

# The use of fuel cells to enhance the underwater performance of conventional diesel electric submarines

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## Abstract

Air Independent Propulsion (AIP) systems have the potential to improve the underwater performance of conventional diesel electric submarines and to reduce their vulnerability. Many different types of AIP systems are being considered, either for integration into new submarines or for retrofitting to existing submarines by the insertion of an additional section or 'plug'. Based on a generic submarine, this paper presents conceptual designs for fuel cell-based AIP plugs that could be retrofitted to an ocean-going conventional submarine of about 3 000 t displacement. The designs are based on solid polymer electrolyte fuel cells that use hydrogen and oxygen as reactants to produce a nominal 100 MWh of electrical energy. Three hydrogen storage methods are considered: metal hydrides; liquid hydrogen, or hydrogen generated from the reforming of methanol. The metal hydride method is mass limited and requires a longer plug than the other two options. The liquid hydrogen and methanol reforming methods are both volume limited and the plug displacement is much greater than the system mass. To maintain neutral buoyancy, considerable ballast has to be added to the plug, or elsewhere in the submarine. Equipped with a 600 kW fuel cell, the generic submarine's maximum speed on fuel cell alone is about 8 knots. The submarine is much harder to detect, because, at speeds below 8 knots, it does not need to snorkel. With a nominal 100 MWh of electrical energy, the submarine's maximum underwater range is increased by a factor of almost five compared with the range of a single battery charge. The maximum endurance is about 14 days. At speeds greater than the maximum possible with the fuel cell only, the range and endurance of the submarine is increased considerably when the fuel cell and battery are used together.

## Introduction

There is worldwide interest in Air Independent Propulsion (AIP) systems because they promise to improve markedly the underwater performance of conventional diesel electric submarines and to reduce their vulnerability [1–6]. A conventional submarine is much easier to detect either when surfaced or when snorkelling to recharge its batteries. A submarine equipped with an AIP system could greatly reduce its 'indiscretion time' by patrolling underwater for extended periods, without the need to snorkel for battery charging. The Australian Defence Science and Technology Organisation (DSTO) is assessing two AIP options for submarines—fuel cells and the Stirling engine. Other AIP options include closed-cycle diesel engines, gas turbines, and small nuclear power plants [1].

Most designs for retrofitting AIP systems to existing submarines envisage cutting the submarine and inserting a plug that contains the AIP unit and reactants. They

are called hybrid AIP systems because the conventional diesel generators and batteries are retained. Sweden is currently building submarines with a Stirling engine integrated into the initial design. Germany has also designed a hybrid submarine using fuel cells for the AIP unit. Later generations of submarines may be solely fuel cell powered.

Based on the performance of a generic submarine, this paper presents conceptual designs for fuel cell-based AIP plugs that could be incorporated into an ocean-going conventional submarine of about 3 000 t displacement. The designs are based on solid polymer electrolyte fuel cells that use hydrogen and oxygen as reactants. Liquid oxygen (LOX) is the most efficient method of storing the large quantities of oxygen required for AIP systems [1]. For the hydrogen supply, three options are considered: hydrogen stored in metal hydrides; liquid hydrogen (LH<sub>2</sub>), or hydrogen generated from the reforming of methanol. A discussion is presented on how these three hydrogen storage options influence the design of the plug that is required for a given fuel cell power and AIP endurance. Calculations are also given that indicate how submarine underwater range, endurance and indiscretion time depend on submarine speed and fuel cell power.

## Submarine requirements

### *Power and endurance*

The power required to drive a submerged submarine comprises two parts: the main propulsive power and the 'hotel' power that drives the auxiliary systems. Both these terms will increase with the addition of an AIP plug. A reasonable estimate of the power,  $P$  (kW), required to drive a generic submarine can be made by using the following expression:

$$P = [(D/22) + 25] + 0.075P_m + 0.0026D^{2/3}V^3 \quad (1)$$

where  $D$  is the submerged displacement of the submarine (t),  $V$  the submarine velocity (knots), and  $P_m$  the maximum power of the fuel cell (kW).

The first term estimates the normal hotel load of the submarine [2, 7], the second term estimates the additional hotel load due to the fuel cell [3], and the third term estimates the propulsive load [2]. The displacement of the standard submarine is taken to be 3300 t [8]. In Fig. 1, the required power has been plotted as a function of submarine speed and AIP plug length for plug lengths from 10 to 20 m. The AIP plug increases the submarine's hotel load by between 45 and 65 kW and decreases the submarine's top speed by up to one knot, because of the increased drag of the additional displacement. It is expected that the larger submarine will be less manoeuvrable unless the size of its control surfaces is increased.

Typically, a submarine patrols at a speed of about 4 to 6 knots, because these speeds give good manoeuvrability and near-maximum underwater range. In Fig. 2, the total electrical energy requirements have been plotted as a function of submarine speed (up to 8 knots) for endurances from 10 to 20 days. It is assumed that greater endurance will require a larger AIP plug. Consequently, the plug length is assumed to increase linearly from 10 to 20 m as the endurance increases from 10 to 20 days. To have a useful endurance at typical patrol speeds, the AIP system requires sufficient reactants to produce between about 50 and 150 MWh of electrical energy.

### *Fuel cell power*

The speed at which the maximum AIP power is equal to the submarine power requirements is called the 'balance speed' [2]. At speeds above the balance speed,

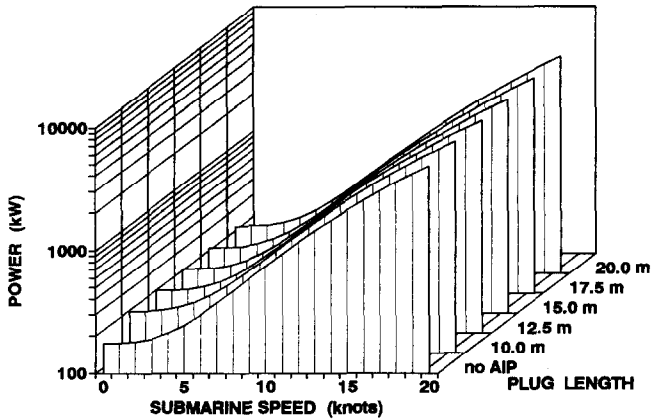


Fig. 1. Required power as a function of submarine speed and AIP plug length.

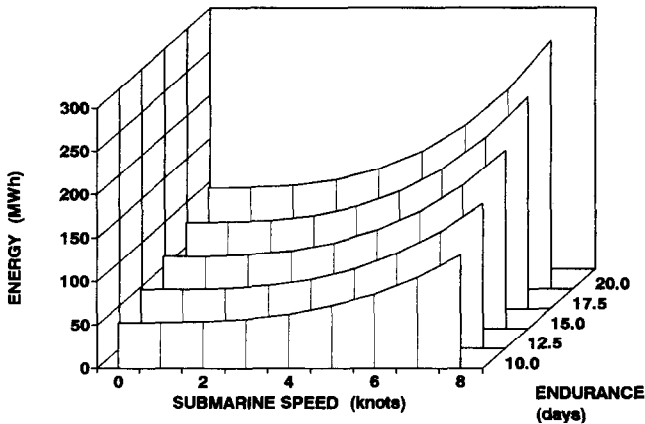


Fig. 2. Total electrical energy required as a function of submarine speed and endurance.

additional power will be drawn from the submarine's batteries, while below the balance speed, power will be taken exclusively from the AIP system. To be useful, an AIP system must produce sufficient power to drive the submarine at 4 knots or more.

If long endurance is required, there are several reasons why it is better to install a more powerful fuel cell system than that is necessary to meet the power required at patrol speeds. First, the submarine will have a higher balance speed and can travel faster without having to use its batteries. Second, it may reduce the total mass of the components. Fuel cells are more efficient when lightly loaded. A more powerful fuel cell system will weigh more, but will use fewer reactants when operating at less than maximum load. Over long periods, the increased mass of the fuel cell system may be more than compensated for by the reduction in the mass of the reactants required. Third, it will give greater system reliability. If the fuel cells are built in modules, faulty modules can be replaced at sea.

Siemens are developing a fuel cell module that uses a solid polymer electrolyte (SPE) and has a power output of about 30 kW [9]. Ten of these modules, connected

in series, will give a power output of 300 kW with a voltage of about 475 V, which is compatible with submarine requirements. Two banks of modules connected in parallel would give a maximum power output of 600 kW. The AIP plug designs discussed later (Figs. 6 to 8) are based on this configuration. A submarine with a 600 kW fuel cell might normally patrol at about 4 knots, but speeds up to about 8 knots would be possible without using the batteries.

*Fuel cell reactant consumption*

The overall fuel cell reaction is described by the equation:



Faraday's law is used to calculate the hydrogen consumption of the fuel cell. For every gram-atom of hydrogen consumed, 96 500 C of charge are generated. The work done per gram-atom consumed is 96 500  $E$  (J), where  $E$  is the cell voltage. As 1 kWh = 3.6 MJ, the work performed per kg of hydrogen consumed is 96.5 $E$ /3.6 kWh. When allowance is made for the stoichiometric factor,  $S$ , the hydrogen consumption rate,  $\dot{H}$ , is given by:

$$\dot{H} = 3.6S/96.5E = 3.73 \times 10^{-2}S/E \text{ kg (kWh)}^{-1} \quad (3)$$

The stoichiometric factor is the ratio of the supply rate of a reactant to its consumption rate. The oxygen consumption rate,  $\dot{O}$ , is eight times the hydrogen consumption rate, so that:

$$\dot{O} = 0.298S/E \text{ kg (kWh)}^{-1} \quad (4)$$

In the reactant calculations, it is assumed that  $S=1$  and  $E=0.7$  V, independent of load. Actually, the cell voltage is a function of the load and the operating point for a SPE fuel cell lies typically in the range  $\sim 0.9$  to 0.5 V.

**AIP plug design**

*Reactant storage: metal hydrides*

Metal hydrides reversibly absorb and desorb hydrogen with some hysteresis. For hydrogen storage applications, the hydrides are packaged in pressure vessels with heat exchangers. FeTiH<sub>2</sub> holds up to 1.9 wt.% H<sub>2</sub> [10], but the alloy must be cooled while absorbing the hydrogen under pressure (35 bar at 17 °C [11]). Conversely, heat must be applied to desorb the hydrogen. For FeTiH<sub>2</sub> at 40 °C, the desorption hydrogen pressure is 7 bar, which is sufficient to operate the fuel cell. The waste heat from the fuel cell is sufficient to heat the hydride. FeTiH<sub>2</sub> has been successfully used in the fuel cell powered German Type 205 submarine 'U1' [4, 12].

The Ti-V-Mn alloy developed by Töpler and Feucht at Daimler Benz [13] has a hydrogen capacity of 1.8 wt.%. Because of its absorption/desorption isotherms and heat requirements, this alloy is also suitable for the use with low-temperature fuel cells. Other hydrides, such as Mg<sub>2</sub>NiH<sub>4</sub>, have higher hydrogen concentrations (3.8 wt.%), but also have higher desorption temperatures (300 °C) that are not compatible with low-temperature SPE fuel cells.

*Reactant storage: liquid hydrogen and liquid oxygen*

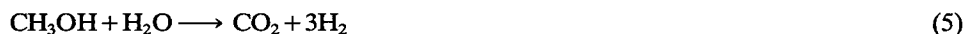
Liquid hydrogen (boiling point: -253 °C) and liquid oxygen (boiling point: -183 °C) are stored in cryogenic tanks. The tanks are designed to limit evaporative losses

to a particular rate, typically 0.25% per day. Typical construction is a stainless-steel tank, insulated with high-vacuum multilayer insulation and suspended in an evacuated, outer, mild-steel pressure vessel. A heat exchanger is required to evaporate the liquid for supply of gas to the fuel cell. The heat exchanger can be driven by the cooling water from the fuel cell.

The use of LOX for AIP applications has been demonstrated in the Stirling engine equipped Swedish submarine 'Näcken' [6], as well as in the fuel cell equipped German 'U1' [4, 12].

#### *Reactant storage: methanol*

Methanol can be easily steam reformed over a catalyst (at about 250 °C) to produce hydrogen. The overall reaction is:



The heat to drive the reaction can be supplied by burning methanol in an atmosphere replenished with oxygen from LOX. Alternatively, if excess hydrogen is fed to the fuel cell ( $S > 1$ ), the unused gas can be burnt to heat the reformer.

The mass of product water from the fuel cell will exceed the mass of water required in the steam reforming. Reformer efficiency is typically about 80%. A considerable effort is being made to decrease the mass and volume of reformers for use in methanol-fuelled, hybrid fuel cell/battery vehicles and submarines [5, 14–17].

Small amounts of CO produced in the reforming process must be removed from the reformat (e.g., by catalytic oxidation to CO<sub>2</sub>) to prevent poisoning of the platinum catalyst in the fuel cell electrodes. CO<sub>2</sub> does not poison the electrodes, but does reduce the efficiency of the fuel cell compared with the performance on pure hydrogen. Depending on the energy cost, it may pay to substantially remove CO<sub>2</sub> from the reformat gas (by membrane separation techniques) before feeding it to the fuel cell.

The chief requirement is to match the response of the reformer to the varying hydrogen demand of the load-following fuel cell. For both metal hydrides and reformed methanol, it is practical in a submarine to use a storage buffer of compressed hydrogen to accommodate transient changes in the fuel cell load.

#### *Mass and volume balance*

In the design of the plug, two main conditions have to be satisfied. The total mass of the system has to be less than the net buoyancy of the plug. Also, the total volume of the components has to be considerably less than the volume of the plug, so that the AIP system can be accommodated. The aim is for the plug to be neutrally buoyant, otherwise the mass distribution in the rest of the submarine will need to be modified. In Fig. 3, the net buoyancy has been plotted as a function of plug length, based on a pressure hull diameter of 7.8 m [8]. In calculating the net buoyancy, reasonable allowance was made for the mass of the hull, hull stiffeners, decking, bulkheads and water ballast.

Table 1 shows the masses of reactants and products for both hydride and LH<sub>2</sub> storage (H<sub>2</sub>/O<sub>2</sub> in column 1) and methanol storage (CH<sub>3</sub>OH/O<sub>2</sub> in column 1) for a fuel cell output of 100 MWh. The total mass of reactants for methanol storage is 105 t compared with about 48 t for the other two options. In the methanol case, about 58 t of CO<sub>2</sub> is produced. The mass of methanol consumed includes that required to heat the reformer. The burner efficiency is conservatively assumed to be 30%. With current technology, higher efficiencies are achievable and will, therefore, reduce the methanol consumption rate.

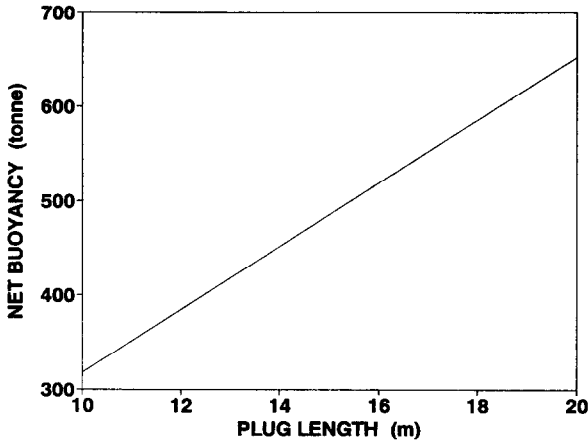


Fig. 3. Net buoyancy of AIP plug (unloaded) as a function of plug length.

TABLE 1

Masses of reactants and products for different hydrogen storage options to give 100 MWh of electrical energy

Fuel/ oxidant	Mass of reactants			Mass of products	
	H <sub>2</sub> (t)	O <sub>2</sub> (t)	CH <sub>3</sub> OH (t)	H <sub>2</sub> O (t)	CO <sub>2</sub> (t)
H <sub>2</sub> /O <sub>2</sub>	5.4	43		48.4	
CH <sub>3</sub> OH/O <sub>2</sub>		63	42	47.2	57.8

In Figs. 4 and 5, the masses and volumes of reactants, storage tanks, the fuel cell and auxiliary systems are compared for the three different methods of hydrogen storage. The common oxidant is LOX and the energy output of the fuel cell is 100 MWh. The net buoyancy and volume of three different plug lengths are also shown.

The masses and volumes of the fuel and oxidant storage containers have been calculated by using the gravimetric and volumetric fractions given in Table 2. Storage efficiencies are based on commercial cryogenic tanks of similar capacity with 'super insulation' and designed to give evaporative losses of about 0.25% per day. The commercial literature indicates that typical storage pressures are about 1600 kPa. The analysis is very sensitive to the form of insulation that is chosen. The use of Perlite insulation will lead to much greater masses and volumes for cryogenic reactant storage. Literature information has been used to formulate estimates for the hydride heat exchangers [10], methanol reformer [14, 15] and SPE fuel cell [9]. Reasonable estimates are made for the masses and volumes of auxiliary plant such as electrical power conditioners, heat exchangers, pumps, pipework and ballast and product water tanks. Note that in Fig. 5, for the FeTiH<sub>2</sub> case 'fuel' denotes the volume of the metal hydride.

Table 3 lists the mass and volume of the various components, including product water tanks and ballast tanks. The mass of product water is not listed as it merely balances the mass of reactants consumed. For the methanol case, as CO<sub>2</sub> is expelled

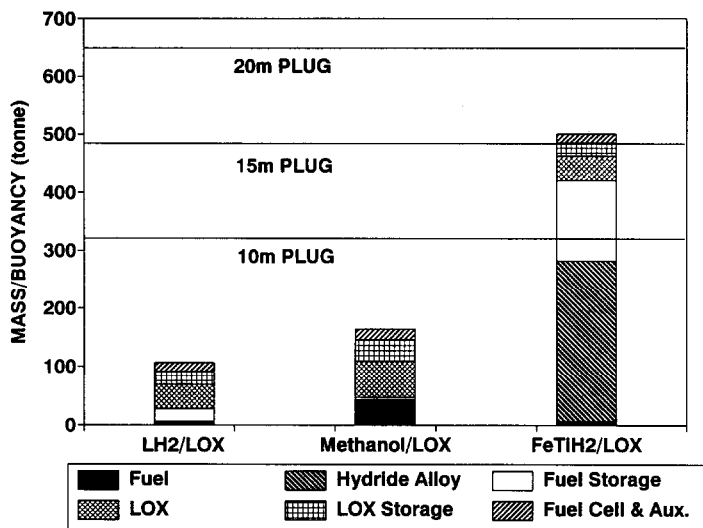


Fig. 4. Masses of reactants, reactant storage and other components for three different hydrogen-storage methods for fuel cell with 100 MWh energy output.

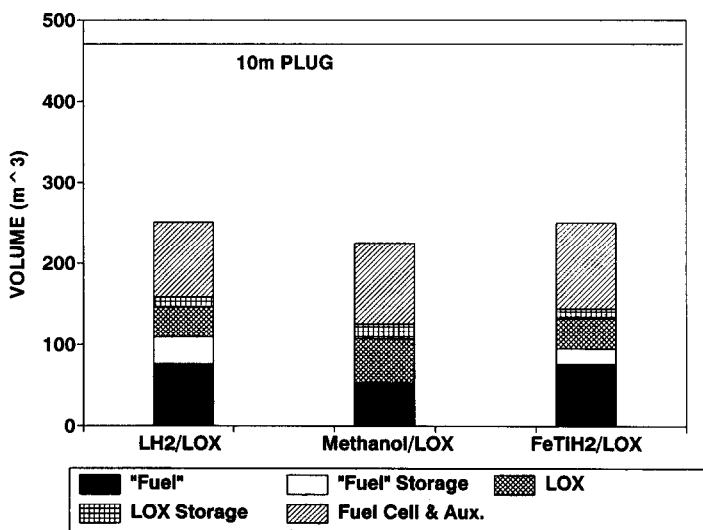


Fig. 5. Volumes of reactants, reactant storage and other components for three different hydrogen-storage methods for fuel cell with 100 MWh energy output.

from the submarine, it is assumed that an equal mass of sea water will be taken on board. Ballast water is not listed as it has been accounted for in calculating the net buoyancy of the plug (Fig. 3). The volumes of the product water and ballast water tanks have been listed in Table 3, but are not included in Fig. 5. If these volumes are included, the volumes shown in Fig. 5 will increase by about 90 m<sup>3</sup> for the hydride case, and by about 75 m<sup>3</sup> for the other two storage methods.

TABLE 2

Gravimetric and volumetric fractions for hydrogen and oxygen storage

Compound	Gravimetric fraction	Volumetric fraction
Liquid oxygen (LOX)	0.65	0.75
Liquid hydrogen (LH <sub>2</sub> )	0.20	0.70
Methanol	0.90	0.99
Hydride alloy	0.67	0.80

TABLE 3

Mass and volume of components in fuel cell plug

Component	Mass (t)			Volume (m <sup>3</sup> )		
	Hydrogen storage method			Hydrogen storage method		
	Hydride	Liquid hydrogen	Methanol	Hydride	Liquid hydrogen	Methanol
Fuel	5	5	42	76	77	53
Fuel storage	417	22	5	19	33	1
Oxidant	43	43	63	38	38	55
Oxidant storage	23	23	34	13	13	19
Fuel cell and auxiliaries	15	15	18	17	17	24
Product water tanks	1	1	1	50	50	50
Ballast tanks	a	a	a	39	26	26
Total	504	109	163	252	254	228

<sup>a</sup>Mass of ballast tanks taken account of in calculating net buoyancy of plug.

It is important to note that the mass of reactants and storage is far greater than the mass of the fuel cell and auxiliary systems, especially for the hydride system. Total system masses are estimated to be about 110 t for LH<sub>2</sub> storage, 165 t for methanol storage, and 505 t for hydride storage. Also, the volume of the reactants and storage is larger than the volume of the fuel cell and auxiliary systems. Total volumes are estimated to be about 250 m<sup>3</sup> for LH<sub>2</sub> storage, 230 m<sup>3</sup> for methanol storage, and 250 m<sup>3</sup> for hydride storage.

Figure 4 shows the net buoyancy of 10, 15 and 20 m long plugs. Figure 5 shows the total volume of a 10 m plug. Clearly the hydride storage approach is mass limited, while the methanol and LH<sub>2</sub> storage options are volume limited, especially in the last case because of the low density of the LH<sub>2</sub> (0.07 t m<sup>-3</sup>). The plug displacement would be much greater than the system mass. For the metal hydrides, a plug about 15 m long has a buoyancy equal to the total mass of the system. The volume of the system is about one-third that of the plug. Thus, the components should fit easily in a 15 m plug.



For  $\text{LH}_2$  storage, it is not likely that all the components could fit into a plug of less than about 10 m long. The net buoyancy of the plug would be about 320 t, while the system mass is only about 110 t. To keep the plug neutrally buoyant would require the addition of about 210 t of lead ballast, or if there was sufficient volume available, extra batteries could be added. Alternatively, the equivalent mass could be added elsewhere in the submarine, but would involve a redesign of the submarine. The volume/mass imbalance is less for methanol storage, but to maintain neutral buoyancy for a 10 m plug, the addition of about 155 t of lead ballast, or other mass, will be required.

#### *AIP plug with hydride storage*

The proposed layout of the 15 m plug with hydride storage is shown in Fig. 6. The LOX is stored in a conventional cylindrical tank with high-vacuum, multilayer insulation. The metal hydrides are stored in 15 cylinders, each 14 m in length and 0.8 m in diameter. The hydride cylinders are shown mounted within an outer tank that is designed to contain the water produced by the fuel cell. The area above the upper deck is used to mount the fuel cell and other auxiliary systems. These components are not shown in detail.

This AIP plug adds 15 m to the length of the submarine. Thus, it must be determined if the hydrodynamics of the submarine are still satisfactory, given that both the drag and the turning circle will be increased. In the 'U1', the hydrides were stored outside the pressure hull. This option further increases the drag, but not by a large factor because the high-density hydrides occupy a relatively small volume.

#### *AIP plug with liquid hydrogen storage*

The proposed layout of the plug with  $\text{LH}_2$  storage is shown in Fig. 7. This design is based on using toroidal cryogenic tanks for both  $\text{LH}_2$  and LOX, as this maximizes the storage volume per unit length of plug, given that there has to be a passage way through the plug. Toroidal tanks are more difficult and expensive to make. If cylindrical tanks are used, then the plug length has to be much greater and the amount of ballast correspondingly greater.

It is proposed that the  $\text{LH}_2$  tank be located inside the product water tank, like a tube in a tyre. In this design, the plug has two decks. The fuel cell system is mounted on the lower deck, while the auxiliary systems are situated on the upper deck. Lead ballast and the ballast water tanks are located beneath the lower deck.

#### *AIP plug with methanol reforming*

The proposed layout of the plug using methanol reforming is shown in Fig. 8. To minimize the plug length, each reactant tank is located inside another tank. The

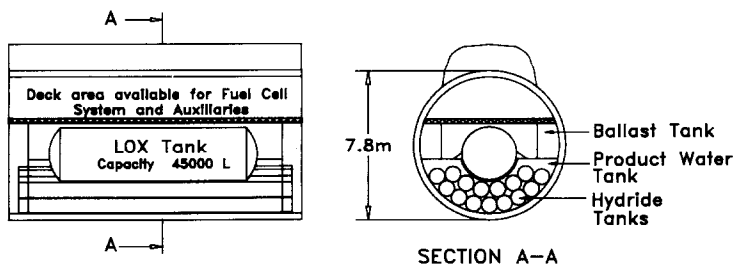


Fig. 6. Sections of AIP plug with metal hydride storage.

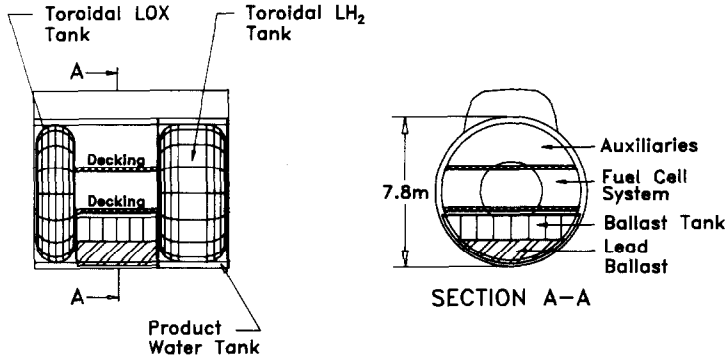


Fig. 7. Sections of AIP plug with liquid hydrogen storage.

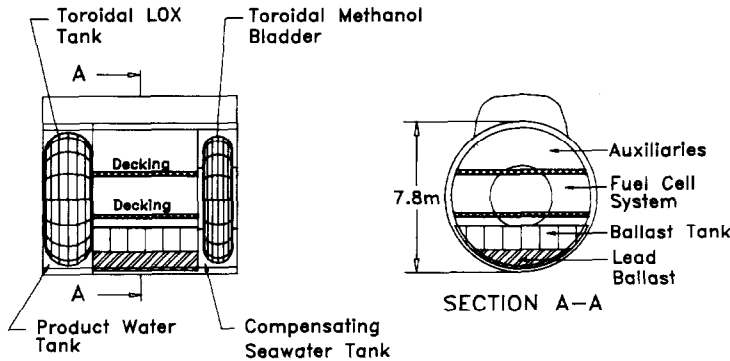


Fig. 8. Sections of AIP plug with a methanol reformer.

LOX is shown stored in a toroidal cryogenic tank that is surrounded by the product-water tank. Methanol is stored in a toroidal bladder inside the compensating seawater tank.

CO<sub>2</sub> is produced during the methanol reforming, i.e., about 58 t for 100 MWh of reactants (Table 1). The CO<sub>2</sub> could be pumped overboard by dissolving in sea water, using a pressure-balanced water-management system [18]. If the reformers are operated at high pressure, depth-independent discharge of CO<sub>2</sub> can be accomplished without a separate compressor. An equal mass of sea water must be admitted to the compensating tanks to maintain the mass balance of the submarine.

#### *Reactant safety and logistics*

Reactant safety is an important issue for all forms of AIP. LOX is routinely safely stored in industry. External and internal LOX storage systems have been developed for submarines by the German and Swedish Navies, respectively. The ability of a cryogenic vessel to withstand shock loads has been demonstrated from tests performed on an external LOX storage vessel [19].

Hydrogen has a lower flammability limit in air of only 4 vol.% (lower explosive limit is 18 vol.%) and, hence, significant hydrogen leaks must be prevented. With a low molecular-weight gas such as hydrogen, leaks are harder to prevent. Catalytic

converters can be used, however, to scavenge small amounts of hydrogen, as is currently done with hydrogen generated in lead/acid batteries.

Metal hydrides are safer than high-pressure, hydrogen gas tanks. A ruptured metal hydride tank will self cool and limit the rate of hydrogen escape. The German Navy favours the storage of metal hydrides outside the pressure hull, with a minimum of internal pipework. As an additional safety measure, double piping is used with nitrogen between the two pipes to prevent hydrogen leaks forming an explosive mixture. Similarly, each fuel cell module is enclosed in a nitrogen-filled container [3, 4].

LH<sub>2</sub> presents a greater safety hazard. Cryostats must be shock resistant and must minimize temperature gradients to avoid problems such as 'roll over'. Normal evaporative 'boil-off' of LOX and LH<sub>2</sub> can be utilized by periodically operating the fuel cell and using the electrical power produced. The use of super insulation and high-pressure tanks, however, minimizes the need to vent.

Methanol, while toxic and flammable, is routinely and safely handled in industry. A fast-response reformer would minimize the storage buffer of hydrogen required within the submarine.

Compressed hydrogen (for metal hydrides), methanol and LOX are readily transported and are available throughout Australia. By contrast, there is currently no production of LH<sub>2</sub>. Only replenishment of methanol and LOX are feasible at sea, since recharging metal hydrides may take up to 10 h.

### **Submarine performance with AIP**

The maximum battery endurance of the submarine is equated to the estimated performance of a modern ocean-going diesel submarine, namely, 120 h at 4 knots and 1.6 h at 21 knots [20]. From the estimates of the submarine power requirements in Fig. 1, the effective battery capacity is calculated to be about 25 MWh at 4 knots and 8.6 MWh at 21 knots. With only this limited information available, the battery capacity is assumed to vary linearly with load.

#### *Underwater range*

The underwater range as a function of speed is estimated for the submarine operating solely on its battery and then using both a fuel cell and the battery. In the calculations, the submarine displacement is increased by the displacement of a 15 m AIP plug.

Figure 9 shows that, on battery alone, the maximum range of this larger submarine is about 420 nautical miles at 5.8 knots. If a 600 kW fuel cell produces 100 MWh of electrical energy, then the maximum range on fuel cell and battery would be about 1950 nautical miles at 5.8 knots. At this speed, the maximum underwater range would be increased by a factor of about 4.7 compared with using the battery alone.

Below the balance speed, it was assumed that the fuel cell would be operated until the reactants were consumed and then the battery would be used. Above the balance speed, it is more effective to run both power sources together, because the more lightly loaded battery has a larger effective capacity.

In Fig. 9, the upper curve has a cusp at 9.3 knots. This corresponds to the situation when both fuel cell and battery completely use their reactants at the same time [2]. For speeds greater than 9.3 knots, the battery would be exhausted but the fuel cell would still have reactants available. These reactants could be used to extend the range of the submarine, but only at speeds equal to or less than the balance speed of about 8 knots.

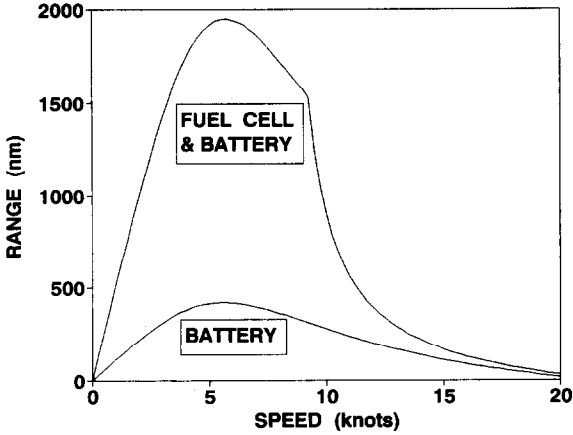


Fig. 9. Underwater range as a function of submarine speed for battery only and for fuel cell plus battery, calculated for a 600 kW fuel cell with a 100 MWh energy output.

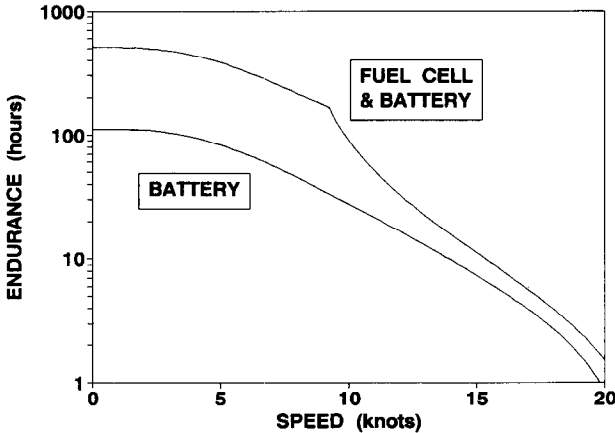


Fig. 10. Underwater endurance as a function of submarine speed for battery only and for fuel cell (100 MWh) and battery.

*Underwater endurance*

In Fig. 10, the underwater endurance has been plotted as a function of speed. The ratio of the fuel-cell-plus-battery endurance to battery-only endurance increases from 4.6 to 5.0 as the speed increases from zero to 9.3 knots. At greater speeds, the ratio rapidly decreases because not all the fuel-cell reactants are used. Even at speeds of 15 to 20 knots, however, the use of the fuel cell increases the endurance and range by about 50% compared with the battery alone. This points to the possibility of trading off some battery capacity for increased fuel cell range or power. Hence, low-speed endurance could be even greater without any loss of endurance at high speeds.

*Indiscretion ratio*

A conventional submarine is much easier to detect when surfaced or when snorkelling to recharge its batteries. Reducing this 'indiscretion' time reduces the vulnerability of

the submarine. The indiscretion ratio,  $I_r$ , is the fraction of time that the submarine spends snorkelling to maintain the state-of-charge of the battery and can be calculated from the expression:

$$I_r = t_s / (t_s + t_b) \quad (6)$$

where  $t_b$  is the time spent discharging the battery, and  $t_s$  is the time spent snorkelling to recharge the battery to its original state-of-charge.

If the submarine is travelling with a constant speed and the batteries are being cycled between two charge states, so that the net load on the batteries is  $P'$ , the time to discharge from initial capacity  $C_1$  to final capacity  $C_2$  is given by:

$$t_b = (C_1 - C_2) / P' \quad (7)$$

where  $C_1$  and  $C_2$  are both functions of the net battery load. For the submarine operating on battery power alone,  $P'$  is equal to  $P$ , the power calculated from eqn. (1). For speeds below the balance speed, the submarine is expected to operate solely on the fuel cell and the indiscretion rate is zero. For speeds above the balance speed, the submarine must operate on both battery and fuel cell, so that  $P' = (P - 600)$  kW.

The recharging time can be estimated from the expression:

$$t_s = C_b (f_1 - f_2) / \epsilon_c P_c \quad (8)$$

where  $C_b$  is the battery capacity, kWh,  $f_1$  the fraction of total charge after charging,  $f_2$  is the fraction of total charge before charging,  $\epsilon_c$  is the charging efficiency, and  $P_c$  is the charging power, kW.

A modern conventional submarine has an installed diesel capacity of about 4 MW [21]. To estimate the indiscretion ratio, the expressions for  $t_b$  and  $t_s$  are substituted in eqn. (6). To first order, the indiscretion ratio is independent of  $f_1$  and  $f_2$ , because similar fractions appear in both the numerator and the denominator. The indiscretion ratio has been calculated as a function of submarine speed, with the assumption that there was battery power only, or battery power plus 600 kW of fuel cell power. The following parameters have been used in the calculation:  $C_b = 25\,000$  kWh,  $\epsilon_c = 0.90$ , and  $P_c = 4000$  kW.

Figure 11 shows the calculated indiscretion ratio as a function of submarine speed for the battery alone, and for the fuel cell and battery together. For the battery alone, the indiscretion ratio increases from a minimum of about 7% at low speeds. For the fuel cell and battery together, the indiscretion ratio is zero for speeds up to the balance speed of about 8 knots, until the fuel cell reactants are consumed. The calculations are given in greater detail elsewhere [22]. The use of AIP greatly reduces the submarine's indiscretion ratio and, hence, reduces its vulnerability.

## Conclusions

Conceptual designs have been presented for a fuel cell AIP plug that could be retrofitted to a large ocean-going conventional submarine of about 3000 t displacement. Three different methods of hydrogen storage have been considered, namely metal hydrides, liquid hydrogen and hydrogen generated from the reforming of methanol. All three options are feasible, based on a nominal 100 MWh (electrical energy equivalent) of fuel cell reactants. The metal hydride option is mass limited and would require a plug about 15 m in length in order to have sufficient buoyancy to support the mass of the system. The methanol reforming and liquid hydrogen options are volume limited

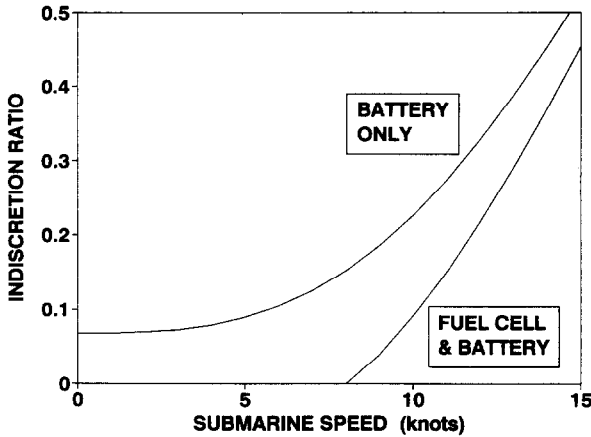


Fig. 11. Indiscretion ratio as a function of submarine speed for battery only and for fuel cell (600 kW) and battery.

and plug displacement would be much greater than the system mass. Using toroidal tanks to minimize volumes, both options would require a plug of about 10 m in length. Moreover, about 150 and 200 t of lead ballast (for the respective options) would have to be added to produce neutral buoyancy.

Based on the performance of a generic submarine equipped with a 600 kW fuel cell, the maximum underwater speed on the fuel cell alone would be about 8 knots. The indiscretion ratio below 8 knots would be zero; this would greatly reduce the submarine's vulnerability. With sufficient fuel-cell reactants to produce 100 MWh of electrical energy, the maximum underwater range of the submarine would be increased by a factor of almost five compared with operation on batteries alone. The maximum endurance would be about 14 days at about 6 knots. For speeds greater than the maximum speed on the fuel cell alone, the range and endurance of the submarine would be increased considerably if the fuel cell and battery were used together.

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