Submarine Power and Propulsion
- Trends and Opportunities

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INTRODUCTION

The aspiration to improve submarine Power and Propulsion System (P&PS) performance without hazarding the platform's safety and increasing whole life cost continues to challenge the designers of the world's SSKs.

In-service costs can be reduced through judicious manning reductions achieved through improved automation and improved Availability, Reliability and Maintainability (ARM). The technologies under review will seek to improve these aspects in the context of the use of more COTS type equipment.

Recent technological developments and improvements have created the potential to improve overall power and propulsion performance and therefore overall submarine capability with a reduced risk to these hazards.

To bring to maturity, prove and ultimately integrate such technology into a submarine design requires a firm understanding of the actual technology in terms of the benefit it offers and its limitations, complemented by knowledge of integrating such technology within the host submarine.

This paper will begin by defining the future challenge for SSK designers and then consider how this could be translated into P&PS requirements. The technologies that may allow such a requirements set to be met and the anticipated performance that may be achieved are then explored. The paper will emphasis energy storage, power generation and propulsion trends and opportunities.

The paper will conclude by proposing a vision for a future putative submarine that exploits appropriate technologies that would enter service in the near (e.g. 2020) term.

THE CHALLENGE

The current challenges facing today's SSK designers can be considered to be:

- To achieve an SSK design which allows for a much greater submerged role for prolonged periods and with greater reach and endurance;
- To achieve this with no loss of military performance or increased threat of safety to the crew;
- To identify the opportunities to achieve this with currently developing technology;
- To identify the programme for the implementation of such a design;

Such a set of challenges can only continue to be met with the adoption of new technologies: chiefly, energy storage, power generation and electric propulsion. The first two topics are firmly part of the Air Independent Power (AIP) technology set and since one of the keystone AIP presentations by Donaldson [Ref. 1] and before him Thornton [Ref. 2], this technology has matured into viable and in-service SSK designs.

BACKGROUND/CONTEXT

SSK Population

The world's population of SSK has been growing through the increased number of user nations and through the acquisition of larger and more capable platforms. New submarine are likely to have a longer range (submerged and surfaced) than their counterparts of twenty years ago. These trends are a consequence of the need for the SSK to perform across wider spans of ocean and to be ever more independent from external support. Whilst the speed and range may not be co-incident as with an SSN, long ranges at slow speeds and high speeds at low ranges are possible with an SSK such that an operational deployment can still have the same duration as an SSN, being limited only by stores capacity and human endurance.

Type 214

The German HDW Type 214 export-design is a good example of the current state-of-the-art of SSK design in terms of P&PS. The design has evolved from the excellent Type 212A to become an export variant of notable success.

The use of two Siemens BZM 120 (120kW) Polymer Electrolyte Membrane (PEM) fuel cells units with onboard stores of oxygen and hydrogen gas has allowed a considerable performance to be achieved.

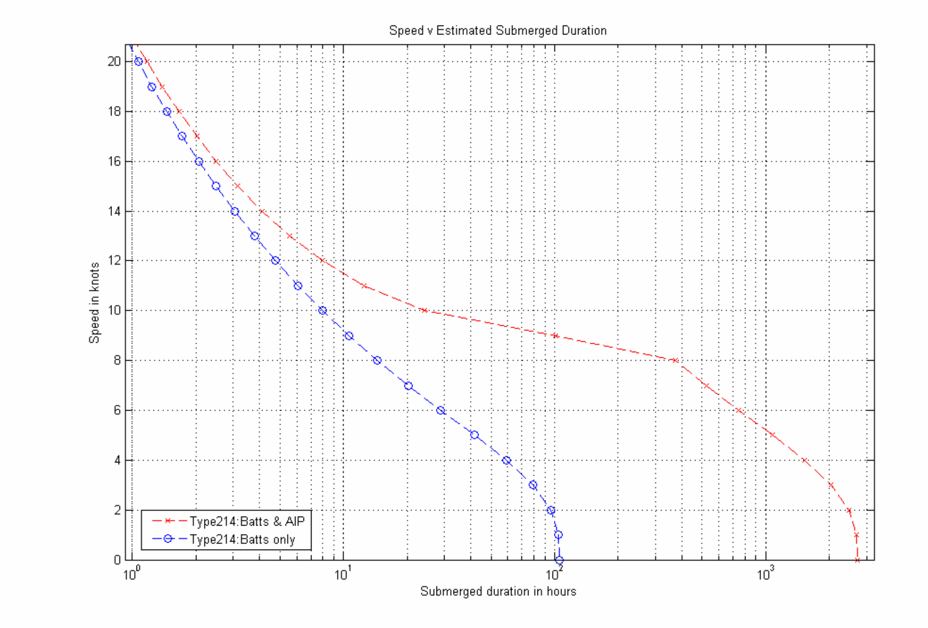

Figure 1 – Type 214: Estimated Submerged Propulsion Performance

Figure 1 shows the estimated performance of the HDW Type 214 submarine with battery only operation and with batteries and fuel cells operating together. The simple assessment shows clearly (on the x-axis in log format), how the AIP provides a significant increase in reach for a wide range of speeds below the top speed. For speeds below 4 knots the duration would be dominated by the ships onboard power demands which exceed those of the propulsion.

REQUIREMENTS

General

The key to achieving a successful SSK design is to fully capture the whole panoply of P&PS requirements at the outset so that the requirements can be turned to a virtue through technology synergies. The P&PS requirements will stem from operational analysis for which the following aspects are key:

- Top speed and time at top speed;
- Submerged range at the most economic speed of advance;
- Poise: Submerged endurance when at rest in elapsed time;
- Ice operations;
- Littoral Operations;
- Manning;
- Platform size.

These requirements will now be explored in a little more detail.

Speed

The top speed of many of the modern SSK designs is around 20 knots. This speed is partly selected due to the self-noise created above this speed which makes it difficult to detect other vessels. Due to the era of modern high-speed torpedoes and other munitions, the top speed of an SSK is not set to outrun a torpedo as the power penalty would be immense.

Technical opportunities may permit higher powers to be put into the water with the same footprint, this is not likely to lead to higher sustained top speeds. Higher rated motors would also allow for more rapid acceleration and better thrust for manoeuvring purposes.

Range

The key requirement is range, not top speed: a good range will permit operations far from base-port, as well as extended duration in theatre once the submarine has arrived. The transit to the theatre may allow snorting and be on batteries to avoid depleting the AIP fuels and oxidant. Self-noise on such occasions is still critical but to arrive in a realistic timescale, the speed in transits needs to be greater than the submerged speed of economic advance where the propulsive power equals the ships base cruise electrical power demand. Transit speeds of 8 to 10 knots are therefore to be expected with snorting between once and twice a day. A reasonable future transit requirement would be 12,000nm in 50 days at 10 knots.

When on patrol in theatre, the AIP would be used and the duration at speeds between 4 and 5 knots can now be over 3 weeks. A reasonable future requirement would be 30 days at such speeds giving a patrol period of up to 80 days.

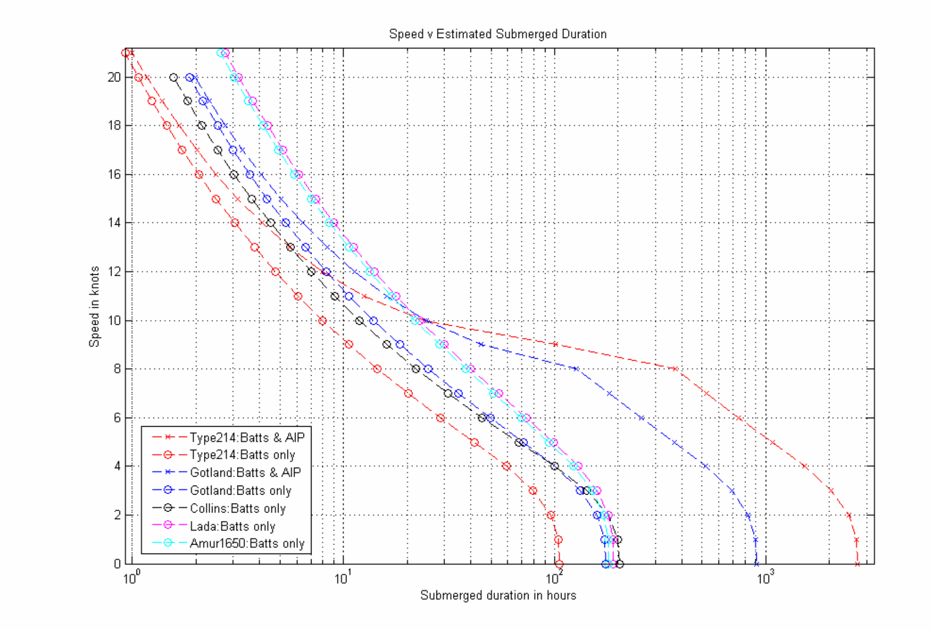

Figure 2 - Estimated Submerged Speed v Endurance for a Range of SSKs

The actual performance of the current set of modern SSK designs is difficult to discern but some basic analysis has allowed their overall likely performance to be estimated. Figure 2 shows how the smaller Type 214 battery set is compensated by the AIP capability. In general the analyses indicated that an AIP feature will allow an extra 6% top speed as the batteries are assisted by the AIP but once exhausted the AIP cannot sustain top speed.

Figure 2 also shows that the future AIP-based Type 214 will be able to stay immersed for over 1 month. This compares with the Type 212A record of 2 weeks submerged without snorting with fuel-cells between Germany and Spain in April 2006 [Ref. 3].

Poise

The ability to stay on the sea bed for extended periods of time for deployment of UUV and their recovery and simply for the reconnoitring of passing shipping with a possible view to trailing them is also a key part of the requirements set for an SSK.

The SSK would be expected to stay put for one to two weeks and thus the AIP would have to cope with the steady ships services electrical demand.

Future operations will probably have a higher component of UUV deployment and recovery [Ref. 4] which will require the boat to poise, loiter or stay grounded to avoid propulsion noise and to avoid navigation errors and any contact with other maritime traffic in the littoral environment.

The time on station will have to be extended to allow such reconnoitre operations to be concluded and such operations may take-place far from a home or friendly port. One or both of such events would tend to lengthen the patrol duration and a 50 day submerged patrol is a valid design target. The putative design should therefore allow 3 weeks submerged without snorting [Ref. 5].

Under Ice Operations

The opening up of the North-West Passage in North America and the claims being made over territories in that region has raised the likelihood of a greater military presence in the arctic in the near future. Those countries which wish to demonstrate their ability to police such areas would be likely to need a submarine which could handle operations under 60cm first year ice and this would seem to be a suitable “first-pass” requirement.

The provision AIP for such under ice operations would offer a much greater degree of safety margin than conventional batteries allow.

Littoral Operations

The usual role of an SSK in peacetime is the need to monitor events near shore. This leads to a real need for stealth and so low indiscretion and noise reduction and elimination are key objectives.

With the improved passive sonar performance of many MOTS products and a greater number of potential adversarial SSK’s at sea, it is evermore necessary to sustain stealth. These operating conditions have changed the need for power and the storage of energy.

Therefore the use of diesel engines to recharge batteries is increasingly seen as a limiting feature to achieving the necessary stealth. The AIP would provide the direct power to the ships services in this mode. The excess power from the AIP would also be used to replenish batteries so that top speeds could continue to be reached if so demanded.

In the past, power delivery and energy storage has been predicated around sprint conditions for evasion after a strike. Whilst this continues to be a key design requirement, noise from hull turbulence is difficult to avoid at speeds above 20 knots and so although such speeds may be required for sprint, they are not necessary for transits.

Consequently the challenge is less power-driven but centred more around energy storage and submerged air-independent methods to recharge the energy storage.

A suitable requirement would be to consider how best to recharge the batteries without the noise of diesel engine operations. This might comprise an alternative passive surface-breathing power-source (SBPS) such as a fuel cell which is much quieter. Its reduced noise would allow for longer snorting without the risk of indiscretion. Therefore the SBPS could be rated at a lower power than the current diesel engines.

Manning

The number of crew is predicated by a range of factors. Those required to sail the vessel and man its combat system are determined by factors outside the scope of this paper. The number onboard has a significant impact on ships service and hotel power demand. However there is certainly scope for the manning of the Marine Engineering Department to be carefully managed through suitable training, the selective use of automation and the careful choice of equipment.

The former Royal Navy Upholder class vessel had 11 members in the Marine Engineering Department. A realistic target would be nearer to 7 and this might be achieved by replacing the diesel engine and the lead acid batteries with more modern alternatives. A reduction of 4 staff would lead to significant relaxation of accommodation, hotel services and provisioning demands.

Size

The construction and outfit of larger submarines do cost more money, especially if the available space is all consumed with equipment. A good design will comprise a boat length which incorporates the necessary weapon fit and crew accommodation without the need for an unduly large proportion being allocated to P&PS equipment. However experience of a range of craft does indicate that such equipment usually consumes 30% of weight and 50% of volume [Ref. 6].

Summary

This section has identified the main features which influence the requirements set for an SSK and has offered some indicative future requirements which will be used to assess the scope for benefits from modern day and emerging technologies.

The key aspect that emerges is that the design of the P&PS of a modern class SSK is determined by energy considerations whereas the ability to put power into the water may have been a leading challenge of past designs.

TECHNICAL OPPORTUNITIES

General

The main topics of interest are: Energy Consumption; Power generation; Energy storage; Propulsion Motors.

Many developing energy storage and power generation technologies have now been trialled in automotive applications where high cycle rates and concerns for public safety have made great inroads into their reliability and ability to graceful degradation.

Energy Consumption

The solution to the current issue lies behind the combined use of the range of ideas and approaches identified above. The key lies with the use of technologies which allow:

- More efficient and compact electronics;
- Whole submarine to operate in a manner which is less consuming of energy;
- Equipment to match its operating load (variable speed pumps and fans);

An average consumption of 1kW per person could be achieved as a cruise average but with additional peak power demands of up to 100kW due to increased operational tempo.

Power Generation

General

The selection of power generation now appears to be reduced to the following: Closed-cycle diesel engines, Diesel engines; Fuel cells; MESMA; Stirling engines.

Closed-Cycle Diesel Engines

The scope for the use of closed-cycle diesel engines has declined with the significant reduction of the Dutch submarine building capability who developed the Spectre design [Ref. 7]. Although they continue to be considered for specialist commercial applications [Ref. 8] they do not have a growing industrial base to draw upon for technological development and they also have a low overall thermal efficiency of around 30%.

However they do offer an AIP capability at a very affordable cost. They can use the same fuel as the main diesel engines and they would require little new training for the crew.

Diesel Engines

The use of diesel engines for snorting at Periscope Depth (PD) to recharge the batteries presents a noisy solution to a necessary function. Although such engines could be acoustically enclosed the confines of a submarine make this difficult to achieve and the future pressing stealth targets mean that a diesel has to be seen as a prime target for replacement.

To allow an alternative to fit in the same footprint as a 1580kW 16V396 MTU genset it would have to have a volume which is less than 10 m^3 (or less than 150kW/ m^3).

PEM Fuel Cells

The use of PEM Fuel Cells in SSK has been championed by the German firm of HDW [Ref. 9] in their Type 212A and Type 214 designs[Ref . 10]. In the Type 214A designs as used by Greece, the two Siemens BZM120 fuel cells are rated at 120kW each and weigh 900kg with a volume of 500 litres each.

The design of the Fuel Cell permits a building-block approach and the use of a greater number of smaller rated units will offset concerns about single point of failure.

Considering that the fuel cell is a static device with few moving parts it may be a reasonable decision to employ between two and four units to service the likely demand. However these units are often subject to high inlet fuel and oxygen pressure to increase the concentrations and performance. Therefore compressor reliability performance is also of the utmost consideration.

Part load efficiencies also need to be considered and a multiple unit approach would allow the right number to be on-line to match demand. Start-up times are in the order of minutes and as there will always be battery back-up this is an acceptable aspect.

The fuel needs to be free of sulphur and this leads to use of volume-intensive high-quality methane or hydrogen. The extended life of units is not yet fully proven and this may have a cost implication in years to come.

SOFC Fuel Cells

The Solid-Oxide Fuel Cell (SOFC) is a popular concept for a future power generation application as its high operating temperature (> 600°C) makes its catalysts largely resistant to sulphur pollution in the fuel. Such technologies are being developed by Rolls Royce, Siemens, Alstom and Wartsila [Ref. 11].

The SOFC has a theoretical electrical efficiency (or yield) of 50% [Ref. 12] which is better than the PEMFC. Its higher operating temperature also gives it scope for operations with a turbo-charger (or gas turbine-type device) which serves to increase the overall efficiency.

The device offers a role as the surface-breathing power-source (SBPS) to replace the diesel genset. The SOFC would be much quieter for operability and stealth purposes and its lack of reciprocating parts would make the upkeep burden lower. However, current designs are for land-based applications and are in their field trials stages. There are still issues with design for acceptable degradation and this is subject to ongoing studies. [Ref. 13].

Due to their early stage of development the current designs are not small and the equivalent SOFC for a 2MW diesel gensets would be five times more bulky: clearly not a proposition yet. Much of the bulk is due to the Balance of Plant (BOP) with a single Rolls-Royce 250kW generator module being about 2m tall and 1.5m diameter [Ref. 12].

The fuel for many SOFC applications is still natural gas but for marine applications the use of methanol is being research by Wartsila as part of the METHAPU project [Ref. 14]. Methanol is flammable with a flash point of 11°C which is considered to be far too low for safe storage inboard in on a submarine. For this and other safety reasons, methanol could be stored outboard as hydrogen is currently stored on the HDW SSK designs. Methanol has a calorific value of 23MJ/kg compared to 42MJ/kg for F76 and so almost twice as much fuel by volume would have to be carried but this would be countered by the greater efficiency of the SOFC.

An SOFC design solution for snorting power generation is therefore likely to require outboard storage of methanol in addition to the hydrogen for the PEMFC. The removal of the inboard diesel fuel storage would allow for the extra balance of plant associated with the methanol-driven SOFC. The time for the SOFC to achieve operating temperature can be up to 30 minutes. However this is acceptable as the submarine can run on batteries and the AIP system until the SOFC is at operating temperature for snorting at PD.

MESMA

MESMA (Module d’Energie Sous-marine Autonome) comprises a steam turbine system whereby the heat from burnt ethanol creates steam. The design is based on a Rankine cycle which has a typically efficiency of 25% which is poor compared to a fuel cell.

The design has been operationally proven at sea in an Agosta class of the Pakistan Navy (PN). The system will be fitted to PN’s Scorpene design by DCN of France. A simple assessment of the limited data available suggests the Scorpene performance will be similar to that shown in Figure 3.

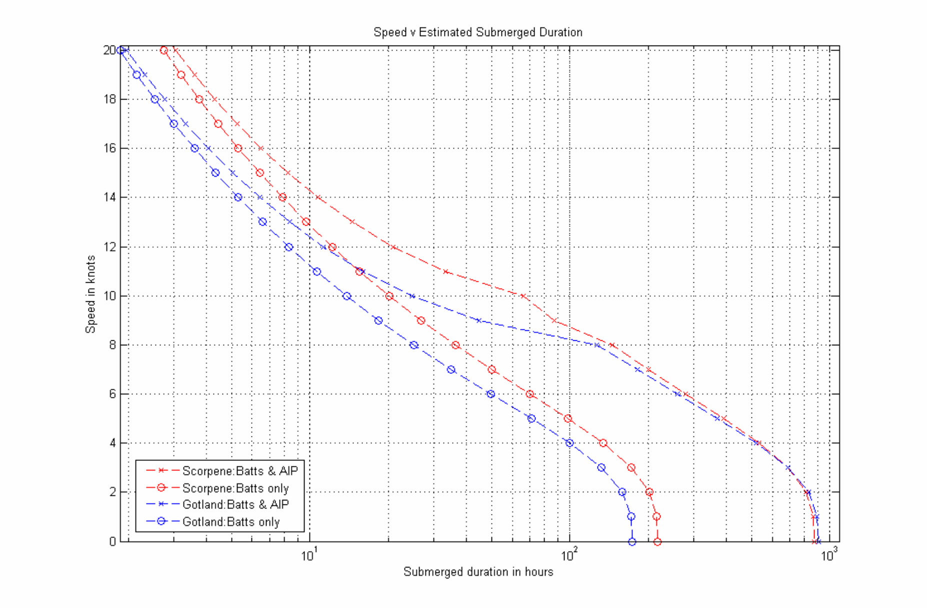

Figure 3 - Estimated Scorpene & Gotland Speed v Endurance

Figure 3 indicates that the MESMA allows a tripling of the range at patrol speed (4 knots). However with MESMA waste combustion products are discharged overboard at pressure and so there may be a noise penalty associated with this method of gas management.

Stirling Engines

Although well established as a feasible AIP device since their introduction into the Gotland class in 1992 [Ref. 15], they do not appear to have been further developed for SSK use. This is not withstanding the innovative efforts being conducted by Whisper Tech of NZ, where multiple cylinder arrangements are being progressed to provide 1kW sets but at a low power density of 5W/litre [Ref. 16].

Figure 3 shows the estimated performance of the Swedish Gotland class when operating with and without the currently installed battery set and AIP. The plot shows how the 150kW Stirling engine AIP starts to give the SSK endurance below 8 knots thus allowing extended poise in the Baltic Sea operating area where transit times to the patrol areas would be small.

It is likely that the trend away from Stirling engines is due to their poor industrial infrastructure and their upkeep and noise which would be greater than a passive fuel cell system notwithstanding enclosures and modern rafting methods.

Energy Storage

Energy storage can be considered to be: Batteries; Fuel Storage; Oxygen storage.

Batteries

The technology of batteries is undergoing a sea-change with the emergence of the Zebra product from Rolls-Royce and the development of lithium ion designs [Ref. 17]. This comes on top of the use of sodium sulphide batteries in the HDW Type 212A class.

The Zebra battery [Ref 18].] is a sodium nickel chloride battery which has been developed for marine use by Rolls-Royce. Zebras and the sodium sulphide batteries allow for distributed energy storage throughout the boat and may enable dc systems with less installed copper. They can produce twice the energy of a lead acid battery at the one hour rate as can be seen in the cell-based data in Table.1.

Table.1 - Battery & Fuel Cell Technologies

Description	*Power Density*	*Specific Power*	*Energy Density*	*Specific Weight*
	kW/litre	*kW/kg*	*Wh/litre*	*Wh/kg*
Lead acid	0.12	0.08	90	44
Zebra	0.24	0.16	167	114
Sodium Sulphide (NaS)	0.021	0.17	170	117
Lithium ion	0.22	0.11	270	120
Silver Zinc				
Siemens PEMFC BZM 120	0.257	0.13		

Lithium ion designs have successfully been developed for automotive applications [Ref. 19]. Their energy density is over twice that of lead acids batteries and it is less than half the weight for the same energy at the 5 hour discharge rate. A unit which is 50cm by 40cm by 40cm has energy of 21kWh and can develop 100kW continuously (i.e. five hour discharge) or 200kW for short periods of time. In energy density and specific weight terms it promises to be better than the sodium sulphur batteries as used in the German 212A class.

The lithium ion batteries would be used both centralised and for distributed energy storage. Lithium ion batteries would be:

- rated to a higher current than other battery types;
- durable to experience more full-charge cycles than NaS or Zebra;
- capable of sudden changes in demand;
- have a documented developed record of in-service reliability.

The collective increase in stored energy will make for more operational flexibility and allow for oceanic operations such as those undertaken by the Collins class. The use of lithium ion batteries for the centralised main battery banks would more than double the stored energy.

Distributed Energy Storage

The use of Zebra batteries in forward spaces near to the consumers will allow for a greater installed energy storage with a small impact on the total volume. Such a distributed energy storage arrangement if adequately sized could allow for fewer pumps with no need for alternative and emergency supplies to each essential equipment.

Such arrangements should mean that boat capability could be increased without leading to their enlargement which would itself become a penalty in the littoral.

The greater the energy storage, the lower rated can be the power source as it need only address the time-averaged power demand.

Fuel Storage

Kerosene could be stored inboard or even outboard. Ever since the adoption of the Walter cycle by the Russians and then the exploratory UK submarines the Explorer and the Excalibur, (Ref. 20),. there have been records of kerosene or other fuels being stored outside the pressure hull in collapsible bags. However inboard storage allows for a reliable water-free fuel stability.

Methanol could be used for the SOFC but consideration could be given to the use of liquefied natural gas which would be fully contained and isolated from atmospheric air unlike a methanol-based solution. However energy storage density favours the methanol approach.

It is envisaged that hydrogen will continue to be stored in metal hydrides for the foreseeable future. However for larger energy storage and vessels there may be issues with scaling up the current arrangements.

Oxygen storage

Whatever the power generation design there will be always be a need for stored oxygen in one form or another.

For modern day SSK design the emphasis is on energy and hence large amounts of oxygen needs to be embarked to allow for extend range. The HDW approach is to have one single bottle of liquid oxygen (LOX) located inboard. In this way the bottle can be monitored and contained in the event of a mishap. The criticality of the supply of oxygen suitably heated and fed to the AIP is such that the pipework is kept to a short length for hygiene reasons. Oxygen pipework needs to be kept clean of hydrocarbons as experience with the HMS CHALLENGER demonstrated [Ref. 21].

The use of LOX at temperatures near 100K would in theory allow for synergy with the use of a High-Temperature Superconducting (HTS) motor aft. However for independent reliability and also safety concerns, it is likely that such a synergy in terms of reduced cooling plant would be difficult to achieve although there would doubtless be a cryo-plant cross-connection for emergency use.

There has been much research in the field of compact energy dense oxygen storage. The kind of medium can vary from oxygen candles through to liquid oxygen. In 2006, Davies et al [Ref. 22] showed the wide range of over 10 different storage solutions and showed LOX to be amongst the best practical storage solutions.

For simplicity and convenience two large LOX tanks would be located inboard each one dedicated to a PEMFC unit. The amount of stored oxygen is the limitation for submerged operations on AIP. Consideration should also be given to using bottle air as a back-up should the LOX be depleted. This could be replenished by the HPAC when snorting.

Propulsion Motors

The developments of more power-dense / compact electric propulsion motors and their matching converters should allow the rated shaft power to be increased at no penalty to the weight or volume of the installation. Companies such as Converteam Ltd [Ref. 23] are known to be developing designs where the converters are located inside the rotor thus saving a great deal of space.

But how is this mean of placing extra power into the water to be used? If the current SSK are effectively blind at speeds above 20 knots due to the flow-noise over the sonar, then what use is a faster vessel? The increasing use of network-centric battle-space technologies means that future SSK will be able to gather better navigation data and speeds above 20 knots would be acceptably safe for short distances. If this does come to pass, then the extra power capability could be use to good effect for a rapid transit or very short sprint bursts (30mins at higher speeds possibly to allow a target to be attacked.

The current surface speed of 10 knots for many SSK is slow for keeping part of a convoy with merchant ships. Notwithstanding the issue of extra power from the surface-breathing power-source, a motor of double the power and 58% more weight for the same design would allow 12.5 knots to be achieved as well as extra thrust for manoeuvring and acceleration

PUTATIVE SUBMARINE

A future putative submarine is offered which is based on the AIP Type 214. It would comprise the following:

- A larger displacement (3500 tonnes) to offer ocean-going performance;
- A brushless DC propulsion motor rated at 6MW (Twice the rating of the Type 214).
- PEMFC for submerged endurance[1];
- Liquid oxygen for submerged fuel combustion 1;
- Hydrogen located outboard 1;
- A SOFC for snort power generation;
- Methanol for fuelling the SOFC;
- Zonal power supply units with lithium ion other batteries;

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[1] As is currently the case.

- Four fewer staff due to removal of reciprocating machinery (i.e. diesels).

Figure 4 shows how the putative submarine might perform for submerged endurance v speed.

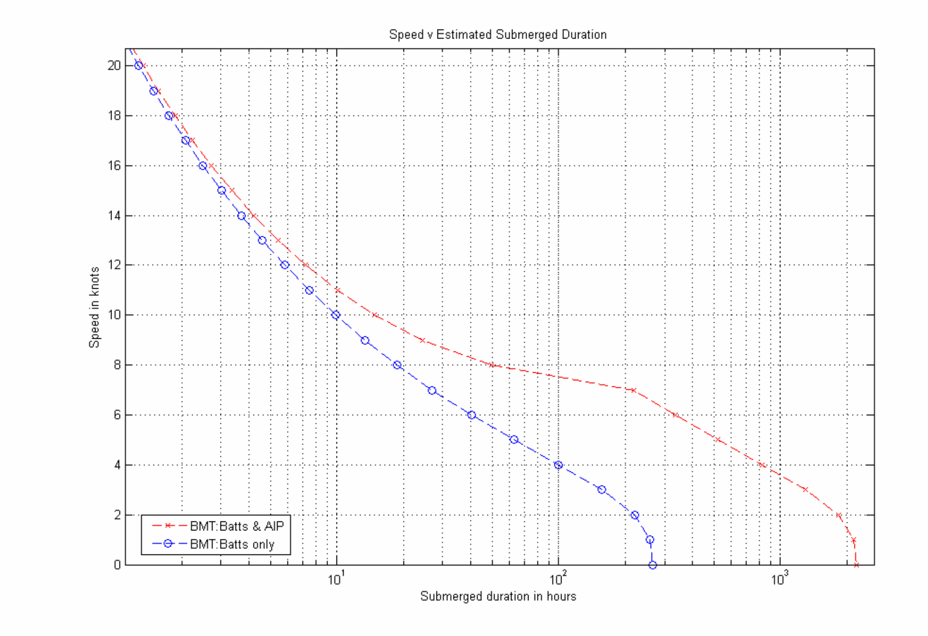

Figure 4 - BMT design performance

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