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State of the Art of Fuel Cells for Ship Applications

Jingang Han[1, 2], J. F. Charpentier [1], Tianhao Tang[2]
1French Naval Academy Research Institute, 29240 Brest Cedex 9, France
2Department of Electrical Engineering, Shanghai Maritime University, 200135 Shanghai, China
E-mail: jingang.han@ecole-navale.fr

***Abstract*-Fuel cells promise to be far more efficient, produce lower or zero emissions, and operate cleaner than conventional internal-combustion engine and gas turbine. They are already used for transportation application (buses, cars and tramways). Fuel cells can also be an interesting solution for ships power. However the developments of fuel cell systems for ship are in infancy. The only exception is the PEMFC in the submarines. This solution allows obtaining an air-independent propulsion (AIP) system, which has been adopted in several countries. This paper presents a comprehensive review of different fuel cells and their application on ships. The pro and the cons of the use of fuel cell in ship application are discussed particularly in terms of lifetime and cost.**

***Key words*- Fuel cells; ships; Submarines; AIP**

I. INTRODUCTION

Fuel cells (FC) promise to be far more efficient, produce lower or zero emissions, and operate cleaner than conventional internal-combustion engine (ICE) and Gas Turbine (GT). There are many researches, developments and demonstrations of fuel cell applications for stationary power plant, mobile and backup power. However in many cases the cost limits the commercial applications. Many researches and developments of FC based on power systems concern also land transportation (cars, buses, etc.) [1, 2]. It is obvious that these kinds of systems can also be used successfully in naval application (ship power systems). But till now fuel cell systems on board of surface ships are still in the first stage of R&D. The only exception is the PEMFC in the HDW (Howaldtswerke-Deutsche Werft GmbH) submarines working as AIP, which have entered service in several countries.

There are several types of fuel cells: the proton exchange membrane (PEMFC), alkaline fuel cell, phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), solid oxide fuel cells (SOFC) and direct methanol fuel cells (DMFC).The basic principles of different fuel cells and recent developments are presented basically in section 2. The main requirements concerning ships are discussed in sections 3. The development of FC applications in submarine and surface ships are presented in section 4 and 5.

II. FUEL CELL TECHNOLOGY

A. PEMFC

PEMFCs are characterized by a solid phase polymer membrane. Thanks to its excellent selective exchange membrane, the polymer membrane can conduct protons or H^+ ions. The hydrogen fuel is fed continuously to anode electrode, and protons and ions are produced with an oxidation reaction. Oxygen is simultaneity fed to cathode electrode. The positive ions flow from anode to cathode by the electrolyte exchange membrane which does not conduct electrons. If an external circuit is connected electrons can move through this circuit creating a current flow. All the positive or negative ions from anode to cathode combine with oxygen to produce water. The schematic of such fuel cell is shown in Fig.1. Because of the material construction of the PEMFC, the operating temperatures of these types of fuel cells are usually as low as around 100 ℃.

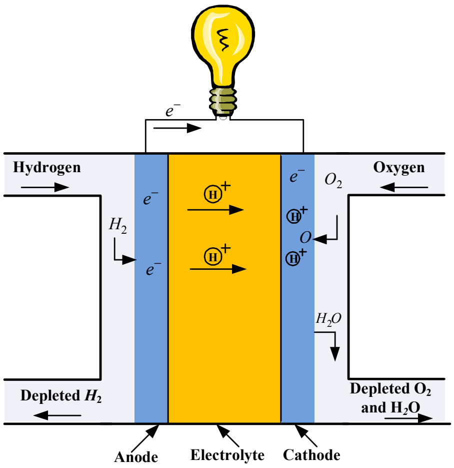

Fig.1 Schematic of an individual fuel cell

The low operating temperature PEMFC allows rapid start-up without the use of corrosive materials in the cells. PEMFCs are capable of high power densities of over 2kW/L and 2W/cm^2 [1]. Recently, a FC has run with a power density of 5.5W/cm^2 at 10A/cm^2 with pure hydrogen and oxygen in laboratory conditions [3]. Water management is another significant challenge for low working temperature PEMFC. PEMFC is also quite sensitive to poisoning by carbon monoxide and high cost platinum catalyst is needed.

The application of PEMFC focuses on transportation and commercial applications because of its zero emission, high power density and quick start up [2]. Another successful application of PEMFC for transportation is in the field of submarines propulsion [4]. The PEMFC power systems are also developed and demonstrated for distribution power generation system, such as residential and building electricity and hot water applications [5]. A 50kW (at 57% efficient, 70kW 53%) PEMFC was installed in the Netherlands in April 2007 [6]. A 1MW PEMFC has been installed in a Belgian chlorine plant by Nedstack Corp. and it is fueled with hydrogen as a by-product of this plant [7].

B. AFC

The electrolyte in this kind of fuel cell is KOH operating at a temperature range from 50~250°C. Some noble metals, such as Ni, Ag, metal oxides, are used as electro-catalyst. For the alkaline electrolyte, the fuel is limited to no-reactive constituents. This fuel cell is mainly used in transportations, space shuttle and portable power.

Operating at low temperature, the fuel cell is characterized by a quick start up. Another advantage is that it is possible to use a wide range of electro-catalysts. One of the main drawbacks of AFC is that the KOH solution is very sensitive to the presence of CO_2 [1]. It requires the use of highly pure H_2 as fuel. And if air is used as oxidant, the CO_2 must be removed from the air. This kind of cell can reach high level of electrical efficiency up to 60%. The global combined heat and power (CHP) efficiency can be more than 80% [8]. The volumetric power densities of AFC are around 180W/kg and 500 W/L and the cell power density is about 130mW/cm^2 [10]. Recently, research focuses on anion-conducting polymer electrolytes to replace the KOH solution. This new solution allows to eliminate the negative effect of CO_2 and operate at a low temperature range of 20~90°C [10].

C. PAFC

In this kind of fuel cell, phosphoric acid is used as the electrolyte. The system operates in a temperature range between 50 to 250°C. The chemical reaction is the same than in a PEMFC but pure hydrogen must be used as fuel. This solution also needs platinum as electro-catalyst in both anode and cathode.

PAFCs are much less sensitive to CO than PEMFCs and AFCs. With the high operating temperature, it is possible to use the waste heat in cogeneration. PAFCs have demonstrated system efficiencies around 40%, which is a higher value than values obtained in many PEMFC systems [1, 11]. The phosphoric acid needs also expensive corrosion-resistant materials in the stack.

The phosphoric acid fuel cell has been the first fuel cell technology to be commercialized. They have been mostly developed for stationary applications. In 1976, a 1 MW PAFC power station was built by UTC Power Corp., and a 4.5MW PAFC power station operated in Japan in 1984 developed by the same company [12, 13]. Now in the world, more than 260 PAFC systems have been installed across 19 countries before 2009, and have demonstrated their commercial maturity.

D. MCFC

Molten Carbonate Fuel Cells operate at a very high temperature range of 600 to 700°C. In this temperature range the molten alkaline carbonates can conduct positive and negative ions. Due to the high operating temperature, hydrocarbons reacting on CO can be converted to hydrogen in the stack. MCFC does not need expensive platinum as catalyst but it needs nickel and nickel oxide for anode and cathode [1, 14].

For the high operating temperature, MCFC can reform common hydrocarbon fuels (e.g. Nature Gas), and achieve a high efficiency (65% mated to a GT) [15]. The main drawback of MCFC is that it uses nickel and high-grade stainless steel. This technology is also characterized by a slow start up. The focus of MCFC development has been large stationary applications. This system can also be suitable for marine applications, where the relatively large size and weight of MCFC and slow start-up time are not real issue [16, 17, 18].

E. SOFC

SOFC uses a ceramic material electrolyte. The ceramic electrolyte can conduct oxygen ions. These ions produced at the cathode, travel from the cathode to the anode, and then combine with hydrogen to produce water. These types of fuel cells usually operate at very high temperatures range of 600-1000°C.

The main advantage is that SOFCs operate at a high efficiency range usually from 40% to 60%, can achieve an efficiency of 70-80% if they are integrated with a gas turbine (SOFC-GTs) [1]. Ref. [19] shows that an internal-reforming hybrid SOFC-GT system could achieve an electrical efficiency of up to 60% and a CHP efficiency of 80%. Due to the high operating temperature, CO and some hydrocarbons can be directly used as fuel. High operating temperature, slow start up, high cost and corrosion of metal stack components are some of the main SOFC drawbacks. These factors limit this kind of FC power density and stack life. This is why they are only used for auxiliary power unit, medium and large power generation applications [20].

F. DMFC

Using a liquid rather than a gaseous fuel confers considerable advantages to DMFC systems. As a liquid, methanol can be integrated more easily with existent transmission and distribution systems. One drawback is that direct reforming of the methanol within the FC stack means that the electrodes require large quantities of platinum [21].

DMFCs operate between 50°C and 120°C with a high efficiency (up to 40%). DMFC could achieve energy density as high as 1.8 kWh /kg and 1.7 kWh/ L based on pure methanol [22]. Thanks to this high energy density and safer handling, DMFC appears as an excellent candidate for very small to mid-sized applications, such as mobile phones and other consumer products, up to automotive [23].

III. GENERAL TECHNICAL REQUIREMENTS FOR SHIPS

Fig.2 which has been extracted from [24] shows efficiencies of different fuel cells for electric power plants. It can be seen that fuel cell have a significant higher efficiency than traditional internal combustion engines. But the specific requirements of ship power and some technical barriers limit the application of fuel cells in ships.

The range of power requirements of ships are presented in Table I (data from [25]). The rated powers of the energy plant of a ship vary with its specifications. The power for submarine AIP is less than 500kW, but can be up to more than 100 MW for surface ships (the passenger ship "Queen Mary 2" has for example a 118 MW electric power system). Even if it can be noticed that a high level of compactness and power density is a common requirement in naval applications, this point is particularly challenging for submarine.

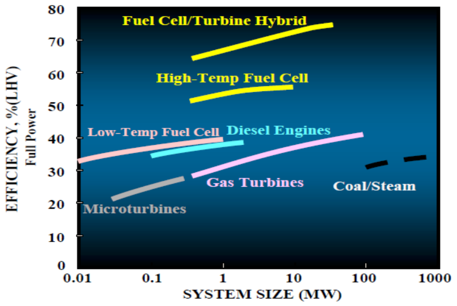

Fig.2 Comparison of efficiencies of different fuel cells for electric power plants from [24]

Fuel availability is an important factor for application of fuel cells on ships. For submarines, pure hydrogen is a good choice for the AIP system because PEMFC allow reaching the noise level requirements associated with this military application. For surface ships, classical fuels based on hydrocarbon have to be considered as the first choice of fuel considering the low volumetric energy density of the hydrogen and the difficulties to obtain hydrogen in harbors. This is why high temperature fuel cells with fuel reformer can be a good solution for the developments of marine FC in the next years [26, 27]. This technology allows decompose hydrogen from traditional hydrocarbon fuels. However they are unfortunately characterized by a slow start up.

Generally, fuel cell systems must meet the specific high level requirements of the navy systems. These specifications are related to efficiency, reliability, maintainability, cell life duration, marine environment, vibration and noise level.

IV. FUEL CELLS FOR SUBMARINE APPLICATIONS

A. *Review of the main known projects*

Military submarines are characterized by very severe requirements. Submarines require stealth operation, long-duration underwater operations, low noise level and low magnetic signatures. Conventional submarines are classically equipped with a diesel-electric propulsion system. The energy is stored in batteries for underwater operations. In this case, the energy capacity of the battery limits strongly the range of underwater operations. This is why fuel cells are an attractive candidate to meet the specifications associated to the energy source of AIP. They are characterized by high efficiency, silent operation and modular and flexible design [25, 28, 29].

TABLE I

PERFORMANCE RANGE FOR SHIPS [25]

Surface ships	Propulsion	5-80MW
	Electrical supply	<10MW
	Emergency power Supply	0.1-1MW
Submarines	Mono propulsion	2-5MW
	AIP	200-400kW

In 70's, the first studies on submarine propulsion systems using fuel cell were carried out. But the PEMFC were not a mature technology. Since the 80's German navy in collaboration with Siemens Corp. have developed research and test in FC system for submarine applications. In 1984, a 100 kW AFC AIP (FC built by Siemens) which have been firstly tested in an experimental onshore laboratory, was set up in a Class 205 U1 German submarine for practical navigation tests. These tests show the feasibility of fuel cell for submarine applications [29].

With the developing of PEMFC, the class 212 submarine equipped with a PEMFC AIP was started to be produced in 1998 for German navy [30-33]. The total power of the fuel cell system is about 300kW. It consists of nine 34kW PEM fuel cell modules (BZM34) from Siemens Corp. These modules are connected directly to the DC main power system without DC/DC converter.

In 2005, the class 214 submarine has been launched [31, 32]. This submarine uses two 120 kW "SiNavy" PEM fuel cell modules (BZM 120) from Siemens Corp. They are connected to the ship's main power grid by DC/DC converter. The fuel cell works at a temperature between 70-80℃ and achieves high efficiency (56 % at full load). The class 214 submarine with fuel cell AIP and batteries shows that this system has higher capabilities in terms of top speed and underwater time and distance than a system with only batteries. The recent version of the class 209/1400 mod submarine can work in an underwater range of 12,000nm during 50 days at 10 knots.

In such submarine application oxygen is classically stored in liquid form in double-walled vacuum-insulated tanks and hydrogen is stored in metal hydride cylinders. It is obvious that the weight of the storage system limits the underwater endurance of a submarine. This is why PEM fuel cells with reformer have been studied [28, 32]. HDW started a program for the development of a methanol steam reformer with high H/C ratio, high efficiency of reforming process and low working temperature of 250℃.

A new type of submarine is also now being built for Spanish Navy by Navantia factory. This submarine uses a 300kW PEM fuel cell with an ethanol reformer which is provided by UTC Power Corp. [33].

Another project (Project 677 Lada) started from 1993 in Russia. One aim of this project was to design submarines based on PEMFC AIP. The FC is made by Rubin bureau [34, 35].

The Canadian Department of National Defense (DND) started also a project for AIP for submarine based on PEMFC designed by Ballard Corp. in the 80's [36].

B. *Key features of FC in submarine AIP*

The key problems related to the development of an AIP with fuel cells for submarine are lifetime, hydrogen storage, oxygen storage and fuel cell cost.

Lifetime: The average lifetime of PEMFC for stationary power plants (SP) and electrical vehicle application (EV) in 2011 is about 16000h for SP and 4000h for EV with less than

10% performance decay and about 20000h for SP and 6000h for EV with less than 20% performance decay in lab tests [37, 38].

For submarine applications, the lifetime of ship is more than 15 years. In this kind of systems the lifetime absolutely decrease compared to civil application because of serious military specification requirements, such as magnetic signature, transient power command and shock/vibration criteria. This is why the fuel cell stack of submarine should be replaced in service because of the performance decay.

Hydrogen and oxygen storage: The capacity of stored hydrogen and oxygen limits the underwater operation time and distance of a submarine with FC. Storage weight and volume also have strong influence in underwater performances. This is why maximizing volumetric and gravimetric energy density of the stored fuel is an important challenge for these applications. Currently hydrogen is used as fuel and can either be stored or produced where it will be used. Basic requirements of a hydrogen storage system are low total volume and weight of the system. The following methods can be used for the hydrogen storage: storage of liquid hydrogen or compressed hydrogen and hydrogen storage in hydride cylinder. Another interesting way is hydrogen production by reforming or by reactive with chemicals [39, 40].

The density of hydrogen is about 0.08988g/L in the gaseous state at 1atm [41]. However compressed hydrogen will achieve a density of 31.04g/L at 350bar. Although liquid hydrogen seems to be interesting in term of storage capacity, it requires a refrigeration unit for keeping a cryogenic state, which adds extra cost. Due to the risk of explosion, physical hydrogen storage doesn't meet the requirements of safety for submarine.

Currently, hydrogen is mainly stored in metal hydride cylinder in submarine. This solution allows a good safety and comparatively higher volume density. But the mainly disadvantage of the storage system is the low weight percentage of hydrogen. This percentage is about 2% for titanium-iron alloy and up to 7.7% for magnesium hydride cylinder. However the high working temperature of the latter limits its applicability in submarine application [39].

Table II shows a comparison of various choices of fuel supply (data from [18, 32, 41]). Compared to hydrogen, the methanol and ethanol are liquid in ambient temperature, which reduces weight, space taken and thermal constraints. This is why some recent R&D projects study PEMFC solutions with reformer [33, 34]. However absorbing the product of CO_2 and managing the heat for the high reforming temperature are the key issues for future developments of this solution.

It can be noticed that DMFC have been envisaged for submarine AIP. The DMFC system can use methanol as fuel and work at temperature of 50°C-120°C, which represents an advantage over the methanol reforming PEMFC system. Theoretical comparison of an AIP based on PEMFC with methanol reforming and an AIP base on DMFC was shown in [44]. This study shows that the latter achieves better ability of reducing weight and volume at quite similar efficiency than the former. But the technical barriers of DMFC limit its marine applications [23, 24].

Cost: Although the cost of fuel cell is less sensitive for military ship applications than for commercial applications as EVs and stationary plants, reducing the cost of the FC system is even a challenge for submarine application.

Target of the US Department of Energy for PEMFC cost is $45/kW in 2010 and $30/kW in 2015 [42]. It can be noticed that the increasing number of manufactured FC can minimize the production cost. As shown in Fig.3 (data from [42]), the cost of an 80kW fuel cell has decreased from $275/kW in 2002 to $51/kW in 2010 because it is manufactured at a volume of 500,000units/year.

TABLE II

COMPARISON OF VARIOUS CHOICES OF FUEL SUPPLY FROM [19, 34, 43]

Fuels	Symbol	Energy density MJ/kg	Energy density MJ/L	Reforming °C
Hydrogen (350Bar)	H_2	51.8	1.70	-
Methane	CH_4	50.0	3.55	800
Methanol	CH_3OH	21.1	2.11	250
Ethanol	C_2H_5OH	27.7	2.90	700
Diesel	$C_{12}H_{26}$	43.3	4.98	850

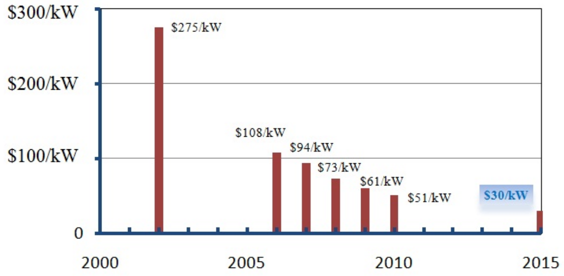

Fig.3 Modeled cost of an 80-kWPEM fuel cell system from [42]

V. FUEL CELL FOR SURFACE SHIPS

A. Context

One of the main challenges in ship propulsion is to reduce the emissions and the fuel consumption. All-Electric Ship (AES) concept is now a classical solution for the energy systems in military and civilian ships [43, 44]. In this solution, power distribution system for propulsion, sensors, weapons (for military ships) and general ship network is fully electric. AES concept allows a better energy management and flexibility and lower fuel consumption than diesel or gas turbine propulsion.

In this context fuel cell system can be an attractive solution for a full integration of energy sources in AES concept. For an existing surface ship platform as the DDG-51 ship class, it is estimated that the use of a 3-6MW fuel cell based electric power system would result in 30% fuel savings per year [45].

This is why applications of fuel cell on shipboard have been studied [16, 17, 46, 47]. But the use of fuel cells on board has not leave the stage of Research, Development & Demonstration because of the technological barriers and cost.

B. Some main projects for high power ship

Some researches in FC for ships have been developed in many countries.

The Office of Technology Assessment of USA started a program to evaluate the benefits and problems of using fuel cells for marine propulsion and auxiliary power in the 80's [48]. With the developing of fuel cells technology, the US Office of Naval Research (ONR) has launched a ship service fuel cell (SSFC) program in 1997. The aim of the three-phase program is to design and demonstrate that the fuel cell can be used for ships using classical hydrocarbons fuels [49, 50]. During the first phase, a conceptual design of 2.5 MW SSFC power plants was presented. This work has focused on risk reducing, cathode tolerance to marine environment, tolerance to shock and vibration and diesel fuel reforming process [50]. The first phase has been completed in 2000. In the second phase, a 500 kW EPM fuel cell with reformer was constructed and tested in a laboratory which was manufactured by Ballard and BWX Technologies Inc.. It worked at efficiency of 45% at 50% load using JP5 logistic fuel. The volumetric and gravimetric power density was estimated to be up to 35W/L and 80W/kg respectively for a future 2MW fuel cell using this technology [51]. Meanwhile a 625kW MCFC for SSFC was developed by Fuel Cell Energy Corp. and achieved an efficiency of 48% at 50% load in demonstration tests. This system will achieve a volumetric power density of 36 W/L with improved reforming process operating on low-sulfur fuel [52].

Continued research and development efforts are underway to improve performance of SOFC. A 5MW shipboard SOFC system was designed based on the testing of 5kW prototype and estimated to achieve nearly 50% efficiency. It will also work at high power density of 35W/L and 40W/kg [53].

C. Key features for the use of FC in surface ships

Currently, the traditional fuels, such as diesel, gas, or JP-5, have to be considered as the first choice for fuel cell because of the limited availability of pure hydrogen. This is why the types of fuel cell which have been studied in R&D project of surface ships are PEMFC with fuel reformer, SOFC and MCFC. The main barriers related to the development of an AES with fuel cells for surface ships are lifetime, fuel cell cost, requirements of quick dynamic response and adaptation to marine environment.

Lifetime: The key factors in term of lifetime for MCFC are: nickel oxide, nickel metal losses, and electrolyte losses. Now the designed lifetime is around 5 year for a MCFC [54].

It can be noticed that the lifetime of stacks has been increased a lot with recent technology developments. A 250kW MCFC developed by MTU CFC Corp. worked more than 30000 hours in Magdeburg at the end of 2009 [55]. A Siemens-Westinghouse CHP-100 SOFC achieved a lifetime of 30000 hours, and up to 70000 hours in lab test [56]. These recent R&D projects seem very promising for naval FC applications.

Cost: It was estimated that the relative stack module cost has decreased by 60% from 2002 to 2009 as shown in Fig. 4 (data from [54]). At present, the cost of the stack module makes up two-thirds of the total cost of a MCFC power plant. This Stack cost is about $4000/kW for a 1.4MW power plant [56]. Considering SOFC technology, it is reported that current factory cost for FC system is up to $9,000/kW at low production volume [57]. However it was estimated that the SOFC stack module cost can decrease to $750/kW if the produced volume of Stacks is up to 10MW/yr [58].

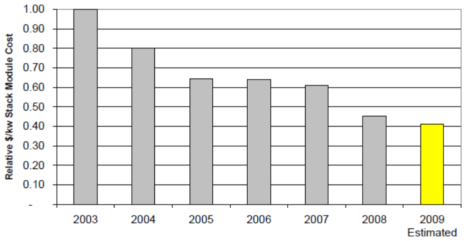

Fig.4 Cost drop down of MCFC (data from [54])

VI. CONCLUSION

Fuel cell system seems to be a very attractive solution for on board ship power generation. Fuel cells promise to be more efficient and cleaner than conventional ICE and GT and allow to be fully integrated in All Electric Ship Concept. Currently the more mature power application of FC in ships is PEMFC in the HDW submarines working as AIP. This kind of submarines has entered service in several countries from the 90's. However fuel cells for high power systems on surface ships are still in the R&D or demonstration stages. Some technological barriers limit the development of FC in surface or submarine ship. Firstly, due to the poor availability, low density and heavy storage system of hydrogen, it seems necessary to use classical hydrocarbon fuels in the next years marine FC developments. This is why some research projects focus on FC associated with reformer which can use classical fuels. Another challenge is to reduce the cost of the system. In this point, the development of stationary and EV applications is very promising because it allows a drastic cost reduction related to mass production effect. A last challenging point is to increase the lifetime of FC. Some recent works have reported a significant increase of new generation fuel cell in lab test. These recent facts and R&D results offer hope that FC can be developed in an industrial scale for naval applications in the next ten years.

REFERENCES

[1] EG&G Technical Services, Inc., *Fuel cell handbook*, 7th ed., 2004, US Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory.
[2] Jerram LC, 2009 light duty vehicle survey, Fuel Cell Today, 2009.
[3] http://www.itm-power.com/.
[4] Albert E. Hammerschmidt, "Fuel Cell Propulsion of Submarines," Advanced Naval Propulsion Symposium 2006, October 30-31, 2006, Arlington, VA, USA.
[5] Geiger S, Copper MAJ, Fuel cell small stationary marker, Fuel cell today, 2003.

[6] A. Verhage, J. Gerits, T. Manders, “Duration Tests of PEM Fuel Cells in a 50 kW Pilot Power Plant,” Proceedings of the WHEC, May 2010, Essen, pp.63-67.

[7] Nedstack fuel cell technology BV, Arnhem, TheNetherlands. <http://www.nedstack.com>.

[8] I. Staffell, A. Ingram, “Life cycle assessment of an alkaline fuel cell CHP system,” International journal of hydrogen energy 35 (2010) , pp.2491-2505.

[9] O. Führer, S. Rieke, “Alkaline eloflux fuel cells and electrolysis cells using a new kind of gas diffusion electrodes,” International Journal of Hydrogen Energy 1994;19 (4):343–348.

[10] Géraldine Merle, “Anion exchange membranes for alkaline fuel cells: A review,” Journal of Membrane Science 377 (2011), pp.1– 35.

[11] Robert Remick, Douglas Wheeler, Molten Carbonate and Phosphoric Acid Stationary Fuel Cells: Overview and Gap Analysis. Technical Report NREL/TP-560-49072 September 2010.

[12] Leo J. M. J. Blomen,Michael N. Mugerwa, Fuel cell systems, Plenum Press, New York, 1993.

[13] John Ferro, PAFC History and Successes, MCFC and PAFC R&D Workshop, November 16, 2009.

[14] Robert J. Remick, MCFC and PAFC R&D Workshop Summary Report, MCFC and PAFC R&D Workshop, November 16, 2009.

[15] F. Orecchini, E. Bocci, A. Di Carlo, “MCFC and microturbine power plant simulation,” Journal of Power Sources 160 (2006) 835–841.

[16] E. Ovruma, G. Dimopoulosb, “A validated dynamic model of the first marine molten carbonate fuel cell,” Applied Thermal Engineering 35 (2012) 15-28.

[17] Wei jiang, Ruixian Fang, “Performance Prediction and Dynamic Simulation of Electric Ship Hybrid Power System,” IEEE ESTS07, 2007, pp. 490 – 497.

[18] T.J. Leo, J.A. Durango, E. Navarro, “Exergy analysis of PEM fuel cells for marine applications,” Energy 35 (2010) 1164–1171.

[19] Chan SH, Ho HK, “Modeling of simple hybrid solid oxide fuel cell and gan turbine power plant,” Journal Power Source 109(2002), pp. 111-120.

[20] Ulf G. Bossel, “Solid Oxide Fuel Cells for Transportation,” Journal of KONES Internal Combustion Engines 2005, vol. 12, pp. 43-50.

[21] Hamnett A. “Mechanism and electro catalysis in the direct methanol fuel cell,” Catalysis Today 1997; 38:445–57.

[22] S.K. Kamarudin, “Overview on the application of direct methanol fuel cell (DMFC) for portable electronic devices,” International Journal of hydrogen energy 34 (2009), pp.6902-6916.

[23] Imdat Taymaz, “Application of response surface methodology to optimize and investigate the effects of operating conditions on the performance of DMFC,” Energy 36 (2011) 1155-1160.

[24] Don Hoffman, Marine Fuel Cells, presentation at Marine Vessel and Air Quality Conference, San Francisco, CA, February 2001. <http://www.epa.gov/region9/air/marinevessel/pdfs/hoffman.pdf>.

[25] Gunter Sattler, “Fuel cells going on-board,” Journal of Power Sources 86 (2000) 61–67.

[26] J Heinzel, M Cervi, D Hoffman, J Kuseian, Fuel Cell System Models for U.S. Navy Shipboard Application, AIChE 2005. <http://www.nt.ntnu.no/users/skoge/prost/proceedings/aiche-2005/topical/pdffiles/T1/papers/322b.pdf>.

[27] Vasilis Tsourapas, Jing Sun, Anthony Nickens, “Modeling and dynamics of an autothermal JP5 fuel reformer for marine fuel cell applications,” Energy 33 (2008) 300–310.

[28] Gunter Sattler, “PEFCs for naval ships and submarines: many tasks, one solution,” Journal of Power Sources 71 (1998) 144–149.

[29] Angela Psoma, Gunter Sattler, “Fuel cell systems for submarines: from the first idea to serial production,” Journal of Power Sources 106 (2002) 381–383.

[30] Albert E. Hammerschmidt, “Fuel Cell Propulsion of Submarines,” Advanced Naval Propulsion Symposium 2006, October 30-31, 2006, Arlington, VA, USA.

[31] John Buckingham, “Submarine Power and Propulsion- Trends and Opportunities,” Proceeding of Pacific 2008 IMC, Sydney, Australia.

[32] S. Krummrich, “Fuel Cell Methanol Reformer System for Submarines,” Proceedings of the WHEC, May 2010, Essen

[33] Vicki P. McConnell, “Now, voyager? The increasing marine use of fuel cells,” Fuel Cells BulletinVolume 2010, Issue 5, May 2010, pp. 12-17

[34] Weaver, G., World Fuel Cells: An Industry Profile with Market Prospects to 2010. UK: Elsevier Advanced Technology

[35] CMDR D. Sc., M.E. Tomasz Lus, “Submarine hybrid propulsion systems,” Journal of Kones. Combustion Engines, Vol. 8, No. 1-2, 2001, pp.265-270.

[36] Julie H. Ferguson，Deeply Canadian: New Submarines for a New Millennium, Beacon Publishing, 2000 <http://www.hydrogen.energy.gov/pdfs/review11/fc081_kurtz_2011_o.pdf>.

[37] Borup R, et al. PEM fuel cell durability. 2008 DOE hydrogen program review, June 2008. <http://www.hydrogen.energy.gov/pdfs/review08/fc_26_borup.pdf>

[38] Jennifer Kurtz, Fuel Cell Technology Status –Voltage Degradation, 2011 DOE Annual Merit Review, May 2011. <http://www.hydrogen.energy.gov/pdfs/review11/fc081_kurtz_2011_o.pdf>.

[39] Scott W. Jorgensen, “Hydrogen storage tanks for vehicles: Recent progress and current status,” Current Opinion in Solid State and Materials Science 15 (2011) 39–43.

[40] B.V. Nikiforov, A.V. Chigarev, “Problems of designing fuel cell power plants for submarines,” International journal of hydrogen energy 36 (2011), 1226-1229.

[41] Yuan, J., Sun, C., Sun, “Marine Application of fuel cell technology, Fuel Cell science,” Engineering and Technology, 2004, pp.251-257.

[42] Jacob Spendelow and Jason Marcinkoski, Fuel Cell System Cost -2010, September 2010. <www.hydrogen.energy.gov/pdfs/10004_fuel_cell_cost.pdf>

[43] Alf Kåre Ådnanes, Dr. Ing., MScEE, “A Survey of Concepts for Electric Propulsion in Conventional and Ice Breaking OSVs,” 30th Propulsion & Emissions Conference 2008.

[44] Alf Kåre Ådnanes, Dr. Ing., MScEE, “Fuel Saving and Reduction of Environmental Emissions in OSV and AHTS by use of Electric and Hybrid Propulsion,” OSV Singapore 2009.

[45] Ronald O’Rourke, Navy Ship Propulsion Technologies: Options for Reducing Oil Use - Background for Congress, December 2006. <http://www.globalsecurity.org/military/library/congress/2006_hr/060406-rourke.pdf>.

[46] L. K. C. Tse, “Solid oxide fuel cell/gas turbine trigeneration system for marine applications,” Journal of Power Sources 196(2011), pp.3149-3162.

[47] Federico Ghirardo, “Heat recovery options for on board fuel cell systems,” International Journal of Hydrogen Energy 36(2011) 8134-8142.

[48] U.S.Congress, Office of Technology Assessment, Marine Applications for Fuel Cell Technology—A Technical Memorandum, OTA-TM-O-37 (Washington, DC: U.S. Government Printing Office, February 1986).

[49] U.S. Coast Guard Research and Development Center, U.S. Department of Transportation, Marine molten carbonate fuel cell demonstration module: USCGC VINDICATOR ship interface studies, CG-D-12-99, 1999.

[50] Don Hoffman, U.S. Navy Shipboard Fuel Cell Program, U.S. Maritime Administration Workshop on Maritime Energy and Clean Emissions, January 2002.

[51] Vasilis Tsourapas, Jing Sun, Anthony Nickens, Modeling and dynamics of an autothermal JP5 fuel reformer for marine fuel cell applications, Energy 33 (2008) 300–310.

[52] Pete Devlin, Fuel Cell Technologies Program, 2011 Joint Service Power Expo, May, 2011.

[53] Don Hoffman, System Design: Lessons Learned, Generic Concepts, Characteristics & Impacts, Presentation for DOE-DOD Shipboard APU Workshop, March 2011.

[54] Mohammad Farooque, DFC Opportunities, Presentation for MCFC and PAFC R&D Workshop, Palm Springs, November 2010.

[55] J. Robert Selman, MFCF in Europe and elsewhere, MCFC and PAFC R&D Workshop, Palm Springs, CA, November 2010

[56] Robert Remick, Molten Carbonate and Phosphoric Acid Stationary Fuel Cells: Overview and Gap Analysis, Technical Report NREL/TP-560-49072,September 2010.

[57] National Renewable Energy Laboratory, 1–10 kW Stationary Combined Heat and Power Systems Status and Technical Potential, May 2010.

[58] Jan H. J. S. Thijssen, J.Thijssen, LLC, The Impact of Scale-up and Production Volume on SOFC Stack Cost, Presentation for 7th Annual SECA Workshop and Peer Review, September 2006.