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Fuel cell systems for submarines: from the first idea to serial production

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Abstract

The future submarines of Howaldtswerke-Deutsche Werft AG (HDW) will be equipped with fuel cell power plants for air independent propulsion. In the 1970s the decision for a fuel cell system on submarines was made. Tests in the 1980s confirmed the feasibility of fuel cells on submarines. Positive development results in the 1990s led to series production of fuel cell equipped submarines, which will be in operation from 2003 onwards. Strictly controlled development work was necessary to reach the goal of series production. The train of thought behind this process of development is described in this paper starting with the initial idea and ending with the description of the serial production of the fuel cell power plant. The future outlook gives an impression of current development work.

Keywords: Submarines; PEMFC; Metal hydrides; Reformer

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. The batteries are charged during snorkelling periods by means of diesel generators. While snorkelling the submarine is exposed to a higher risk of being detected. Therefore, it was essential to develop an air independent propulsion (AIP) system, which allows longer underwater endurance. 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.

Different systems were investigated, such as the closed cycle diesel, which was developed in Germany for over 25 years, the Stirling engine, closed cycle gas and steam turbines as well as fuel cells. In the 1970s based on a trade-off study the German submarine industry and the German Ministry of Defence (MoD) decided that the fuel cell offered the most effective solution for application on submarines to fulfil the mentioned requirements, because of the following advantages:

- high efficiency of up to 70% (H_2/O_2 operation),
- absolute silence of the energy generation process, normally only achievable with battery operation,
- depth independence of the process,
- very good operational and control features,
- balance of weight by easily storing the product water.

Furthermore, it was decided that polymer electrolyte membrane fuel cells (PEMFC) seemed to be most suitable. Advantages for application in submarines are the low operation temperature, short start-up time and flexibility concerning dimensions and power. From the field of possible fuel cells, Siemens' alkaline fuel cells (AFC), United Technologies' phosphoric acid fuel cells (PAFC) and General Electric's solid polymer electrolyte fuel cells (SPEFC, = PEMFC) were subjected to a detailed evaluation process. The PEMFC was selected and defined as propulsion system for the projected German submarine Class 208 by the German MoD. However, the PEMFC were not then matured and therefore the project was terminated in 1979. Based on the concept design for Class 208, the technical specification for PEMFC was already written then and the necessary development was initiated by the German MoD by implementation of technology transfer from General Electric to Siemens.

In 1980, development of the first generation of fuel cell plants for submarines was started by a consortium consisting of Howaldtswerke-Deutsche Werft AG (HDW),

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Ingenieurkontor Luebeck (IKL) and Ferrostaal. Former investigations had shown the enormous development potential especially of the PEMFC. But PEMFC were still under development at the time and therefore AFC were used for the first tests, since AFC and PEMFC have similar performance data for submarine application. The system comprised 16 × 6.2 kW modules, which were manufactured by Siemens. Testing of different AFC modules of 3.5, 6.2 and 7 kW each to adapt the voltage of different submarine lead acid batteries showed the high flexibility of fuel cell (FC) modules. 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 feasibility of fuel cell operation and hydrogen and oxygen storage in submarine conditions was proved. Great emphasis was laid on the safety concept and its realisation. The tests were very successful and satisfactory, so the German Navy decided to order the concept phase for the new Class 212A submarines. Although operation of the FC system by the naval crew on board was so successful that it was even possible to reduce the test period by 3 months due to the system's high degree of reliability and availability, it had to be removed because the submarine was still assigned to NATO and the necessary submarine standards (e.g. proven shock resistance, logistic supply of reactants and spare parts, documentation etc.) could not be achieved. Incidentally, after decommissioning of the submarine, Thyssen Nordseewerke (TNSW) in Emden took the chance to test their closed cycle diesel engine on-board the same submarine, since the prolongation of the pressure hull that was done to accommodate the fuel cell system also enabled the whole diesel engine system to be integrated for their purposes.

By 1980, the German MoD had finally commissioned the development of special PEMFC modules for the submarine application from Siemens.

Parallel to the development of the Siemens fuel cell module, which operates using hydrogen and oxygen, tests were performed with a Ballard air breathing fuel cell module in 1996/97 at HDW in Kiel. The aim was to evaluate the possibility of naval standard PEMFC for stationary and mobile applications with hydrogen/air operation, hopefully at low cost because of mass production. These fuel cell modules were operated in a shore test plant with a nitrogen/oxygen closed cycle gas compound applicable for use on board submarines. Due to this closed cycle gas compound, the system was space-consuming and heavy. In addition to the lower efficiency, the complex system design was disadvantageous.

The Class 212A submarines for the German and Italian Navies are under construction now and will be delivered from 2003 onwards. The fuel cell system, based on Siemens' PEMFC technology under contract to the German MoD, was developed by HDW with a total fuel cell output of about 300 kW. For reasons of safety, the modules are protected by a pressure-tight container. The free container volume is filled with inert gas and monitored for leaks.

Based on the 30–50 kW module for Class 212A an advanced 120 kW PEMFC module was developed by Siemens. It is ready for series production today. Two of these modules forming a 240 kW FC system will be used for refits of the existing Class 209 and in Class 214, which has already been ordered by the Greek and South Korean Navies, and they are also foreseen for the German Class 212B. The 120 kW module achieves almost four times the performance at roughly the same weight and dimensions as its predecessor.

For all FC systems up to now, the hydrogen is stored in metal hydride cylinders, the oxygen is stored in liquid form in tanks. These storage systems will be described in the following paragraphs.

The oxygen needed to supply the fuel cells is stored in liquid form (LOX) in double-walled vacuum-insulated tanks. This method of oxygen storage is well known for transportation tanks. The storage tanks for submarine application have a special design to withstand shock loads and diving pressure because they are situated outside the pressure hull. The fittings, safety and monitoring equipment and the evaporator are provided in a pressure-tight and watertight cabinet. The fittings and the evaporator are installed in a resiliently mounted rack for reasons of shock. The safety valve is designed to withstand the full diving pressure and the tank is provided with frames to increase its strength. The tanks are made of amagnetic steel, the same material as used for the pressure hull. It meets all standards for low temperature structures.

Storage outside the pressure hull for class 212A is the result of naval requirements, which demand closure of the pressure hull valves in case of a gas leakage inside the submarine. For future submarines, oxygen storage inside the pressure hull is foreseen. Storage inside the pressure hull allows improved flexibility for integrating LOX tanks in different submarine designs. The safety measures have been cleared with the German classification society Germanischer Lloyd, so the same safety level as outside storage can be reached.

Besides oxygen, the fuel cells need hydrogen for operation, which can be stored in different ways. The storage of gaseous hydrogen leads to a heavy and bulky storage system, which is not suitable for general use on board submarines. Light aramid fibre pressure bottles used for mobile systems, e.g. buses, do not yet fulfil submarine shock requirements. So this method of hydrogen storage is limited to special applications only.

The storage of liquid hydrogen (LH_2) is state-of-the-art in industrial land based and transport applications. The hydrogen is stored in superinsulated double walled tanks due to its low boiling point. Modifications would be necessary for application on board submarines to withstand high shock loads. The main disadvantage of LH_2 storage on board submarines is the limited holding time due to the high temperature difference between the hydrogen and the surrounding seawater and the resulting safety issues and signatures.

The chosen hydrogen storage method on board HDW submarines is using metal hydrides. The hydrogen is absorbed in the inter-metal lattice places. Low-temperature metal hydrides like TiFe or TiMn alloys can absorb up to 2% in weight of hydrogen. During loading, the metal hydride cylinders have to be cooled by means of a land based cooling device. For unloading during the submarine's mission, the cylinders are heated by cycling the fuel cell cooling water to free the hydrogen. The process is fully reversible, which was proved in many test cycles. The metal hydrides offer the possibility to store hydrogen at low gas pressure and ambient temperature. It is the safest way to store hydrogen because there is nearly no free-flowing gas. The maximum possible mass flow of hydrogen depends on the heat transfer to the hydride. A further advantage of hydrogen storage in metal hydrides is the fact that the metal hydride can take up more hydrogen than liquid storage with respect to volume. In addition, the system is maintenance free and can therefore be located in tanks in the outer hull area of a submarine.

The metal hydride alloy chosen by HDW was developed by Daimler Benz in the early 1970s with support from the German MoD. After building several test units in the beginning of the 1980s, 16 metal hydride cylinders were built for the tests on the submarine U1, where they stored the hydrogen for the operation of the above-mentioned AFC system. For activation, the cylinders had to be heated to a few hundred degree centigrade and purged with hydrogen. This procedure was cost intensive. Therefore for serial application for Class 212A and 214, a more cost effective production method and a simplified way of activating the cylinders was developed. The metal is melted in a vacuum furnace and can absorb hydrogen in inter-metal lattice places. When hydrogen is absorbed, the metal lattice expands. This effect disintegrates the metal block into a fine powder during the first hydrogenation. Series production has already started. The quantity and dimensions of the metal hydride cylinders can be adapted to the respective mission profile.

The described storage systems for hydrogen and oxygen as well as the fuel cell modules and the auxiliary systems reached the stage of serial production at the beginning of the 1990s, and all components are now available for a submarine FC system.

From the technical point of view, FC systems operated on hydrogen/oxygen and generating electrical energy and product water are superior to all other AIP systems. Unfortunately, requirements for very long underwater endurance lead to weight-critical submarine designs because of the heavy hydrogen storage. Thus alternative means of reactant storage have to be taken into consideration.

The underwater endurance of a submarine depends on the amount of stored energy or reactants. The storage of LOX in superinsulated tanks is proven and alternatives are not in sight. Hydrogen storage has to be improved, because with increasing AIP time, the weight and also the cost of the metal hydride cylinders would rise. Therefore, HDW started development of a methanol steam reformer. While the volume-related energies of hydrogen and methanol are in the same range, the weight-related energy of methanol is higher by a factor of 2.7.

Steam reforming was chosen because it has the following advantages compared with partial oxidation:

- higher hydrogen yield,
- lower oxygen demand,
- lower CO_2 generation.

Furthermore, steam reforming of methanol is well proven on an industrial scale. A disadvantage is posed by the CO_2 generated, which has to be treated. It can be stored on board in liquid form or released to the ambient seawater.

The reformer system for HDW's future submarines consists of two main components. The hydrogen generation unit (HGU) produces hydrogen-rich gas, which is filtered through a palladium membrane in the hydrogen purification unit (HPU) to guarantee high purity of the hydrogen to feed the dead end fuel cell. Except for the HPU, all components are arranged in a common frame.

The HDW steam reformer system is suitable for generating the hydrogen needed by a 240 kW_{el} fuel cell plant in a sufficient quality for PEMFC operation. All components fulfil submarine requirements with respect to inclination, shock (which is residual shock, for the plant is resiliently mounted on a platform), acoustics and ambient conditions.

Development started with a study in 1995 and continued with technical clarification. As a result, the decision for a development programme was taken. The construction of the first test plant began in 1999 and was completed at the end of 1999. After having passed the factory acceptance tests the plant was shipped to HDW in May 2000. Since then a test programme has been carried out. The current test plant is a full scale technical demonstrator, using COTS components where submarine proven components were not available at short term. At present these COTS components are being replaced with submarine proven components, and peripheral systems are being developed and tested (oxygen storage, methanol storage, exhaust system, etc.).

To sum this paper up, it can be said that the advantages of H_2/O_2 fuel cell AIP for submarines like high efficiency, low noise level, low magnetic signatures and low heat transfer to the sea water clinched the decision to select the fuel cell based propulsion system for the new German submarines. Six units of Class 212A are now under production for the German and Italian Navies at the HDW and TNSW yards in Germany and in La Spezia, Italy, at the Fincantieri yard. The new Class 214 submarine is on order for the Greek and South Korean Navy, and production started in February 2001. This shows that the user has understood and accepted that fuel cell propulsion is the ultimate selection amongst the non-nuclear AIP candidates.