject to the limitations already noted.

The category titles for these tables are somewhat subjective and most are self-explanatory. "Stationary" refers to units in the larger size ranges (up to megawatt sizes) that are more or less permanently placed after installation. "Remote" means smaller units that are either portable or more easily

TABLE 3.8. U.S. Public and Private Funding in Fuel Cells by Fuel Cell Type, 1960-1988 (Current Dollars, in Thousands)

Type Fuel Cell	Public	Private	Total (a)
PAFC	224,276	327,615	551,891
MCFC	101,953	26,376	128,329
SOFC	22,760	6,631	29,392
PEM	7,881		7,881
Generic	5,841		5,841
Other	91,427		91,427
Unassignable	<u>89,080</u>		<u>89,080</u>
Total	543,618	363,122	906,740

(a) Totals may not sum due to rounding.

Sources: 1) Interagency Advanced Power Group, Electrochemistry Division, Project Briefs, Power Information Center, CSR Inc., Washington, D.C. 2) U.S. House of Representatives, Hearings Before a Subcommittee of the Committee on Appropriations, 1975-1989. 3) Personal communication with DOE staff.

moved than larger units. Much of the Army effort, for example, has examined 5-kW and smaller units for powering forward-area telecommunications equipment. The "cross-cutting" category encompasses "generic" research that could be applied to more than one application.

In Table 3.8, the only category requiring discussion is that of "unassignable." Much of the funding information uncovered in this report combined more than one type of fuel cell under a single funding amount or did not identify the fuel cell type under discussion. In addition, it was often difficult to correlate funding expenditure information from different sources without risking double-counting some of the values. As a result, it was necessary to add a category for "unassignable" expenditures.

The tables show total public and private expenditures in fuel cell technologies of more than \$900 million (in current dollars). Given that the information obtained in this study is incomplete, the total shown is somewhat conservative.

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