By ing. R.P. Dingemanse

Alternative Power Sources for Submarines

The turn of the twentieth century marked a change in the development of submarines. Diesel electric propulsion would become the dominant power system. Batteries were used for running submerged and gasoline or diesel engines were used on the surface and during snorting to recharge the batteries. Early boats used gasoline, but quickly gave way to diesel, because of reduced flammability. Yet, over the years, other power sources have been investigated, and successfully applied.

The key aspect of any submarine is its stealth. Submarines operate quietly, submerged in hostile waters, mainly to gather information. Having to recharge the submarine's batteries is a huge disadvantage for these covert operations. Conventional submarines rely on snorting to charge their batteries while staying just below the surface. However, the air intake and diesel exhaust mast and periscope make them vulnerable to detection by radar or visually. Furthermore, running diesel engines is a noisy operation. A submarine's indiscretion rate is defined as the percentage of time a submarine spends snorting. This indiscretion rate depends strongly on the energy discharged from the batteries and the diesel generators' capacity to recharge the batteries. Typical snorting indiscretion rates are between five and twenty per cent.

First Air Independent Propulsion Source

In the 1930s, the German engineer Dr Hellmuth Walter proposed a completely new submarine propulsion plant, based on highly concentrated (up to 85 per cent) hydrogen peroxide (H_2O_2). Hydrogen peroxide can easily be decomposed into water and oxygen in an exothermic reaction. By using hydrogen peroxide, no air based oxygen was required and the first air independent propulsion (AIP) for submarines was demonstrated. Dr Walter used this same technology for jet and rocket engines. In 1940, the first experimental, 76 tonnes, 22-metre-submarine, the V 80, was secretly tested at the Friedrich Krupp Germaniawerft in Kiel.

Highly concentrated hydrogen peroxide is very unstable. When the "Walter technology" was used in the 1950s, some serious accidents happened and the technology was abandoned for submarine use.

When looking at ways to increase submerged endurance, important aspects are reducing power demand when submerged (propulsion and auxiliary loads), enlarging the battery capacity, and generating power without the need for outside air.

Any fuel required to generate power will take up space for storage and conversion, and will contribute to the weight of the boat. When investigating alternative power generation plants, fuel properties are important. A way to compare various fuels is to look at energy density per weight and per volume, refer to the table below.

Nuclear Power

The enormous energy density of uranium makes it a very good candidate for air independent power generation. The US Admiral H.G. Rickover recognised the potential and strongly promoted nuclear powered submarines and surface ships. In 1955, the first US nuclear submarine Nautilus (SSN 571) started its sea trials. Nuclear power was also introduced to commercial shipping. In 1962, the US NS Savannah was completed and served primarily as a technology

Fuel	Chemistry	kg/dm³	MJ/kg	MJ/dm³	kWh/kg	kWh/dm³
Uranium	U^{235}	19.0	83,140,000	1,575,503,000	23,094,444	437,639,722
Hydrogen (liquid/700 bar)	H_2	0.071	142.0	10.1	39.4	2.8
Gasoline (petrol)	$\sim C_8H_{18}$	0.716	46.4	33.2	12.9	9.2
Diesel F-76	$\sim C_{12}H_{24}$	0.844	42.7	36.0	11.9	10.0
Ethanol	C_2H_6OH	0.784	29.7	23.3	8.3	6.5
Methanol	CH_3OH	0.787	22.7	17.9	6.3	5.0

Specific densities of some fuels.

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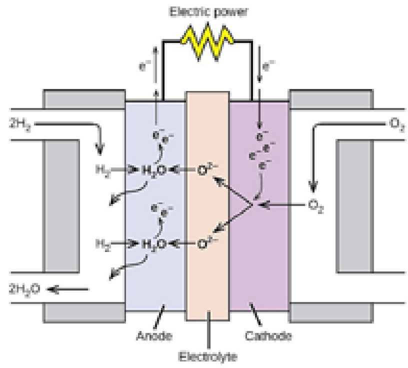
A closed-cycle Stirling system (picture by Saab Kockums).



The workings of a fuel cell.

demonstrator. Around the same time, in Germany the NS Otto Hahn was built as a cargo ship and research facility by Howaldtswerke-Deutsche Werft (HDW). Yet, civilian nuclear ships suffer from the costs of specialised infrastructure, and so far, none are in operation. Recently, the US based company Gen4 Energy started developing a 70 MWt nuclear power module that could power a 155,000 DWT Suezmax tanker. Classification societies need to rewrite their rules to ensure that it is the operator of the nuclear plant that demonstrates safety in operation, in addition to safety through design and construction. In 2014, Lloyd's Register published two papers on marine nuclear propulsion. It was concluded that the concept is feasible, but further maturity of nuclear technology and the development and harmonisation of the regulatory framework would be necessary before the concept would be viable.

Non-nuclear Power Sources

Major naval powers like the United States, United Kingdom, France and Russia turned to the use of nuclear power as the AIP solution for submarines. The growing demand for longer submerged endurance and range has put other AIP technologies on the agenda. Current AIP solutions are:

- A closed-cycle Diesel system (CCD) with liquid oxygen storage (LOX) (Russia 1956); a CCD system was developed by Thyssen Nordseewerke in 1993, and by the RDM in the Netherlands in 1990-1992 for the Moray class submarines.
- A closed-cycle Stirling system (CCS) (SAAB, Sweden 1980).
- A closed-cycle steam turbine, MESMA (Naval Group, France 2001).
- hydrogen oxygen PEM Fuel Cell (PEM FC);
  - with ethanol reformer;
  - with methanol reformer;
  - with metal hydride hydrogen storage (Siemens, Germany 2005);
  - with compressed hydrogen storage.

Closed-cycle Diesel System

A CCD system incorporates a standard diesel engine that can be operated in its conventional mode on the surface or while snorting. Submerged it runs on artificial "air" synthesised from stored oxygen, argon, and recycled exhaust products. The engine's exhaust gasses – largely carbon dioxide, nitrogen, and water vapour – are cooled and scrubbed to extract any remaining oxygen and argon. The remaining exhaust gas is mixed with seawater and discharged overboard. The required oxygen is stored as LOX in cryogenic tanks. The first CCD system was developed in Russia by S.A. Basilevkiy, and was used on the experimental submarine M-401 (1940). After World War II, the Russian Quebec class submarines had a CCD system of 670 kW (1952).

Closed-cycle Stirling System

In a Stirling engine, heat from an outside source is transferred to an enclosed quantity of inert gas through a repeating sequence of thermodynamic changes. By expanding the gas against a piston and then drawing it into a separate cooling chamber for subsequent compression, the heat from external combustion can be converted to mechanical work to drive a generator. The name Stirling refers to the Scottish brothers Robert and James Stirling who patented the concept in 1816 and an improved concept 1827.
In the 1980s, Saab Kockums developed a 75 kW CCS module for the Swedish Gotland class submarines that operates at 20 bar on diesel fuel and LOX. Today, the Saab 75 kW CCS modules are "commercially available" and are used on Japan's newest Soryu class submarines.

Closed-cycle Steam Turbine

The closed-cycle steam turbine, developed by Naval Group in France, also known as *Module d'Energie Sous-Marin Autonome* (MESMA), uses ethanol and LOX to generate steam for a 200 kW turbine driven generator. The steam generation process operates at 60 bar, so the combustion products can easily be expelled when submerged. The MESMA has been used in Pakistan's Agosta 90B submarines since 2001.

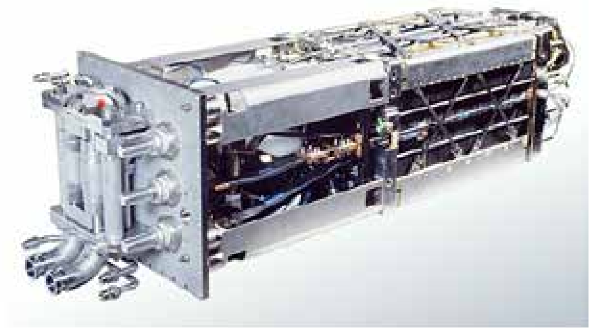
Fuel Cells

Fuel cells are able to convert hydrogen gas and oxygen directly into electric power without any moving parts. For submarine application, Polymer Electrolyte Membrane (PEM) fuel cells are attractive be-

cause of their low (80°C) operating temperature. A single fuel cell generates approximately 0.75 Volts DC. As with batteries, by stacking cells and arranging stacks in parallel, almost any voltage or current can be made available.
The greatest challenge for any fuel cell system is the storage of hydrogen. For its U212 class submarines, Germany developed 34 kW PEM fuel cell modules, using metal hydride to store hydrogen and LOX in containers outside the pressure hull. Hydrogen powered cars use composite high pressure hydrogen storage tanks at 700 bar. New research is looking into the use of nanofibres for hydrogen storage.
Another alternative to hydrogen storage is the use of hydrocarbons such as diesel fuel and methanol. These fuels can be broken down into hydrogen and carbon dioxide in a high pressure "reformer" using super-heated steam.

Fuel Cell-based AIP Using Nanofibres Shows Promise

In ship design, and in submarine design in particular, volume (V) and weight (W) are important aspects. The table below compares some AIP system options based on a 600 kW, 12.6 MWh power generation requirement. A fuel cell-based AIP system using nanofibres promises to become a great alternative. In the meantime, the Stirling engine and other fuel cell based solutions provide viable AIP solutions.



Fuel cell as designed by Siemens (picture by Siemens).

System for 600 kW, 12.6 MWh	LOX		Fuel		Generation		Total	
	V [m³]	W [T]	V [m³]	W [T]	V [m³]	W [T]	V [m³]	W [T]
Fuel cell and carbon nanofibres	6.4	8.2	6.0	4.2	0.9	0.5	13.	12.9
Fuel cell and metal hydride	6.4	8.2	12.2	52.4	0.9	0.5	19.5	61.1
Methanol reformer and fuel cell	9.3	12.2	6.8	5.9	7.1	13.8	23.2	31.9
Closed-cycle diesel/Stirling	11.3	14.5	5.4	4.4	18.8	15.0	35.5	33.9
Li-ion ($LiNiMnCoO_2$) battery	-	-	90	106	-	-	90	106
Submarine lead-acid battery	-	-	100	296	-	-	100	296

Some AIP options compared.