

Air Independent Propulsion - now a necessity

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Air Independent Propulsion, or AIP, will be discussed widely in coming years, as Australia initiates the procurement of new attack submarines to replace the Collins class boats. The first non-nuclear submarines with an AIP power system were trialled during the Second World War, with nuclear propulsion becoming the preferred form of AIP in major navies by the mid-1950s. Given the diversity of systems available to provide this capability to a non-nuclear submarine, there are strengths and weaknesses in the various technologies on offer.

Snorkelling is becoming an increasingly risky operating regime as radar technology advances. AIP becomes not only a necessity for a submarine but also a mission critical and survival critical single point of failure for the boat. If an AIP system fails the odds of submarine survival decline rapidly. Depicted HMAS Rankin during a RIMPAC exercise.



WHY AIR INDEPENDENT PROPULSION?

The imperative for the development of the first AIP systems was the high loss rate of Kriegsmarine U-boats in the Battle of the Atlantic, when confronted by well armed Allied maritime patrol aircraft. Diesel-electric U-boats had to run surfaced to recharge their battery systems, which made them susceptible to detection by the basic radar equipment carried by RAF Coastal Command and US Navy aircraft. Attempts to 'shoot it out' with aircraft using deck-mounted guns were mostly unsuccessful. Crash dives to evade the attacker would only succeed if the aircraft was sighted very early, or its radar emissions detected.

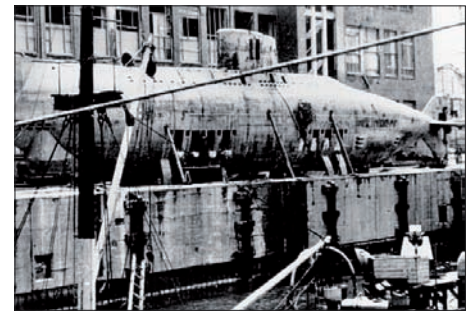
The inventive engineers of the Kriegsmarine developed the snorkel to permit the U-boat to run submerged and draw air in for the diesels, so the batteries could be recharged while the U-boat was submerged. Snorkels however produce a bow wave, a trough and wake, and these were also detectable by improving search radars, albeit at very much shorter ranges than a surfaced boat. By the early 1950s snorkels had become the technology of choice for submarine operators globally.

While snorkels are now clad in radar absorbent materials, and often shaped to minimise their bow wave and wake signature, they continue to provide a detectable signature, exposing the boat to any maritime aircraft with a good search radar system. Evolving radar technology is now challenging the viability of even well designed snorkels. Specifically, high resolution Synthetic Aperture Radar (SAR) provides a capability to detect the wake of a submerged submarine. While this is an immature technology, as it matures it will provide good detection probabilities especially against shallow running submarines. This is because all submerged submarines produce a roughly conical disturbance in the water which expands outward behind the submarine, dissipating in intensity with time and distance. The strength of this disturbance increases with the speed of the submarine. As the disturbance expands behind the submarine, it eventually hits the surface, producing a roughly paraboloid surface disturbance, pointing in the same direction the submarine was travelling when it produced the wake. The strength of the surface wake and how easily it will be detected will depend on the mechanical energy in the wake. The worst

case is for fast running submarines at very shallow depth, and may be exacerbated by the shaping of the boat and its fin (sail). At snorkel depth even a ponderous 10 knots will produce a visible wake, which can be observed on numerous images of submarines at periscope or snorkel depth. Snorkelling will thus present a much greater risk than at any previous time, as the boat will produce a hull wake signature, a snorkel wake signature, a snorkel paint signature, and snorkel shadow signature.

The answer is of course to avoid snorkelling if possible, and spend as much time as possible as deep as possible and as slow as tactically feasible, all of which present major operational challenges for a diesel-electric boat design.

As with the pressures that led to the first attempts at AIP more than half a century ago, it has been an unexpected advance in opposing sensor technology that has forced evolutionary change. With high resolution SAR capabilities being supplied in volume for Western and Russian clientele, it is now only a matter of time before wake detection capable SAR appears as a standard feature in maritime search radars.



A surfaced Ohio class SSBN and Oberon class SSK shows the formation of its wake while underway. Advancing radar technology will make the wake of a submerged submarine increasingly easy to detect, requiring deeper operating depths incompatible with snorkelling. Radars will be deployed on aircraft, high altitude Remotely Piloted Vehicles, and increasingly, Radar Ocean Reconnaissance Satellites (RORSAT) in Low Earth Orbits (LEO).

The first HTP powered AIP system was built in 1944 and deployed on three Type XVIIIB U-boats in early 1945. The Royal Navy rebuilt one and later deployed two HTP powered SSKs, scrapped during the 1960s when nuclear propulsion became available.

CHOOSING AN AIP SYSTEM

One of the realities of this era is that any military Service about to decide on a new technology for a basic force structure component will have to contend with a deluge of glossy brochures, PowerPoint slides and briefings, all of which extol the virtues of a particular solution, and all of which profess to be without 'sin' of any kind.

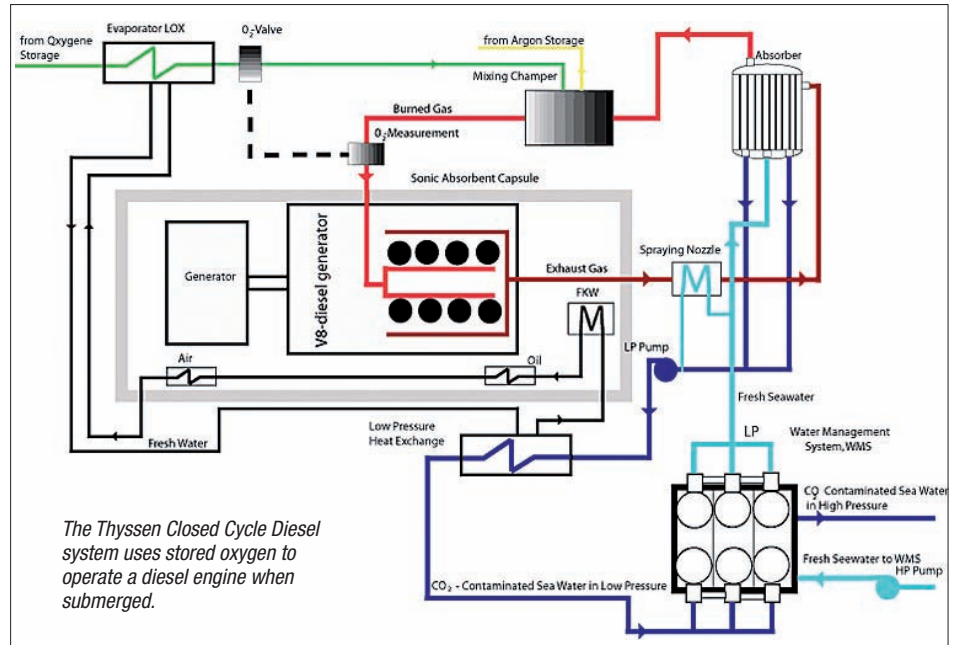
The situation is no different with AIP systems, whether they are offered as retrofits to legacy boats or as part of a new-construction boat. Declining technological skill sets in Defence Department bureaucracies create often irresistible temptation to not fully disclose the limitations of a product. This seems to be de rigeur in these times, and the cause of many tears in the customer camp when hard engineering realities eventually bite, well after contract signature.

In assessing the merits of any AIP system several factors are important:

Submerged endurance achievable with a customer specified profile, comprising specific segments of submerged operation at specific speeds and depths, representative of real sorties;

- Acoustic signature contribution produced by the AIP system in specific operating regimes, but especially at varying speeds and depths;
- Vulnerability of the AIP systems, especially oxidiser storage, to near miss explosive overpressure effects otherwise not lethal to the submarine or its systems;
- Various failure modes of the AIP system and its oxidiser/fuel storage, and to what extent are these repairable if a failure or battle damage arise in a contested patrol area;
- Failover modes and internal redundancy in the AIP system, and what 'casualty' modes exist if a catastrophic failure arises to get the boat out of danger;
- Replenishment of oxidiser and fuel from a tender when operating at large distances from a friendly port;
- Lifecycle cost of operating and maintaining the AIP system, at a representative op-tempo.

In the final analysis, any AIP system will need to be subjected to some representative and tough testing before it even makes a shortlist, since AIP is becoming a mission critical single point of failure for the submarine in a combat environment. If the AIP system fails for whatever reason while the submarine is operating in a contested area, it may not have the option of snorkelling home.



NUCLEAR PROPULSION

A nuclear power train is the ultimate AIP as it presents no restrictions on submerged time. However attractive this choice might be from a strategic, operational and tactical perspective, in many nations including Australia it is politically risky due to high levels of perceived and imagined risks in the public domains. It is unlikely therefore that nuclear propulsion will be studied and publicly assessed from an objective and rational perspective. The politics of perceptions rather than hard fact would dominate any attempt to pursue nuclear powered submarines.

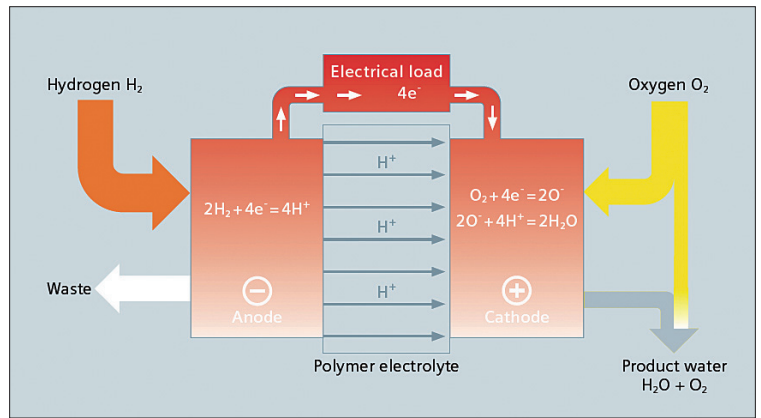
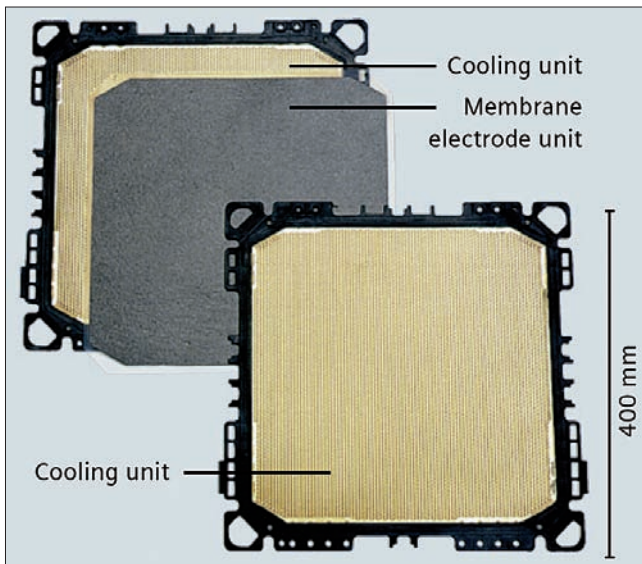
HYDROGEN PEROXIDE SYSTEMS

Arguably, the first viable AIP design was built for the Kriegsmarine in 1944 using a powerplant developed by the Walter company, which developed a range of hydrogen peroxide powered devices during this period. Concentrated hydrogen peroxide at 85 – 98 per cent, also known as High Test Peroxide (HTP), was used to power the turbopumps in the A-4/N-2 ballistic missile. When exposed to a suitable catalyst such as manganese, the HTP completely decomposes into oxygen and steam, which can be used to directly drive a gas turbine, or burned with a fuel to drive a gas turbine. HTP is the key ingredient in the TATP explosive, favoured by many terrorists.

The Kriegsmarine built three Type XVIIIB subs powered by a 210 SHP diesel engine, and a 2,500 SHP Walter gas turbine powered by HTP. All were scuttled in 1945 but the Royal Navy salvaged one, repaired it and trialled it as the HMS Meteorite. Subsequently, the HMS Explorer and Excalibur were built around an improved Type XVIIIB powerplant design, but it proved troublesome to operate due to the difficulty in handling the marginally stable HTP propellant. The 25 knot submerged speed was considered exceptional. Both were scrapped during the 1960s, and no subsequent attempts to use HTP for AIP have been disclosed since.

CLOSED CYCLE DIESEL SYSTEMS

Closed cycle diesel or CCD AIP systems employ a stored supply of oxygen to operate a diesel engine when fully submerged. The technology was trialled initially by the Kriegsmarine and later adopted by the Soviet Voenno-Morskii Flot in 30 boats of the Quebec class, in which one of the three diesels could be used as an AIP system using stored liquid oxygen (LOX). In such designs the oxygen is mixed with exhaust gasses or inert gasses to protect engine components. The Soviet boats proved troublesome to operate, prone to fires, with limited endurance due to LOX boil-off, and were scrapped during the 1970s.



Siemens SINAVY PEM fuel cell schematic and exploded view. Like other AIP systems, LOX is used as the oxidiser.



Stirling engine technology has found an interesting application in solar energy conversion, this system in the US built using Kockums hardware.

While closed cycle diesel AIP is a simple technology, the principal challenge lies in storing the oxygen supply in a way that presents a low risk in operation. A stable liquid fuel that could be catalytically decomposed would present the best choice for such designs. The current CCD AIP systems offered by Thyssen Nordseewerke in Germany use diesel, LOX and Argon as the inert gas component.

CLOSED CYCLE STEAM TURBINE

Closed cycle steam turbine AIP systems could be best compared to nuclear systems, in that heat is used to generate steam, which via a turbine or turbo generator package drives the propulsion system. In effect, the nuclear pile is replaced by a stored oxygen fuel burning heat source. The fuel and oxidiser mix used for the AIP system is then specific to the design in question.

DCN in France offer the MESMA (Module d'Energie Sous-Marine Autonome) system in a lengthened Scorpene class boat, requiring the insertion of an 8.5 metre 305 tonne hull section. The MESMA system burns ethanol, using stored LOX

as the oxidiser. The propellant mix is burned at 60 atm pressure. DCN claim up to three times the submerged endurance of the basic diesel-electric Scorpene class, or up to 18 days. Like LOX based CCD AIP systems, the MESMA will be primarily constrained by the need to store and handle LOX.

FUEL CELL SYSTEMS

Fuel cell based AIP systems typically employ a hydrogen oxygen fuel cell to generate electrical current, which then powers the boat's systems. Fuel cells have been employed successfully for decades in space vehicles that employ LOX and liquid hydrogen as main engine propellants. The principal issue in operating any fuel cell based system is the manner in which the oxygen and hydrogen are stored prior to introduction into the fuel cell. The fuel cell produces distilled water as a waste product.

A key attraction in fuel cell systems is the virtual absence of moving parts in most key components, which makes them exceptionally quiet in terms of machinery noise compared to closed cycle diesel and turbine systems.

The preferred technology is the PEM (Proton Exchange Membrane) cell used in the Siemens SINAVY AIP fuel cell modules. These are employed in the U221A and 214 SSKs, built by HDW in Germany.

The hydrogen propellant supply in the HDW/Siemens system is described as via "reformer gas" in some documents, or solid metal hydride in others. The former scheme typically involves the decomposition of a hydrocarbon fuel to generate hydrogen. The hydrogen must then be purified to remove carbon monoxide, which will otherwise poison the Platinum catalyst in the fuel cell destroying its efficiency. In a metal hydride scheme, the hydrogen is released from a solid metal hydride. Nitrogen is typically used as an inert gas in the system. The oxygen supply is stored as LOX in the HDW/Siemens system.

The Type 212 and 214 boats use this system, which is available also for the Type 209.

STIRLING ENGINES

Stirling engine technology dates back to 1816, but had to wait until very recently to find a volume production application, which is AIP systems in submarines. Stirling engines are often compared to reciprocating steam engines, in that they employ a piston-cylinder assembly, but they differ fundamentally, in that the working fluid in the engine is sealed and separated from the heat source, in a closed cycle arrangement. Heat is provided to the Stirling engine by the external combustion of a fuel and oxidiser.

The Swedish Kockums AIP system employs LOX as the oxidiser and diesel as the fuel, which are combusted at a pressure higher than that of the surrounding water mass permitting the exhaust to be directly vented to sea. The Stirling engine is coupled to a generator that feeds into the boats' primary electrical system.

As with other AIP systems burning diesel and LOX, the LOX supply is the principal constraint to achievable endurance.

Other than Sweden's Kockums, Stirling AIP is reported to be used by the PLA.