PART **TWO: MARINE** USES OF FUEL CELLS

Introduction

Why consider fuel cells for marine applications? As with land-based applications, economic factors drive the search for improved commercial marine power generation. These factors include capital and operating costs of propulsion and auxiliary power systems, cost and availability of fuel, and powerplant efficiency and reliability. Each of these factors has a strong influence on the design of ships and other equipment and powerplants. Fuel cells have been considered as one of several alternative propulsion systems for the ships of the future. Baham, for instance, has evaluated non-traditional propulsion systems for the commercial shipping industry (under contract to the Maritime Administration), and concluded that four systems show merit worthy of further investigation: nuclear, closed Brayton cycle, Stirling cycle, and fuel cells.[39]

Some of the benefits fuel cells would provide to the utility industry could also apply in the marine field. Of special interest is the potential of fuel cells for high efficiency, since this efficiency may translate into fuel cost savings. Moreover, fuel cell efficiency is relatively constant over a broad range of power settings. Such a characteristic suggests that fuel cells might be efficiently employed in ships that frequently vary power demand—e.g., towboats, ferries, offshore supply boats, or icebreakers. In addition to the potential for providing main propulsion, fuel cells could also supply auxiliary power and other needs.

Several other characteristics of fuel cells could provide benefits for specific applications. The fact that fuel cells are of modular design enables flexibility in the arrangement of plant components and could lead to a more cost-effective layout of power and cargo spaces and of basic ship structure. However, overall space and volume requirements of the fuel cell system and fuel will be greater than for present systems. As with other electrical powerplants, the maneuvering problems of ships and tugs might be mitigated by the advantage fuel cells provide in enabling electric power to be quickly switched to various locations to reverse main propellers or to activate side thrust propellers or water jets. Fuel cells have few moving parts, suggesting minimal manning requirements. Fuel cells are quiet, suggesting possible uses on anti-submarine warfare ships and seismic vessels. Finally, fuel cells offer greater endurance over batteries for some types of submerged operation.

Despite potential benefits, the marine market is not in itself large enough to drive fuel cell technology developments. Hence, it cannot be expected that fuel cells will penetrate marine markets before they become firmly established in the commercial utility sector, and shipbuilders will need to use and adapt products developed first either for the power industry or for DOD. In addition, cost advantages to onsite shore users due to large-scale production may not accrue to the marine industry.

Technical barriers, of course, also remain to be resolved. Barriers relating to the commercialization of fuel cells for transportation have been noted by Walsh and Rajan.[40] Most bear directly on cost, and include:

- high cost of platinum and other catalysts;
- thermal control problems;
- difficult fuel processing requirements;
- system complexity;
- startup time, especially in PAFCs;
- high reformer cost, especially in small systems;
- low volumetric power density;
- carbon monoxide intolerance of electrodes;
- high cost of membranes (for solid polymer electrolyte fuel cells);
- low efficiency of the oxygen electrode;
- deterioration of the cost/performance ratio in small systems; and
- need to replace cells periodically.

Required Characteristics

Fuel cells must be competitively priced, reliable, and durable if they are to be accepted by the maritime industry, They will be competing with other types of powerplants, especially with well-established diesel-electric plants, for a share of the

[39] Baham, op. cit,

[40] Walsh and Rajan, op. cit., P. 8.

marine market. Current low-speed diesels operating on residual fuel are very nearly as efficient as present PAFC powerplants, and the efficiency of the conventional powerplants of the future is expected to improve (see table 3). For example, diesel manufacturers are continuing their efforts to improve the heavy fuels capability of their engines. Shipowners will not likely try new propulsion systems without some very clear and convincing reasons to do so. Substantial advantages must be demonstrated, not just incremental improvements in efficiency in order to induce potential buyers to switch from a long-established powerplant to a new and relatively untested type of unit,

What would it take in order for the fuel cell to become competitive in the commercial marine industry? One view is that, for applications such as tugboat propulsion, total efficiency improvements of 10 to 20 percent would be required, that installed capital costs would have to be on the order of $300 to $500 (1985 dollars) per kilowatt (to compete with direct drive diesels), that power densities (kW/cubic foot and kW/lb) would have to be reasonably close to those of the diesel engine, and that the fuel cell (in the near term, at least) must be capable of running on distillate petroleum-type fuels customarily widely available.

Table 3.—Possible Marine Powerplants

	Fuel	Efficiency (%)
Current:		
Steam turbine with reheat steam (1,450 psig, 150 F)	Residual	32-36
Low-speed diesel	Residual	39-41
Future conventional:		
Steam turbine with heat pressure, high temperature reheat (2,400 psig, 1,050' F)	Residual	35-39
Adiabatic diesel	Diesel	49
Naval Academy heat balance engine	Diesel	43
Heavy-duty gas turbine, combined cycle	Residual	36-40
Closed-cycle combustion turbine	Residual	40-41
Fuel cells.[a]		
Phosphoric acid	Naphtha	41
Molten carbonate	Distillate	***50***
Alkaline	Hydrogen	60

[a]Without combined cycle or other forms of heat recovery

SOURCE U S Department of Energy, *Alternative Energy Sources for Non-Highway Transportation*, DOE/CS/05438-T 1, June 1980

Requirements for specific uses could vary considerably, but these will be difficult targets to reach.

The major factor inhibiting fuel cell usage for commercial marine applications is high cost. For military applications—e. g., for submersibles, small surface ships, and other specialized vehicles—mission requirements rather than cost are generally more important. Thus, if fuel cell technology is determined to have unique advantages for a defined mission, high cost may not be the major concern.

Other important factors to consider in selecting a fuel cell or other unconventional powerplant include compatibility with salty air and water; system and fuel safety; ability to withstand the shocks, vibrations, and ship motions commonly encountered at sea; ability to withstand and/or control transient thermal shocks due to rapid changes in load; training and manning requirements; and constraints on weight and volume of the powerplant, auxiliary systems, and fuel. The questions of fuel storage and possible additional en route refueling time, as well as other elements related to fueling along the transportation route, have not been considered in most studies. The volume of fuel required to travel between two points may be much greater for certain types of fuel (e.g., methanol). This may either place additional space and therefore size requirements on the vessel or necessitate additional refueling stops.

The ability to burn less expensive, widely available fuel would be advantageous, as would the capability to cogenerate steam, since, typically, ships have well-established uses for steam. Finally, fuel cells, like any other marine propulsion system, will need to be certified by the U.S. Coast Guard and/or ship classification societies (e.g., the American Bureau of Shipping or Lloyd's of London) that they are safe, durable, and perform to acceptable specifications. Listed below are five significant issues that will affect future marine fuel cell use.

Capital, Operating, and Maintenance Costs

There is no question that it is technically feasible to propel a ship and/or generate auxiliary power using fuel cells. The issue is whether and/or when fuel cells will be economical to purchase, install, operate, and maintain. Manufacturers of fuel cells for the utility industry maintain that $1,000/kW (1985 dollars) is a realistic installed capital cost goal for a mature fuel cell system. As technical improvements are made (e.g., by improving power density, cell stack cooler arrays, catalyst material, electrolyte management, and/or inverter efficiency) and as automated production techniques improve, the capital costs may be reduced further. However, in order for fuel cells to be competitive with direct drive diesel powerplants in the commercial marine industry, capital costs may have to be considerably lower than $1,000/kW.

Several studies of specific marine applications have considered the question of capital costs in detail. Notably, the Los Alamos National Laboratory (LANL) did a levelized life-cycle cost study of a typical 7,000-horsepower (hp) vessel capable of operating on inland or coastal waters. LANL concluded that such a vessel powered by an advanced PAFC using methanol costing $12.30/MMBtu could not compete with a similar vessel powered by a medium- to high-speed diesel powerplant, even if the capital costs for the fuel cells were zero. They then considered the case of fuel cells capable of using less expensive fuels, residual bunker fuel and coal, noting that handling and processing technology for these fuels has not yet been developed. Although their conclusions are tentative, they suggest that the capital costs necessary to make fuel cells competitive for this application would be significantly below $500/kW, even when using low-cost coal.[41] One of OTA's workshop participants estimated the total cost of a fuel cell system for a 5,000-hp vessel, assuming it can be installed for $500/kW, at $2 million.[42] The cost for a comparable diesel would be about $800,000.

The duty cycles and specific requirements of other potential marine applications could vary considerably. Thus, it is not suggested that the required competitive capital cost per kilowatt will be as low for all potential marine fuel cell applications. However, what little evidence there is suggests that fuel cells will have a difficult time capturing a large share of the market for most marine propulsion systems.

The relatively small size of the marine market will not likely encourage volume-based cost reductions; nor is the marine market large enough, by itself, to stimulate development of alternative fuels. For example, it has been estimated that, at best, the U.S. domestic towboat industry might acquire 50 fuel cell powerplants per year.[43] Even if all potential Navy applications utilized fuel cells, the domestic market could still not be considered large. Moreover, there are other reasons why development of marine fuel cells may be difficult. Baham notes that it is possible that competing powerplants could enter the market first and establish long-term commitments with major customers; that ship operators and builders tend to be conservative in their attitude toward changes in propulsion machinery and would likely be skeptical about changes that involve unknown risks; and that potential PAFC users may wish to wait for development of molten carbonate fuel cells, which may offer better performance and cost.[44]

Fuel Costs and Supply

Methanol has been identified in several studies of the possible marine applications for fuel cells as one of the most practical fuels for marine transportation applications. Among its advantages, methanol can be derived from a number of sources (including natural gas and coal, and wood and other renewable resources), it is clean and relatively easy to store (although it takes up more space per unit energy than hydrocarbon fuels), it is easily reformed at low temperatures using conventional heat exchangers, and methanol reforming technology is in a relatively advanced stage. Nevertheless, there are some significant problems and uncertainties associated with the use of methanol as a fuel cell fuel.

It is apparent from the few studies that have been commissioned that the competitiveness of

[41] J.H. Altseimer and J.A. Frank, "An Assessment of Fuel Cell Propulsion Systems," Los Alamos National Laboratory, LA-9954-MS, November 1983.

[42] Francis X. Critelli, Maritime Administration, OTA workshop comment, Sept. 5, 1985.

[43] James Niven, American Commercial Barge Lines, OTA workshop comment, Sept. 5, 1985.

[44] Baham, op. cit., p. 6-6.

fuel cells in the marine industry will be sensitive to the cost of fuel. Researchers who have assumed methanol will be used for marine fuel cells have reached both optimistic and pessimistic conclusions about the future competitiveness of fuel cells.[45] The assumed price of methanol in these studies varied widely. The price of methanol during the mid-1990s—the earliest time that fuel cells could be expected to enter the marine market—is highly uncertain. A 1983 study by FCUG estimated that by **1990** methanol would cost $16.00/MMBtu (1983 dollars).” Recently, the same group lowered their estimate to approximately $10.00/MMBtu (1983 dollars). (The current price is about $7.30/MMBtu.) Although FCUG’s estimate has been reduced, methanol is still expected to be more expensive than No. 2 diesel, propane, and naphtha (see table 2). Moreover, fuel cost is not the only important factor. Experience has shown that improvements to reduce fuel costs are not acceptable if poor reliability is a consequence.

Perhaps as significant as the issue of cost is the fact that methanol and other alternative fuels (e.g., naphtha) are not widely available as transportation fuels and that no network exists to distribute these at present. It is not a simple matter to shift from a well-established fuel to a new fuel, and residual fuel, bunker C, and diesel will likely be available for at least another 20 years. The U.S. Navy considers the fuel availability problem so important that it has all but eliminated methanol from consideration as a potential fuel for its fleet. Similarly, the U.S. Army has major reservations about using methanol as a fuel cell fuel in the field. All Army vehicles use diesel fuel. Thus, the logical fuel to use with the portable fuel cell generators the Army is developing is also diesel. It is not surprising that the Army has initiated development of reformer technology capable of processing No. 2 diesel fuel.

For the short term, methanol appears to suffer from a chicken-and-egg problem. Automotive and vessel manufacturers are hesitant to produce methanol-powered vehicles because the fuel distribution network does not exist. Fuel suppliers, on the other hand, will not be motivated to provide methanol until there are enough vehicles on the road or at sea that require it. From an economic point of view, the future cost of methanol has been estimated to be twice as much as gasoline, on a mileage equivalent basis, if new methanol plants must be built to satisfy U.S. demands.[47] However, methanol may well deserve a much closer look when the traditional fuels, such as No. 2 diesel, become scarcer and more expensive. It is the least expensive high-grade liquid fuel that can be produced from abundant U.S. coal resources, and can be derived from other sources as well. Some automotive industry people believe that a methanol distribution network for automobiles could evolve naturally from the present distribution system, since methanol is already used in small quantities in some places as a gasoline additive.[48] It is not too far-fetched, then, to envision the distribution system expanding to include small boat marinas and eventually to facilities for larger ships, but the costs of establishing such a network are very difficult to estimate.

Several additional concerns have been noted. Methanol has a low flashpoint, which could be particularly troublesome for some military applications. Thus, special precautions would likely need to be taken in handling methanol. Second, a safety problem could arise because methanol burns without a visible flame; hence, a methanol fire cannot be easily detected. And finally, very little information is available on the effects of low concentration, chronic exposure to methanol.

Reformer Technology

Development of reformer technologies capable of using logistic fuels could be an important breakthrough for the acceptance of fuel cells for transportation. The logistic fuel of choice appears to be No, 2 diesel. It is currently widely available and relatively inexpensive. However, currently available reformers are not capable of efficiently

[45] See, for example, Arctic Energies Ltd., op. cit.; and Los Alamos National Laboratory, “Assessment of Fuel Cell Propulsion Systems, ” November 1983.

[46] The Fuel Cell Users Group, “Report on the Availability and Prices of Alternative Fuels to Supply Fuel Cell Power Plants, ” July 1983.

[47] Chevron, U. S. A., Inc., op. cit., pp. 4-5.

[48] Gene Helms, Allison Gas Turbine Division, General Motors, telephone conversation, Nov. 6, 1985.

producing the hydrogen needed by the fuel cell from No. 2 diesel fuel. If efficient reformer technology could be developed enabling fuel cells to use No. 2 diesel, the fuel logistics and safety problems associated with methanol and some other fuels would be moot for the near term. The key challenge is to develop a reformer for liquid hydrocarbon fuels that works for relatively small to medium capacities. As noted above, the U.S. Army has initiated work on this significant problem. Specific development needs include stable catalysts, the reduction of the water-to-carbon ratio, and desulfurization.

Survivability in Marine Environment

For the most part, fuel cells have been designed for terrestrial use and have not had to cope with the special problems related to the marine environment—presence of salty air and water, vibrations, shocks, corrosion, etc. The durability of fuel cells under harsh marine conditions is not known. However, the design of fuel cell systems that can withstand these elements is not expected to be a major challenge. For instance, although it is not yet known how salt will affect fuel cell operation, the filtering system designed for a marine gas turbine might reasonably be expected to remove salt in the air so fuel cells and reformers are not contaminated. Similarly, it is likely that fuel cells can be "hardened" to withstand marine shocks. The Navy, for instance, designed their alkaline fuel cell to withstand the stress associated with a 5G landing in a C5A transport plane, and NASA designed its alkaline fuel cell for use in space. Still, no long-term testing of commercial fuel cells under typical marine conditions has been conducted. The specific mission will control design requirements.

Transient Energy Response

Little is currently known about the response of marine fuel cells to abrupt changes in temperature due to sudden, very large changes in load. It has been suggested[49] that present fuel cells may not be able to withstand the temperature changes associated with abrupt power changes (i. e., changing from full load to "all stop") that occur aboard ships. If this is true, fuel cell durability may be significantly decreased. Problems resulting from temperature changes could include fuel cell fires and acid leaks, either of which would render the fuel cell inoperative. Long-term testing, under controlled conditions, of responses to electrical and thermal transients is needed to determine the nature of the problem.

If design changes of marine fuel cells are required to address this potential problem, the cost of fuel cells for marine applications may increase. Thus, a more sophisticated control system may be needed, requiring the development of quick response sensors imbedded in the cell stack and gas control system. Electrodes, electrolytes, and fuel processors may also need modification.

PAFCs have been the type of fuel cell investigated in most studies of marine applications for fuel cells. Other types of fuel cells offer the potential for greater efficiency than PAFCs, and these may be considered for use as marine powerplants in the more distant future. Molten carbonate fuel cells using distillate fuel, for instance, may be more than so percent efficient, and in addition, have the capability to cogenerate high-quality steam, for which ships have well-established uses. In a 1980 study done for DOE, the Exxon Research & Engineering Co. concluded that future molten carbonate systems will be very close to being competitive with diesel engines and therefore deserved closer examination.[50] Alkaline fuel cells using pure hydrogen fuel, although expensive, have already demonstrated efficiencies in excess of 60 percent in the space program.

Potential Applications

The marine industry may have a wide variety of applications for fuel cells of various power outputs. To date, however, virtually all of the fuel cell development efforts undertaken by manufacturers and funded by government agencies and

[49] Gene Helms, Allison Gas Turbine Division, General Motors, personal communication, Oct. 9, 1985,

[50] U. S. Department of Energy, "Alternative Energy Sources for Non-Highway Transportation, " prepared by Exxon Research & Engineering Co., DOE/CS/05438-T1, June 1980, pp. 6-27. Exxon also concluded that a coal-fired steam boiler/turbine should be able to undercut the molten carbonate system by $100/hp-yr, given coal priced at $0.90 to $1.60/MMBtu.

industry have been associated with advancing the state-of-the-art of fuel cell technology for land-based gas and electrical utility applications. Thus far, the only fuel cell designed and tested specifically for marine use has been an alkaline fuel cell built by UTC for a very specialized Navy deep-sea search mission (this application is described in some detail below). Other than this one project, studies of fuel cell applications in the marine field have been confined to a handful of conceptual and planning studies initiated by DOE, the Maritime Administration, and the Navy.

Given the sparse information available, the Office of Technology Assessment recently invited some industry and government experts to brainstorm about some of the possible marine uses for fuel cells. The suggestions may be broadly placed into seven major categories:

1. Applications in which quiet operation is useful or desired:
   - research ship propulsion and auxiliary power,
   - seismic vessel propulsion and auxiliary power, and
   - anti-submarine warfare vessel propulsion and auxiliary power.
2. Applications in which power settings are constantly changing:
   - tow boat propulsion,
   - Coast Guard cutter propulsion,
   - ferry propulsion, and
   - supply vessels for the offshore oil and gas industry.
3. Submarines and submersibles:
   - submersible propulsion (military or commercial),
   - submarine tanker propulsion, and
   - remote underwater vehicles.
4. Commercial transport ship propulsion:
   - tankers,
   - bulk carriers,
   - containerships, and
   - cruise ships.
5. Naval ship propulsion power.
6. Commercial and naval ship auxiliary power.
7. Other applications:
   - offshore platform auxiliary power;
   - power for remote navigation, radar, or oceanographic data acquisition and transmission systems; and
   - power for refrigerated containers.

Very little effort has been devoted to the specific requirements of the above (or any other) possible marine applications for fuel cells relative to their mission cycles, or to the physical and operating constraints that must be considered for each application and how fuel cells measure up to these constraints relative to competing power systems. Until mission requirements and physical and operating constraints are determined for potential applications, it will be impossible to reach definitive conclusions about the applicability of fuel cells to specific cases.

Quiet Operation Applications

One of the most logical potential applications for fuel cells is for propulsion and/or auxiliary power for ships that require or could benefit from quiet operations. Fuel cells appear to offer a distinct advantage over other powerplants for this purpose. Moreover, cost considerations are not as severe a constraint if quiet operation significantly improves the ability to accomplish the vessel's mission. This is particularly true for the Navy's Anti-Submarine Warfare vessels, where the mission requirement, and not cost, is the main factor controlling selection of the powerplant. It may also be true, but perhaps to a lesser degree, for commercial seismic vessels and for oceanographic acoustic research ships, both of which would be able to collect better quality data if the powerplant made less noise. In addition to propulsion, the fuel cell system could be used for the auxiliary power and hotel load requirements on such vessels.

Applications in Which Power Settings Are Constantly Changing

Some vessels are constantly changing speed and/or varying load requirements. Push= tow boats are a prime example. This type of application may deserve a close look given the capability of fuel cells to maintain their efficiency over a broad range (30 to 100 percent) of power fraction. This capability translates into significant operational savings—in some instances—over diesel powerplants, which lose efficiency unless operated at full power. However, as noted above, sudden large changes in power loads may have negative consequences for marine fuel cell operation. Several conceptual studies of these types of applications have been done.

Inland Waterways Push-Tow Boats .—The Los Alamos National Laboratory (LANL) began studying possible transportation applications for fuel cells in 1981 when it began a fuel cell R&D program jointly funded by DOE's Division of Energy Storage and Office of Vehicle and Engine Research and Development. In particular, Huff and Murray of LANL have investigated the feasibility of using fuel cells for propelling inland-water, 5,000 to 6,000 hp push-tow boats .[51] The push-tow boats now operating on the Ohio and Mississippi Rivers are currently powered by two locomotive diesel engines with direct coupling from each engine to the propeller through a gear reduction and reversing gearbox. The usual tow consists of 15 barges, arranged in 5 rows of 3. With this arrangement the boat can move a 22,500 ton payload at speeds of 5 mph upstream and 11 mph downstream. The Los Alamos researchers determined that it is technically feasible to use fuel cells fueled by methanol to power push-tow boats. Fuel cell systems meet weight and volume constraints, are compatible with existing propulsion components, and provide adequate performance relative to operational requirements.

However, while technically feasible, the researchers concluded that using fuel cells for this application is not particularly attractive. Although the efficiency of both PAFC and SPE powerplants for push-tow boat use was determined to be greater than diesel power efficiency (see table 4), diesels are considered to be very efficient for this application. Methanol was chosen as the likely most practical fuel cell fuel for this application. However, the researchers noted that "the addition of electrical systems reduces the fuel cell system efficiency to the point where the energy cost disadvantage of methanol cannot be overcome. " Moreover, fuel consumption (in gallons/hour) was calculated to be greater in both fuel cell systems considered than in the current diesel system, so that the range possible before refueling is much reduced. In the case considered, two fueling stops would be required for the PAFC-powered vessel to travel the **1,890** mile distance from New Orleans to Pittsburgh. Additional onboard fuel storage could be a problem.

Table 4.—Push-Tow Boat Powerplant Comparisons

	PAFC	SPEFC	Diesel
Total power (hp)	5,760	5,760	5,140
Powerplant efficiency	0.55	0.50	0.36
Fuel consumption (gal/h) (methanol/diesel)	411	457	273
Upstream energy consumption (Btu/net ton mile)	294	327	401
Downstream energy consumption (Btu/net ton mile)	126	140	172
Average energy consumption (Btu/net ton mile)	210	234	286
Upstream range (miles for 120,000 gal tank)	832	1,182	1,976

SOURCE J R. Huff and H.S Murray, "Feasibility Evaluation of Fuel Cells for Selected Heavy-Duty Transportation Systems, " Los Alamos National Laboratory, October 1982, p 28

Coast Guard Cutters.–Arctic Energies, Ltd. (AEL) reached a more optimistic conclusion in a study of the potential fuel cost savings that use of PAFCs on Coast Guard cutters might bring. [52] AEL combined data on fuel usage and duty cycles to determine fuel consumption at various throttle positions. They concluded that for this application fuel cost savings (over diesel-powered cutters) of between **32** and **51** percent were obtainable by methanol-fueled fuel cells and DC propulsion drive. The price of methanol used in calculations was $0.42/gal. It should be pointed out that this study was limited to consideration of fuel cost savings only, and that other factors, such as range, availability of fuel, etc., were not considered. The conclusions reached do suggest, however, that fuel cells used for this application may eventually deserve a closer look.

[51] J.R. Huff and H.S. Murray, "Feasibility Evaluation of Fuel Cells for Selected Heavy-Duty Transportation Systems, " Los Alamos National Laboratory, March 1982.

[52] Arctic Energies, Ltd., "Evaluation of the Ship Fuel Cost Savings Potential of Phosphoric Acid Fuel Cell Power Plants and DC Drive for Coast Guard Cutters," AEL/CGORD 85-1, May 1985. The Coast Guard provided the data for this study but did not sponsor the research and does not necessarily agree with the study's conclusions.

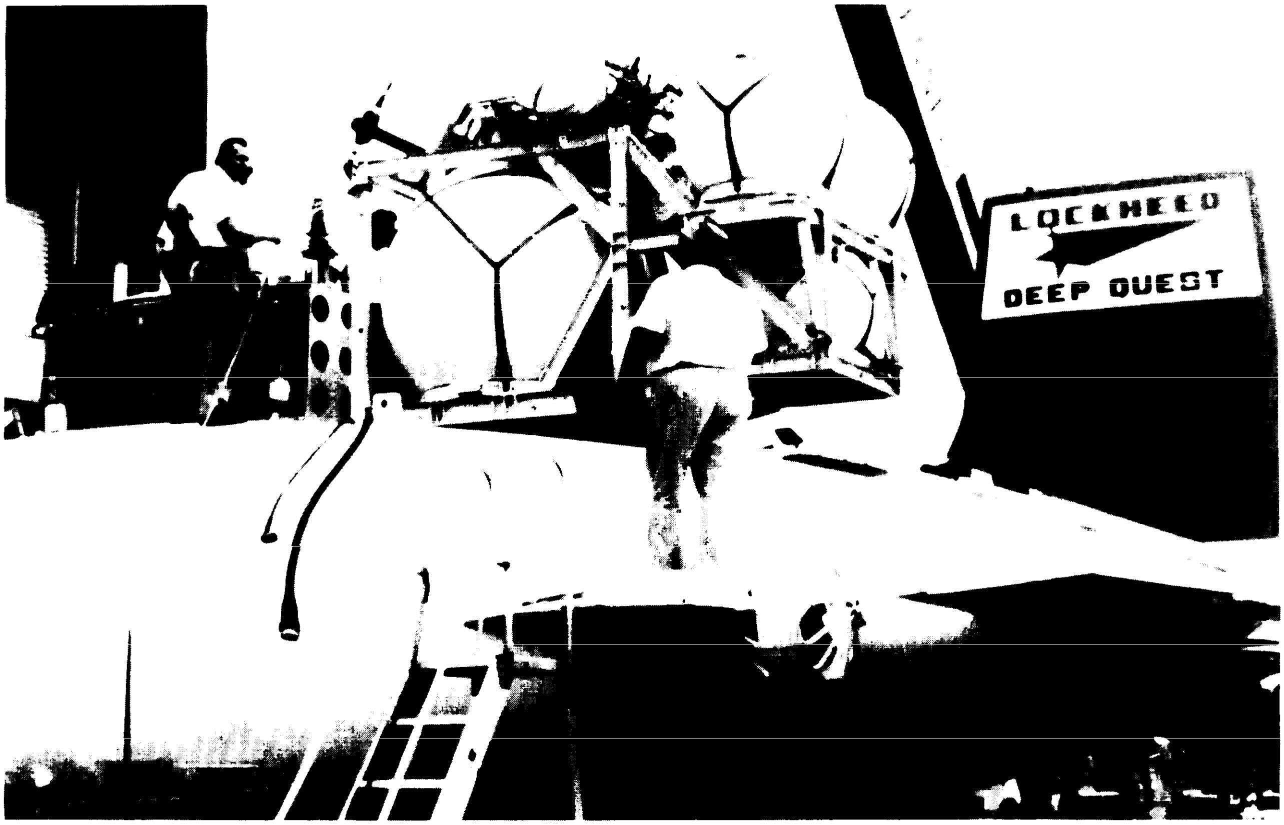

Photo credit U S Navy

Fuel cell being installed in submersible *Deep Quest*

Submarines and Submersibles

A major constraint faced by submerged vessels, whether submarines or submersibles, is endurance. Fuel cells have been considered for submerged operations because they enable undersea vessels to remain submerged for a greater length of time than the batteries that typically propel small submersibles.

The Deep Submergence Search Vehicle (DSSV) and the Deep Submergence Rescue Vehicle (DSRV). —The only fuel cell system developed thus far for a marine application has been the one designed by UTC, using the alkaline fuel cell technology developed by NASA, for use in a deep submergence search vehicle for the U.S. Navy, In 1978, Lockheed installed and tested the UTC 30 kW alkaline fuel cell on board its deep submergence search vehicle, Deep Quest. *Deep Quest* made about **50** successful dives with its fuel cell power system. Nevertheless, the U.S. Congress terminated the program, and the alkaline fuel cell no longer had a mission. The fuel cell was reconfigured for possible application on the DSRV; however, the mission requirements for the DSRV were sufficiently different from those of the DSSV that it did not require a fuel cell propulsion system. The DSRV is designed to be carried piggy-back on a nuclear submarine, so it could get its batteries recharged by the mother submarine, Thus, the initial power supply was more than adequate for the submersible's rescue mission. Moreover, although the fuel cell was technically satisfactory, doubts persisted about reliability and system safety in a real rescue situation. High pressure hydrogen and oxygen to fuel the alkaline fuel cell would have to be stored aboard the mother submarine and transferred to the DSRV for refueling, a potential safety problem. In addition, if large quantities of hydrogen and oxygen were stored on board, it would be necessary to take off a weapons system. In other words, the alkaline fuel cell, technically adequate though it was, did not fill the mission requirement.[53] This example illustrates the fact that for military applications, the mission requirement, and not cost, is the major consideration.

The Navy has no current effort to develop submersible/submarine fuel cell power systems. However, some believe that small submarines are one type of naval vessel for which fuel cells would be well-suited, providing, perhaps, a less expensive alternative to nuclear-powered submarines. For instance, SPE technology is currently being investigated in West Germany as an alternative to diesel power for submarines.

Submarine Tankers. —Several conceptual engineering and economic studies have been done investigating the feasibility of building large submarine tankers to transport oil or products such as methanol and liquefied natural gas from Alaska's North Slope under Arctic Ocean ice to Europe or the U.S. East Coast. In 1982 Arctic Enterprises, Inc., prepared a report for DOE on the feasibility of building a fuel cell propelled submarine tanker system.[54] Although the report concluded that no engineering or R&D breakthroughs were required to build such a vessel, neither technical nor economic feasibility have yet been demonstrated. No oil company at this time is seriously considering transporting oil or oil products under Arctic ice, and the idea is considered by most to be ahead of its time.

Remote Underwater Vehicles.—Remote underwater vehicles used for search, salvage, inspection, and scientific purposes are also constrained by onboard energy sources. The principal users of these vehicles are the oil industry, the Navy, other government agencies such as the National Oceanic and Atmospheric Administration, and the scientific community. It is expected that as the needs arise within the industry and the Navy, systems similar to the DSRV system will be built. The scientific community will probably first ride "piggy-back" on industry or Navy fuel cell equipped remote vehicles until it becomes clear that sufficient need and funding can be identified for such equipment to become a part of the community's University National Oceanographic Laboratory System fleet.

Commercial Transport Ships

Fuel cells have been considered as well for commercial transport ships. The competition with alternative systems is likely to be even stiffer for tankers, containerships, bulk carriers, and the like. This is because these ships operate at constant speeds and currently use high efficiency, low-rpm diesel engines. Use of fuel cells will be limited by industry reluctance to change from a propulsion system that is reliable and efficient. In general, commercial applications for fuel cells, unlike military applications, must prove cost effective. Unless there are clear and significant economic advantages for fuel cells, they are unlikely to be used. These advantages have not yet been demonstrated.

Naval Ships

Cost is not necessarily the major concern in building naval surface ships. Fuel cells will be used if they prove to be the best technology for a particular application. The Navy has not yet determined that there are any missions for which fuel cells are uniquely suited, although some analytical work has been done.[55] Limited availability of fuel cell fuel and the low power density are the biggest constraints in developing fuel cells for naval ships. As presented above, it is no easy task for a fleet to switch to a new fuel. In the Navy's case, before it would do so, the fuel would have to be available worldwide. Thus, the Navy will likely continue to depend on traditional logistic fuels as long as they are available and fulfill mission requirements. A second special military problem concerns the use of low flashpoint fuels such as methanol. A low flashpoint increases the potential for fires, and fuels with low flashpoints

[53] Ted Stanford, U.S. Navy, NAVSEA, discussion in OTA workshop, Sept. 5, 1985.

[54] U.S. Department of Energy, *Fuel Cell Propelled Submarine Tanker System Study*, prepared by Arctic Enterprises Inc., DOE/FE I 15086, June 1982.

[55] For example, Naval Sea Systems Command, *A Total Ship Analysis of Future Candidate Naval Fuel Alternatives*, report No. 313-011-81, July 1981.

could be particularly dangerous in a battlefield situation, where fires are to be expected. Thus, methanol-fueled fuel cells probably would not fit some Navy missions even if fuel cells offered other significant advantages. A different logistic fuel would have to be found, or reformer technology would have to be developed for No. 2 diesel.

Auxiliary Ship Power

Auxiliary power units provide electricity to all systems aboard a ship except main propulsion. These systems include hotel services (lighting, plumbing, and pumps for water); bilge and ballast pumps; fuel transfer systems; cargo-handling systems; navigation systems; etc. Fuel cells could provide electricity for these auxiliary systems. Less capital investment, and hence, less risk would be required than would be the case for investment in main propulsion systems. Hence, the outlook for near-term testing of fuel cells for auxiliary purposes may be better than the outlook for the use of fuel cells as main propulsion units. However, there are some potential drawbacks to be considered. One would not want to have one fuel for the main power units and another fuel for auxiliary power units. Generally, the simpler the fuel logistic system, the better. In addition, although fuel cell auxiliary systems may be more efficient than alternative powerplants, the potential savings possible are not very large compared to savings potentially achievable by switching to more efficient main propulsion units. Cruise ships may be an exception to this rule, because they have big hotel loads; hence, quiet, unobtrusive fuel cell auxiliary power units may be particularly suited for this type of ship.

Other Potential Applications

Several other potential marine applications have been considered. Fuel cells could be used as a power source on offshore oil platforms. Commercial diesel engines and gas turbines provide power at present. Fuel cells could also be used to power remote navigation, radar, or oceanographic data acquisition and transmission systems. As with other marine uses, the long-term reliability of fuel cells used for these purposes has never been tested. Another possibility is to use fuel cells as an auxiliary power source for refrigerated containers. Such containers are transferred from shore to ship and must be kept refrigerated at all times. Sea-Land Corp. has investigated the use of fuel cells for this application and concluded that the idea is not economically attractive at the present time. Finally, large, floating fuel cell power generation systems can be envisioned. Such floating plants might provide power for overseas markets and could be an export opportunity for U.S. companies; however, development of this application is not likely at any time soon.

Other Transportation Applications

Train Applications

Investigations of the application of fuel cells to train transportation systems have been conducted by DOE's Los Alamos National Laboratory. Comparisons were made of phosphoric acid and solid polymer electrolyte fuel cell systems with a conventional General Motors' SD40-2 diesel electric locomotive. The simulation results show that performance goals can be met and that overall energy consumption of heavy-duty fuel cell powerplants can be substantially improved over diesel operation of locomotives. If development of fuel cells for locomotives is pursued, it may eventually stimulate more interest in fuel cells on the part of marine operators. Powerplants developed for locomotives have many of the features and performance characteristics required for a number of marine uses.

Automotive Applications

Potential applications of fuel cell technology for land vehicles have ranged from automobiles to buses and trucks. For automobiles, estimates have been made that the fuel cell equipped auto might be able to achieve **60** miles per gallon. However, the use of a fuel cell alone for automotive propulsion leads to a serious deficiency. In the automotive field, fast acceleration and changing power requirements place quick response requirements on the power system. While fuel cell systems are generally considered good load following systems for industrial applications, they are too slow to respond to fast and often unpredictable car, bus, and truck power changes. Research is underway to combine heavy-duty battery power sources with the fuel cell system to obtain the response needed to accommodate the almost instantaneous peak power increases required by on-road and off-road vehicles. The fuel cell would be used to recharge the battery during steady, low demand driving periods.

Walsh and Rajan are not optimistic about the use of fuel cells in the automotive industry. They note that transportation economics demand radical reductions in the cost of fuel cell systems. PAFCs are currently about 10 times too expensive to be considered for transportation markets.[56] For fuel cells to become competitive with heat engines, major cost breakthroughs must be achieved. Significantly, heat engines can be modified to burn nonpetroleum fuels such as methanol, and therefore, fuel cells will be in direct competition with heat engines. "Present fuel cell technology is grossly inadequate for most transportation applications, and quantum advances are needed. In our opinion, 10 or 20 years of intensive R&D with strenuous attempts at invention will be required."[57] Other factors, such as higher fuel efficiency, reduced maintenance costs, and reduced pollution may compensate, to some degree, for production costs. General Motors, on the other hand, is more optimistic, and is currently investigating the potential of phosphoric acid and SPE fuel cells for land transportation uses. 'g

Some Options for the Federal Government

The outlook for using fuel cells in the electric and gas utility industry appears promising. The Federal Government has supported private sector R&D efforts since the 1960s. Continued Federal support of fuel cell development programs is probably necessary to advance the introduction of fuel cell technology into the land-based utility industry.

The use of fuel cells in the marine industry in the next 15 to **20** years is far less certain. When and if the commercial maritime industry decides that fuel cell power systems would provide significant cost and/or other advantages over competing power systems, these fuel cell systems must be adapted to the unique demands of the marine environment. Very little R&D on fuel cells for marine applications is currently underway inside or outside the government. Since the R&D program for land-based applications is so large in comparison, some believe that the proper course for the marine industry is just to monitor closely that R&D and select developments and applications as they may occur in the future. Others believe that unique marine requirements warrant specialized R&D efforts.

Specific research and development could be supported by the Federal Government and/or industry to improve the potential of fuel cells in the marine market. For example, the near-term use of fuel cells in the marine industry could be stimulated by developing technology capable of reforming diesel oil. Other research that could be undertaken includes: laboratory testing, followed by shipboard analysis and testing, of fuel cell components to determine their suitability and/or vulnerability to the marine environment; basic electrochemical studies to improve catalysts and electrolytes that would not be contaminated by fuel processed from fuel oil; and accelerated investigation of molten carbonate fuel cells and of the vulnerability of this type of fuel cell to the marine environment. The Federal Government's investment in molten carbonate technology could concentrate on those developments needed to support a demonstration of this fuel cell's higher efficiency and fuel flexibility. The private sector could focus on the technology and processes needed to manufacture these fuel cells at a cost competitive with conventional power generators.

The Maritime Administration, and perhaps other agencies within the Department of Transportation, and DOE might be able to offer some assistance for applications more directly relevant for the commercial transportation sector. For instance, funding could be provided to demonstrate and evaluate use of a fuel cell system on a commercial ship or locomotive. One suggestion is that future fuel cell research for heavy-duty transportation applications focus on developing the more efficient molten carbonate fuel cells. Once a small (i.e., 50 kW) molten carbonate system has been

[56]Walsh and Rajan, op. cit., p. 6.

[57]Walsh and Rajan, op. cit., p. 9.

"Gene Helms, Allison Gas Turbine Division, General Motors, telephone conversation, Nov. 6, 1985, demonstrated, these agencies could coordinate a demonstration of a 2 to 4 MW powerplant for the heavy-duty transportation sector. Different types of incentives to private industry might also be used, such as tax benefits for those who use non-petroleum-based fuels or accelerated depreciation.

The Federal Government may also wish to encourage the Navy, Army, Air Force, and Coast Guard to become more involved in developing fuel cells for their mission requirements. OTA's analysis indicates potential benefits of marine fuel cell use in naval applications, and suggests that more in-depth analysis of the potential applicability of fuel cell technologies for Navy missions is needed.

The Navy is currently monitoring fuel cell developments, but it may be useful for the Navy to consider supporting specialized research into marine fuel cell development as well. At present, for example, very little work has been done on developing fuel cells for "quiet" ship operation aboard certain vessels where noise emissions from conventional engines are a major problem. If fuel cells could match these and other unique Navy missions, then naval fuel cell research, independent of private sector efforts, may be justified.

Recognizing that research funds are limited and must be carefully targeted to the most productive avenues of research, it may be best to begin by encouraging the military to develop small fuel cell systems for auxiliary power on naval surface ships. As experience is gained, larger fuel cells (on the order of a megawatt) might be used for naval and Coast Guard auxiliary power. Finally, beyond 2000, the Navy or Coast Guard could be encouraged to focus on developing larger fuel cell powerplants for primary propulsion power. The Navy and Coast Guard have different missions than the civilian sector and some applications developed by them may not be directly useful for the private sector. On the other hand, some applications first developed for military purposes might stimulate development of applications for commercial use.