

## MARINE AND NAVAL APPLICATIONS OF FUEL CELLS FOR PROPULSION: THE PROCESS SELECTION

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The system analysis steps and the tradeoff considerations governing the process selection for the marine application of fuel cells to propel large ships is described. The analytical process was used, in part, during 1987 in the performance of a study of a fuel cell propelled combatant ship conceptual design under a U.S. Navy contract [1]. Figure 1 shows the marine fuel cell process selection procedure. Eighteen steps are involved in the surface ship case. Steps 19 and 20 would also be involved in evaluating fuel cells to power submarines. The steps are discussed in sequence.

### 1. Type

Six types of fuel cells are considered in the analysis. They are:

- (A) Alkaline
- (B) Proton exchange membrane or solid polymer electrolyte
- (C) Phosphoric acid: (a) external reformer, (b) internal reformation
- (D) Super acids
- (E) Molten carbonate
- (F) Solid oxide

Alkaline fuel cells have been used in the NASA space program in the Apollo system and the Space Shuttle system. The others have received varying degrees of DOD, DOE, EPRI and GRI research and development funding. In 1985/1986 the Office of Technology Assessment (OTA) of the U.S. Congress completed a Technical Memorandum on the Marine Applications for Fuel Cell Development [2]. The author participated in the preparation of the OTA report. The report provides an excellent general treatment of the subject. The foreword of the OTA report says: "To date almost no attention has been given to the potential marine applications for fuel cell technologies. Nevertheless, some of the benefits that fuel cells may offer to the utility industry may also apply to some marine uses."

The types of fuel cells considered for marine applications which are listed above (A through F) are in ascending order of operating temperature. As the surface ship sequence of 18 process selection steps is carried forward, various types are dropped from further consideration because their charac-

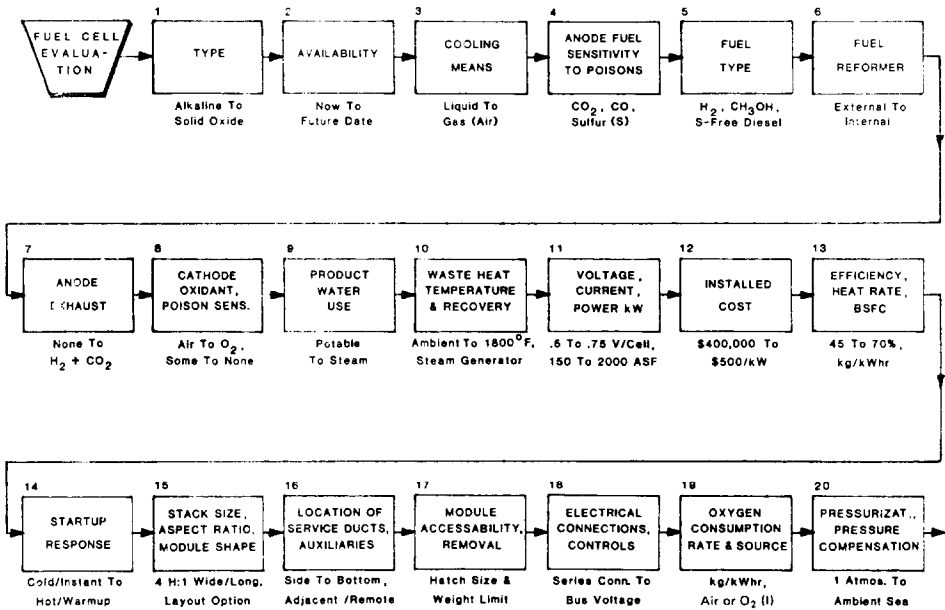


Fig. 1. Marine fuel cell process selection.

teristics are inappropriate to the marine applications, which are typically at multimewatt power levels.

## 2. Availability

The alkaline, proton exchange membrane and phosphoric acid types are available now. The molten carbonate type is classed as being available in the near future. Both the super acids and the solid oxide types are in the further future and appear to offer little advantage over the phosphoric acid and the molten carbonate types respectively, for marine application.

## 3. Cooling means

The primary coolant can be liquid or gaseous. However, the liquid must not conduct electricity. This typically means demineralized fresh water or a dielectric liquid such as mineral oil. However, above the temperature of the proton exchange membrane fuel cells at 180 to 200 °F the coolant water will actually be in two phase flow in phosphoric acid or higher temperature fuel cells. Thus the use of gas cooling, typically air, is common and provides lower system weight, no liquid leakage and ease of access to the fuel cell stacks. The two highest temperature type fuel cells, molten carbonate and solid oxide, are both gas (air) cooled.

One of the main reasons the alkaline fuel cells are not recommended for ship propulsion power use is their total intolerance to carbon and air

contaminants. This fuel cell technology was designed for spacecraft. In that weight-critical and largely cost-unlimited application alkaline fuel cell power plants work well.

#### 4. Anode fuel sensitivity

Many readily available carbonaceous liquid fuels contain contaminants. The fuel cell types listed in Section 1 vary from those with no tolerance (alkaline) to those with some tolerance for the most common and pernicious fuel poison, sulfur. Other fuel contaminants include carbon dioxide and carbon monoxide, both of which are formed in the thermochemical reformation of carbonaceous fuels to hydrogen, which is the fuel actually used by the fuel cells. Alkaline and proton exchange membrane fuel cells are permanently poisoned by carbon monoxide and alkaline fuel cells are poisoned by carbon dioxide. Thus these two fuel cell types are not readily fed from reformed hydrocarbon fuels. Proton exchange membrane fuel cells can be used with reformed sulfur-free fuels such as methanol so long as great care is taken to shift any carbon monoxide produced over to carbon dioxide. The phosphoric acid and super acids fuel cells have complete carbon dioxide tolerance and a degree of carbon monoxide tolerance.

Molten carbonate fuel cells can operate without carbon monoxide tolerance problems but are still affected by sulfur. Only the extremely high temperature solid oxide type has some sulfur tolerance. This effectively means that whatever fuel cell type is contemplated for marine or naval uses the fuel must be sulfur-free. This is most readily done in the U.S. by having the Federal Fuel Supply System specify and stock sulfur-free diesel fuel for marine use on fuel cell powered ships.

#### 5. Fuel type

The sulfur-free fuels for the fuel cell types listed in Section 1 are, in order: pure hydrogen only for the alkaline fuel cells; through hydrogen or methanol for proton exchange membrane; to hydrogen, methanol, natural gas and sulfur-free diesel for phosphoric acid, super acids and molten carbonate fuel cells. The degree of sulfur tolerance of the high temperature solid oxide type makes it (prospectively) the only type which might be able to use ordinary diesel fuel, which contains some sulfur. The heavy bunker C type of marine fuels also have traces of heavy metals such as vanadium, and the desulfurization step could remove such impurities as well.

As a marine fuel sulfur-free diesel has all the characteristics of marine diesel fuel such as high heating value, *i.e.* Btu/lb, high flash point and common usage familiarity in a variety of existing marine power plants of the heat engine type. As major users of such fuel the U.S. federal agencies such as the Coast Guard, NOAA, Army Corps of Engineers and the Navy could

secure the sulfur-free diesel at little cost increase over existing diesel fuel. The sulfur in existing marine diesel fuel does the machinery no benefit and in fact reduces equipment life, particularly exhaust stacks and heat recovery systems. This is due to sulfur and hydrogen sulfide, which in the presence of steam, forms corrosion products such as sulfuric acid.

Methanol is an excellent clean liquid fuel. It reforms readily to hydrogen plus carbon dioxide at a relatively low temperature. It has a lower flash point than diesel fuel. However, a methanol fire onboard a ship can be extinguished with water because methanol and water are miscible. The major system level disadvantage of methanol for the surface ship case is the low heating value, *i.e.* Btu/lb, compared to diesel fuel or even jet fuels such as JP5. As is discussed further below in Section 13, this is an endurance tradeoff matter. If ship's tanks can carry adequate loads of methanol for the mission endurance then methanol fuel is an excellent choice. However, a sulfur-free diesel fueled ship will travel substantially further on the same tank fill.

## 6. Fuel reformer

With the exception of the alkaline fuel cell type, which must use pure hydrogen fuel, all the others can use a reformed fuel. The temperature at which methanol can be thermochemically reformed is in the order of 770 °F. If the fuel cell stack temperature is less than that there has to be an external heat source, or some of the fuel must be burned, to provide the needed temperature for the catalytic function to occur. Proton exchange membrane fuel cells must burn some methanol at the reformer, or permit some of the anode tail gas hydrogen to return to the reformer to be used as its fuel. The same is true of the phosphoric acid or the super acids type fuel cells except that the thermal integration is better and less fuel is burned in the reformation function.

In the case of the phosphoric acid fuel cells there is a further design variant which is possible, which provides a better thermal integration between the thermochemical and electrochemical functions. It involves raising the fuel cell operating temperature to about 450 from 375 °F, with a corresponding reduction in cell voltage of about 10%, and a probable reduction in the service life of the same order of magnitude. In this configuration the thermochemical function would be performed in modified 'cooling passage' plates, located between each group of 5 cells (called a 'substack'). These 'reforming plates' would have appropriate catalysts in their passages and by feeding methanol vapor plus water vapor into their inputs the reformation would be carried out within the fuel cell stack. This type of internal reformation phosphoric acid fuel cell system will only work on methanol fuel because the reformation temperature is low enough. It would not be possible using diesel or other heavy fuels, which require much higher temperatures for reformation to hydrogen plus carbon

dioxide. Internal reformation can reduce cost, weight and volume by as much as 25%, plus increasing energy conversion efficiency, so the approach is promising. It is discussed further below.

The big system-level tradeoff advantage of the molten carbonate fuel cell approach is that it can internally reform desulfurized diesel fuel with high efficiency, because it has a 1200 °F operating temperature. The high quality waste heat can also be used for other purposes onboard, as is discussed in Section 10. Solid oxide fuel cells appear to have the same generic advantage as the molten carbonate but they are further in the future.

## 7. Anode exhaust

In the case of the alkaline fuel cell there is no anode exhaust because all the pure hydrogen is consumed in making water and electricity. In the proton exchange membrane, phosphoric acid and super acids fuel cells there will be some unused hydrogen and carbon dioxide in the anode exhaust. In solid oxide fuel cells the product water (in the form of steam) is formed at the anodes and therefore exits via the anode exhaust manifold along with some unused hydrogen and carbon dioxide.

## 8. Cathode oxidant

The only oxidant acceptable to alkaline fuel cells is pure oxygen. The proton exchange membrane, phosphoric acid and super acids fuel cells can all operate from air or oxygen. At sea the salt must be removed from the sea air but standard marine air purification and handling technology is available to remove salt from the air.

The oxidant requirements of the two high temperature fuel cell types, molten carbonate and solid oxide, are readily met with air.

## 9. Product water use

All fuel cells produce fresh water. In ascending order of operating temperature from the alkaline type, the water produced in the fuel cell stacks will be predominantly in the form of steam. The heat carried in the superheated steam from the two high temperature fuel cell types (molten carbonate and solid oxide) can be used directly or indirectly through a heat exchanger, to operate a 'bottoming plant' such as a heat engine to generate additional electricity. Once the steam has been condensed it is then available for use as potable water for hotel load needs onboard.

## 10. Waste heat

As has been previously explained in Section 1, the various fuel cell types were shown in ascending order of operating temperature, from the low temperature alkaline type to the very high temperature solid oxide type. Only three of the fuel cell types (C(a), C(b) and E) are considered from this point on as appropriate for near term consideration as candidate ship power plants. Only the molten carbonate 1200 °F operating temperature type can be considered for thermal integration at the ship services level. The 375 to 450 °F temperature of the phosphoric acid type fuel cells, whether using external or internal fuel reformation of methanol, only permits their waste heat to be used for fuel cell related functions such as methanol preheating, *i.e.* vaporization and condensed product water reevaporation to feed the steam reforming function. The 1800 °F solid oxide (type F) may well prove to be applicable in a later time period, as may other future fuel cell types.

Waste heat removal can be by the use of air, other gasses in primary coolant loops, demineralized fresh water or a dielectric liquid such as mineral oil. Air cooling provides the lowest weight per installed kW of fuel cell power plant. All the high temperature fuel cell stacks are air or gas cooled.

## 11. Amperes per square foot and volts

These two fuel cell electrical characteristics define the power output possible from typical fuel cell stacks. For the proton exchange membrane recent work has demonstrated substantial increases in the current capacity in A/ft<sup>2</sup>. Values of 2000 A/ft<sup>2</sup> represent significantly higher (by a factor of 10) current capacity than the phosphoric acid or molten carbonate fuel cells. The cell voltage is lower for the proton exchange membrane type, at 0.5 V as compared to 0.6 for phosphoric acid or 0.75 for molten carbonate, but the current capacity factor still dominates in the calculation of the power output of a typical stack, per unit of volume or weight. These considerations make the less energy conversion efficient proton exchange membrane type attractive for weight-limited system applications, but not necessarily for the large installed power level case of surface ships, as is discussed further below, in Section 15.

## 12. Installed cost

The matter of capital cost is customarily described in terms of \$/kW installed, which refers to a power plant with all of its auxiliaries, unless otherwise stated. Certain shipboard services such as air handling blower systems and heat exchangers can be shared among a number of fuel cell power plant modules. Power conditioning, used typically to convert the fuel cell stacks's d.c. output power to a.c., can also be shared by multiple fuel cell power plant modules. An individual module must be able to start

up from cold, from a hot stand-by condition, or with preheaters over a brief start-up time.

Within a fuel cell power plant module, such as a present day methanol fueled phosphoric acid type, the stack represents about 67% of the cost, the external reformer 23% and the control system 10%. In the case of the internally reforming molten carbonate fuel cell type the combined stack represents 90% of the cost and the control system 10%. Typical capital costs in mass production for both phosphoric acid and molten carbonate are expected to be in the order of \$600\* in 1988 dollars. In small quantities, *i.e.* using model shop type assembly, the price per kW could be 5 to 10 times that figure. \$500 per installed kW figure is comparable to the installed cost for a diesel electric generator, so that cost figures are close to equivalence, once fuel cells are in mass production.

### 13. Efficiency, heat rate, BSFC

The energy conversion efficiency of the marine fuel cell system is paramount. Because the endurance or range of the ship is controlled by the size of the fuel tankage, it follows that the lower the rate at which fuel is used, the greater the range. Typical heat engine ship propulsion power plants are 35% efficient. Fuel cell power plants can have efficiencies of as much as 70% on air and even higher in submarine applications on pure oxygen, as discussed in Section 19. The derivation of the 70% efficiency figure for a marine molten carbonate installation is as follows: 55% for the direct energy conversion; 5% is for the potable water credit because a separate fuel-consuming water production system would not be required. A waste heat recovery system would be capable of extracting a further 10% of the energy from the high quality exhaust heat from these fuel cells. The total power plant energy conversion efficiency is thus 70%.

The electric utility industry normally refers to the heat rate of energy converters such as steam generators. The marine equivalent measure is the fuel rate or the brake specific fuel consumption (BSFC), which is expressed in lbs of fuel per shaft horsepower hour, or more conveniently for electric drive ships (and submarines), as kilograms per kilowatt hour (kg/kW h) or metric tons per megawatt hour (tonnes/MW h).

The following calculation shows the relationship between the efficiency of the fuel cell, the heating value of the fuel and the resulting fuel rate or BSFC. The fuel in the calculation is diesel fuel with a heating value of 18 500 Btu/lb.

$$\text{Fuel rate in lb/kW h} = \frac{3413 \text{ Btu/kW h}}{70\% \times 18\,500 \text{ Btu/lb}} = 0.26$$

$$0.26 \text{ lb/kW h} / 2.2 \text{ lb/kg} = 0.118 \text{ or } 0.12 \text{ kg/kW h.}$$

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\*Excluding inverter which is not envisaged for marine applications.

Had the fuel been methanol, with a heat content of 9550 Btu/lb, the fuel rate would be about doubled, to 0.23 kg/kW h. Thus, there is a real ship system-level endurance advantage to using diesel fuel rather than methanol, in a high temperature fuel cell power plant which permits the internal reformation of the fuel, while exhibiting the highest power system energy conversion efficiency.

#### 14. Start-up response

This factor is important in some applications which may require instant start-up from cold conditions. The proton exchange membrane type has the best start-up time, if started on pure hydrogen, as it can operate cold. If a methanol fuel and reformer are used it is the reformer start-up which will govern the warm-up interval.

For the phosphoric acid and for the molten carbonate type, there is a preheat cycle of 10 to 15 min because the stacks must be at the operating temperature for net power to be produced. If a methanol external reformer is involved for the phosphoric acid fuel cell power plant there is also a comparable thermal start-up delay. However, the rapid cold start feature is not a characteristic that a large surface ship propulsion power plant needs to have.

From a hot stand-by condition to 'full throttle' there is some reformer lag on the part of large high temperature fuel cell power plants. However, this lag is of the same order as for a heat engine, and is thus not significant for any large surface propulsion power control condition.

#### 15. Stack, size, aspect ratio, module shape

The proton exchange membrane technology permits large values for the current capacity in A/ft<sup>2</sup>. The ship's electric bus voltage, the onboard physical layout considerations (such as deck height), or both, set the fuel cell stack heights. The voltage of each fuel cell module, such as 150 to 200 V, will thereby be defined. From this the A/ft<sup>2</sup> figure will define the cross-sectional area of the stack. The multiplication of stack height and stack cross-sectional area defines the form factor of the cube. In general, for the same power output the phosphoric acid and molten carbonate fuel cell power plant stacks will have the same shape and form factor. Proton exchange membrane fuel cell power plant stacks of the same power level would tend to be 'tall and skinny' because of the lesser cross-sectional area required due to the higher current capacity. As it is wise not to exceed an aspect ratio of height to either dimension of the base of a stack by more than 3 or 4 to 1, the form factor issue is of some importance when dimensioning power plant stacks and hence modules. This factor is also important in evaluating the shock loading response of fuel cell stacks. The closer the aspect ratio is to unity the more robust the stack will be.



## 16. Location of service ducts, auxiliaries

Modern ship design is increasingly based on replaceable power plant modules and reducing the shipyard time and port turnaround times by rapid removal and change out of such modules. Fuel cell power for ships is modular in nature so the choice becomes one of how best to interface between the modules and the auxiliaries. In general, the presence of multiple parallel service ducts beneath a false floor (above an interior deck), sets both the module height, and from the previously described aspect ratio consideration, in turn sets the width and length of a single-stack module. If multiple stacks are used in each module the position of the parallel service ducts must correspond to the underside of each stack, or a subsidiary manifold to feed the services to the multiple stacks must be placed between the bottom of each stack and the floor of the module. This would shorten the stack height and reduce the stack voltage, which is not desirable. The auxiliaries, such as the air handling system and the cooling and waste heat recovery system, can be placed in separate compartments and serve many modules at a time.

## 17. Module accessibility, removal

As a further refinement on the above described process, the means to physically translate individual fuel cell power plant modules horizontally from their operating locations onboard becomes an important tradeoff and ship interface issue. Horizontal movement approaches plus vertical lift through access openings or hatches to and from the 'fuel cell compartment' (which is analogous to the former 'engine room'), must be provided to facilitate the rapid changeout feature. The modules must not be too big for the hatch openings or too heavy for the lifting systems.

## 18. Electrical connections, controls

High power electric propulsion motors will require voltages of 4000 to 6000 volts d.c. If a typical fuel cell stack height in an available 8 foot high inter-deck space occupies 6 feet of height the stack voltage will then be in the order of 150 V. A 6000 V. d.c. electrical propulsion motor bus would thus require 40 of these stacks electrically connected in series to achieve the needed voltage. On the other hand, a lower power small ship might have a 600 V electrical bus voltage, which would only require 4 such stacks connected in series. The particular application will set the number and type of interconnections needed, plus the alternative connection possibilities in case of combatant battle damage or other outages of individual fuel cell modules.

The control system to keep the multiple fuel cell modules performing over a wide range of power levels must also be considered with care. Because fuel cells are d.c. output devices the use of d.c. power throughout the ship for auxiliaries is entirely appropriate. In the second world war time period and thereafter, many naval, maritime and commercial ships had 240 V d.c. auxiliaries as the standard.

This completes the surface ship process selection steps. The next two sections deal with the submarine application of fuel cells.

The Chief of Naval Operations, Admiral C. A. H. Trost, said in a September 26, 1988 Keynote Address at a Navy Research and Development Symposium, that "... I am declaring that integrated electric drive, with its associated cluster of technologies, *will be* the method of propulsion for the next class of surface battle force combatants, and I am directing all the major Navy organizations involved in these efforts to concentrate their energies toward that objective." [3]. Fuel cell power can be a part of that process.

## 19. Oxygen consumption rate and source

The last two steps in the process selection, No. 19 and No. 20, deal with the submarine application of fuel cells. Just as the fuel rate is important, as was discussed in Section 13 above, the undersea application of fuel cell propulsion power for submarines requires that the oxidant be carried along with the fuel. Because shallow submarines are generally considered to be volume-limited designs (except in the case of submarine tankers), the interior volume allocated to the fuel plus the oxidant will define the submerged endurance and hence the range of the submarine at a given speed. The lower the fuel rate is kept, the lower the oxygen rate will be as well. Thus the highest energy conversion efficiency power plant should be chosen. Because the molten carbonate type was analytically derived as the best approach for surface ship power it is also the best for submarine propulsion power [4]. When operated on pure oxygen the efficiency rises a further 5% compared to operating on air. Liquid oxygen ( $O_2(l)$ ) is the most compact or volume-efficient means to carry the needed oxidant. Many other issues arise in the fuel cell propelled submarine case, but that is the subject of another paper.

## 20. Pressurization, pressure compensation

Another means to improve the energy conversion efficiency, reduce the fuel rate and reduce the oxygen rate (also in kg/kW h), is to pressurize the fuel cell power plant. Because submarines operate under the pressure of the sea at cruise depths, the naturally available ambient sea pressure permits the fuel cell system to be pressure balanced to the ambient sea pressure. For example, a 16 atmosphere pressure, equivalent to roughly a 500 ft depth,

will increase the voltage, and hence the power output, by a further 28% compared to the system's power output with 1 atmosphere of oxygen pressure. Thus, a 5 MW propulsion power plant operated near to the surface would produce 6.4 MW of power at a 500 foot depth of submarine operation. The submarine could thus travel faster at-depth, or the fuel and oxygen could be made to last longer for the same speed of advance.

This completes the Fuel Cell Process Selection discussion. The analytical process selection steps should be undertaken in an ordered sequence. The particular sequence of steps was given considerable thought and the technique is now offered to the reader as a proven system engineering approach.

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