Submarine Power and Propulsion

- Application of Technology to Deliver Customer Benefit

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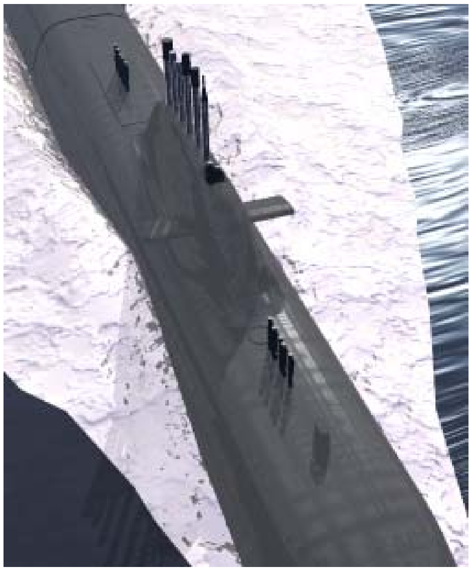
INTRODUCTION

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

Technologies are reviewed in this paper which seek to improve performance in the context of the use of more commercially-based type equipment. Recent technological developments and improvements have created the potential to improve overall power and propulsion performance and therefore overall submarine capability.

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 and its operations.

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 demonstrated in an indicative SSK 3,600 tonne design from BMT Defence Services Limited, known as the Vidar-36.



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 the keystone AIP presentations by Thornton [Ref. 1], Adams [Ref. 2] and Donaldson [Ref. 3], 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 submarines 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 compare 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.

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 they can be turned to a virtue through technology synergies. The P&PS requirements will stem from operational analysis [Ref. 4] 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 using the BMT Vidar-36 design to demonstrate the performance consequences.

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 and hence electric propulsion motor (EPM) penalty would be immense. Technical opportunities with emerging EPM may now allow more power to be put into the propeller with the same footprint. Although this is not likely to lead to higher sustained top speeds, such higher rated EPM would also allow for more rapid acceleration and better thrust for manoeuvring purposes.

Vidar-36 has a baseline 4300kW EPM to reach 20 knots but the design also allows for a 6MW unit with an active stator design.

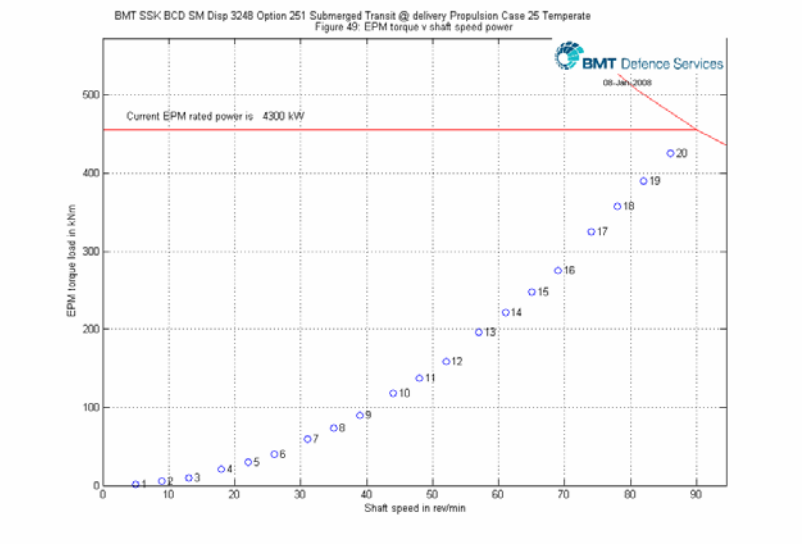


Figure 1: Vidar-36 EPM torque v shaft speed

Range

The key requirement is believed to be 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 will use snorting and batteries to avoid depleting the AIP fuels and oxidant. Such technologies have been subject to study and development for many years.

Self-noise and indiscretion 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. 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.

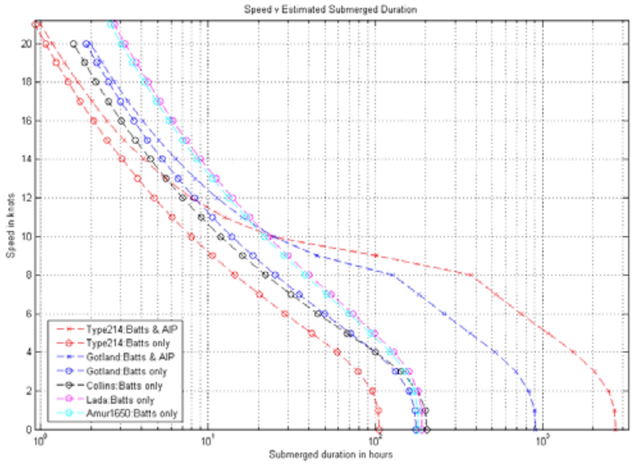


Figure 2 - Estimated Submerged Speed v Endurance for a Range of SSKs

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. 5].

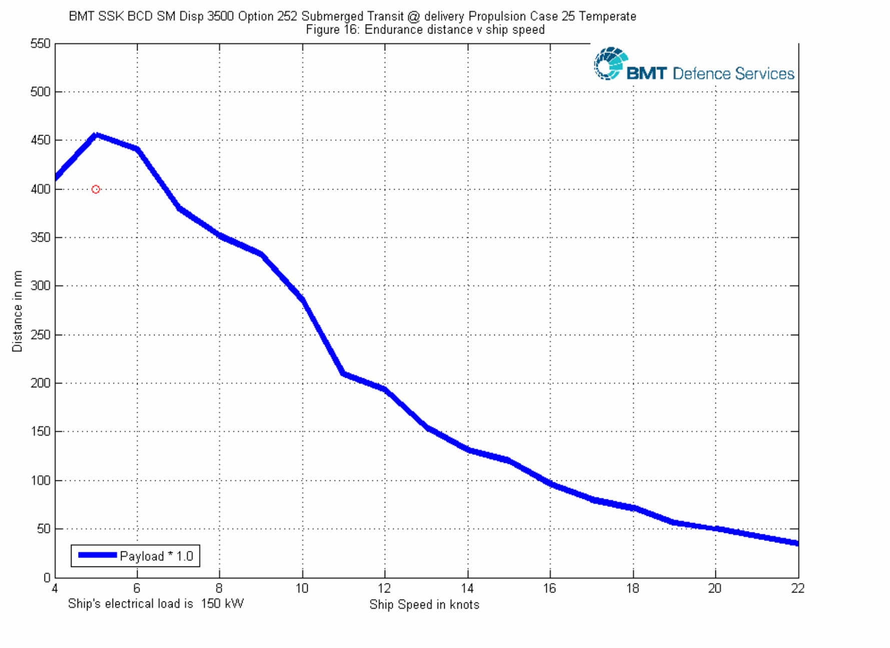


Figure 3: Endurance distance on batteries v speed

Figure 3 shows how the endurance falls away at speeds over 6 knots. Below 6 knots the loss of endurance is due to the predominance of the ships 150kW load.

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. 6] 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. 7].

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 on 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 a valuable reduction of accommodation, hotel services and provisioning demands.

Platform 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. 8].

Requirements 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);

A load chart has been developed to identify the ships services load of 150kW.

Power Generation

General

The selection of power generation now appears to be reduced to the following: Diesel engines; Fuel cells;

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 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.

These units are often subject to increased inlet fuel and oxygen pressure to increase the concentrations and performance, so compressor reliability performance is 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 may lead the designer to use of volume-intensive high-quality methane or hydrogen. However HDW have had limited success with their reforming of F76 grade fuel to supply fuel to a PEMFC [Ref. 11]. If Ultra Low Sulphur Diesel fuel is adopted it is anticipated that any issues with sulphur degradation of the reformer catalysts would be reduced.

The extended life of units (i.e. their annual loss of capacity) is not yet fully proven and this may have a cost implication in years to come.

The Vidar-36 is designed to provide an AIP performance in theatre of

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. 12].

The SOFC has a theoretical electrical efficiency (or yield) of 50% [Ref. 13] 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. 14].

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. 13].

The fuel for many SOFC applications is still natural gas but for marine applications the use of methanol is being researched by Wartsila as part of the METHAPU project [Ref. 15]. Avcat (F44) is also a candidate fuel for use at sea. Methanol is flammable with a flash point of 11°C which is usually considered to be far too low for safe storage inboard 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 partly countered by the greater efficiency of the SOFC (70 %).

An SOFC design solution for snorting power generation is therefore likely to require either the storage of avcat or methanol in addition to the hydrogen for the PEMFC. 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.

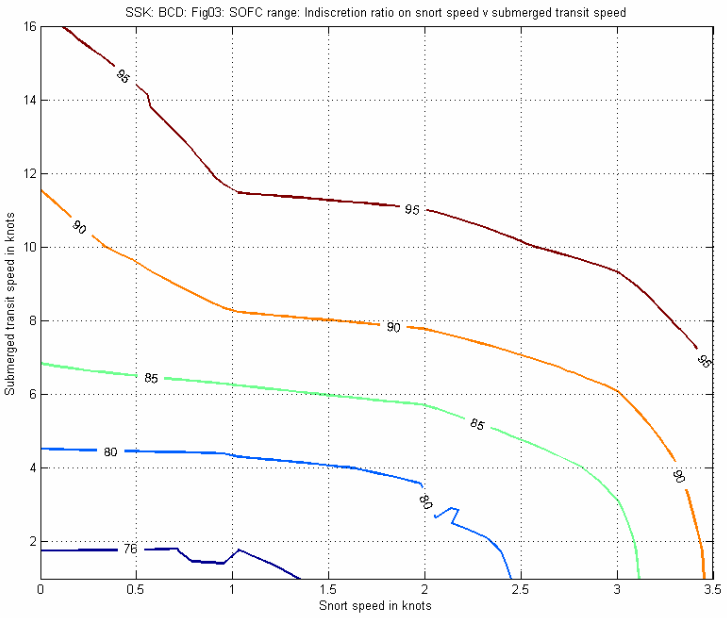


Figure 4: 200kW SOFC Indiscretion Ratio

An SSK design with a 200kW air-driven SOFC would have to service the 150kW ships service demand plus the propulsive power. This does not allow a high speed of advance and nor does it leave much power remaining to re-charge batteries at any speed. A poor indiscretion ratio results as shown in Figure 4. However such an operating mode would occur on-station when transit speeds are not an issue but the need for true discretion is. The SOFC operation is quiet and avoids the need to transit off station to snort on diesels.

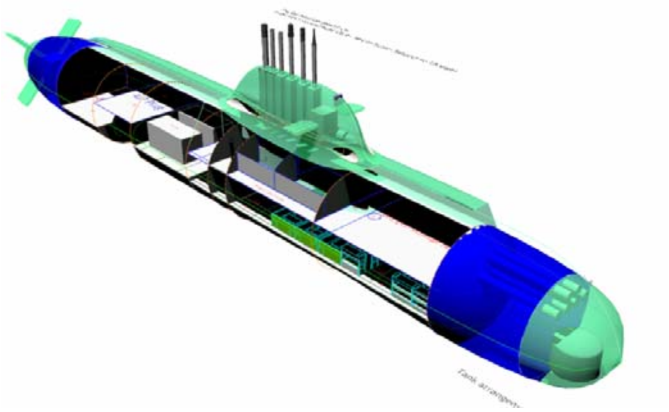


Figure 5: Sectional View of the Vidar-36

Energy Storage

Energy storage comprises: Batteries; Fuel Storage; Oxygen storage.

Batteries

The baseline battery of choice for SSK designs is the flooded lead acid battery which is usually swapped-out after 5 to 6 years. Such batteries are increasingly being replaced by Valve-Regulated lead acid (VRLA) designs in the USN and other navies despite some teething problems. For the foreseeable future such batteries will be an attractive proposition as they are a well known technology and they are accessible. However the price of lead which forms 75% of such batteries has risen by over 100% in the last two years. The cost of lithium ion batteries is therefore increasingly becoming attractive.

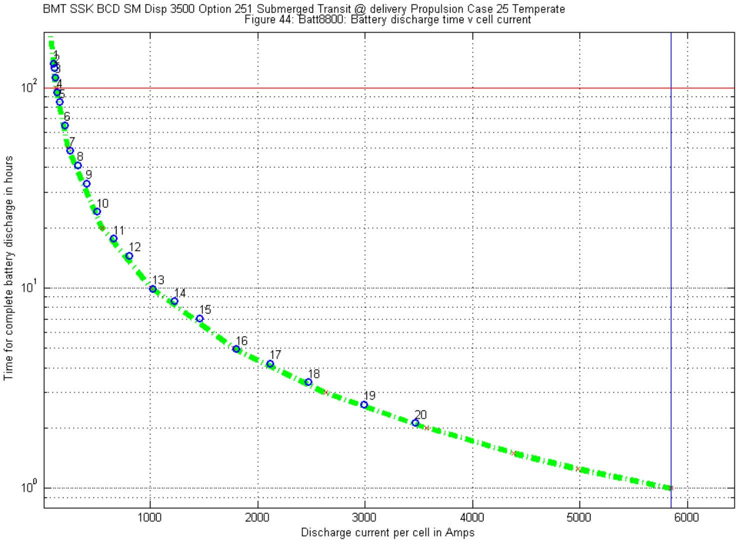


Figure 6: Battery discharge time v Cell current showing ship speeds in knots

The technology of batteries is undergoing a sea-change with the emergence of the Zebra product from Rolls-Royce and Betard [Ref. 16] and the development of lithium ion designs [Ref. 17].

The Zebra battery [Ref 18] is a sodium nickel chloride battery which has been developed for marine use by Rolls-Royce from the design developed by Betard. Non-flooded lead acid batteries such as the VRLA, lithium ion and Zebra batteries may allow for distributed energy storage throughout the boat and may enable for zonal 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
Lithium ion conventional	0.22	0.11	270	120
Lithium ion AltairNano	No limit.	No limit.	89	54
Siemens PEMFC BZM 120kW	0.24	0.13	---	---

Lithium Ion Batteries

Lithium ion designs with large energy capacities have successfully been developed for automotive applications [Ref. 19]. Their energy density is over twice that of lead acid 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.

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

Lithium ion batteries are:

- rated to a higher current than other battery types;
- durable to experience a large number of full-charge cycles;
- capable of sudden changes in demand;
- shown to have an in-service reliability;
- vulnerable to fire if over-charged.

The collective increase in stored energy will make for more operational flexibility and allow for extended oceanic transit and deployment operations. The use of lithium ion batteries for the centralised main battery banks would more than double the stored energy. However, such batteries are not cheap and as with all batteries their rated life is closely linked to the ambient temperature they see and the stored charge level (SCL). The lower the temperature and SCL, the lower the rate of loss of permanent capacity and the longer their life. If the batteries are to be a single fit and forget for the commission of the submarine then they need to have sufficient capacity at the start to ensure the correct remaining energy storage at the end of the commission. There is therefore a trade to be made between the periodicity of swap-outs and new battery buys with the cost-impact of the variable space they may consume onboard.

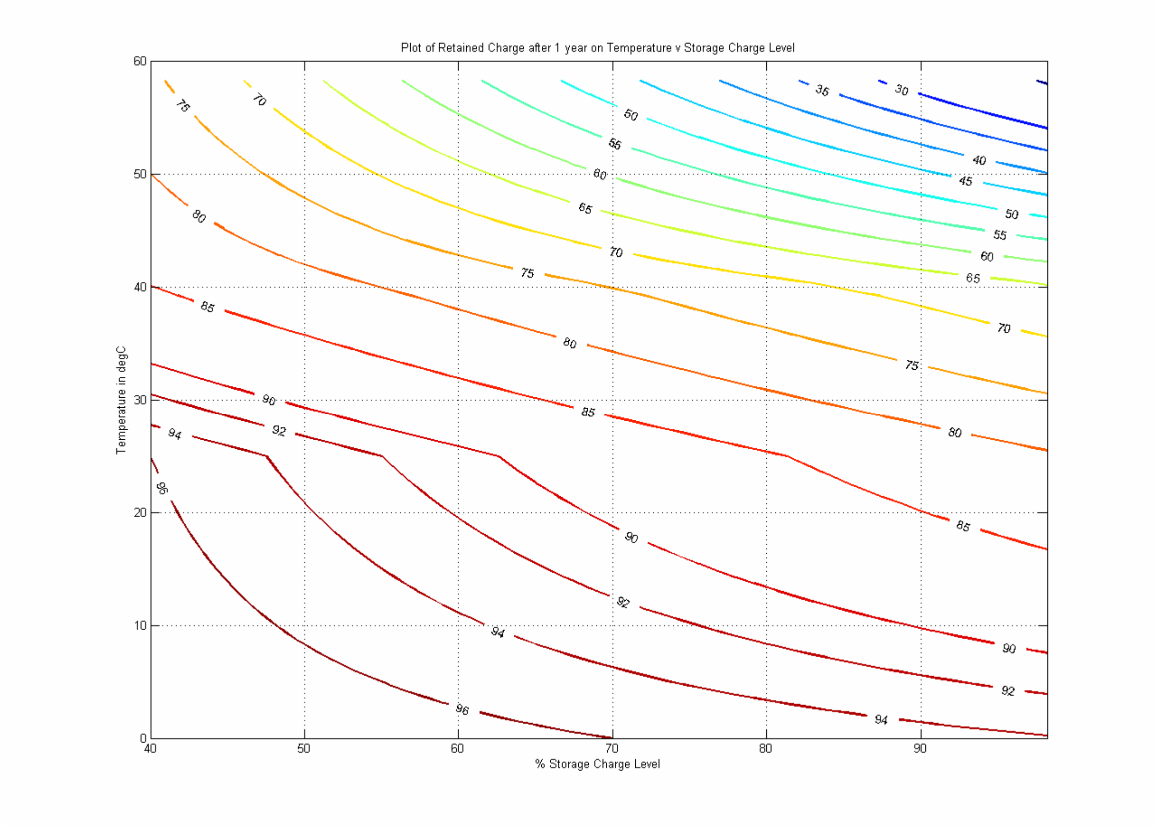


Figure 7: Annual Retained Charge on Ambient temperature v SCL

Figure 7 shows how important it is to recognise the rate of loss and how it is sensitive to ambient temperature and the SCL. Extended operations in warm water would be likely to have a significant influence. It has also been reported that the loss of battery capacity is not linear: it might be greatest in the first year then at a lower rate thereafter. This continues to be an area of study.

Lithium titanate batteries from Altairnano of the USA [Ref. 20] offer a design which has few of the safety risks with a capacity for rapid charging and discharging with little loss of capacity across a range of temperatures.

Distributed Energy Storage

The use of modern batteries in forward spaces near to the consumers will allow for 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. 21], 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.

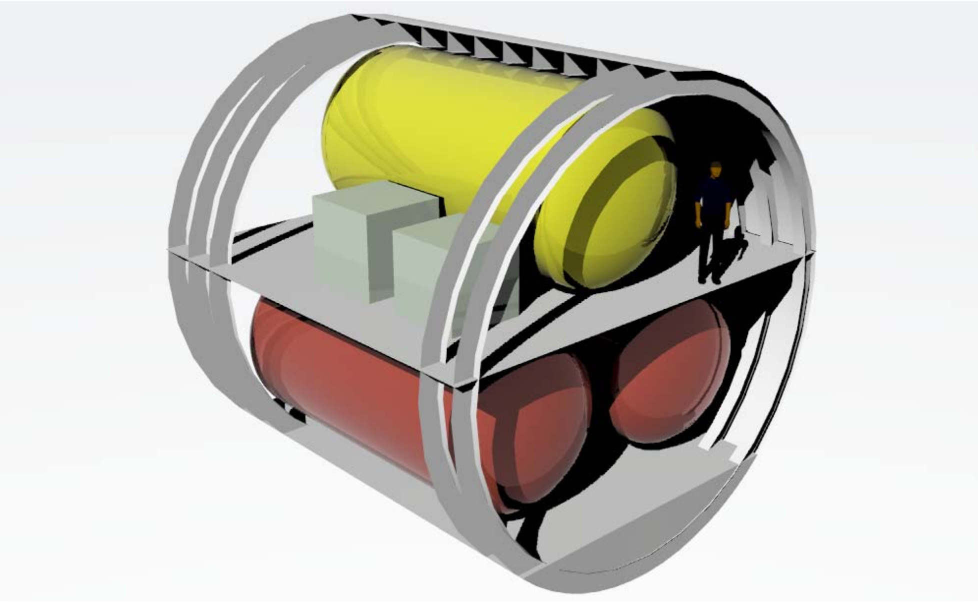


Figure 8: Vidar-36: Section View of Oxygen (Red) and Methanol (Yellow) Tanks

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.

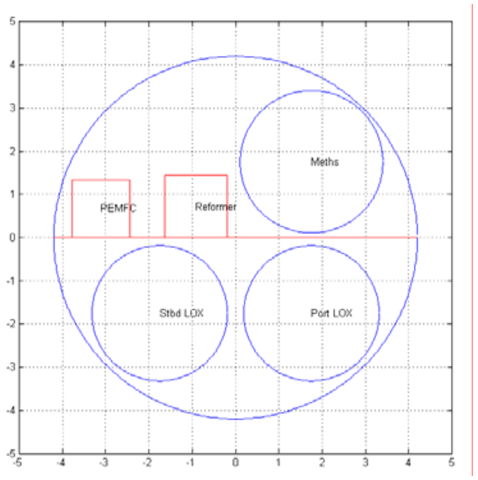


Figure 9: Indicative Fuel & Oxidant Storage

Oxygen storage

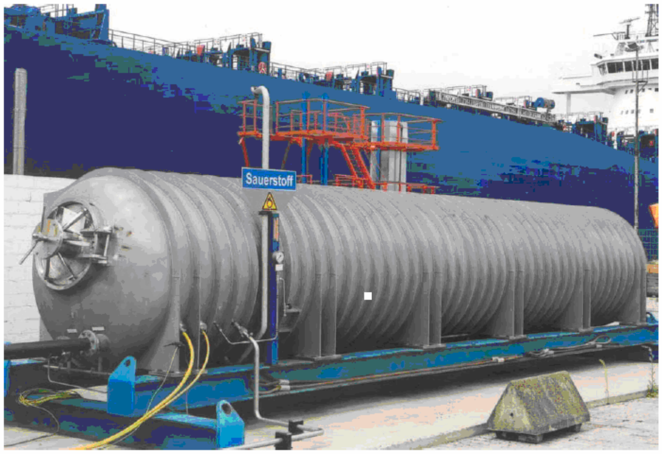
Whatever the power generation design there will be always be a need for stored oxygen in one form or another.

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. 22].

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. 23] 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.



A LOX Tank on the German 212 AIP Submarine (Source: HDW).

Figure 10: LOX tank

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. 24] 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 means 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 used 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.

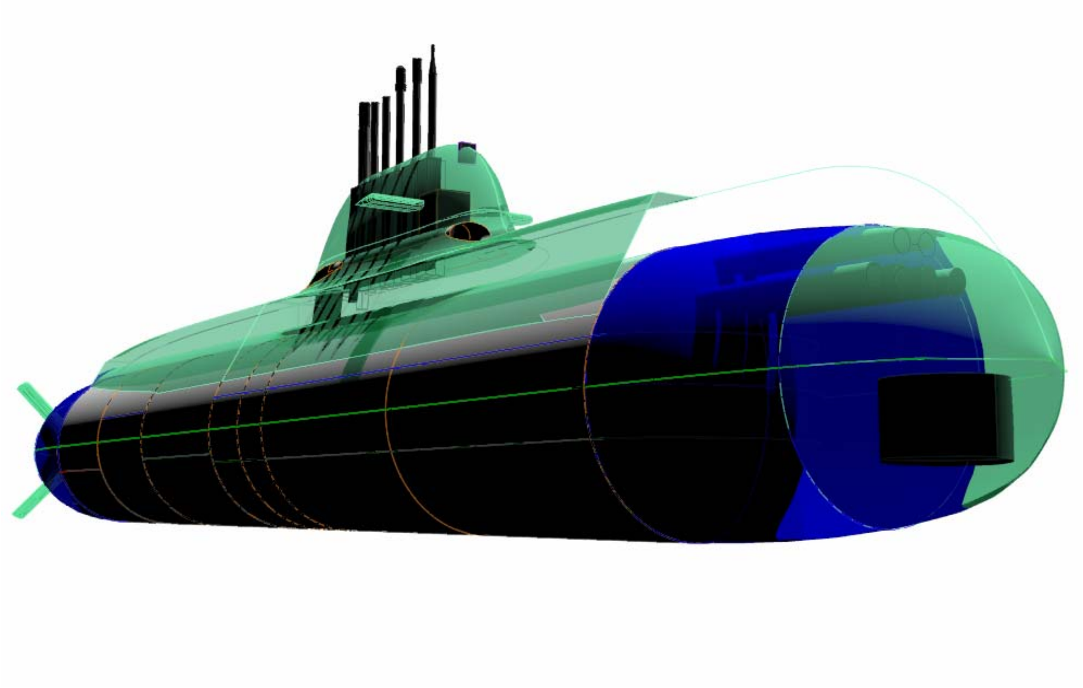


Figure 11: Isometric view of the Vidar-36

PUTATIVE SUBMARINE

BMT Defence Services now offers an indicative submarine design, the Vidar-36 [Ref. 25]. The baseline design is a conventional SSK but this has been developed to create the adapted Vidar-36 which is used to reflect some of the technologies discussed here. The adapted Vidar-36 design and its P&PS comprise the following

- A larger displacement (3,600 tonnes) to offer ocean-going performance;
- A brushless DC (active stator) propulsion motor rated at 6MW;
- PEMFC for submerged endurance[1];
- Liquid oxygen for submerged fuel combustion [1];
- Hydrogen located outboard [1];
- A 200kW SOFC and 1200kW (snort) diesel engine for snort power generation;
- Methanol for fuelling the SOFC;
- Zonal power supply units with lithium ion batteries;
- Four fewer staff due to removal of reciprocating machinery (i.e. diesels).

Figure 12 shows how the Vidar-36 performs for submerged endurance v speed.

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[1] As is currently the case.

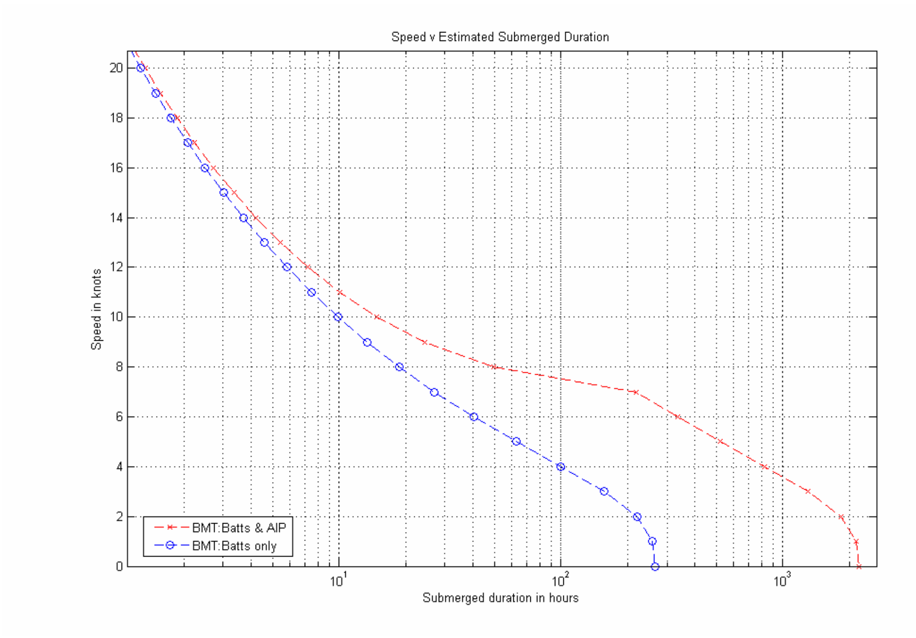

Figure 12 - BMT Vidar-36 design performance

The endurance when snorting is a key performance criterion for a platform which may have to travel long distances to theatre. For such a role it is envisaged that the diesel engine and the SOFC both use avcat. Figure 13 shows the anticipated performance for such an arrangement.

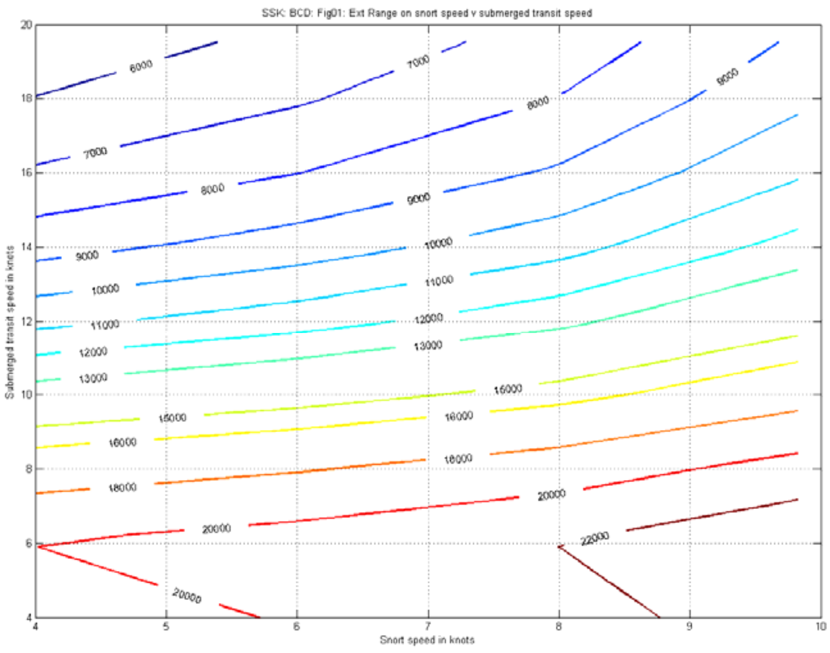

Figure 13: Extended range on snort speed v submerged transit speed.

Figure 13 shows how the use of additional fuel load of 50 tonnes permits a range of 22,000 miles if a very slow speed of advance is achieved. However the elapsed time is so long as to affect the limit of onboard provisions. A practical snort speed of 10 knots and a submerged speed of 15 knots is likely to be adopted to achieve 10,000nm.

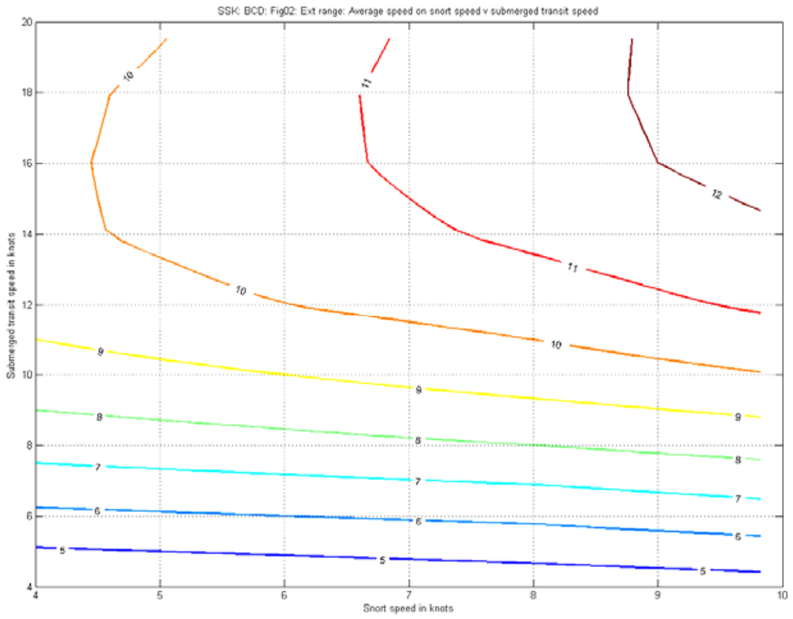

Figure 14: Average speed on submerged speed v snort speed

Figure 14 shows how an average speed of 12 knots is achieved with the snort and submerged speeds stated above. In such a case a distance of 10,000nm would be covered in 34 days which is consistent with the likely provisions assigned to the mission. Clearly too small a speed will have implications for the required number of submarines to achieve continuous patrol in theatre whilst others are on their way, re-provisioning or returning.

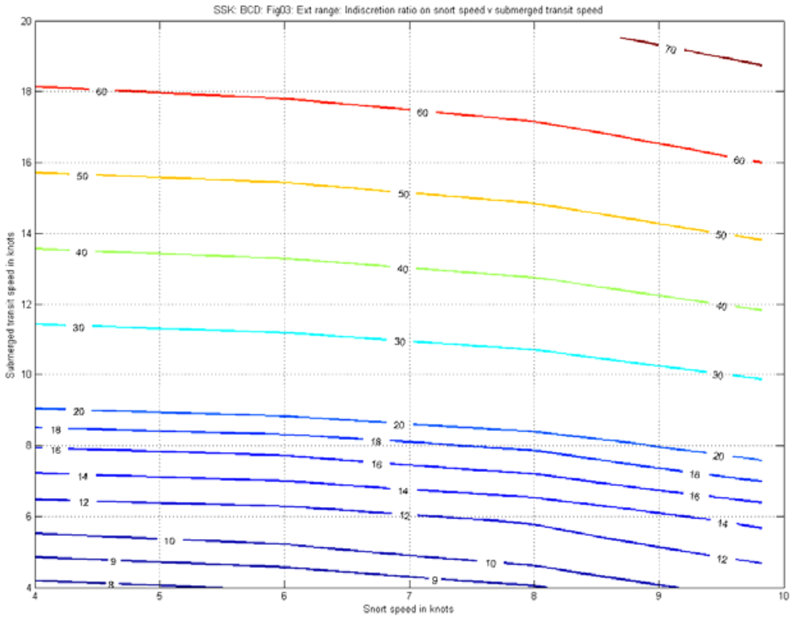

Figure 15: Transit Indiscretion ratio on submerged speed v snort speed

Figure 15 shows that once the transit speed increases the time spent recharging the batteries becomes a larger proportion of the elapsed time even if it does take less time to reach the destination. Once close to the theatre of operations the submarine would operate at much slower speeds and use the 200kW SOFC alone for battery recharging. Even though this would take longer with the much reduced power, there would be little or no underwater radiated noise. Figure 16 shows the likely indiscretion ratio with such an arrangement.

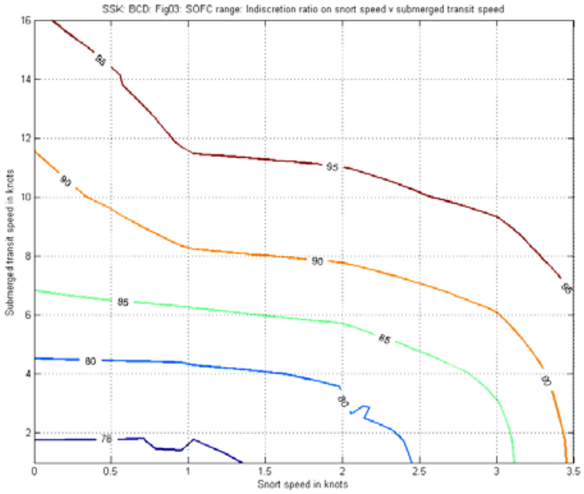

Figure 16: In Theatre: Indiscretion ratio on submerged speed v snort speed

SUMMARY

This paper has identified the key aspects which need to be considered when approaching the design of the power and propulsion system for an SSK, key of which are range and speed.

The emerging technologies which will enable performance improvements have been identified, chief of which are batteries, electric propulsion motors and advanced high temperature fuel cells.

The BMT Defence Services SSK design, the Vidar-36, has been used to demonstrate some of the performance improvements that can be achieved as well as the different operating modes that might be considered.

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