

## PEM Fuel Cell Systems – An attractive energy source for submarines

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**The possibility of air-independent propulsion (AIP) is essential for modern non-nuclear submarine operations. An AIP system permits submarine missions to be conducted for several weeks, continuously submerged, and in complete independence of an outer air supply.**

During the 1970s several different AIP technologies were showcased in Germany, including closed cycle diesel, closed cycle gas and steam turbine, fuel cell, and Stirling engine technologies. The final result of these early activities was that the German Navy appointed Howaldtswerke-Deutsche Werft AG (HDW), Siemens AG, Ingenieurkontor Lübeck and Ferrostaal AG to develop an AIP system based on fuel cells. The reasons for this decision are obvious in view of the benefits of this technology:

- Favourable low signature
  - No noise
  - No exhausts
  - Minimum waste heat transfer to ambient seawater – closed loop fuel cell/metal hydride
- cylinders
- No power limits
- No diving depth restrictions
- Modular design of the entire propulsion system
- High efficiency, especially at partial load
- Low maintenance requirements
- No extra complement
- Ease of automation

The German MoD made this early and clear decision in favour of the fuel cell solution in spite of other relevant options for AIP on board submarines available in Germany and supported by German industry. Options available at the time were:

- H<sub>2</sub>/O<sub>2</sub> fuel cell power plant by Siemens and HDW / Ferrostaal/ IKL
- Stirling motor by MAN Technologies and HDW
- Closed cycle gas turbine by mtu
- Closed cycle diesel by NSWG and mtu

- High capacity batteries by VARTA, Friwo etc.

So the German MoD was in the splendid position of not favouring home against foreign solutions, but rather basing the selection on operational submarine requirements only. The fuel cell system passed through development and extensive testing stages under the supervision of the Federal Office for Military Technology and Procurement (BWB) and by the end of the 1980s was successfully used in practical operations in a plug-in section installed in the Class 205 submarine U1. This was the first submarine with fuel cell AIP.

The consequence of the successful tests with the refitted U1 was the contract in 1995 for the new Class 212A equipped with fuel cell AIP. U31, the first of four new German submarines, was christened in March 2002 and is currently undergoing sea trials in the Baltic Sea.

In addition, two identical Class 212A submarines are being built under licence by Fincantieri Navali Italiani S.p.A. for the Italian Navy. For export customers, HDW has started to build Class 214 submarines, which are also equipped with a fuel cell system. At the present time seven Class 214 submarines are being built for the Hellenic and the South Korean Navy. Furthermore, three Class 209 submarines of the Hellenic Navy are being refitted with a fuel cell AIP section.

### **Fuel cell technology**

The basis for the excellent suitability of fuel cells is found in their functional principle: Conversion of the energy in the fuel into electricity takes place silently, without combustion, by way of a direct electrochemical conversion. Hydrogen and oxygen react by means of a catalyst at a low temperature of about 80°C to produce only electricity and water. HDW submarines employ the PEM (polymer electrolyte membrane) fuel cell, which contains a solid polymer electrolyte. On the anodic side of the proton exchange membrane, hydrogen is decomposed into its electrons and protons. The electrons are by-passed to the submarine's power supply, while the protons cross through the membrane.

On the other side of the fuel cell, the electrons return via the cathode to re-combine with the protons, and together with the oxygen molecules form pure water as the only reaction by-product.

In addition to the PEM fuel cell there are other types of fuel cells, where the ion-conducting material can range from a liquid alkaline or acid solution fixed in a matrix as carrier to molten inorganic salts or even ceramic material. Closely correlated to the kind of material used in the fuel cells are the operating temperatures, which range from room temperature up to 1000 °C in

high temperature fuel cells.

For use in submarines PEM fuel cells were chosen, which operate at temperatures of 80°C. The advantages are obvious: low operating temperature (= low signature), highly efficient energy conversion using hydrogen and oxygen, favourable switch-on/switch-off, dynamic behaviour, no exhausts and no limits in power nor diving depth.

For the first tests with the above-mentioned submarine U1, the AIP system was based on alkaline fuel cell technology because of the availability of that technology at the time. However, parallel to this test phase, PEM fuel cell technology was developed and adapted to the specific requirements in submarines such as signatures, interfacing standards or use with pure oxygen.

The Siemens PEM fuel cells reflect a metal-based technology combining favourable mechanical properties, e.g. shock resistance, high integration of the processes resulting in low volume and high reliability at high power density.

A PEM fuel cell module with a power output in the range of 30-40 kW was developed by Siemens for application in the Class 212A submarines for the German and Italian Navies. These fuel cell modules consist of a stack comprising several single cells, an integrated humidifier for hydrogen and oxygen and all the peripheral process equipment like valves, sensors, connection parts for the media like cooling water, hydrogen, oxygen etc. which are necessary for the operation of the fuel cell module. The fuel cell module is connected to the module electronics as part of the fuel cell control board, which controls and monitors the processes within the fuel cell module. Additionally for application in the submarine the fuel cell module is encapsulated in a container filled with nitrogen as part of the integral safety philosophy of the system.

After successful finalisation of the 30-40 kW fuel cell module, development work at Siemens continued. Increasing the power density by a factor of two and a more compact arrangement of the peripheral process equipment resulted in a 120 kW module – a fuel cell module with the fourfold of power output at nearly the same dimensions as its predecessor. This cost-optimised module is used in the submarines of Class 214.

Moreover, a fuel cell power plant in its modular design is agile and prepared for later refit into already operational submarines during a normal main overhaul sequence or a mid-life conversion, as is currently being realised for Class 209 submarines.

## **The fuel cell AIP system**

Beside the fuel cell modules, the fuel cell AIP system consists of reactant storage ( $H_2$  and  $O_2$ ), reactant water storage, interface to the submarine's control system and to several auxiliary systems. Oxygen is stored on board in liquid form. The tanks are double-walled and vacuum-insulated. To give evidence of sufficient tank strength and insulation the first tank was exposed to extreme impact achieved in submarine shock tests. Since the size of the liquid oxygen storage facility is the limiting factor of all AIP options, the fuel cell system with the lowest oxygen consumption of all known systems offers the highest underwater endurance.

The hydrogen is stored in metal hydride cylinders, where it is bonded in the metal lattice structure of a special alloy. This method of storing hydrogen gives a higher volumetric density than liquid or especially high pressure gas storage and is conceivably the safest method of hydrogen storage.

The metal hydride storage cylinders are completely maintenance-free, so they can be accommodated in the outer hull of the submarine. Due to their location outside the pressure hull, there is no danger of fuel leaking into the boat's atmosphere. HDW pioneered the construction of hydride storage cylinders of this size world-wide and readied them for series production.

The plant's modular concept permits incorporation in the submarine either as an additional section (e.g. in Class 209) or as part of the whole design (as realised in the submarines Class 212A and 214). Class 214 is the first fuel cell-equipped submarine specifically designed for export customers. Class 214 combines the benefits of Class 212A with the proven design principles of Class 209. The Hellenic and the South Korean Navy decided in favour of these boats also due to the AIP advantage. The fuel cell system of Class 214 comprises two fuel cell modules of 120 kW each. In contrast to Class 212A, the oxygen tank is arranged inside the pressure hull, which offers greater flexibility in design and lower production cost. The oxygen tank and the hydride cylinders are clearly visible in outline and cut-away diagrams of the submarine.

## **Conclusion**

During recent years several navies decided in favour of a fuel cell AIP system. This is a clear indication of the general acceptance level of the fuel cell by navies operating submarines throughout the world, due to its advantages of low noise and infrared signatures, high efficiency and low maintenance requirements. Such qualities are essential for submarines that

are expected to serve well into the future.

HDW and Siemens offer a cost-effective, mature and fully operational fuel cell AIP system, the most successful AIP system on the market today. The fuel cell is suitable for integration into basically any conventional submarine as a plug-in solution or in a new submarine. But besides all the advantages of the AIP fuel cell solution as mentioned above, there is a lot of future growth potential in this technology for more power and for longer submerged endurance.

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**Fig.: U1 – the first submarine which was equipped with a fuel cell propulsion system for test purposes**

**Fig. : U31 on sea trials**

**Fig.: Working principle of a PEM fuel cell**

**Fig.: 120 kW PEM fuel cell module**

**Fig.: 30-40 kW PEM fuel cell module without and with pressure container**

**Fig.: Fuel cell AIP system**

**Fig.: Submarine Class 214**

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