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EVALUATION OF FUEL CELL TECHNOLOGY FOR COAST GUARD APPLICATIONS

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16. Abstract

Recent proposals and the literature show promise of fuel cells being commercially available in the next decade. We searched the literature to determine the current state of fuel cell technology, to determine if fuel cells can be used by the U.S. Coast Guard, and to make proposals for possible ~~R&D~~ efforts by the Coast Guard. Alkaline and phosphoric acid fuel cell technologies are now technically capable of full scale commercial production. Molten Carbonate and Solid Oxide fuel cell technologies should be commerically produced within the next decade. Phosphoric Acid Fuel Cell (PAFC) technology is the most promising for Coast Guard use. However, there is no operational need for fuel cells at present and high capital costs and low energy prices make them economically noncompetitive. We suggest three areas of R&D to prepare for changes in operational needs or energy economics. They are: operation of a 200 kW PAFC cogeneration plant to gain fuel cell experience; development of low-maintenance/ high availability PAFC system for remote power; and development of fuel cells for ~~vessel~~ or aircraft propulsion in case there is a strategic crisis in petroleum distillate supplies.

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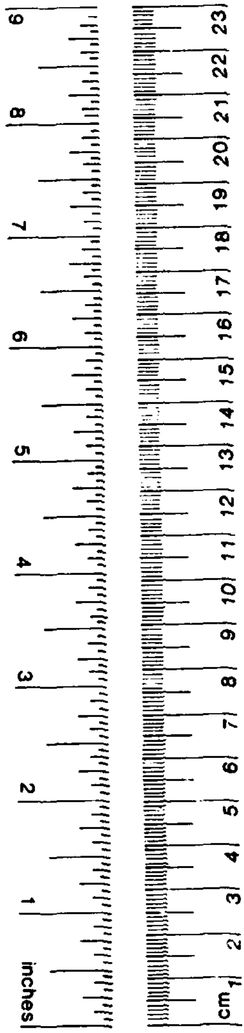
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

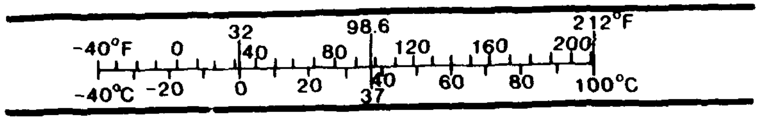
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286. Units of Weights and Measures. Price $2.25. SD Catalog No. C13.10.286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

Fuel cells offer distinct advantages over conventional Carnot cycle power systems. The largest advantage is an energy efficiency of 40 to 80 percent compared to present Carnot efficiency of 15 to 30 percent. Additional advantages that have been touted are high power density, modularity in construction, low maintenance, long life, rapid load-following, quiet operation, multi-fuel capability, and non-polluting exhaust. These advantages have lead to use of fuel cells in manned space flights and to proposals for terrestrial use in a variety of applications. These applications include transportation (land, sea and air), central and dispersed power stations, remote power supplies, and on-site cogeneration plants. Specific applications in the Coast Guard include minor aids to navigation[1,2], major aids to navigation[3,4], and marine propulsion[5,6,7].

The Coast Guard considered fuel cells in the late seventies but terminated the work because the technology had not progressed to the point of commercial production. Units offered at the time were essentially one-of-a-kind, custom models. However, recent proposals and the literature show promise of fuel cells being commercially available within the next decade. As a result, the Coast Guard R&D Center started a special project in late 1986 to study fuel cell technology. Topics of discussion include:

- current state of fuel cell technology
- realistic Coast Guard applications
- proposals for R&D funding

A literature search identified 750 abstracts on fuel cell applications through May 1988. Approximately 100 of the most promising source documents were reviewed. In addition to the literature search, we interviewed employees of DOE, DOD, and NASA, the principal administrators of fuel cell R&D efforts.

As a result of the literature search and interviews, the author concludes Alkaline and Phosphoric Acid cell technologies are technically capable of full scale commercial production. In addition, Molten Carbonate and Solid Oxide fuel cells should be commercially produced within the decade.

Phosphoric Acid fuel cell technology is the most promising for Coast Guard use. This technology is applicable to on-site cogeneration at shore facilities and remote power in the 1 kW to 50 kW range. Additionally, fuel cells could be used for marine or aircraft propulsion if there was a strategic shortage of petroleum distillates. However, there is no operational need at present for the Coast Guard to use fuel cells. High capital costs and current low energy prices make them noncompetitive.

Beginning in 1995, fuel cell prices may decrease and energy prices may rise to where fuel cells will be competitive. To prepare for that possibility, we could pursue three R&D efforts. First, we could purchase and operate a medium-cost, low-risk, on-site cogeneration plant to gain experience with fuel cells. Second, we could develop a low-cost, medium-risk, high-availability remote power plant. Finally, we could develop a high-cost, high-risk fuel cell for marine or aircraft propulsion.

2. STATUS OF FUEL CELL TECHNOLOGY

There are now seven major fuel cell technologies under study or active development. Two technologies, Phosphoric Acid Fuel Cell (PAFC) and Alkaline Fuel Cell (AFC), are sufficiently developed for commercial production. The Molten Carbonate Fuel Cell (MCFC) is under active development in the USA, Japan, and the USSR. It shows promise of being commercially available as early as 1995. The Solid Oxide Fuel Cell (SOFC) is also under development and may be available commercially by the year 2000. The other three technologies are still in the basic R&D stage.

2.1 Alkaline Fuel Cells (AFC)

AFCs were the first to reach full scale development and have been available in small numbers since the late sixties when they were first used in the space program. They have found a strong niche in the high value aerospace and military markets where the advantages outweigh their high capital cost and stringent fuel requirements. However, few organizations consider them commercially viable.

The disadvantages inherent in AFC technology make them unsuitable for almost all Coast Guard applications. Chief among the problems is that AFCs require a supply of fuel and oxidant with no carbon oxides present. For practical purposes this limits the fuel supply to pure hydrogen. Additionally, they have comparatively short lifetimes, comparatively lower efficiencies, high catalyst loads, a requirement for water rejection systems, and a strong temperature/pressure interdependence.

There are no commercially available AFCs on the market at present. However, the space shuttle makes use of 18 kW units. A 40 kW unit is under development in Germany; however, the market for the unit is still speculative.

AFCs do have advantages that would make them candidates for Coast Guard use in limited quantity. These advantages are low operating temperatures (60-80°C), immediate start up and load following with hydrogen fuel, 25-50% efficiency at low temperature and ambient pressure conditions, high cell voltages, high specific power and low infrared signature. The Coast Guard could consider AFCs for a high-value, zero-maintenance, emergency or uninterruptable power supply. Consideration should be especially strong if the application is in the polar regions.

2.2 Phosphoric Acid Fuel Cells (PAFC)

PAFCs are the state-of-the-art in fuel cell technology. Many prototypes have been installed and operated since 1982. Research is focused on on-site cogeneration (electrical and thermal) applications or central station electric utility applications. Forty-six 40 kW PAFCs were successfully operated as part of the On-Site Fuel Cell Field Test Program[8] from 1983 to 1986 by a U.S. government/private industry consortium. The Tokyo Electric Power Co. successfully operated a 4.8 MW power plant from 1983 to 1985.[9] Current efforts in the United States include a demonstration of 200 kW on-site cogeneration plants by the Gas Research Institute (GRI) and demonstration of 11 MW utility power plants by the Electric Power Research Institute (EPRI).

PAFC technology is mature enough to make market penetration the major focus of current efforts. Government involvement is minimal with only a modest R&D effort to lower costs by 10%[10]. Private industry involvement is heavy with two companies offering PAFCs commercially. Additionally, there are at least nine U.S., five Japanese, and four European companies with major investments in PAFC R&D efforts. The largest single commercial force at present is United Technologies Corporation (UTC) with over 600 employees at its South Windsor, CT, plant and over a half a billion dollars invested to date.[11]

PAFCs available commercially include a 5.6 kW forklift motor from KTI/Englehard, a 200 kW cogeneration demonstration plant from UTC, and an 11 MW utility demonstration plant also from UTC. Current plans show that additional systems available by 1995 will include 25 kW stacks from KTI/Englehard, a 1.5 MW utility plant from Westinghouse, and 200 kW, 1 MW, and 10 MW systems from Japan's New Energy Development Organization (NEDO). Furthermore, many one-of-a-kind demonstration units could be available if there is a demand.

These cells were the first offered for commercial markets. The largest problem at present is high capital cost which restricts market penetration. Current U.S. production capacity for PAFC systems is about 20 MW per year resulting in quotes for commercially available systems of approximately $3,000/kW with custom systems as high as $35,000/kW. These production levels and current economic factors will allow an 8-10% market penetration in the utility market by the year 2010. A market penetration of 40% with annual production of 500 MW could decrease cost of PAFC systems to $1,500/kW. The economics for on-site cogeneration market penetration are similar but very dependent on the cost differential between natural gas and electricity.

Compared to AFCs, PAFCs have good stability and the ability to use light hydrocarbon fuels. In addition, PAFCs have a higher thermal efficiency for electricity production (36-44% HHV) and a total energy efficiency approaching 80% HHV with full use of thermal output (150°C steam). This high efficiency is available over nearly the entire power range. Other advantages for PAFCs include low levels of pollution in exhaust emissions, quiet operation, and modularity in sizing and construction.

Coast Guard applications for PAFCs include on-site cogeneration for facilities with high thermal loads, power supplies for remote locations, and prototype power plants for vessel or aircraft propulsion.

The major disadvantages to Coast Guard use are high costs and a requirement for premium fuels. In addition to the high capital costs discussed above, PAFCs may have a high life cycle cost because the fuel cell stacks will have to be replaced after five years at about 35% of initial cost. Present technology limits fuel choices to light hydrocarbons easily reformable into hydrogen (e.g., natural gas or methanol).

2.3 Molten Carbonate Fuel Cells (MCFC)

MCFCs show promise for the next generation of fuel cells. Major advantages over present systems include up to 65% electrical generation efficiency, better quality waste heat (700°C), cheaper construction, ability to use coal derived fuels, and capability for internal reforming.

MCFC R&D is worldwide and demonstration scale power plants are under construction. Major efforts are under way in the U.S., Japan, Italy, and the USSR.[11,12] Efforts are almost exclusively devoted to central power stations for utilities with some minor work being done on larger cogeneration facilities. Current plans are for MCFCs to reach commercial capability by 1995. Cost projections show that MCFCs will eventually be less expensive than PAFCs. For the first decade, however, costs will remain high.

At this time there is no Coast Guard application for MCFC technology. The technology is almost exclusively for large central utility power plants with ready access to coal or natural gas.

2.4 Solid Oxide Fuel Cells (SOFC)

SOFCs are very attractive and offer the possibility of being the first commercial system for high volume transportation applications. Theoretical advantages include high electrical efficiency (62% HHV), high specific power (97 kW/Kg), high quality waste heat (1000°C), internal reformation of fuel, sulfur tolerance, solid state with no liquid electrolyte, and no requirement for precious metal catalysts.

The company closest to commercial development is Westinghouse. This company has a 20 MW demonstration plant under construction and may be able to proceed to commercial availability as early as 1990. German and Japanese companies are also working on designs but are still several years from producing large demonstration level power plants. These designs are based on 25 years of research. Different designs have the same electrochemical cell (Ztek) but vary in the mechanics of stack assembly. Because SOFCs are made of ceramics, cost could be very low. However, problems in mass producing ceramics to operate at temperatures greater than 1000°C makes all cost estimates speculative.

Two recent fuel cell designs are touted in the literature for volumetric power densities two orders of magnitude greater than previous designs. Argonne National Laboratory has developed the monolithic fuel cell and Imperial College, London, has developed a honeycomb design based on technology from automotive catalytic converters. Both technologies are still in basic R&D, and realistic cost and time estimates for commercial availability are unavailable. Strategic Defense Initiative (SDI) funding for monolithic cells could accelerate their development. However, any attempt to extrapolate commercial availability from technology of high value military aerospace applications is speculative.

The single largest problem in SOFC technology is in fabrication of the ionically conducting ceramic cells. Present production techniques do not provide the required mechanical, thermal, and chemical properties required in commercial products. Additionally, the problem of microscopic inhomogeneity must be solved for a ceramic electrolyte with predictable electrical properties. Ceramic construction technology must mature before mass production can occur.

The Coast Guard should not consider SOFCs now. We should monitor the technology and reconsider use in aircraft or vessels when mass production techniques are mastered.

2.5 Three Additional Technologies

The literature discusses three additional fuel cell technologies. These three are Solid Polymer Electrolyte (SPEFC), Direct Methanol Conversion (DMCFC), and Proton Conducting (PCFC). All three are in the basic R&D stage with SPEFCs closest to commercial production.

The Gemini space program used SPEFC technology. Selection was based on theoretical advantages of high power density and mechanical stability. However, problems arose with maintaining the equilibrium of the polymer and the space program switched to AFCs. Finding a good electrolytic polymer has been the focus of R&D efforts for the last 30 years. Stable polymers exist but are expensive. Current cost is about eight times that of PAFC technology. Work continues worldwide with applications split between military, aerospace, and transportation.

DMCFC technology is seen as the best long term prospect for vehicles because fuel is transported and converted directly from the liquid state. Understanding and controlling the electro-oxidation of alcohols is still in the laboratory stage and prospects for commercialization are unknown. Most work is presently being conducted in university laboratories. Hitachi of Japan is the only commercial organization with a R&D program in this technology.

PCFCs offer the possibility of easily managed construction with a mid range (300°C) cogeneration capability and a 60% HHV electrical efficiency. However, much basic R&D remains in the area of solid state proton conducting membranes.

3. STATUS OF AUXILIARY SYSTEM TECHNOLOGY

In addition to the fuel cell stack, fuel cell power plants require various auxiliary systems to operate. These auxiliary systems fall into three broad categories; fuel reformers, power core auxiliaries, and power conditioning equipment. The technology is mature and components are available commercially. However, demonstrations of commercial grade fuel cell systems show auxiliaries are the major cause of system failure. Additional research and development is required to eliminate present constraints.

Although fuel cell auxiliaries are mature and readily available commercially, the engineering knowledge and experience for properly designing and operating these auxiliaries is still immature. This problem will decline in the next two decades as design evolution continues and new generations are built and operated.

Purchasers of fuel cells in the next decade should expect system availability below those of competing technologies. First generation systems will have average availability in the 50-70% range. Second generation systems such as the UTC 200 kW PAFC system will have 80-90% availability. System availability exceeding 90% will be available by the third or fourth generation of commercial systems.

3.1 Fuel Reformers

Simple steam reformers are commercially available. They are used extensively for converting light hydrocarbons to hydrogen and carbon oxides. However, this technology has major limitations in efficiency, start up time, and load following capability. It is also impractical for heavier hydrocarbons such as diesel. Efforts to reduce or eliminate steam reformation constraints are in progress.

Simple steam reformers are based on the endothermic reaction between hydrocarbons and water resulting in hydrogen and carbon oxide products. The technology is well established as is the engineering to properly match a reformer to a particular fuel cell's characteristics.

There are limitations inherent in present commercial grade reformers. The first is thermodynamic efficiency of the reaction. A good estimation is that reformation of fuel will lower the overall fuel cell system efficiency to 30-50% of pure hydrogen systems. For example, a fuel cell operating at 60% efficiency on pure hydrogen will have an efficiency of 40% with reformed methanol. Reformed diesel will lower the efficiency to 30%.[13]

The second limitation is formation of carbon oxides in the reformer. Any carbon oxide introduced into an AFC will poison the cell and stop the reaction. In an AFC, an intermediate absorption unit must be placed between reformer and fuel cell to scrub the carbon oxides from the fuel gas. This has proven impractical on an industrial scale so AFCs are limited to pure hydrogen fuel sources.

The third limitation is the temperature of reaction. Natural gas (methane) reforms at 120°C and methanol reforms at 200°C. Longer hydrocarbon chains require proportionately higher temperatures up to 1000°C. Commercial fuel cells use the waste heat/steam feed to heat the reformer. For PAFCs, methanol is the longest hydrocarbon chain that can be realistically reformed. When MCFCs and SOFCs become available commercially this could change but at present they use only lighter hydrocarbon fuels.

The fourth limitation on conventional steam reformers is thermal transients. The first transient of interest is at start up where a steam reformer requires auxiliary heaters for a minimum of 30 minutes before temperatures are sufficient to start reformation. These heaters must run for an additional four to five hours until the fuel cell reaction is self sustaining. The other transient of interest deals with load following. All long term testing to date with fuel cell/reformer combinations has been at near constant load. We found no sources detailing reformers in variable load applications such as those in transportation. Present technology is not applicable to transportation applications because reformers' thermal time constants are on the order of 15 minutes. This could result in sluggish acceleration/deceleration or leaks and fires resulting from large temperature swings.[7]

The final problem with present reformer technology is the removal of sulfur and other contaminants from the fuel gas. This technology is immature and again limits fuel choices to light hydrocarbons.

3.2 Power Core Auxiliaries

In order for a fuel cell to convert hydrogen to unregulated DC power output, several major subsystems to the fuel cell stack in the power core are required. All fuel cells require control and air filtering systems. PAFCs and MCFCs require a thermal management system to keep the electrolyte at the proper temperature and a start up heating system for the first four to five hours. AFCs require electrolyte rejuvenation. All fuel cells using reformed fuel require a heat recovery system. The design and construction of these subsystems is an engineering task but success has not been easy. Failure of these power core auxiliaries has been the major problem in reliability of demonstration systems to date.

The 40 kW On-Site Fuel Cell Field Test Program is the largest demonstration to date and an excellent example of the requirements for sound engineering in auxiliary systems. During the life of the program the system was unavailable 22% of the time from failures in the power core. None of the shutdowns were from problems in the fuel cell stack. All of these shutdowns came from failures in power core auxiliaries. Major changes were made in the follow-on 200 kW design.[8]

3.3 Power Conditioning Systems

Fuel cells have typical electrochemical power characteristics of DC current and voltage inversely proportional to load. Regulated DC or AC output requires a power conditioning system. The technology is well established and systems are commercially available. However, systems for large power sources have only been commercially available in the last decade and engineering improvement continues. The market for power conditioning equipment is much larger than for fuel cells because this equipment is also used for natural energy systems such as photovoltaics.

4. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Fuel cell technology is not mature enough for operational Coast Guard use. Present high capital costs of fuel cells and low price of petroleum distillates prevent fuel cells from being economical. By 1995, however, technological advance and mass production should allow use of fuel cells in the Coast Guard.

Appendix A lists steps the Coast Guard could pursue to prepare for that possibility. In the interim, the R&D staff will continue to monitor the development of fuel cells.

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APPENDIX A

There are three R&D activities which the Coast Guard could pursue to prepare for the use of fuel cells. The first program is a medium-cost, low-risk operation of a PAFC cogeneration plant. The second possible program is a low-cost, medium-risk effort to develop a PAFC remote power supply. The third program is a high-cost, high-risk effort to develop fuel cells for marine or aircraft propulsion.

The cogeneration demonstration plant would provide experience in fuel cell operations with the least technical effort. A 200 kW PAFC plant would be purchased from United Technologies Corporation and operated as a demonstration plant with the help of the Gas Research Institute. A building at an operational shore unit with a high thermal load (i.e. mess hall, domestic hot water, or swimming pool) and access to natural gas would be an appropriate site. It would take about two years to design and construct such a plant and three years to evaluate its performance. Total cost estimate for the project is $1 million.

The remote power system design option could give the Coast Guard a power system in the 1-50 kW power range that is capable of unattended operation and nearly maintenance free. The PAFC system would use a 60% methanol/40% water mix for fuel, be air cooled, sized for mean load, and contain a battery in parallel to handle short term load changes. The only moving parts in the system would be the fuel pump and a thermostatic louver thereby eliminating the auxiliaries which have caused fuel cells' reliability problems to date. The technical risks are that the design is conceptual and the Coast Guard may not wish to use a fuel that requires 3.5 times the tankage of a comparable diesel fueled system. Cost would be $250,000 for a two year prototype development effort and a three year demonstration program. The requirement for an air cooled PAFC would effectively limit contractors to the Westinghouse or Energy Research Corporations.

The program for developing a fuel cell for vessel or aircraft propulsion would give the Coast Guard an option for hydrogen or methane fueled platforms in the event of strategic shortage of petroleum distillates. In addition to the normal technical risks involved in developing an entirely new propulsion system there are risks that hydrogen/methane fueled fuel cells may not be necessary. One risk is the possibility that Fischer-Tropsch reformers (which converts coal gas to petroleum) mature to a point that petroleum distillates will remain available after natural supplies are exhausted. Another risk is that new Carnot cycle technologies may equal or exceed fuel cell performance. New technologies such as adiabatic diesels, combined cycle gas turbines, and high pressure steam have achieved thermal efficiencies of 35-40%. Program cost will exceed $20 million for a ten year effort. Westinghouse or United Technolgies Corporation are likely prospects for prototype development in the first five years. System demonstration requires five additional years.