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Fuel cells application in subsea industries

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Abstract
Air Independent Propulsion (AIP) improves the underwater performance of conventional diesel electric submarines and unmanned undersea vehicle (UUV). Many different types of AIP systems are being considered, either for integration into new section or plug. Fuel cell technology is an AIP system that much broader in undersea application than other AIP systems. Fuel cells chemically convert fuels into direct current electrical energy and unlike heat engines, are not limited by the Carnot cycle. Many different types of fuel cell used from the first up to now in undersea application. This paper surveys the various types of fuel cell systems and assesses them against the AIP requirements.

Keywords*:* Fuel cells, Submarine, PEMFC, AFC, SOFC

Introduction
Conventional submarines are equipped with a diesel–electric propulsion system. For submerged operation the energy for propulsion and hotel load is stored in a lead acid battery. The capacity of this battery limits the range of submerged cruising [1]. A diesel-electric submarine needs to surface periodically to run its diesel powered generators in order to recharge its batteries, and this increases its vulnerability to attack by surface vessels and aircraft. Conversely, a submarine which has a reduced requirement to surface, and is more free to choose the timing and location of surfacing, has a significant tactical advantage [2]. Air Independent Propulsion (AIP) systems have the potential to improve the under water performance of conventional diesel electric submarines and to reduce their vulnerability [3]. An AIP system permits submarine missions to be conducted for several weeks, continuously submerged, and in complete independence of an outer air supply [4]. The requirements to be fulfilled by an AIP system on board submarines are:

- Operation without surface contact over longer periods,
- Low noise level,
- Low magnetic signatures
- Low heat transfer to the sea water [1].

There are several different AIP technologies including closed-cycle diesel, Sterling engines, closed-cycle gas, steam turbines and fuel cell. Fuel cells and semi-cells are the only non-heat engine technologies under development. The main aim of this paper is to evaluate different types of fuel cells used in undersea application from the first up to now and selects the best of them in undersea application. It is interesting to note that a low temperature fuel cell, running on hydrazine hydrate and gaseous oxygen, was developed in 1964 by Allis Chalmers Manufacturing Company under contract to the Electric Boat Division of General Dynamics. This 750 W fuel cell system was used to power a one-man underwater research vessel, and is believed to be the first example of fuel cells used in a submersible or submarine [5].

Alkaline fuel cell (AFC)

In 1964 for submarine application ASEA in Sweden developed a 200 kW alkaline fuel cell system. In this system ammonia was used as a fuel, and cracked catalytically to produce hydrogen for the fuel cell and oxygen stored in liquid oxygen tank. This system was run for 4000 hours, but a catastrophic fire occurred in 1967 due to failure in the project [2]. In 1978 Lockheed installed two United Technologies Corporation (UTC) 30 kW alkaline fuel cells on Submarine. Efficiency was about 60%.Although technically satisfactory; the system was not adopted for the Deep Submergence Rescue Vessel (DSRV) due to different mission requirement [2]. In the 1970 the German submarine industry and the German Ministry of Defense (MOD) decided the fuel cell used for application on submarine. From the field of possible fuel cells, alkaline fuel cells (AFC) phosphoric acid fuel cells (PAFC) and solid polymer electrolyte fuel cells (SPEFC or PEMFC) were subjected to a detailed evaluation process. The PEMFC was selected but PEMFC were still under development at the time and therefore AFC were used for the first tests. The 100 kW AFC system was tested in a shore test plant from 1983 to 1985 and later on in practical sea trials on board the Class 205 submarine U1. The test was very successful and satisfactory [1]. In 2004 the first military autonomous underwater vehicles(AUV) HUGIN1000 was delivered to the Royal Norwegian Navy [6]. An alkaline aluminum hydrogen peroxide semi-fuel cell developed at FFI powers HUGIN 3000. The cell stack is composed of six serially connected cells and uses circulating electrolyte (7M KOH) [6].

Aluminum-Oxygen Fuel Cell

The aluminum - oxygen (Al-02) cell is a hybrid battery/fuel cell system and has been variously described as a power cell or a semi-cell [2]. For an AUV application, where the volume available for the power plant and reactant storage is very limited [7]. Aluminum-oxygen cell reduce oxygen consumption so for AUV application is suitable. Alupower Canada Limited was granted a contract by the Canadian Defense Department to develop designs for a 300 kW100 MWh Al-02 fuel cell for submarine. This system consisted of sixty-four 5 kW stacks in a 6.35 m plug, requiring only 28 tonnes of LOX and 27 tonnes of aluminum [2].Alupower was also developing several systems for UUV and AUV. These systems include a 2.5 kW, 100 kWh systems for the American XP-21 UUV in 1973 [2]. Alupower developed a similar system for UUV application in the UK [8].Eltech Research Corporation and Loral Corporation has also developed Al-o2 fuel cell to power along rang AUV [2].

Solid Oxide Fuel Cell

The solid oxide fuel cell (SOFC) is a high temperature fuel cell with electrical efficiencies of 50 to 60%. Solid oxide fuel cells (SOFC) an emerging technology are being targeted for UUV applications, because of their ability to utilize hydrocarbon fuels without extensive fuel processing [9]. It has been reported that Babcock & Wilcox in the USA is developing a solid oxide fuel cell stack of planar design for UUV and stand-alone power generation applications [2]. In 2007 a novel carbide – based fuel system in SOFC used for UUV application [9]. This SOFC uses calcium carbide and calcium hydride that react with water to generate acetylene and hydrogen as the fuel and calcium hydroxide as a carbon dioxide scrubber [6].In another work, Vidar- 36 submarine used from PEMFC and SOFC to power generation [10]. A 200kW SOFC and 1200kW diesel engine used for snort power generation and PEMFC for submerged endurance in 2008 [10].

Proton exchange membrane fuel cell (PEMFC)

The history of SPFC technology for underwater applications dates back to the late 1960's, when General Electric (GE) developed two small power sources (1.8 kWh and 44 kWh) for the U.S. Navy for submerged buoy applications. In 1978 the Canadian Defense Research Establishment for a 17 kW, 96 kWh power plant to provide propulsion, heating and emergency life support for a 13 tonne deep diving submersible [2]. GE also reported a 2.6 MW, 338 MWh power plant for a 1815 tonne submarine. In 1980s Siemens in Germany licensed solid polymer electrolyte fuel cell technology from General Electric (USA). After it German MOD was concluded that PEMFC technology was preferred to alkaline fuel cell technology for submarine application [2]. The consequence of the successful tests of AFC in U1 submarine German MOD decided to use PEMFC for the new Class 212A submarine in 1995. U31, the first of four new German submarines, was christened in March 2002 and is currently undergoing sea trials in the Baltic Sea [4]. For export customers, Howaldtswerke-Deutsche Werft AG (HDW) builds Class 214 submarines, with a PEM fuel cell system for the Hellenic and the South Korean Navy [4]. The submarine of the *Class S-80* of the Spanish Navy is a series of high-tech submarines. The first this class submarine will enter service in the Spanish Armada in 2013 and the second in 2014 [11]. The full AIP system will be accommodated in a 7.89 m section. The AIP system developed for the S-80A is a 300 kW PEMFC system based on reformed ethanol and liquid oxygen [12].

Conclusion

Different types of fuel cells were used for underwater applications. For UUV applications SOFC, PEMFC and AFC are options. But PEMFC and AFC equire pure hydrogen for reliable performance, and hydrogen storage methods cannot yet compete with liquid hydrocarbon fuels on an energy density basis. But SOFCs has excellent ability to utilize hydrocarbon fuels without extensive fuel processing. So SOFC is a suitable option for UUV applications. For submarine applications proton exchange membrane fuel cell (PEMFC) identify as the most suitable type in submarine air independent propulsion. Its advantages in comparison to other fuel cell systems include low temperature operation, fast start-up, high power density and mechanical and chemical stability.

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