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Fuel cells going on-board

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Abstract

Fuel cells provide great potential for use on-board ships. Possible fields of application for fuel cells on merchant ships and naval surface ships can generally be summarised as: (1) emergency power supply; (2) electric energy generation, especially in waters and harbours prescribing particular environmental regulations; (3) small power output for propulsion at special operating modes (e.g., very quiet run); and (4) electric power generation for the ship's network and, if required, the propulsion network on vessels equipped with electric power plants (e.g., naval vessels as all-electric ships, AES). In addition, the fuel cell has special importance for realising air-independent propulsion (AIP) on submarines. In the 1970s, the PEMFC system was chosen for AIP on German Navy submarines. Subsequently, this system underwent advanced development up to series maturity including storage on-board of the energy needed. This publication illustrates worldwide activities in this field, taking the various fuel cell system requirements for operation on-board merchant ships, naval surface ships and submarines into consideration. The focus is especially on AIP systems for German submarines because these have already gone into series production. Further developments are discussed which aim to improve the efficiency of hydrogen storage or to generate hydrogen on-board.

Keywords: Fuel cells; Surface ships; Submarines; All-electric ship; Reformer

1. Introduction

Tighter resources and increased awareness of environmental issues have caused increased importance to be attached to new, alternative propulsion systems for ship's networks and/or propulsion systems in recent years. A central role is played by fuel cell systems due to their considerable development potential. The advantages of fuel cells for air-independent propulsion (AIP) systems on conventional, i.e., non-nuclear, submarines were recognised at an early stage. In the case of surface ships, in particular merchant ships, the wide use of fuel cells is likely to be delayed until cost and technical reliability are at par with more conventional propulsion systems.

2. Fuel cells on-board ships

2.1. Fuel cell types and reactants

In principle, all the fuel cell types listed in Table 1 are suitable for the production of electric energy and/or for propulsion systems on surface ships. The fuels used by these fuel cells are hydrogen, gases with a high hydrogen content (such as methane) or liquid hydrocarbons (e.g., methanol, diesel fuel), which have to be suitably reformed for use in fuel cell systems. Pure oxygen or air may be used as oxidising agent.

In the case of surface ships, for logistic reasons, the most acceptable fuel is diesel, except for special-purpose tankers carrying hydrogen or other gas with a high hydrogen content as cargo. The most readily available oxidising agent is air. For submarines, polymer electrolyte membrane (PEM) fuel cells using hydrogen and oxygen in a dead-end configuration have proved suitable. This particular process is referred to as a ‘‘dead end’’ because the entire amount of gas supplied is used within the fuel cell, so that only the inert residual gases from the fuel cell enter the boat's atmosphere. Instead of storing hydrogen in metal hydrides, in the future, for reasons of weight, it may prove advantageous for submarines to generate hydrogen on-board from methanol.

2.2. Type of ship, performance ranges, operational characteristics

To ensure optimised adaptation of the selected fuel cell configuration to the ship's requirements, types of ship are distinguished as shown in Table 2.

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Table 1
Fuel cell types for surface ships

Fuel type	Reactants	Operating temperature (°C)	Efficiency (%)
PEMFC	Air/reformate (H_2)	80	39–42
PAFC	Air/reformate (H_2)	300	38–42
MCFC	Air/methane	650	40–55
SOFC	Air/methane	900	45–60

Table 2
Types of ship

Surface ships	Merchant ships	Passenger ships/ferries, container ships, tankers
	Naval ships	Destroyers, frigates, corvettes
Sub-surface vessels	Civilian	Submersibles, manned/unmanned
	Military	Submarines, manned AUV/UUV, unmanned

Performance ranges and requirements for the various types of ship can be summarised as follows (Table 3).

Fuel cells provide the following operational requirements on-board ships: propulsion, generation of electric energy for ship's network, emergency power supply, or, where appropriate, a combination of these uses. In addition, special requirements have to be catered for, such as silent running, etc. Apart from operational requirements, the kind of fuel cell selected must also meet specific performance criteria, such as power density of the system, load alternation/dynamic capabilities (upward/downward load change, sudden release, short circuiting) or fuel replenishment capabilities.

2.3. General technical requirements

In principle, all systems on-board must be dimensioned and installed in such a way that general safety is not prejudiced in any way. Fuel cell systems must, therefore, meet the specific requirements of classification societies or of the navy concerned. These requirements include such criteria as operational conditions on-board (e.g., temperature, humidity, salinity), system concepts, redundancies, operating methods, noise, etc.

Generally speaking, fuel cells are inherently capable of fulfilling most technical requirements for operation on-board a ship, as becomes clear if we consider their main features: clean, quiet, small, modular, efficient. Furthermore, electrical propulsion systems on ships provide additional advantages due to the decentralised location of the propulsion system and the resulting possibilities of optimising space allocation and utilisation.

3. Fuel cells on surface ships

Efforts to introduce new components or systems to the market can be divided into the following areas of activity:

- 'idealistic' projects;
- R&D projects;
- pilot and demonstration projects; and
- attempts at commercialisation.

Retaining these definitions, the use of fuel cells on-board merchant ships has not yet left the stage of 'idealistic' projects, largely due to the present high cost of these systems today, although serious studies have already been carried out worldwide. For naval surface ships, a more advanced stage of preparation for fuel cell operation has been reached, in particular in connection with the concept of the all-electric ship (AES).

3.1. Fuel cells on merchant ships

The advantages of a fuel cell system for merchant ships are evident: high potential for fuel savings, reduced exhaust emission, lower operating costs, quieter and cleaner propulsion. But the subject of fuel cells on-board merchant ships has so far not progressed beyond the stage of feasibility studies and demonstration. The main reasons for this are, on one hand, the market situation, which will not make allowances for the higher costs typical of the fuel cell system, and, on the other, the technical availability of the system itself and of replenishment with fuel, which are deterrents for ship owners.

In the Netherlands in 1992, molten carbonate fuel cells (MCFC) were described as a solution to ships' propulsion systems for the next 20 years [1]. The proposed fuel is low-sulphur diesel.

In Iceland, within the scope of a joint venture, work is progressing on setting up hydrogen processing plants. In this connection, one of the possible aims is to convert the Icelandic fishing fleet to fuel cell operation [2].

In Germany in 1995, in the scope of a joint study with Messrs. Ballard, HDW investigated the use of fuel cells on merchant ships, together with suitable fuels. The results of this investigation showed that fuel cells are especially well-suited to certain applications:

- emergency power supply, e.g., passenger ships, ferries;
- electric energy generation, particularly for environmentally conscious use in harbours with heavy, contamination levels, e.g., container ships;

Table 3
Performance ranges for ships

Surface ships	Merchant ships/naval ships	Propulsion	5–50 MW
		Electrical supply	<10 MW
		Emergency power supply	0.1–1 MW
Sub-surface vessels	Submarines	Mono propulsion	2–5 MW
		Hybrid propulsion	200–400 kW

- electric energy generation/propulsion power for ships with special noise-reduction requirements, e.g., passenger ships, research vessels; and
- propulsion plant on ships with hydrogen or methane ''boil-off'', e.g., LH_2 tankers, LNG tankers.

The operation of pure hydrogen and air PEM fuel cells is, however, likely to be restricted to ships carrying hydrogen as cargo. This is because the low volumetric energy density requires very sizeable fuel tanks and because additional safety precautions are also necessary [3]. In Germany, the Association of Mussel Fishers decided in 1996 to aim to equip the mussel-fishing fleet with the most environmentally friendly propulsion possible. One possible solution is the use of fuel cells instead of conventional diesel generators [4]. Reports have been presented on two ships in Germany and Italy that are already equipped or being equipped with fuel cell systems [5]. In Germany, the excursion ship ''MS Weltfrieden'' is being fitted with a PEM fuel cell propulsion plant as a project for Expo 2000. The boat will have 10 kW power and fuel will be stored in two metal hydride storage facilities with a total capacity of 27 N m^3 hydrogen each. Safety engineering aspects and components are being developed in cooperation with German Lloyd.

In Italy, a boat was modified to take a hybrid propulsion system in 1998. The propulsion plant consists of a 40-kW fuel cell system, liquid H_2 storage and a 100-A h lead-acid battery. The hybrid system at maximum performance provides 100 kW to an asynchronous motor with a nominal performance of 120 kW. Range is about 300 km with a capacity for carrying 90 passengers. Acceptance tests were scheduled for the summer of 1998 on Lago Maggiore.

From the USA, Allen et al. [6] reported in 1998 on various fuel cell activities within the Navy, the US Coast Guard (USCG) and Maritime Administration (MARAD). A series of activities investigating the use of fuel cells for ships' networks and/or propulsion has been summarised by a Federal Interagency Working Group under the title, ''Fuel cell technology development for marine applications''. This working group is made up of representatives from both civilian and military offices, such as the USCG, MARAD, National Oceanic and Atmospheric Administration and Naval Sea Systems Command. In a similar way to developments for non-shipboard applications, the aim is to develop fuel cell systems for maritime use, concentrating on different specific requirements. As examples, the following investigations deserve brief mention.

- Selection of the diesel-electric USCG cutter ''Vindicator'' as a platform for installation of a fuel cell propulsion system. The idea is to exchange four diesel generators for a 2.5-MW MC fuel cell system of approximately the same size with internal reforming. The system is manufactured by Energy Research Corporation, which has already set up a demonstration power plant using the same direct fuel cell technology in Santa Clara, CA. The fuel used there is sulphur-free diesel (< 1 ppm) according to NATO standard specification F-76. The diesel fuel is converted into a methane-rich gas in an external reformer and then supplied directly to the MC fuel cell.
- In 1998, MARAD investigated the application of fuel cell propulsion for a feeder ship on the New York–Boston route. The ship is a diesel-electric 434 TEU container ship with a total power requirement of 5440 kW. Unlike the tests for the US Navy and the USCG, in this particular case, there is no need to fall back on diesel as the logistically most appropriate fuel. Due to the short distances involved and the good replenishment facilities, LNG is foreseen as fuel. In addition, the ship does not require integrated fuel tanks, because as a container ship, it has all the prerequisites for storing compressed natural gas (CNG) in containers. The fuel load in 8×40 ft containers is enough for a distance of some 560 nm. Further advantages for the ship are that CNG as fuel is about 30% cheaper than diesel, and that it frequently operates under partial load conditions of about 67% (including waste heat recovery) due to its deployment in coastal navigation. A disadvantage is the relatively short life expectancy of the MCFC, which is given as about 5 years of shipboard operation.

Results of investigations in Japan have also been published on the employment of 2×500 kW PEM fuel cells with methanol reformer for a 1500 DWT merchant ship and on the concept and design for a 499 GT coastal vessel with a PEM fuel cell propulsion plant. In the latter case, fuel savings of 5–10% and improved environmental compatibility were forecast.

3.2. Fuel cells on naval surface ships

In the field of naval surface ships, work and studies both in Europe and in the USA and Canada are mainly being concentrated on the AES. The AES concept stands for a ship with integrated electric energy production and a distribution system for propulsion, sensors, weapons and general ship's network. Unlike merchant ships, where integrated, full electric propulsion systems are not unusual, this kind of propulsion will not be seriously implemented on frigates and other larger naval ships until the next generation. While Europe and Canada mainly foresee PEMFC and optional diesel reformer systems as energy producers, work in the USA is concentrated on direct MCFC manufactured by the Energy Research Corporation.

In the Netherlands, Schmal et al. [7] carried out and reported on a number of studies on the topic of AES between 1992 and 1998. Using fuel cell systems, fuel savings of 25–30% are forecast in comparison with conventional gas turbine/diesel generator power. The advantages quoted in favour of the fuel cell are: good performance characteristics under partial load, low maintenance (no rotating parts), low noise and vibration (low acoustic signature transmitted under water), low exhaust gas temperature (low IR signature), low emissions, modular concept (decentralised equipment location).

In Great Britain, the Defence Evaluation and Research Agency is evaluating the use of PEM fuel cells for future ships of the Royal Navy [8]. Plans include providing electric power for the ship's network of about 1–2 MW from PEM fuel cells during harbour and anchored operations. PEM fuel cells were selected due to high power density, system simplicity and advanced state-of-the-art. In 1998, the British Ministry of Defence awarded Vosper Thornycroft a contract to build the research vessel ''RV Triton''. This is a trimaran, intended as technology demonstrator for future component developments in connection with the AES. The research vessel is due to be finished in the autumn of 2000. In addition to other developments, fuel cell systems can also be tested on-board this vessel.

In Germany, a number of feasibility studies have been carried out at the national and international level within the NATO Industrial Advisory Group (NIAG) and European Cooperation Long-Term in Defence (EUCLID) under the Western European Armaments Group [9].

In the USA, the Navy had a study performed in 1995 to evaluate the influence of fuel cell technologies (PEMFC, MCFC, PAFC, SOFC) for ship's network and propulsion systems on design and performance of future naval warships, such as destroyers and corvettes [10]. Positive results led in 1997 to the contracting of a three-phase program by the Office of Naval Research in cooperation with Naval Sea Systems Command. The aim of the program is to demonstrate that commercially developed fuel cell technologies can be operated in the naval sphere using naval fuels. Phase 1 incorporates the concept of a 2.5-MW energy production system, phase 2 the design and construction of a scale model 0.5-MW system for testing in a land-based test site. Phase 3 covers testing the system using diesel fuel (up to approximately 1% sulphur) under naval operating conditions [11].

4. Fuel cells and submarines

Status reports on PEM fuel cell development for submarines have been given at regular intervals for many years, also within the scope of the W. Grove FC Symposium [12]. After nearly 20 years of developmental work, HDW now has a fully operational AIP system for submarines on the basis of PEM fuel cells in series production.

4.1. Land-based test site and submarine Class 205 (U1)

When HDW decided early in the 1980s that the time has come to equip future submarines with AIP, this was on the basis of almost 10 years of intensive research work for the German MoD and the German Navy. The investigations clearly showed the enormous development potential of the fuel cell as a source of electric energy, in general, and especially of the PEM fuel cell, as compared with combustion engines in closed-cycle operation. The scope of these studies ranged from the use of the fuel cell for mono boats (i.e., the fuel cell is the sole source of propulsion power and electric network energy) and hybrid boats (i.e., submerged endurance of diesel-electric submarines is extended at the low signature speed range by fuel cell operation) to retrofitting existing submarines with a fuel cell system by way of a plug-in solution.

While Siemens began to develop a 34-kW PEM fuel cell module under contract for the German MoD, HDW developed the fuel cell system. This was based on a highly detailed concept incorporating stringent safety engineering aspects. High priority was given to safety right from the beginning, and still today, additional safety engineering factors continue to be added to system features.

In 1984, electric energy was produced for the first time from hydrogen and oxygen by a 100-kW fuel cell plant in the land-based test site at the HDW shipyard, using alkaline fuel cells as energy converters (the PEM fuel cells were still at the laboratory stage at the time). Metal hydride storage cylinders to store hydrogen and tanks for liquid oxygen had been developed for full functional testing (Fig. 1).

Integration of a plug-in fuel cell section on the German Navy's submarine U1 and subsequent operational testing for 9 months during 1988/1989 were concrete proofs and demonstration of the ability to retrofit an existing submarine with fuel cell technology. It was the first time in the world that an AIP system had been integrated into a commissioned submarine and piloted by the naval crew. The fact that U1 was retained on active duty in the German Navy after the fuel cell refit, was the main reason why the system, at the time not ready for series production, was removed from the submarine at the end of the 9-month test period under fully operational conditions. The tests were so successful and satisfactory that the German

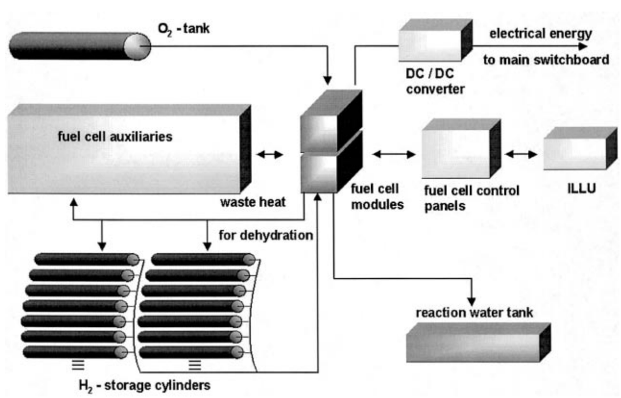

Fig. 1. Overview of fuel cell plant.

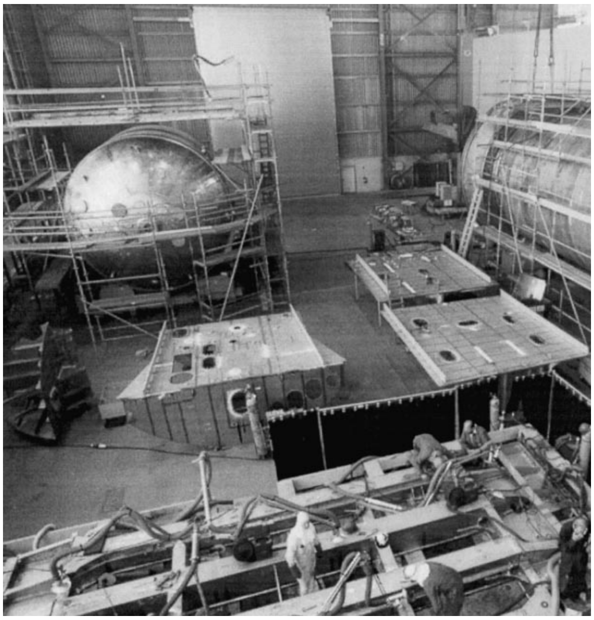

Fig. 2. AIP submarine under construction.

Navy decided to order the concept phase for the new Class 212 submarines.

4.2. Class 212 submarines

Starting in 1992, components for series production were developed.

· PEM fuel cells progressed from single cells with low cell area to a high-performance module with 34 kW nominal output. We know today that this module is quite capable of operating at maximum output between 30 and 50 kW.

· Hydrogen storage using metal hydrides is now fully submarine-tested and ready for cost-optimised series production.

· LOX tanks are also submarine-tested and available for series production.

Integration of the individual mature components into a submarine system that constitutes a fuel cell propulsion system capable of meeting all requirements of submarine operations was successfully demonstrated with the original components for the first Class 212 submarine. Production began on the Class 212 boats in the summer of 1998. Altogether, six submarines are being built, four for the German Navy at the shipyards of HDW in Kiel and TNSW in Emden (Fig. 2). Two identical boats are being built to HDW plans at the Fincantieri shipyard for the Italian Navy. The air-independent fuel cell propulsion system will be built by HDW and delivered to Italy as a complete system.

The fuel cell system consists of nine PEM fuel cell modules of the Siemens 30–50 kW type. Hydrogen is carried in metal hydride storage cylinders, oxygen in liquid form in tanks, both located outside the pressure hull.

4.3. Class 214 submarines

On the basis of the 34 kW module PEM fuel cell technology, which has been amply demonstrated as totally reliable in many thousands of operating hours, Siemens has meanwhile almost concluded the development of 120 kW fuel cell modules for equipping the second batch of Class 212 boats for the German Navy. These modules achieve four times the performance at roughly the same weight and dimensions. Two such modules together will make up the nucleus to a 240-kW standard fuel cell system for future submarines, whether as an integrative solution, e.g., for Class 214, or as a plug-in solution for retrofitting existing submarines, such as Class 209.

The Class 214 submarines combine the proven design and construction features of Class 209 (export submarines of German design and construction, originally with advanced diesel-electric propulsion) with the advantages of the Class 212 AIP fuel cell propulsion system. To ensure flexible adaptation of the fuel cell voltage to that of the lead acid battery, the submarines are equipped with a DC/DC converter. The hydrogen for fuel cell operation is carried in metal hydride storage facilities outside the pressure hull. Liquid oxygen is carried inside the pressure hull in a vacuum-insulated tank.

4.4. Submarine retrofitting

In this context, retrofit is understood to mean providing existing conventional submarines with an air-independent fuel cell propulsion system.

As successfully shown on submarine U1 in 1988/1989, modern submarines, such as those of Class 209, can be equipped with a mature fuel cell propulsion system to increase their submerged range. To this end, the submarine is sectioned aft of the bridge fin and lengthened by the addition of an extra section of about 6 m. The entire fuel cell system consisting of 2 × 120 kW fuel cell modules, a LOX tank inside the pressure hull, all necessary pipes and electric equipment such as switchboards and DC/DC converter is installed in this section and subjected to Factory Acceptance Test (FAT) at the shipyard. The hydride storage cylinders required to store the hydrogen are installed

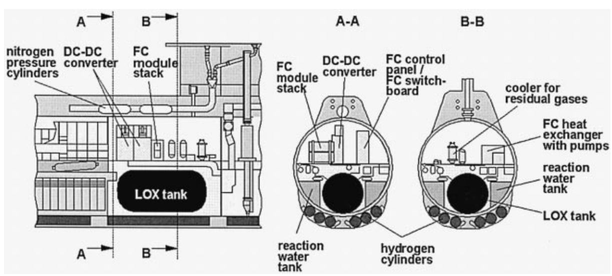

Fig. 3. General arrangement plan of FC for refit.

in the keel for reasons of trim and stability. Addition of the section to the submarine can take place during a regular refit or main overhaul at the shipyard. The entire refit period can be reduced to a minimum if the section is prefabricated and the entire fuel cell system subjected to full FAT before the submarine arrives at the yard for conversion (Fig. 3).

In principle, the installation of an AIP system is not restricted to the 240-kW PEM standard fuel cell system. The modular design of the individual components allows the entire AIP system to be adapted to meet the specific requirements of the navy concerned. Upgrading with a fuel cell system enables the submerged endurance of a Class 209 boat to be increased approximately by a factor of 5 as compared to battery–electric operation only (100–20% battery discharge). Subsequent refitting of submarines with an air-independent fuel cell system is, of course, not restricted to Class 209 submarines built by HDW, but can be undertaken on any submarine at the request of the customer.

5. Future perspectives

The submerged range and endurance of submarines equipped with air-independent fuel cell propulsion systems is essentially determined by the amount of energy carried on-board in the form of hydrogen and oxygen. Storage of oxygen in liquid form is the optimal solution. No more efficient storage method is known. In the case of hydrogen, in medium to long term, two alternative methods may become practicable:

- hydrogen storage in carbon-nanofibres (CNF); and
- storage of liquid hydrocarbons (e.g., methanol) and generation of the hydrogen required on-board.

In recent years, optimistic figures have been published with respect to hydrogen storage in CNF. This method of hydrogen storage would obviate the need for heavy and expensive metal hydride cylinders. Although research into this form of hydrogen storage is in progress all over the world, we are still waiting for a technical breakthrough. It has so far not been possible to clearly establish the kind of CNF or the storage mechanism. That means that today, we still do not have an efficient and reproducible storage method. In addition to this, such technical parameters as temperature, pressure and bonding energy have not yet been sufficiently researched. More comprehensive basic investigations will be necessary before hydrogen storage using CNF is ready for safe and reliable use on-board submarines. A development period in the region of 20–30 years seems likely.

Generation of hydrogen from liquid methanol on-board a submarine is technically less complicated. Methanol can be split into its component parts of hydrogen and carbon dioxide by steam reforming at about 300°C. HDW has begun developmental work on a reformer of this kind for the performance range of 240 kW fuel cell output. In the course of the current year, the first hydrogen will be produced in the land-based test site at the shipyard in Kiel (Fig. 4). A complete system ready for series production will be available within the next 10 years. This system will encompass not only hydrogen generation but also methanol storage on-board, gas purification and signature-free elimination of the CO_2 as well as functional integration into the fuel cell system.

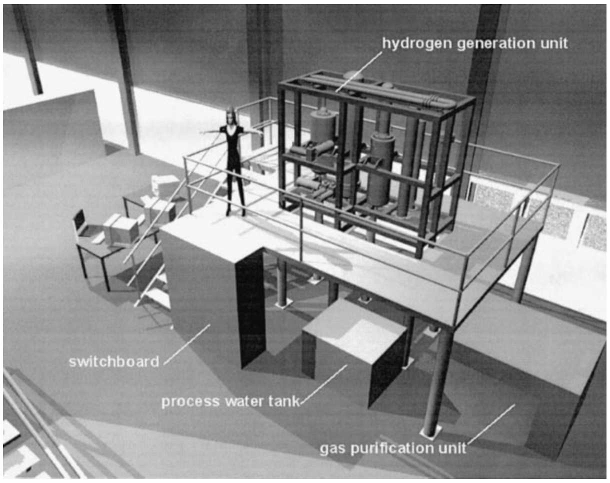

Fig. 4. Reformer test plant.

6. Summary

As in land use for decentralised power supply and in mobile application for buses and cars, fuel cells have also found their way into ships' propulsion systems. While the use of fuel cells in civilian and military surface ships is still at the investigation and demonstration stage, PEM fuel cells using hydrogen and oxygen have reached series maturity for submarines. In order to further increase the submerged range, the trend here is towards generating the hydrogen on-board from easy-to-store liquid hydrocarbons. As submarines are not subject to the same restrictions with respect to fuel choice, methanol is used as a relatively easy-to-reform alcohol.

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