AN INTRODUCTION TO FUEL CELLS AND THEIR POTENTIAL IMPACT ON WARSHIP DESIGN

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ABSTRACT

Fuel Cells are increasingly seen as the future replacement of heat engines as they offer significantly lower emissions, noise and vibration, with a higher net electrical efficiency than for the current technologies. Their adoption is by no mean certain however, as there are a number of costs and technological difficulties associated with their marinisation that must first be overcome. This article briefly outlines the differences between the two technologies and then goes on to summarize the features of the main types of fuel cells contending for marine power generation applications. The final section considers some of the potential impacts that fuel cells will have on surface warship design and the problems and challenges that the adoption of fuel cells will present.

INTRODUCTION

History

A barrister W. GROVE invented the fuel cell in 1838, the results being published the following year[1]. It therefore predates the four stroke spark ignition engine, 1876, and the diesel engine 1892. As the 20th Century progressed fuel cells were virtually forgotten as the internal combustion engine came to the fore. Interest was rekindled in fuel cells as the space race progressed, their low mass and high efficiency made them an attractive alternative to batteries. The alkaline fuels cells developed for the APOLLO missions were capable of a power density of 1.6kWh/kg for a 200-hour mission[2] while the best batteries of the time could only achieve 0.2kWh/kg. Production of potable water as a 'waste' product was a bonus. Unfortunately these cells are not suited to terrestrial use. Over the next 20 to 30 years development and research into fuel cells again diminished apart from niche applications such as breathalysers. More recently research has exploded and 2000 was the first year that more papers were published on fuel cells than diesels, (FIG.1). A more detailed history of the Fuel Cell can be found in an earlier volume[3].

Improvements in materials technology, coupled with the realization that batteries will not provide the solution to low and zero emission vehicles, has lead to the recent massive investment in fuel cell research. Since April 1997 FORD and DAIMLERCHYRSLER have invested nearly two billion dollars and production models are expected in 2003/2004. It is estimated by DAIMLERCHRYSLER that 60 companies world-wide are working on fuel cell vehicle power trains, and of these 60, seven are amongst the world's top ten in terms of revenue.[4]

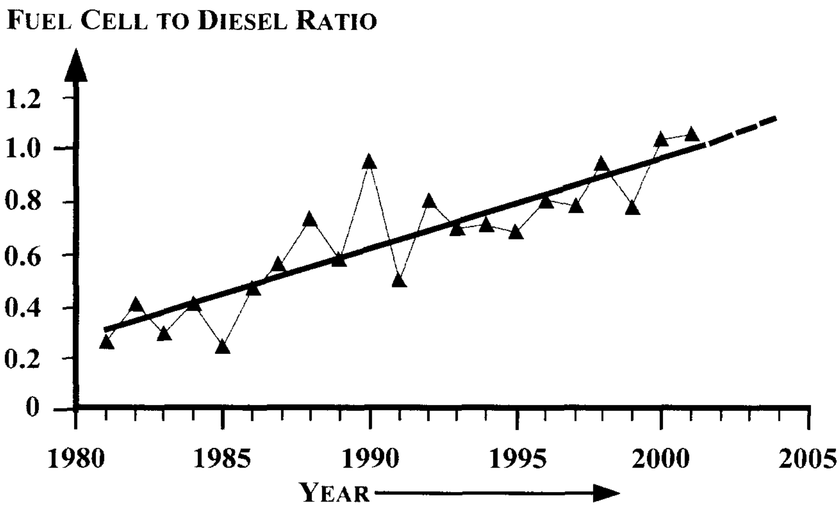

FIG 1 – RATIO OF PAPERS PUBLISHED PER YEAR ON FUEL CELLS COMPARED TO DIESELS. DATA BASED ON A KEYWORD SEARCH OF ABSTRACTS AND TITLES IN THE SCIENCE CITATION INDEX USING 'FUEL CELL*' AND 'DIESEL*'

Marine Industry

Surface

Until recently fuel cell development in the marine field has been limited, the exception being AIP (Air Independent Propulsion) for submarines and Autonomous Underwater Vehicles (AUVs). At Expo 2000 in Hannover MS *Weltfrieden* was fitted with a 10kW PEMFC (Proton Exchange Membrane Fuel Cell), the hydrogen was stored in metal hydride.[5] A detailed concept study was conducted for the USCG cutter *Vindicator*[6] into replacing a diesel generator set by a 2.5MW MCFC (Molten Carbonate Fuel Cell). The package includes a reformer*, for low sulphur NATO standard F-76. The US Office of Naval Research is developing a 2.5MW Ship Service Fuel Cell.[7] It is based on a MCFC and will reform naval distillate fuel (NATO F-76). The goal is to achieve this using commercial or near commercial technologies, and for it to be highly reliable and maintainable and be self-contained in respect to water and energy balance. The steam reformation of NATO F-76 has been demonstrated for over 1,400 hours and has fuelled a sub-scale MCFC for 1,000 hours. It has also demonstrated adequate tolerance to salt, shock and vibration. Sea trials of a 625kW demonstrator are planed for 2004 to 2006. The Royal Netherlands Navy is testing a 1kW DeNora PEMFC to investigate their feasibility for use in surface ships. This is a direct auto derivative fuel cell and RENAULT is also using it in their demonstration car. The Italian navy has proposed a 1MW MCFC system for surface ship applications and four other NATO countries are supporting distillate fuel reforming demonstrators, up to 100 kW.

AUVs

The HUGIN II AUV[8] uses a 35kWh Aluminium/Oxygen fuel cell. The hydrogen peroxide fuel and electrolyte need to be replaced after every mission and the anodes every third mission. The mission time is 40 - 45 hours depending upon the conditions, operating speed and the sensors in use. A number of other operational

*A Reformer extracts the hydrogen from a fuel. Reformer technology is a major field in its own right.

AUVs also use Al/O_2 fuel cells including XP-21, ARCS3 and ALTEX[9]. The Japanese Marine Science and Technology Center's (JAMSTEC) latest vehicle the Urashima, rated to 2000m, will use either pressure compensated Lithium-ion batteries (300Ah 120V), or a PEMFC, (4kW 120V). The estimated ranges at 3 knots are 100km or 300km respectively[10]. The US Navy is considering fuel cells for its MANTA AUV.

Submarines

The first practical application of a fuel cell for motive power was in 1964, Allis-CHALMERS produced a 750kW fuel cell for the Electric Boat Company to power a one-man underwater research vessel. More recently Siemens, at the behest of the German Government, has developed a successful PEMFC for the German Navy. It was originally rated at 34kW, which incidentally is similar to a typical small car power requirement. The latest version is rated at 120kW and is about the same mass and volume as its predecessor. A pair of these are used for the AIP pack in the new class 214 submarines (batch 2 class 212) which are under construction for the Italian and German Navies. The class 209 boats (mainly produced for export) are now being offered with a 6m long AIP plug and retro fitting to existing boats is an option. It is claimed that the submerged endurance of the class 209 is increased by a factor of 5 with the inclusion of the AIP plug compared to conventional battery operation with a 100% to 20% discharge[5]. In practice the ratio will be closer to ten because due to operational considerations batteries are rarely discharged below 50% capacity. But batteries can be recharged while at present there is no plan to permit a submarine to recharge her oxygen and hydrogen tanks while at sea. Both submarine types carry liquid oxygen (internal for 209 externally for 214) and store the hydrogen in external metal hydride tanks. The extended submerged range provided by a fuel cell AIP plant make a SSK a much more effective weapon and this technology is available to most existing SSK, not just new builds, by insertion of a plug.

Iceland

Due to Iceland's unique geographical location the Icelandic Government is seriously considering converting to a hydrogen economy. This would include converting the entire fishing fleet to fuel cells within about 20 years. Iceland is in a unique situation in the western world, it has abundant natural power sources and virtually no fossil fuels. Of its estimated 30TWh/year of economically recoverable hydroelectric and 200TWh/year geothermal energy reserves only 15% and 1% respectively are currently exploited.[11] Of its liquid fuel imports approximately one third goes to transportation and another third to power its fishing fleet. On the 17 February 1999 the Icelandic Hydrogen and Fuel Cell Company Ltd. was formed (since renamed The Icelandic New energy Co. Ltd.) with the express aim of replacing the use of fossil fuels with hydrogen for land and sea transport within 30 – 40 years. The company has the full support of the Icelandic Government. Usually Hydrogen is very expensive to produce using electrolysis of water but on Iceland with abundant 'free' hydroelectric and geothermal energy the cost is only 0.02US$/kWh, or about three times that of imported gasoline when based on a comparison by energy content.[11] When the relative efficiencies of an i.c. engine burning gasoline and a hydrogen fuelled Fuel Cell are taken into consideration then the relative prices approach parity. A point of particular interest is the partners in The Icelandic New energy Co. Ltd., other than the Vistorka hf the Icelandic holding company they are Daimler Chrysler, Shell International bv and Norsk Hydro ASA. It would appear that Iceland is being turned into a huge hydrogen economy laboratory. No decision has yet been made about the means of storage and distribution of the hydrogen or potential export.

Potential Market

A report,[12] commissioned by the U.S. Coast Guard, assesses that the marine market potential for fuel cells (both commercial and naval) could be tens of thousands of units sold by 2015. Of these a large fraction of the power demand is concentrated below 2MW. It concludes that if the life cycle cost of the fuel cell can be made economically competitive with traditional sources of marine power, then they could potentially capture a substantial share of the marine market. As the naval market is only around 2–3 % of the total market, it cannot be considered a driver for investment, and therefore naval systems are likely to be driven by developments for the commercial sector. It could be argued that fuel cells will be the gas turbines of the 21st Century, in that the marine industry will wait for another industry to develop the technology. Only once it has started to mature will it be marinized and exploited in the marine market. The automobile industry is driving research into PEMFC of about 50-100 kW size and will probably be responsible for many developments of fuel reformers – once they agree on which fuel to use. The power generating industry is more likely to develop the higher temperature fuel cells. For example the chief executive of the German utilities giant, RWE, recently stated that:

> "By 2015, we intend to cover 10% of our power supplies with fuel cells. ... roughly equivalent to the total energy consumption of the whole of Belgium."

This will be achieved using SOFC (Solid Oxide Fuel Cell) in the high kW low MW range. Two problems with developments for the land based power generation industry are that plant volume is not a key design driver nor is intermittent operation. These two design features are both important for shipboard systems.

THE FUEL CELL

Comparison of the fuel cell to other prime movers

All existing power plants for ships derive mechanical power from the expansion of a hot fluid, be it steam or gas through a turbine, or a gas in a cylinder. Discounting nuclear power, the fuel used to heat the fluid is a liquid hydrocarbon, (FIG.2).

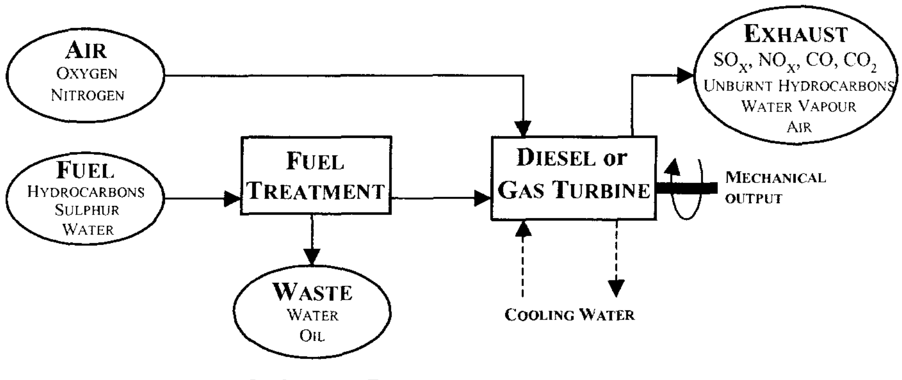

FIG.2 – HEAT ENGINE INPUT OUTPUT DIAGRAM

A fuel cell is totally different in concept, there is no combustion, the output is DC voltage and the ideal fuels are hydrogen and oxygen, (FIG.3).

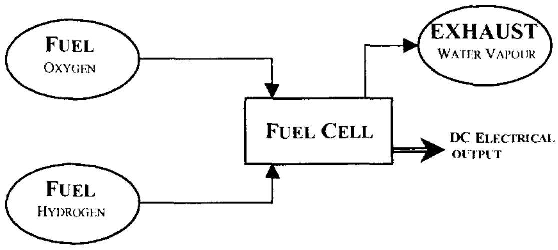

FIG.3 – IDEAL FUEL CELL INPUT OUTPUT DIAGRAM

How a Fuel Cell works

In simple terms a fuel cell combines oxygen and hydrogen electrochemically to produce water and electricity, (FIG.4).

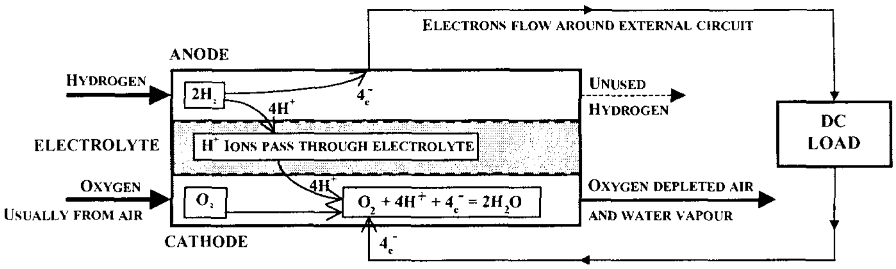

FIG.4 – HOW A FUEL CELL WORKS

The electrolyte must act as a barrier between the two gas streams and yet permit the passage of H^+ ions (protons) while being impervious to electrons. Because the process takes place over a surface the performance of a fuel cell design is often quoted in terms of current per cm^2. Fuel cells are constructed of a multitude of cathode-electrolyte-anode sandwiches or cells combined together in stacks. The surface area of any one cell is limited by the supply of reactants. As the reactants flow through the cell they become depleted and the amps/cm^2 declines. Also the longer the path the more power required to pump the gases through the cell. This flow through process explains why fuel cells have their highest efficiency at part load and also why it starts to fall away at full design load.

Different fuel cells operate at different temperatures each using a different material for the electrolyte and each is suitable for a different application. The main types of fuel cell that can be considered for marine applications are discussed below and summarized in Table.1.

TABLE.1 – *Comparison of fuel cell types*

Type of fuel cell	**PEMFC (SPFC) Proton exchange membrane**	**AFC Alkaline**	**PAFC Phosphoric acid**
Operating Temp(°C)	50-90	50-200	190-210
Full DC power Efficiency %[5]	39-42 Air and reformate (H_L)	Up to 70% Pure O_2 and H_2	38-42 Air and reformate (H_L)
Poisons[13]	CO > 10ppm S no data	CO_2 & CO no tolerance S no tolerance	CO > 5% S >50ppm
Fuels	H_2 O_2	H_2 O_2	H_2 O_2
Electrolyte	Sulphonic acid Incorporated in a solid Polymer membrane	Potassium hydroxide	Phosphoric acid
Power range[13]	1W to 300kW	100W to 10kW	10kW to 1MW
Applications[14]	CHP, distributed power, Portable power, transport	Space, transport	CHP, power generation
Development Status[14]	250kW CHP systems and several cars and buses being demonstrated, but not yet commercial.	Fully developed for space systems. Transport systems available for initial demonstrations.	200kW systems offered for sale, but not commercially competitive in the UK.

Type of fuel cell	**MCFC Molten carbonate**	**SOFC Solid oxide**
Operating Temp(°C)	630-650	700-1000
Full DC power Efficiency %[5]	40-55 Air and methane	45-60 Air and methane
Poisons[13]	S >0.5ppm	S >1.0ppm
Fuels	H_2 O_2 CO	H_2 O_2 CO
Electrolyte	Molten lithium carbonate	A ceramic, solid oxide, zirconia
Power range[13]	100kW to 10MW	5kW to 10MW
Applications[14]	CHP, power generation, Ship propulsion, trains	CHP, power generation, ship propulsion, trains
Development Status[14]	250kW systems being demonstrated, also previously 2MW, but further R&D needed.	Tubular systems available for demonstration; planar technology still under development.

In general the higher the operating temperature the less fuel reforming is required. The downside is that high temperature fuel cells have longer start up times and poor efficiency at low power when they require external heating. The theoretical maximum efficiency of the fuel cell also decreases with temperature but at low temperatures overall efficiency is compromised by the need for extensive fuel reforming (if hydrogen is not used) but at higher temperatures there is a greater opportunity of useful co-generation, (FIG.5).

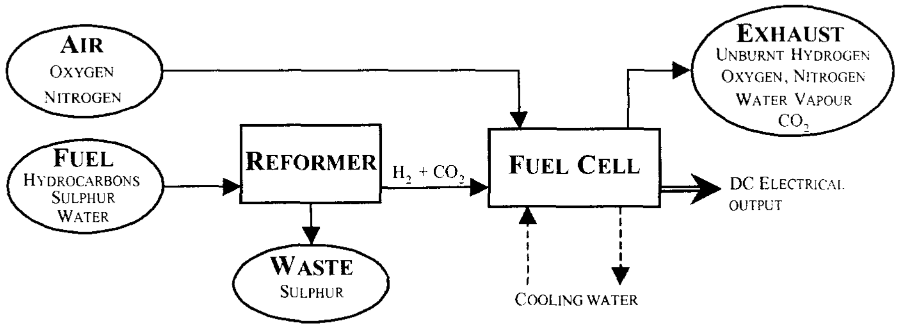

FIG.5 – PRACTICAL FUEL CELL INPUT OUTPUT DIAGRAM

Proton Exchange Membrane Fuel Cell (PEMFC)

Also known as the SPFC (Solid Polymer Fuel Cell), the PEMFC uses a thin plastic sheet at the anode, the proton exchange membrane, coated with an active metal alloy catalyst (mostly platinum) that encourages electron separation and lets the hydrogen ions pass through. The sulphonic acid electrolyte is incorporated into the solid polymer membrane. The PEMFC is being aggressively developed for use in automobiles. The PEMFC has a very flat efficiency curve across the bulk of its range. Approaching maximum power, efficiency falls off slightly because the ideal oxygen and hydrogen mix cannot be maintained across the whole cell area. This is typical for most types of fuel cell. At low powers the energy required for the fuel cell auxiliaries and reformer become increasingly significant and efficiency falls off. Except for very small stacks (typically a few watts) humidity control of the fuel streams is important, a humid air supply is required. They operate at around 50-90°C, the low operating temperature rules out improving system efficiency through co-generation. The fuel cell itself can respond rapidly to load changes and because of its low operating temperature has a start up time of a few minutes, but this performance is degraded if a fuel reformer is used. PEMFC require a clean hydrogen supply and cell efficiency is dramatically reduced for CO levels above 20ppm. Sulphur in either fuel stream can permanently damage the stack. If pure hydrogen is not used then extensive fuel reformation will be required. The fuel reformer operates at about 600°C.

Molten Carbonate Fuel Cell (MCFC)

These types of fuel cell are candidates for stationary power and Combined Heat and Power (CHP) applications. They operate at around 630-650°C. The elevated operating temperature permits considerable improvements in cycle efficiency (up to 65% has been claimed) if the waste heat is used to power a turbine. They can operate on a variety of fuels and offer a limited capacity for internal fuel reformation, some external reformation is required for naval distillates and they have a low sulphur tolerance. The electrolyte is molten lithium carbonate, and no noble or rare earth metals are used so MCFC are cheaper than equivalent PEMFC technology, but have lower power densities. The fuel and water is initially reformed to produce hydrogen and carbon dioxide. These react with carbonate ions at the anode to produce water, carbon dioxide and free electrons. The carbonate ions are produced at the cathode by the reaction of the oxygen and carbon dioxide with the free electrons in the presence of the catalyst. They are CO tolerant and have been demonstrated in stationary applications between 10kW and 2MW. The MCFC, as with all high temperature fuel cells, has a significant start up time due to the need to bring it up to its operating temperature. Once there it is self-sustaining and like the PEMFC has a flat efficiency curve over the majority of its power range. At low powers its efficiency drops off much more rapidly than a PEMFC once the MCFC can no longer sustain its operating temperature and requires external heating. At idle a MCFC is a power drain. MCFC suffer from electrolyte stability problems, and currently their power density is also poor.

Because of their higher operating temperatures existing MCFC (and SOFC) have start up times of about 10 hours. These are experimental stacks and no development has been done on reducing the time or even to investigate the effect of an accelerated start up. The long time is used to ensure that all the different components warm through at a uniform rate to prevent any damage from differential expansion. They are being designed for onshore power production where uninterrupted, continuous operation is typical. They will only be shut down for maintenance or repair. As a consequence start up time has not been identified as a critical issue. If these were to be developed for naval application start up time would have to be addressed, as too would the operating philosophy. The excellent part load performance of fuel cells coupled with start up times would require reconsideration of the single generator operation philosophy. For merchant vessels, which have more predictable operating profiles and less requirements for peak (sprint) power demands, long start up times would be less of a constraint.

Solid Oxide Fuel Cell (SOFC)

These are most promising for large stationary power and CHP applications, some development is also being conducted for use in auxiliary power units. They have a ceramic as opposed to a liquid electrolyte, zirconia doped with yittria and operate at temperatures between 700-1,000°C. They are able to reform fuel internally to a limited extent and consume carbon monoxide as a fuel, they have more tolerance to sulphur but it is still a poison. Operation is similar to a MCFC. They can be tubular or planar in design, with the tubular requiring less complicated sealing arrangements while the planar design promises greater power density. Tubular systems have been demonstrated up to 220kW. A significant amount of development is still required for this cell to achieve its commercial market potential. The efficiency profile of SOFC is similar to MCFC, and have the same long start up time. Once running they are claimed to have very good load following capabilities, (fuel reformer permitting) of 0-50% load change in 3 seconds. Compared to MCFC, SOFC are less developed, currently having lower power density, but they benefit from a more stable electrolyte and can achieve lifetimes, twice those of MCFC. If current research predictions come to fruition SOFC will have better power densities and efficiencies than MCFC.

Others

The alkaline fuel cell has been successfully developed for the space industry. They are expensive and require a very pure oxygen and hydrogen supply and consequently are not suited to marine applications. Until recently the Phosphoric Acid Fuel Cell (PAFC) was the only fuel cell that could be claimed to be commercially available. It is marketed as a very reliable high quality power source. PAFC are not suited to intermittent use typical of a ship board generator. Phosphoric acid freezes at 42°C, once commissioned PAFC are usually kept above this temperature to avoid the stresses of freezing and thawing. The desirability of quantities of phosphoric acid aboard is questionable. Paradoxically despite being the first commercially available fuel cell, research in to PAFC has lagged behind PEMFC and consequently they are still very expensive (high platinum content) and have low power density. The direct methanol fuel cell is similar to the PEMFC, it operates at a slightly higher temperature and can use methanol directly, eliminating the need for a reformer. It is still in the early stages of development but could become a serious challenger to the PEMFC for land transport applications. This could have implications for the future global fuel infrastructure. The Al/O_2 fuel cell is not practical for primary power production because the Aluminium Anodes have to be regularly replaced. Its high power density and low oxygen consumption makes it ideal for niche applications such as AUV powering, emergency and portable power units.

Practical Fuel Cell

It is often stated that fuel cells have no moving parts and therefore are maintenance free, and this is the case for very small fuel cells of a few watts. The stack itself has no moving parts but its support infrastructure has many. PEMFC require careful control of the humidity of both fuel streams. MCFC and SOFC require temperature control and all fuel cell stacks of any size require cooling and pumping of the fuel streams through the stack. The reformer must also be included if diesel is to be the hydrogen source, CO_2 produced from the reformer is usually combined with the hydrogen in the anode fuel stream. Sulphur is a poison to fuel cells and must be removed from the fuel either at source or in the reformer. The sulphur is absorbed into a bed of zinc oxide forming zinc sulphide. The adoption of zero sulphur fuel would limit the flexibility of operation of the fleet.

Efficiency

Many values are quoted for the efficiency of a fuel cell and all should be treated with caution and considered in context. The fuel types, storage conditions, inclusion of a reformer and type of output power must all be considered. Comparison of fuel cell performance with that of diesels or gas turbines cannot be done by considering just the engines themselves. If IFEP (with AC bus) is assumed and diesel is used as a common fuel then useful comparisons can be made, (FIG.6).

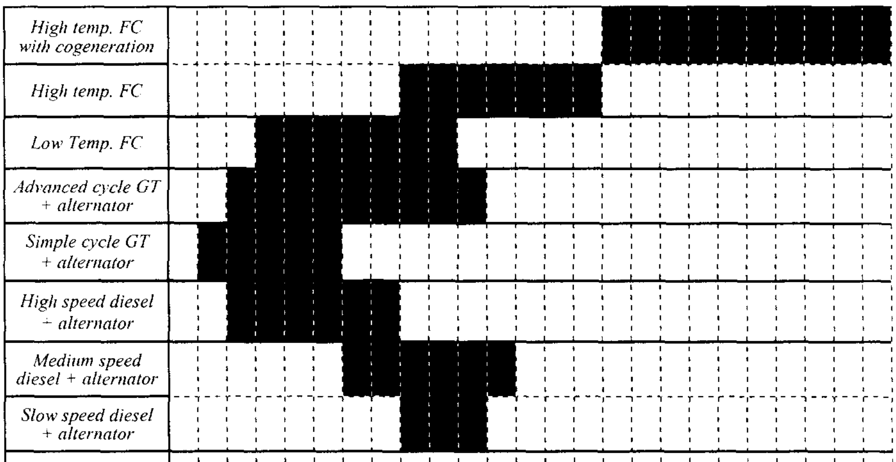

FIG.6 - FUEL TO AC POWER THERMAL EFFICIENCY FOR DIFFERENT PRIME MOVERS[15]

Argument still rages over the relative efficiency and performance of diesel and gas turbines and these are both heat engines, comparisons with fuel cells are going to be more contentious. An alternative view is to consider the theoretical maximum efficiency of a heat engine and a fuel cell[13], (FIG.7). The heat engine limit is calculated using the Carnot cycle with a lower reservoir temperature of 100°C. The fuel cell is supplied directly with gaseous hydrogen and oxygen

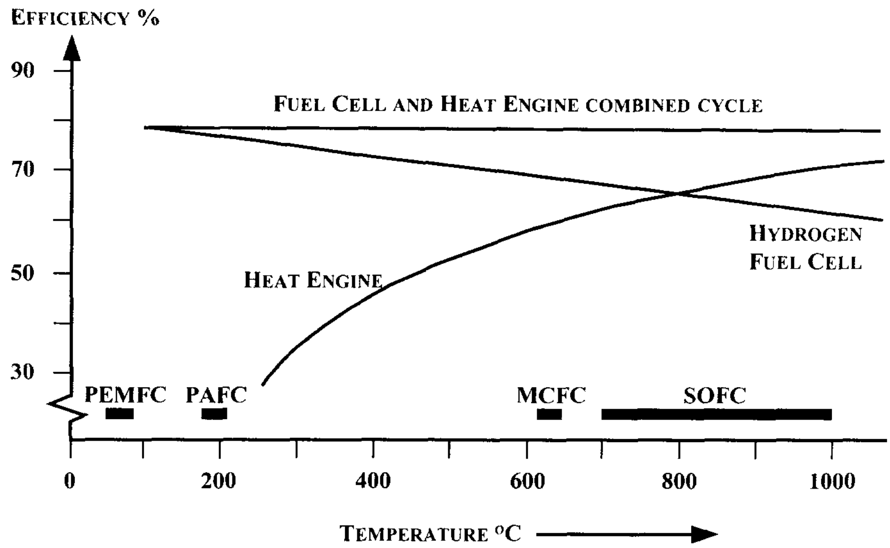

FIG.7 – THEORETICAL HEAT ENGINE AND FUEL CELL EFFICIENCIES[13]

Fuel

While oxygen and hydrogen are the ideal fuels these are not the most practical. On the cathode side air can replace oxygen, the loss in efficiency being compensated for by access to a 'free' fuel source. The problem is the hydrogen fuel supply to the anode. The choice lies between hydrogen, light hydrocarbons (e.g. methanol) or existing fuels. Table.2 provides a summary of their properties, THOMAS et al[16] and ADAMSON and PEARSON[17] presents these in more detail.

TABLE.2 – *Comparison of fuels.*

Fuel	Advantages	Disadvantages
Hydrogen	No reformer need. Non toxic. Safe in open environments. No CO or CO_2 production at fuel cell.	Low energy storage density. Cannot use existing infrastructure. Risk of explosive mix in enclosed environments. Some storage methods e.g. Croygenic introduce extra risk. Requires special pipe work.
Methanol	Could use existing infrastructure with minor modifications. No reformer need for high temp. fuel cells.	Toxic in vapour form, ingestion of 100ml can be fatal. Hygroscopic. Lower energy storage density than petroleum. Simple reformer needed for low temperature fuel cells. Burns with non-luminous flame.
Diesel	Existing fuel – infrastructure in place. Low toxicity.	Complex reformer needed for low temperature fuel cells. Pre-processing needed for high temperature fuel cells. Contains sulphur that must be removed

The automobile industry still has not made a decision which fuel to favour. The choice is significant for the marine industry because it will influence investment in infrastructure and development of reformers. For warships the preferred option is diesel used in conjunction with a reformer. The requirement for long range makes the energy density of the fuel important and the higher volumetric energy density of diesel compared to methanol or hydrogen quickly offset the extra volume need for the reformer. Methanol is currently banned as a fuel at sea, ethanol while less toxic has an even lower energy density. In the open forecourt of a filling station hydrogen is arguably a safer fuel than petrol, in the confines of a ship such a flammable gas is not desirable. Even if hydrogen could compete on safety and energy density the cost of refitting the fleet for a hydrogen infrastructure would be considerable.

One of the main problems of using hydrogen as a fuel is its low density especially as a gas. Liquefaction can greatly increase this but at the cost (money and energy) of a cryogenic plant and storage. But even in liquid form it does not have a particularly high density. Surprisingly significantly greater volumetric packing densities of hydrogen are possible when it is forced to bind with other atoms rather than itself, for example hydrocarbons or even water, Table.3 shows a few examples.

TABLE.3 – *Comparison of hydrogen vectors*

	State	Symbol	Atomic mass	Density kgm^{-3}	Volume (litre) and mass (kg) per kg of Hydrogen*	
Hydrogen	Gas (STP)	H_2	2.016	0.095	10,500.00	1.00
Hydrogen	Liquid	H_2	2.016	71	14.08	1.00
Water	Liquid	H_2O	18.015	1000	8.94	8.94
Methanol	Liquid	CH_3OH	32.042	794	10.01	7.95
Dodecane (Diesel)	Liquid	$C_{12}H_{26}$	170.340	748	8.69	6.50
Titanium hydride	Solid	$TiFeH_2$	105.763	5470	9.59	52.46

*Excludes containment vessel

The hydrogen host of choice must be safe to handle and require a minimum overhead to extract the hydrogen and also not require a significant support infrastructure. For ships and especially submarines it is acceptable to have a slightly higher overhead in initially binding the hydrogen, for example a shore based liquefaction plant. Unfortunately water is not practical hydrogen vector as the means to extract the hydrogen, electrolysis, is very energy intensive. Table.3 also demonstrates that Diesel is an effective hydrogen vector, it is represented here by Dodecnae, which is accepted as a representative average of its many constituents. Metal hydrides are particularly noteworthy because it is a very simple, low energy and reversible process to bind hydrogen with the metal alloy. Further metal hydrides are stable, safe and contain no volume of free flowing gas[18]. Metal hydrides have the disadvantage of high density. Other compounds such as Lithium Hydride (LiH) and Titanium hydride (TiH_2) have even greater packing densities of hydrogen, 6.5 l/kg and 5.8l/kg respectively. Unfortunately the former is highly caustic and the later requires high temperatures to bind and liberate the hydrogen. Considerable research is being conducted into carbon nano-fibres and other materials that have high hydrogen packing densities rapid binding with easy discharge, low self density and can be stored close to atmospheric conditions. Again this is mainly being driven by the automotive industry with the goal to be able to store sufficient hydrogen safely in a volume equivalent to an existing car's petrol tank to permit a fuel cell driven the car to achieve a similar range to current vehicles. Binding hydrogen to a solid has particular attractions for ships, there is no free surface, it is in a stable form so less of a fire or explosion risk and its bulk can provide shielding and protection.

Design considerations

Existing studies[12, 15] indicate that with current projections fuel cells will have power to mass and power densities slightly better than diesels but will be unable to match high power gas turbines on either count. Between the fuel cells themselves projected values for planar SOFC are the best followed by PEMFC. Efficiency comparisons show that low temperature fuel cells can compete with existing engines while high temperature fuel cells have the potential to exceed the best currently available from diesels or gas turbines. If the waste heat of the fuel cell is utilized then much higher efficiencies are possible, but this is also true of gas turbines and diesels. These comparisons assumed a common fuel (NATO F-76) and electrical transmission with AC bus. Allowances are made for converters and fuel reforming but ducting was not considered. As fuel cells output electrical DC power, adoption of a DC bus would weight the values in their favour and conversely mechanical transmission would favour the heat engines. The advent of IFEP acts in the fuel cell's favour.

The long lead time for warships means that it will be at least 10 years before a warship is built that is designed specifically for fuel cells, as a consequence the first fuel cell systems will be fitted as replacements for existing generator sets in the 0.5-2MW range. Studies have shown[6, 12, 15] that PEMFC and MCFC can compete with diesel generators in this range in terms of volumetric and power density. These diesel replacement units are envisaged as individual self-contained plants each with its own fuel reformer etc. Installation of fuel cells in this power range has many attractions. The higher cost of fuel cells can be offset by the reduction in maintenance, noise, and emissions. Ever-tightening emission legislation, and the modifications required to meet them, could seriously erode the competitiveness of diesels. Fuel cells have a low acoustic signature and are ideal for slow speed ASW operations. This is particularly important, as the SSK with a fuel cell AIP system will become a significant threat. Also in the low megawatt power range fuel cells will be competing with the new high-speed gas turbine generators. The main advantages of fuel cells here are the small ducting required, flexibility in sizing and excellent part load performance.

Fitting a fuel cell plant into the volume vacated by a diesel generator does not permit exploitation of all the benefits a fuel cell offers, this will only come when a warship is designed specifically for a fuel cell power plant. Replacement of main (or boost) prime movers is a more radical step for a navy. It is unlikely that this can be achieved in an existing warship and will only be possible with a new build, even then for small ships that are volume critical gas turbines are likely to remain the engine of choice for large power production. A cruise liner may well be the first to use fuel cells for main propulsion because of the low vibrations of the plant, high efficiency, green credentials, short design and build time for the ship and the regular, continuous operating profile.

Size and cost

Comparisons of cost are extremely difficult not only for initial cost but also through life cost. The different nature, maintenance requirements, operating requirements and ship impacts of fuel cells compared to heat engines make direct comparisons difficult. Further all fuel cell costs are based on projections. The first PEMFC were very expensive partly due to the considerable quantity of platinum required in the catalyst. An early experimental 7kW cell cost in excess of £6,000, aggressive development by the automobile industry has caused this to drop by over 99% to about £35 for a similar cell. Similar dramatic improvements are being achieved in size and mass. BALLARD has recently unveiled its Mark 900 fuel cell which is half the volume and is 30% lighter than its predecessor the Mark 700 which is currently used in many prototype cars. The Mark 900 has a power density of 1.3kW/l. It has improved dynamic performance and uses less expensive material, significantly it has been designed for mass production. PEMFC have been driven by the need to compete with the internal combustion engine in terms of performance and size for automobiles. In larger power applications fuel cells are being developed for land based power generation where thermal efficiency is the driver, plant volume is not a main consideration. So while the cost of MCFC and SOFC may be driven down this is less likely to happen for volume or mass. But as these fuel cells do not require expensive metals as catalysts, the potential for cost reduction is not so great. Remember that the last power plant adopted for marine propulsion was originally also developed for an industry where size and mass were as important as efficiency – the areo-gas turbine.

Intakes and exhausts

A major impact of an engine on any ship is its intakes and exhausts. It will be shown that for a given electrical power output fuel cells require about twice the air mass flow rate of diesels. Limited tests by BALLARD have shown no minimal degradation of performance and no damage to PEMFC when exposed to salty air.[15] Fuel cells require humid air so operation close to water is advantageous. Potentially more damaging is fine particles that may get trapped in the cells and block the air flow or the ingestion of gasses. The inlet air must be filtered to remove particulate matter and monitored for CO and sulphur compounds. This is particularly important for PEMFC that are more vulnerable. Gases harmful to fuel cells particularly sulphur compounds could come from the exhaust of a diesel, volcanic activity or from deliberate release with the express purpose of incapacitating the ship. The exhaust of a PEMFC will be oxygen depleted, cool, and humid. The low temperature eases problems of radar and antennae location on the upper deck and helicopter operations. The high relative humidity could pose a problem. While the ship might have a greatly reduced IR signature it may leave behind a cloud of water vapour as the exhaust cools and the vapour condenses. This could also impinge on helicopter operations and add to icing risk in cold weather. Condensation in the exhaust trunking could also be a problem. Injection of high temperature CO_2 directly from the fuel reformer could assist here. High temperature fuel cells have exhausts in the region of 900°C and consequently much lower relative humidity, vapour formation is therefore less of a problem.

At full power the specific fuel consumption of a diesel or gas turbine is roughly similar to that of a fuel cell and for naval applications they will all use the same fuel. For a heat engine the equation of combustion is:

$$C_nH_{2m} + (n + m/2)O_2 \rightarrow nCO_2 + mH_2O \qquad (1)$$

For a fuel cell the hydrocarbon must first be reformed and any sulphur removed:

$$C_nH_{2m} + nH_2O \rightarrow nCO + (n + m)H_2 \qquad (2)$$

High temperature fuel cells can internally reform CO (the water shift reaction usually takes place first in preference). For PEMFC the water shift reaction, or some other process, must be performed externally to remove the CO:

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (3)$$

This is followed by the fuel cell reaction itself:

$$2H_2 + O_2 \rightarrow 2H_2O \qquad (4)$$

Combining (2), (3) and (4) gives:

$$C_nH_{2m} + 2nH_2O + (n + m/2)O_2 \rightarrow nCO_2 + (2n + m)H_2O \qquad (5)$$

For one mole of hydrocarbon fuel the same amount of oxygen is required for both processes and the same amount of CO_2 is produced. Hence for stoichiometric operation the air flow rate is the same. Note the fuel reformer requires water as an input while the fuel cell itself generates water. The output of water is $2n$ larger for a fuel cell. It can be shown that 1kWhr of fuel cell operation produces about 0.5kg water.

Details on the airflow rates of fuel cells are scarce. It is suggested[13] that much below twice the stoichiometric value the partial pressure of oxygen will become too low towards the end of its passage through the cell and the efficiency of the cell will suffer. For combustion the stoichiometric air fuel mass ratio is about 14.5:1. In diesel engines the air/fuel ratio is always weak of stoichiometric in order to achieve complete combustion,[19] (for gas turbines the air fuel ratio is typically 45:1 to 130:1[20] which corresponds to a range of about 3 to 9 times stoichiometric). If it is assumed that a fuel cell plant has the same or slightly higher efficiency than a diesel then it requires about twice the air of a diesel per kW_e, which in turn suggests bigger inlets unless the velocity is increased. Considering gas flows alone exhaust trunking is more difficult to compare because of the different densities and pressures. However fuel cell exhaust gasses are clean and quiet so no silencers or scrubbers are required as is the case for diesels.

Emissions and signatures

In terms of emissions fuel cells are far superior to heat engines, even when using diesel as a base fuel, which is good for reducing signatures and the environment, compare FIG.2 and 5. The requirement to meet increasingly stringent emissions legislation may force the marine industry away from diesels to cleaner engines, mirroring what is already happening in land transportation. As the entry of sulphur to the fuel cell is carefully controlled SO_x production is negligible but the sulphur removed from the fuel by the reformer still has to be disposed of. Operating temperatures, even for SOFC, are too low for any significant NO_x production. For low temperature fuel cells CO is avoided as it is a poison and for high temperature fuel cells it is consumed as a fuel. The analysis in the previous section shows that the production of CO_2 per unit mass of diesel fuel consumed is the same for a fuel cell as for a heat engine. The higher efficiency of a fuel cell will reduce the CO_2 production per kW_e, but it will still be significant. The unburnt fuels of a fuel cell are not classed as pollutants and the fuel reformer has a feed back loop for any fuel not reformed on the first pass. Disposal of life expired fuel cells is not seen as a problem, unlike many batteries.

Radiated noise from a fuel cell stack is very low, the main source of noise is from the pumps and compressors required for reforming and controlling the flow of fuel. The infra-red signature depends on the type of fuel cell used but PEMFC can produce an extremely low temperature exhaust. The problem of low temperature, high relative humidity exhaust has already been highlighted. The reduction in signatures will require a matching change in emphasis in detection systems to combat similarly powered ships and especially submarines.

Maintenance

Data from the ONR Ship Service Fuel Cell Program[6] suggests that with present technology a 625kW fuel cell generator set requires about 75% of the maintenance hours compared to an equivalent heat engine. The bulk of the maintenance was on the support infrastructure and not the stack itself. The potential for crew reduction is significant. Maintenance of fuel cell stacks will almost certainly be repair by replacement partly due to the complexity of dismantling a stack in situ and also because of the limited skill base available. Modular construction will facilitate this. Since no silencers or scrubbers are required the exhaust can also be used as a removal route. Support infrastructure and fuel reformer equipment consists of smaller units more familiar to existing crew. These are the components more likely to fail and can either be repaired in situ or by replacement. Careful design will be required to minimize the maintenance load.

The main risks are poisoning of the fuel cell by ingestion of Sulphur (or CO for PEMFC) or thermal stressing. Overheating and the sudden build up of steam within the stack is another danger. Generally fuel cells slowly degrade rather than fail catastrophically and 40,000 hour life is expected for SOFC. This is also the target for PEM and while this is not yet achievable with the large investment by the automobile industry it is a realistic goal. It is not certain that MCFC will be able to achieve this due to problems with electrolyte stability. The fine passages in the stack could suffer form blockage while the warm moist conditions in the stack and the exhaust, especially for PEMFC, risk encouraging biological growth.

Sizing, layout and design

The power output is proportional to the cell surface area and the area of any one of the cells is limited. The upper limit is dictated by flow rates, chemistry, fuel cell type etc. The result is that the height (or length) of the fuel cell stack determines the power from any stack, cooling loads limit the volume of any one stack. The result is that a 1MW fuel cell power unit would consist of a number of stacks, perhaps of 200kW each, rather than one big stack. This gives the designer much more flexibility in the layout of the power plant. Sizing to demand is relatively easy because fuel cell technology is inherently modular and the modules are typically a few meters cubed which means they can easily be configured to fit within standard deck height. There are no high inert rotating parts so gyroscopic loads are not an issue and stacks can be orientated in any direction.

Stacks could be distributed throughout the ship making full use of IFEP and zonal philosophies. In practice this might not be so desirable. Each fuel cell needs a fuel supply, air supply, exhaust and cooling water supply. Efficiencies of scale are possible especially with fuel reforming and also with some auxiliary functions of fuel cells so it is desirable to keep the stacks to together. A central fuel reforming unit with distributed stacks is a not a good compromise as this would involve pumping H_2 and CO_2 gas mix about the ship. Because of hydrogen's small molecular size and high velocity any pipe work containing hydrogen requires special consideration. Hydrogen embrittlement, blistering or even cracking of steel are dangers and hydrogen can leak through the smallest of fissures even those that are air tight, so high quality (and therefore expensive) welding is required. As hydrogen is difficult to detect an easily detectable tracer should be mixed with it.

Start up times are related to operating temperatures. PEMFC have already demonstrated start up times of less than two minutes and the automotive industry would like to reduce this much further. The fuel reformer takes longer as it needs to heat up to 500 to 600C before it can start to operate. As already mentioned MCFC and SOFC have much longer start up times. It is not clear what would be the result of a rapid start up, catastrophic failure of the fuel cell or degradation of its performance. In the latter case start up time might be able to be traded against stack life. With IFEP low load running of high temperature fuel cells will not be such a problem and so the cells will only have to be 'flashed up' after periods alongside. Very rarely does a ship have to leave at less than 10 hours notice.

The response time of a fuel cell stack to sudden change in load is good but this is cannot be matched by the fuel reformer. One solution is to have a 'surge tank' between the reformer and the fuel cell stack. Tanks of pressurised hydrogen would require careful design. Like diesel engines, fuel cells can be run at greater than 100% load, with adverse consequence for efficiency and plant life, but they will not suffer from the sudden tripping problems being experienced with gas turbine generators.

An interesting development is combined fuel cell power plants, for example hybrid PEMFC and SOFC.[21] It is similar in some respects to a CODAG plant. The PEMFC provides the rapid start up and low load power and the SOFC is brought on line when high power is required (e.g. flight operations on a aircraft carrier). One added attraction for combined operation is that the SOFC can act as a reformer for the PEMFC. Many other combinations of fuel cell types with and without co-generation are possible, presenting an almost limitless range of options to the marine engineer.

Conclusions

In the last few years development of fuel cells has grown dramatically. They will soon vie with the internal combustion engine as the main contender for land transportation prime movers. Their widespread use in local power generation plants is also envisaged within the next ten years. The rapid development and potential inroads into existing power production is much faster than for the gas turbine. The marine market must be ready to embrace this 'new' power source. It could be argued that fuel cells will be the gas turbines of the 21st Century, in that the marine industry will wait for another industry to develop the technology. Only once it has started to mature will it be marinized and exploited in the marine market. However fuel cells are being developed for two distinct markets, the automobile market and the fixed power generation market. The former is developing compact, light and robust PEMFC in the 50 – 100kW, these have ideal characteristics for surface warship use except for their power. The later is developing power units in the Mega watt range and as with gas turbines before them this is the power plant size of interest to Marine Engineers. The problem is that gas turbines were developed for the areo industry and it also required lightweight, robust engines with heavy duty cycles. High power fuel cells are being developed for the power generation industry that has a different requirements which do not match as well to those of marine engineers, for example power density, operating cycle and shock.

A second difficulty is reconciling the long lead-time for warship design with the rapid developments of fuel cells. Designing a warship now for fuel cells that will be available in ten or fifteen years time would be a high risk operation having to rely on many predicted values. In the short term fuel cells will be used to replace diesel generators of a few megawatts. This is a safer strategy but does not allow for exploitation of the full potential promised by fuel cells. The marine market is a small fraction of the global power generation market and it will have to follow the trends set by land based fuel cell plants. The main marinization efforts will not be to the fuel cells themselves, but to the supporting infrastructure, air supply, cooling and especially the fuel reformation process. One exception to this might be the start-up time of high temperature fuel cells.

For small, volume critical warships, gas turbines are likely to remain the engine of choice for large power production. Fuel cells could easily provide the hotel and cruise power. To take full advantage of fuel cells IFEP is required, but as the output of fuel cells is DC voltage this reopens the argument of DC versus AC for the main bus. They offer lower noise and emissions with higher efficiency, which is a benefit or a threat depending upon in whose ship or submarine they are fitted.

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