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Fuel Cell Propulsion of Submarines

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Polymer-Electrolyte-Membrane (PEM) Fuel Cells are known for the efficient conversion of chemical energy stored as hydrogen and oxygen into electricity. Comparative studies of fuel cells and other air independent propulsion (AIP) systems such as Stirling engines, closed cycle diesels, and steam turbine systems in conventional (non-nuclear) submarines have clearly shown the superiority of the low temperature fuel cells to combustion-based solutions. The PEM fuel cell was selected to provide a new generation of conventional submarines with an AIP system enabling heretofore unattainable durations for submerged operations together with exceptional acoustic performance.

Siemens PEM fuel cells are based on metal technology with a compact design, fully meeting the volume constraints of the submarine designer (Figure 1). Additionally, the technology allows high power density together with excellent thermal management of the cells. The latter is an important prerequisite to acceptable service life.

The two fuel cell designs currently installed in active submarine construction programs are the Product Family SiNavy[(cis)] PEM Fuel Cells, BZM 34 and BZM 120, operating in the rated power range of 34 and 120 kW respectively. The BZM 34 (Figure 2a) was designed for the Type 212 submarine, which is being delivered to both the German and Italian Navies at present and has been successfully integrated into a fuel cell power plant configured to feature redundancy. The subsequent development of the BZM 120 (Figure 2b) enabled an application suitable for the Type 214 export submarines in addition to upgrade or retrofit programs of previous submarine designs (e.g. Type 209).

Electrical and mechanical data of both fuel cell modules are listed for comparison in Table 1. As the data illustrates a significant improvement of integration density was realized from the BZM 34 to the BZM 120 design.

The fuel cells show excellent dynamic behavior (Figure 3) with a capability to accept short-term overload conditions. The reduced efficiency apparent in the BZM 120 compared to the BZM 34 is a design compromise between achievable technical performance (size, power) and economic requirements (cost).

The following table gives an overview of essential process interface data:

Oxygen @ ~ 2.3 to 2.6 bar (abs)
Oxygen purity ~ 99.5 %
Hydrogen @ ~ 2.3 to 2.6 bar (abs)
Hydrogen purity ~ 99.99 %, no S, no CO
Cooling water – secondary cooling loop
Ambient pressure ~ submarine atmosphere pressure
Residual gases oxygen/hydrogen: extremely low quantities to be released uncontained into the submarine's breathable atmosphere

The automated safety feature of the fuel cell module is achieved by maintaining an inert gas in the void between the container wall and the fuel cell stack at higher pressure than all media inside the stack. In the event of leakage (gaskets, etc.) the inert gas will penetrate into the stack creating conditions (pressure increase, voltage drop, and similar physical parameters) recognized by the control system to initiate emergency shutdown.

The design principles follow the demand for high power, low volume fuel cells and can be summarized in the following way:

High Current / Power density
- ~ 600 mA/cm2 @ 0.72 V (BZM 34)
- ~ 1000 mA/cm2 @ 0.70 V (BZM 120)

Water cooling of each metal bipolar plate
Thickness of single cell ~ 2.2 mm
Dead-ended system for hydrogen and oxygen
Integration of gas humidification into the fuel cell stack
Control of process and safety-related functions

Oxygen is stored in liquid form and hydrogen in metal hydride canisters to feed the fuel cell power plant. Storage quantities are sufficient to enable continuous production of electricity and support sustained submerged operations measured in weeks (Figure 4). The fuel cells generate electricity for low speed propulsion, the operation of the electrical equipment during silent run and for battery recharge. In case of high power demand, e.g. for escape purposes, the lead acid batteries provide burst speed capability.

In Type 212 submarines the fuel cell stack, which consists of nine fuel cell modules, is connected directly to the ship's main power system. Redundancy is achieved through an installed spare module which engages automatically in the event of a fault in any of the installed modules (Figure 5, right side).

In Type 214 submarines the two BZM 120 fuel cell modules are connected to the ship's power system via a DC/DC converter allowing adaptation of the fuel cell power plant to different battery voltage levels (Figure 5, left side). This becomes important in retrofit projects in which an integrated fuel cell system, consisting of the fuel cells, oxygen and hydrogen storage tanks, control system, process equipment and product water tanks, is integrated into an already existing submarine during a major overhaul. The DC/DC converter allows flexible adjustment of the fuel cell power plant to the electrical requirements of the retrofitted submarines varying significantly across different navies and different hull designs.

This submarine fuel cell system design can be considered as the first commercial application of PEM fuel cells without subsidies. The following submarines equipped with fuel cell power plants are on order or have already been delivered:

<u>Class 212 (BZM 34, 9 modules/sub)</u>

4 submarines for the German Navy (to date 3 submarines commissioned)

2 submarines for the Italian Navy (to date 1 submarine commissioned)

<u>Class 214 (BZM 120, 2 modules/sub)</u>

4 submarines (+ 1 land based test station) for the Hellenic Navy

2 submarines for the South Korean Navy

2 (+1) submarines for the Portuguese Navy (called 209 modified)

Class 209 MIDLIFE Conversion (Plug-In section)

3 plug-in sections for the Type 209 (Neptune retrofit)

Several additional contracts will be concluded in the near future.

Summary and Conclusions:

Siemens hydrogen/oxygen consuming SiNavy PEM Fuel Cells have been developed for the power range of 34 and 120 kW for application as Air Independent Propulsion systems for conventional submarines. These service proven components completely satisfy military specification requirements with respect to magnetic signature, low electrical stray field characteristics, system safety standards, acoustic properties, and shock/vibration criteria. Continuing interest in this application of fuel cell technology demonstrates its viability and has established PEM fuel cells as the standard for AIP solutions for conventional submarines.

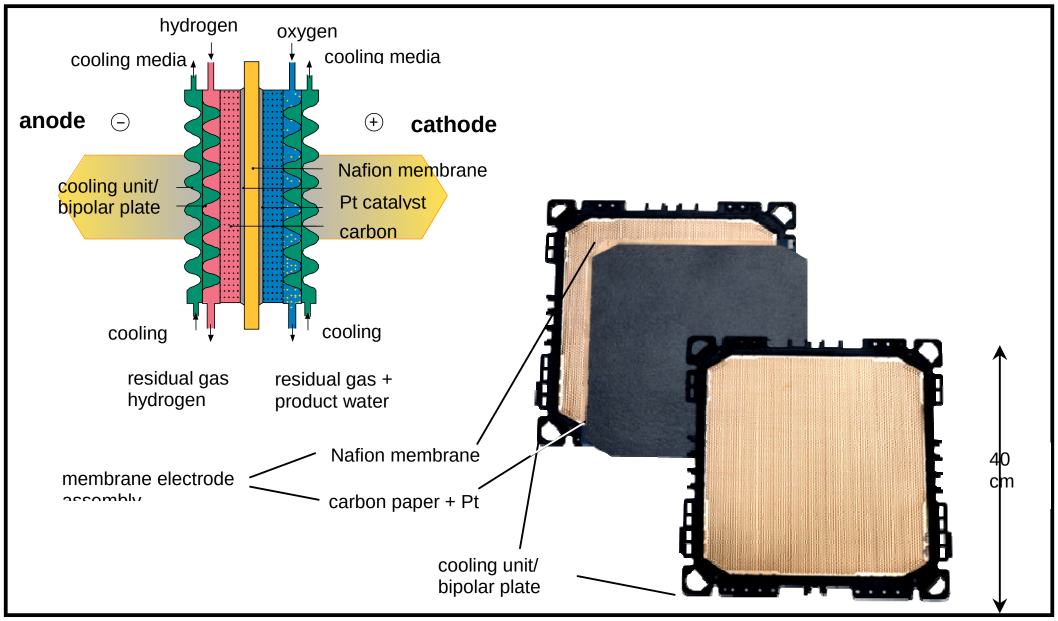

Fig. 1: Design features of a Siemens PEM fuel cell

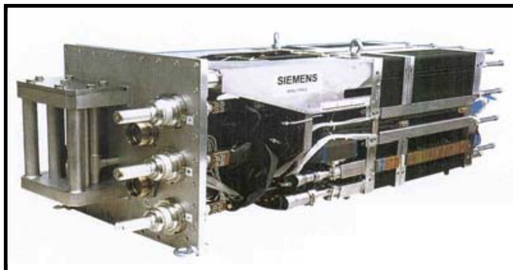

Fig 2 a: SiNavy(cis) PEM Fuel Cell BZM 34

Fig 2 b: SiNavy(cis) PEM Fuel Cell BZM 120

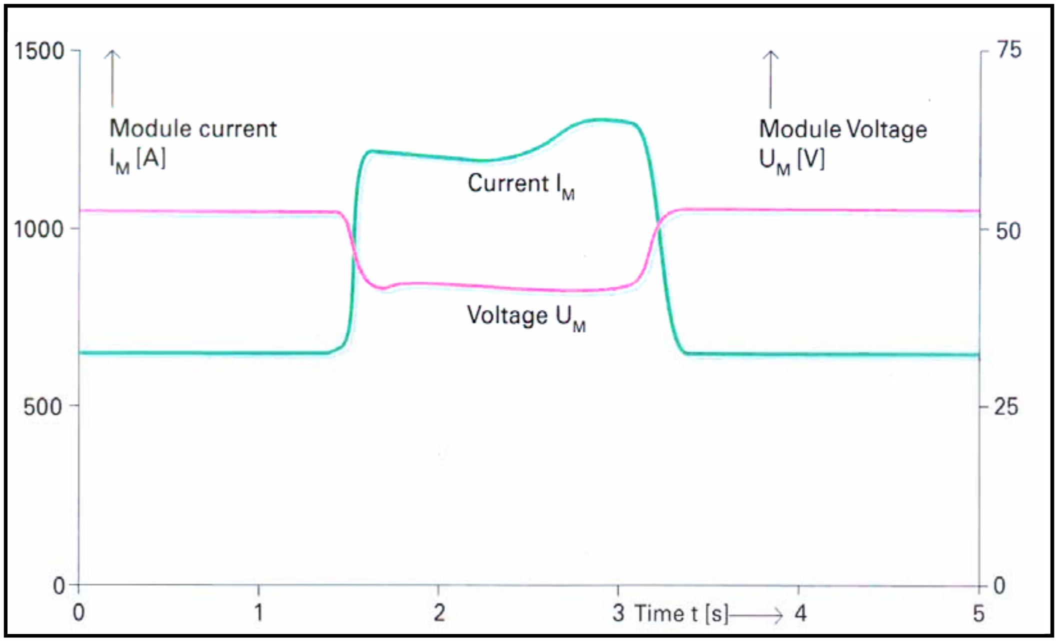

Fig. 3: Dynamic and overload behaviour of BZM 34

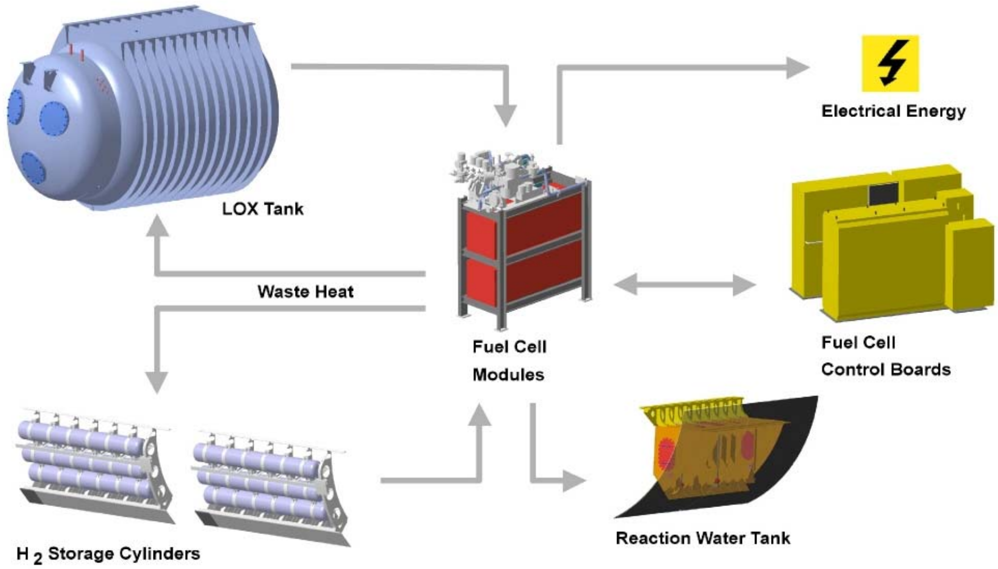

Fig 4: Main components of fuel cell power plant (FCPP) for a submarine (example: FCPP for a type U 214 submarine). Source: Howaldtswerft Deutsche Werft - HDW

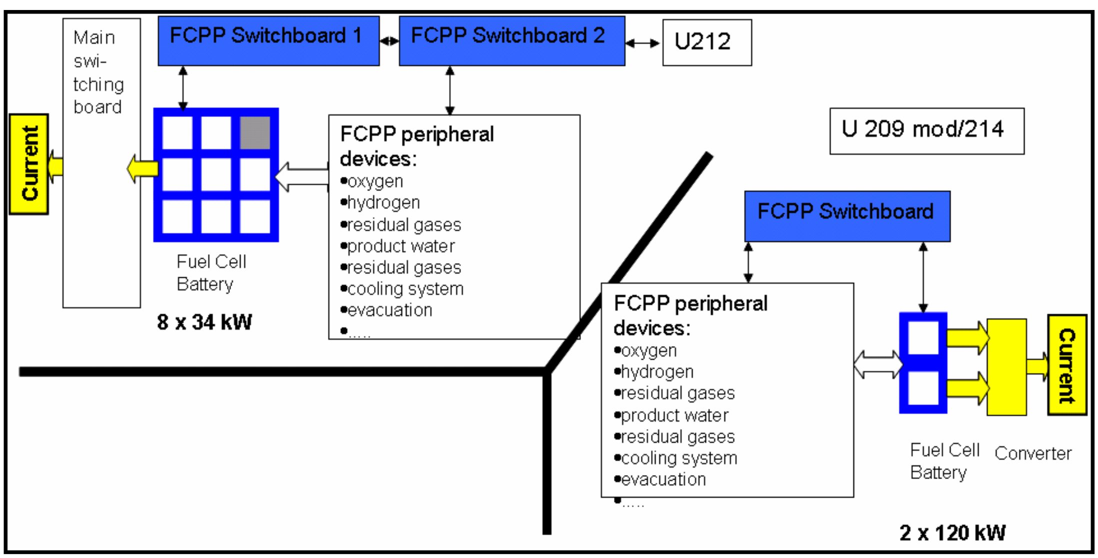

Fig. 5: Fuel Cell Power Plant: Block Diagram U212 (left side) and 209mod/214 (right side)

	BZM 34	**BZM 120**
Rated Power	34 kW	120
Number of Cells	72	320
Rated Current	650 A	560 A
Rated Voltage	52,3 V	215 V
Hydrogen Pressure	2,3 bar a	2,3 bar a
Oxygen Pressure	2,6 bar a	2,6 bar a
Working Temperature	70 - 80°C	70 - 80°C
Size	47x47x143 cm3	176x53x50 cm3
Weight (incl. press. container)	650 kg	900 kg
Efficiency at full load	62%	56%
Efficiency at 20% load	72%	68%

Tab. 1: Comparison of Electrical Properties of BZM 34 vs. BZM 120