The importance of submarine air-independent power for operational agility

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Synopsis

Based on present technologies for the conventional submarine that are intended to improve stealth in the patrol area and using some key figures for the options that are available now, the authors propose to define agility of a non-nuclear submarine in a rational way. Using this methodology a comprehensive study was carried out for a large ocean going submarine that must also be able to operate in littoral waters. The major results are highlighted in the paper.

Keywords: Conventional submarines, Air independent Power generating concept, Submarine design, Submarine operation

1. Introduction

Submarines need to strike a balance between silent operation and operational speed. Operational speed is not a problem for nuclear SSN's but silent operation and manoeuvring in shallow water still is the strong point of a conventional submarine, even more so when some form of air independent power (AIP) generation is present.

The hybrid character of such boats requires more ingenuity to arrive at an operationally acceptable design. In order to combine operational agility with silent operation it is tempting to increase AIP power as characterised by the balance speed, but energy, represented by an oxidant (LOX) and possibly non fossil fuel (H2), must be increased too unless one is prepared to deplete the electrical energy in the (advanced Li-ion) batteries slowly during the mission, reducing the boat's operational capability at the end of its mission. Or alternatively some indiscrete snorting on diesel generators must be allowed but this is in violation of silent operation in theatre.

From a design viewpoint the main parameters of power for propulsion and auxiliary load on the one hand and generating power of diesel driven and AIP driven generators on the other, must be fine tuned with the division of the three ways of storing energy on board, i.e. in fuel, batteries and LOX (plus H_2 if necessary). Somehow these design parameters must be translated into the required agility of the submarine.

The case is for a relatively large submarine of around 3000 ton with ample internal space and adaptable to unknown future operations. The Concept of Operations calls for large range, high redundancy, Special Forces and stealth. The operational areas are both blue water and littoral. The missions are either low speed surveillance or contact trailing at appropriate speeds or a combination of both in order to arrive at a realistic translation of the clients requirement of agility in the operational theatre. The AIP systems considered will at least be Fuel Cell with H_2 storage, idem with reformer, a Stirling Engine and possibly Closed Cycle Diesel (CCD), the rationale being that mechanical AIP systems are easily scalable, less complex and present proven technology. An overview of the state-of-the-art of AIP and battery technologies is given in a parallel paper [Prins, 2020].

The paper intends to put forward the issues raised and will try to come forward with a quantitative analysis and ideas to support the decision making during the early design process.

Author's Biography

Douwe Stapersma graduated in 1973 as a mechanical engineer at Delft University of Technology in the field of gas turbines and then joined Nevesbu - the Dutch design bureau for naval ships - where he was involved in the design and engineering of the machinery installation of frigates and submarines, in particular the integration aspects, shock & noise and machinery control & automation. After that he was in charge of the design of submarines in a joint project organisation with RDM. In 1993 he became professor of Marine Engineering at the Royal Netherlands Naval College, now part of the Netherlands Defence Academy. In 2000 he was appointed a part-time professor of Marine Engineering and Marine Diesel Engines at Delft University of Technology. His main fields of interest are: energy generation and conversion on board ships, gas turbine and diesel exhaust emissions and ship propulsion and machinery dynamics. In 2013 he retired from NLDA but is still affiliated to TUD to supervise some PhD students.

Carel Prins graduated in 1964 as mechanical engineer at Delft University of Technology and was awarded a PhD in nuclear power engineering 1972. He joined the Rotterdam Dockyard Company in 1971where he held various positions and was general manager for design and engineering at RDM Submarines in Rotterdam until 2000, when he retired from the company. He is cofounder of the Dutch Underwater Knowledge Center (DUKC).

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2. Characteristics of Benchmark Submarine

The reference submarine is an approx. 3000 ton submerged displacement boat, with a single or semi-double hull. It is an ocean-going submarine that can be summarily defined by the following requirements.

- Expeditionary operations that shall include anti submarine warfare in defence of own units and hostile sea denial actions. This includes projection of threat.
- Protection of own surface units during expeditionary operations in potential hostile theatre. This may be in littoral waters, where the submarine is the ‘first on in’. The submarine establishes the situational awareness through Intelligence, surveillance and reconnaissance to establish possible presence of hostile submarines. There may also be the need to explore potential location of mines. At the end of the operation the submarine is ‘last one out’.
- The submarine mission includes the gathering of tactical and strategic intelligence on a worldwide scale.
- Covert deployment of Special Forces (SF) shall be supported by the submarine. This involves accommodation of SF personnel and their equipment. Furthermore, the submarine shall be provided with lockout facility. This includes a launching facility for UUVs and or AUVs, also required for Intelligence, Surveillance and Reconnaissance (ISR) missions.
- When on patrol, either in home waters or near distant areas, the submarine may be advised of suspect shipping nearing a harbour. With the information like position, heading, and speed the submarine may be ordered to intercept and investigate. When nearing the location of the Contact of Interest (COI) the submarine shall establish own speed for possibility of covert intercept capability.

These requirements necessitate a flexible capability for the submarine. Not only is there a large range to cover to enable the expeditionary mission, but also very covert local, often littoral, operations are to be executed. These almost surgical proceedings require stealth, almost continuous movement and sometimes relative high speed. It determines the desired agility of the boat. There are several atmosphere independent propulsion systems to choose from to best fit the requirements and furthermore Lithium-ion batteries are becoming available as an alternative for the lead-acid battery [Prins 2020].

The range of functional requirements of the submarine reflecting the targets for an analysis of the AIP capabilities initially include the following characteristics.

Length overall	m	approx.. 70
Beam	m	approx. 8.0
Inboard volume for battery	m3	175
Inboard volume for LOX	m3	125 - 225, to be decided
Range	nm	10 000 at10 kn submerged and 6 kn snorting
Autonomy	Weeks	8, at mean SOA of 8 kn
Max speed submerged	kn	20
Max covert speed on AIP	kn	4 - 9, to be decided
Endurance on battery	hours	100 – 200 at 2 kn submerged
Endurance on AIP	hours	300 – 500 at 2 kn submerged

Table 1 Main characteristics reference submarine

3 Analysis

3.1. Variations around a 3000 ton Submarine

Starting from the main characteristics in Table 1 a non-AIP boat would have a submerged displacement of around 2700 ton, see Fig. 1. With a modest or large AIP Plant & Storage the displacement would increase to around 3000 ton and 3200 ton respectively, refer to Fig. 2. The same enlargement could also be used to install a larger advanced battery. Some assumptions were made in order to carry out a quantitative analysis of and a comparison between alternatives, refer to Appendix I.

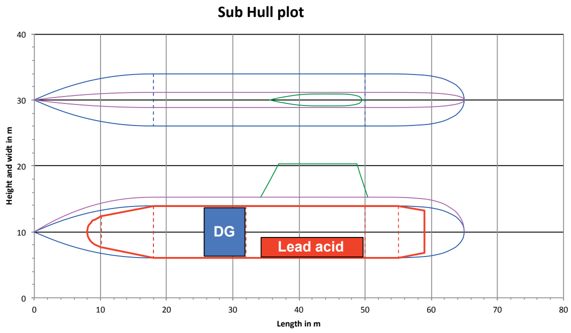
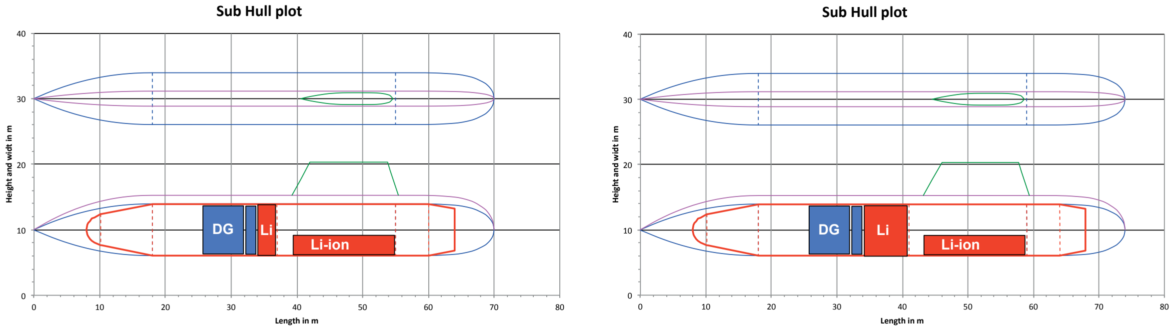
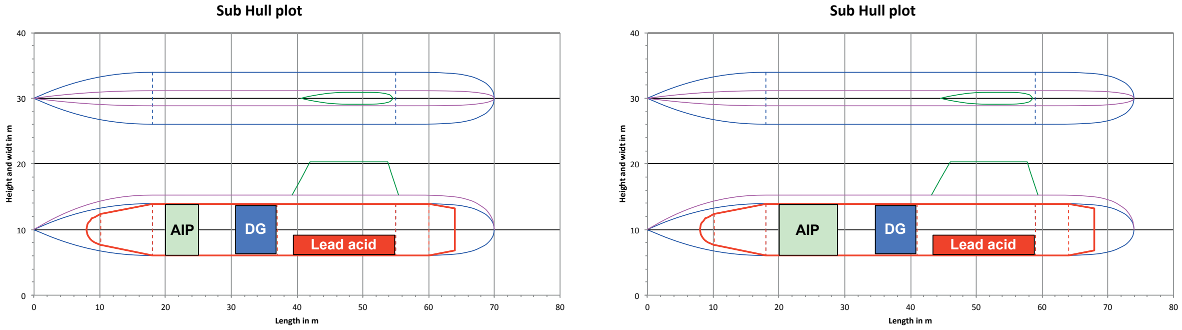


Fig. 1 Basic benchmark design: Subm displ 2714 ton, length 65 m



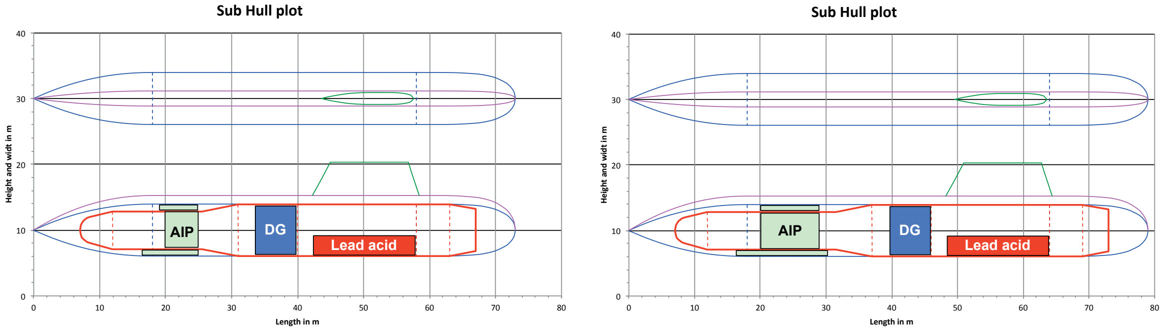
Subm displ 2965 ton. length 70 m

Subm displ 3186 ton, length 74 m



Subm displ 2965 ton. length 70 m

Subm displ 3186 ton, length 74 m



Subm displ 2865 ton, length 73 m

Subm displ 3076 ton, length 79 m

Fig. 2 Boat sizes for AIP (internal LOX or external LOX + H_2) and Li-ion options

3.2. Modes of Operation

Modes of Operation Conventional Submarine

The classical conventional submarine has the following operational modes:

0 Buffering (surfaced): DG on, controlled power
No recovery

1 Submerged: DG off
Recovery (snorting): DG on, full power
Recovery speed: = submerged speed

2 Submerged: DG off
Recovery (snorting): DG on, full power
Recovery speed: = 2 kts

In this paper only underwater operations will be considered, so mode 1 and 2. Range and endurance on fuel as well as the indiscretion ratio were calculated with SUBRANGE and electrical submerged range and endurance on batteries with SUBTIME. For a description of these tools see the Appendix II.

Modes of Operation for AIP:

An AIP submarine essentially has the same operational modes, however Mode 0 could be normal when submerged as well. And furthermore there is an extra mode where the AIP charger is running continuously but the boat still is alternating between a ((high) submerged speed and a (low) recovery speed :

0. Buffering (submerged): AIP on, controlled power
No recovery

1 Submerged: AIP off
Recovery : AIP on, full power
Recovery speed: = submerged speed

2 Submerged : AIP off
Recovery: AIP on, full power
Recovery speed: = 2 kts

3. Submerged: AIP on, full power
Recovery: AIP on, full power
Recovery speed: = 2 kts

These modes were already introduced in [Prins 1990] and are illustrated in Fig. 3.

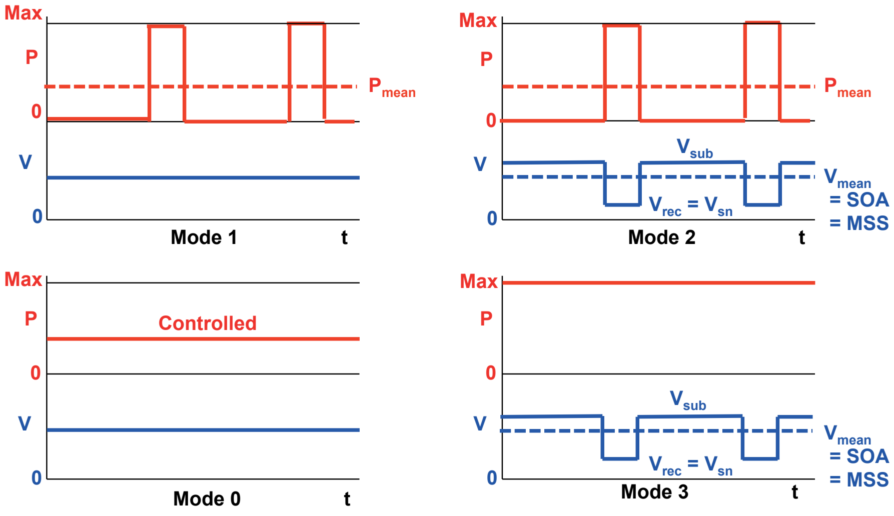


Fig. 3 Modes of operation conventional and AIP submarine

3.3. Operational Variables

Speed of Advance (SOA) versus submerged speed (SubSp)

It will be assumed that the battery during the operation in the long run will not be charged or discharged, i.e. there is energy equilibrium when battery power (P), being at least a function of speed (v), is integrated over the operational time (t) until end of mission (T):

$$\int_0^T \left\{ \delta_{Charge}(\mathrm{t}) - \delta_{\mathrm{Disharge}}(\mathrm{t}) \right\} \cdot \mathrm{P_{BAT}}(\mathrm{v}) \cdot \mathrm{dt} = 0 \qquad (1)$$

Where the block functions are pulses with pulse-width scattered over time and defined as:

$$\delta_{Charge}(\mathrm{t}) = 1 \quad \textit{and} \quad \delta_{Discharge}(\mathrm{t}) = 0 \quad \textit{during charge} \qquad (2a)$$

$$\delta_{Charge}(\mathrm{t}) = 0 \quad \textit{and} \quad \delta_{Discharge}(\mathrm{t}) = 1 \quad \textit{during discharge} \qquad (2b)$$

Charge/discharge power P_{BAT} is at least f(v) and velocity v is f(t). Together with pulse-width of δ-functions they define the *mission profile*. The times for charging and discharging:

$$\mathrm{T}_{Charge} = \int_0^T \delta_{Charge}(\mathrm{t}) \cdot \mathrm{dt} \qquad (3a)$$

$$\mathrm{T}_{Disharge} = \int_0^T \delta_{Discharge}(\mathrm{t}) \cdot \mathrm{dt} \qquad (3b)$$

Since an AIP submarine is discrete during recharging the battery, [Prins, 1988] introduced the term (submerged) Recovery Rate (RR) but its definition is the same as Indiscretion Rate (IR):

$$\mathrm{IR} = \mathrm{RR} \overset{\mathrm{def}}{=} \frac{\mathrm{T}_{Charge}}{\mathrm{T}_{Charge} + \mathrm{T}_{Discharge}} = \frac{\mathrm{T}_{Charge}}{\mathrm{T}} \qquad (4)$$

The Speed of Advance (SOA) is in fact a Mean Submerged Speed (MSS), i.e. the mean value of boat velocity (v) during *submerged* discharging (v_{Subm}, deep or at periscope depth) and during charging whether that is done during snorting (v_{Sn}, at periscope depth) or AIP recovery (v_{Rec}, deep or at periscope depth):

$$\mathrm{SOA} = \mathrm{MSS} \overset{\mathrm{def}}{=} \frac{1}{\mathrm{T}} \cdot \int_0^t \left\{ \delta_{Charge}(\mathrm{t}) \cdot \mathrm{v}_{\mathrm{Sn}/Rec} + \delta_{Discharge}(\mathrm{t}) \cdot \mathrm{v}_{Subm} \right\} \cdot \mathrm{dt} \qquad (5)$$

This mean speed characterises the operation and a navy should be capable to express its operational requirements in terms of range or endurance at a certain mean speed. For transit this results in a requirement for range and endurance on F76 for a certain SOA. For a conventional non-AIP submarine one could argue that only the deep and PD operations are relevant to the military mission and that during snorting the submarine is "not active in the mission". In that case submerged speed is the tactical speed for the commanding officer and there is a ground for presenting range and endurance on battery as well as the associated indiscretion rate in terms of submerged speed instead of the mean speed. That was the position taken in [Prins, 1990]. An AIP submarine however is military fully operational also when the AIP charger is running (which may be continuously!), so the Mean Submerged Speed is the important parameter. *In fact the Maximum Mean Submerged Speed (Max MSS, sometimes called the "balance speed") is a measure of the agility of the boat: for a nuclear sub it could easily be equal to the maximum speed of the boat. For a conventional non-AIP submarine it is essentially lower than maximum speed (typically 12 kn) and for an AIP boat it could even be much lower than that, but that raises the question whether such a boat is military credible.*

For constant recovery and submerged speed, as shown in the idealized speed profiles in Fig. 3 that were used for the analysis, this simplifies to a weighted sum of the two operational speeds:

$$\begin{aligned} \mathrm{SOA_{id}} = \mathrm{MSS_{id}} &= \frac{1}{\mathrm{T}} \cdot \left\{ \mathrm{v}_{Sn/Rec} \cdot \int_0^t \delta_{Charge}(\mathrm{t}) \cdot \mathrm{dt} + \mathrm{v}_{Subm} \cdot \int_0^t \delta_{\mathrm{Disharge}}(\mathrm{t}) \cdot \mathrm{dt} \right\} \\ &= \mathrm{v}_{Sn/Rec} \cdot \frac{\mathrm{T}_{Charge}}{\mathrm{T}} + \mathrm{v}_{Subm} \cdot \frac{\mathrm{T}_{Discharge}}{\mathrm{T}} \end{aligned} \qquad (6)$$

It is however argued that the results of such an analysis with an idealized speed profile is representative for the real operation profile with varying speeds. [Prins, 1990] used a typical intercept action to illustrate a submarine's operational profile, but ideally such an operation profile should be available as a histogram.

Range or Endurance?

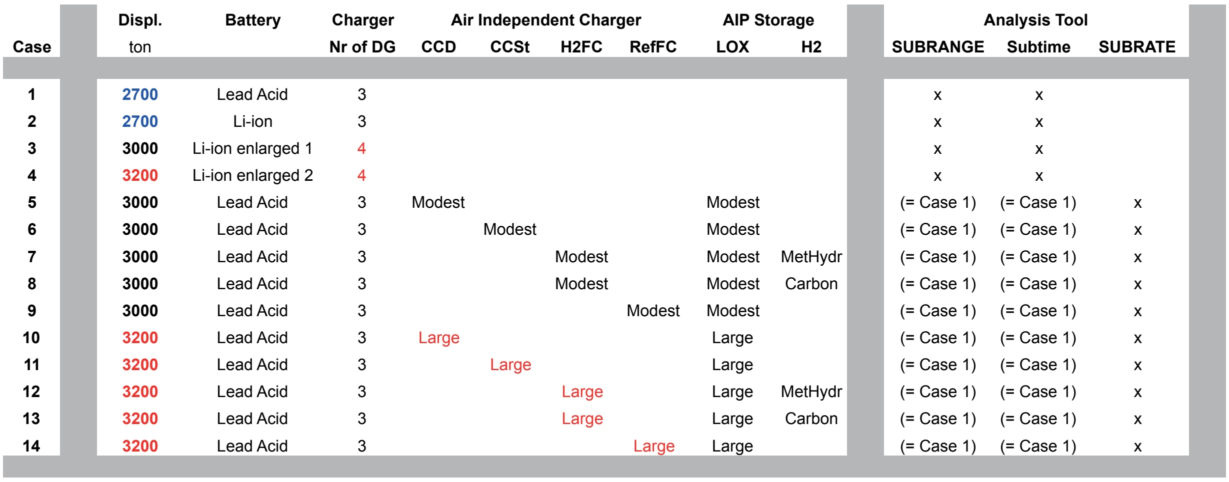
Finally there could be a discussion what is more important from a military tactical viewpoint, range or endurance. For a good reason the performance on fuel is expressed as a required range since the endurance (or rather autonomy) of the submarine is not only determined by the fuel but also on food, drinking water, torpedoes and last but not least staying power of the crew. For a less good reason performance on battery or AIP is often expressed in terms of endurance. However the submarine during patrol is normally designated to a certain area and it must be able to traverse that area several times during the mission, *so it is nautical miles that matter*. Also the range characteristic shows a proper optimum at a certain speed that occurs as a result of the auxiliary loads and all sorts of parasitic losses, i.e. all loads that are not speed dependent. Endurance has just a trivial maximum at minimum speed (in fact at zero speed: bottoming). In a characteristic of the endurance the range optimum is not only invisible but even lost when only an endurance is specified at the lowest speed (as in fact was done in Table 1 initially!).

In conclusion: a commanding officer needs a range at certain mean underwater speeds, so naval requirements should be formulated in those terms and the results of the analysis must preferably be presented in that way.

4. Parameter Variation: some Results

4.1 Overview of Cases

A comprehensive study was carried out into improving the capabilities of the submarine by a number of AIP options as summarised in Table 2 for which the boat was increased in size in two steps. Also improvements of the conventional non-AIP submarine were investigated by installing advanced batteries and additional DG sets. In order to compare with the AIP options the boat was increased in the same way for these non-AIP options. The cases will be discussed in more details when presenting the results. In the following only the most interesting results will be highlighted.



	Displ.	Battery	Charger	Air Independent Charger				AIP Storage		Analysis Tool		
Case	ton		Nr of DG	CCD	CCSt	H2FC	RefFC	LOX	H2	SUBRANGE	Subtime	SUBRATE
1	2700	Lead Acid	3							x	x	
2	2700	Li-ion	3							x	x	
3	3000	Li-ion enlarged 1	4							x	x	
4	3200	Li-ion enlarged 2	4							x	x	
5	3000	Lead Acid	3	Modest				Modest		(= Case 1)	(= Case 1)	x
6	3000	Lead Acid	3		Modest			Modest		(= Case 1)	(= Case 1)	x
7	3000	Lead Acid	3			Modest		Modest	MetHydr	(= Case 1)	(= Case 1)	x
8	3000	Lead Acid	3			Modest		Modest	Carbon	(= Case 1)	(= Case 1)	x
9	3000	Lead Acid	3				Modest	Modest		(= Case 1)	(= Case 1)	x
10	3200	Lead Acid	3	Large				Large		(= Case 1)	(= Case 1)	x
11	3200	Lead Acid	3		Large			Large		(= Case 1)	(= Case 1)	x
12	3200	Lead Acid	3			Large		Large	MetHydr	(= Case 1)	(= Case 1)	x
13	3200	Lead Acid	3			Large		Large	Carbon	(= Case 1)	(= Case 1)	x
14	3200	Lead Acid	3				Large	Large		(= Case 1)	(= Case 1)	x

Table 2 Overview of cases (x = Analysis carried out with tool)

4.2 Results of Analysis

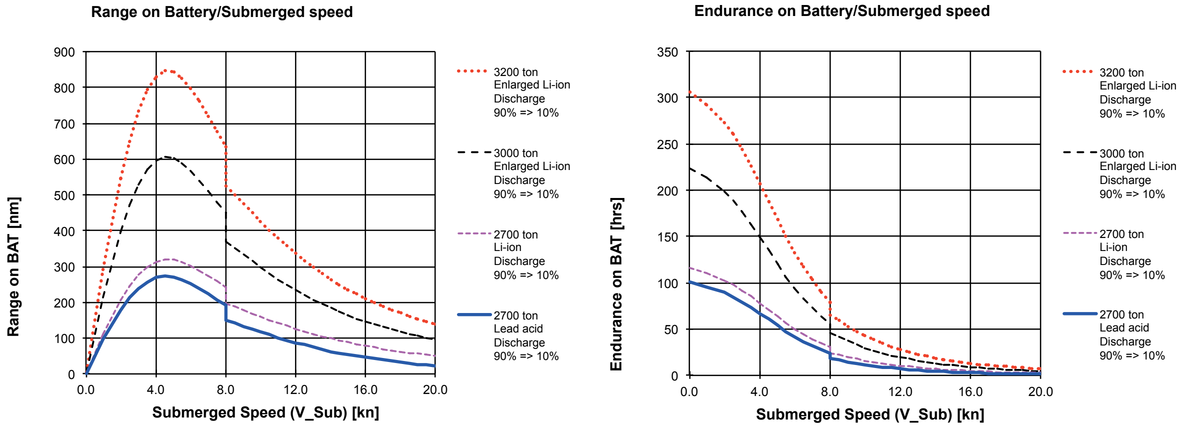
Conventional Submarine with Lead Acid or Li-ion Batteries

The benchmark was a conventional submarine of around 2700 ton with lead acid battery and a snorting power limited by the latter. Referring to Table 2, first the influence of Li-ion batteries was investigated in a boat of the same size assuming that the same battery volume could be installed see Table 3 for details. Note that due to the very low specific mass of Li-on batteries the boat will be lighter which, if not balanced by other equipment, must be compensated by adding ballast.

	Unit	**Lead Acid** HAGEN	**Li-ion** U-charge	Factor rel to LA	**Li-ion Enl 1** U-charge	Factor rel to LA	**Li-ion Enl 2** U-charge	Factor rel to LA	
Submerged displacement	ton	**2750**	**2700**		**3000**		**3200**		
Nr of batteries		**2**	**2**		**2**		**2**		
Nr of cells in string per battery		**212**	**64**		**64**		**64**		Adapted such that open battery voltage is 440/880 V
Open Cell Voltage at 10% DOD	V	**2.07**	**13.76**		**13.76**		**13.76**		
Battery voltage idem	V	439	881		881		881		
Cell weight	kg	**575**	**19.5**		**19.5**		**19.5**		
Cell Volume	Liter	**210**	**11.8**		**11.8**		**11.8**		
Spec density	kg/m3	2736	1647		1647		1647		
Nr of strings		**1**	**60**		**116**		**172**		Adapted such that volume is equal or larger
Total nr of cells		424	7680		14848		22016		
Total weight	ton	244	150	0.61	290	1.19	429	1.76	
Total volume	m3	89	91	1.02	176	1.97	261	2.93	
Ratio battery/compartment		**0.51**	**0.51**		**0.51**		**0.51**		For Li-ion: assumption !
Battery compartment	m3	175	178	1.02	345	1.97	511	2.93	
Spec density installed on board	kg/m3	1396	840		840		840		Li-ion is not contributing to ballasting the boat
Nr of DG's	[-]	**3**	**3**		**4**		**4**		
DE installed power	kW	**3900**	**3900**	1.00	**5200**	1.33	**5200**	1.33	

Table 3 Details of sizing the batteries and charging power

Due to the modest increase of energy density on a volumetric basis of present Li-ion batteries [Prins, 2020], the increase in underwater range and endurance - see Fig. 4 - is not too impressive. Increasing boat size commensurate with that what is necessary for AIP options however could dramatically increase underwater performance as shown in same Fig. 4. The earlier discussion "range or endurance?" is illustrated by comparing Fig. 4 (a) and (b): range exhibits a real optimum speed that the commanding officer can use to its advantage.



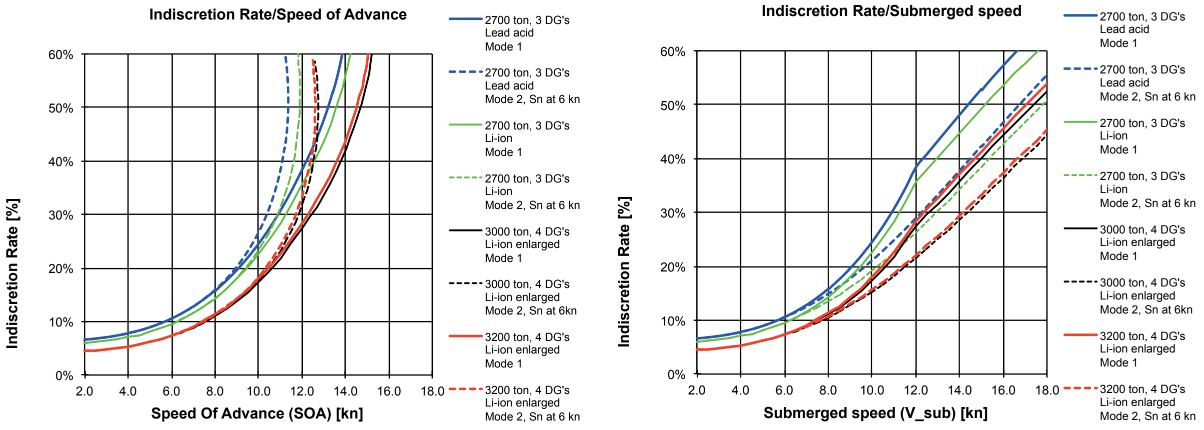
(a) (b)

Fig. 4 Range and endurance on batteries and options for improvement by installing Li-ion batteries

Another advantage of Li-ion batteries is the substantial lower cyclic losses, see Fig. 7 (b). This in itself improves the indiscretion rate, see Fig. 5. A main advantage of the Li-ion battery is its faster charging potential as already mentioned by [v.d. Mheen, 2014] which could further improve indiscretion rate. The market for submarine engines is very small. The power of the MTU 16V396 under snorting conditions over the years increased from 900 to 1200 kW. The new MTU 12V4000 within the same physical envelope even produces 1300 kW. Adding such an engine as a 4th DG set increases charging power and has important consequences for indiscretion rate: see Fig. 5. For that purpose and also to increase the Li-ion battery the boat was increased, first to 3000 ton and then further to 3200 ton, but the latter of course was done because of an ultra long range on batteries as previously shown in Fig. 4

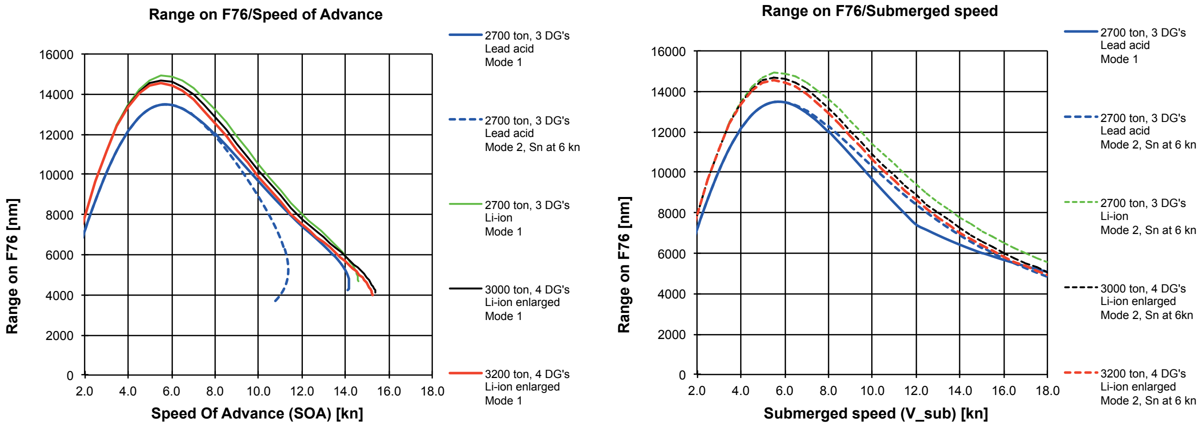
Like [v.d. Mheen, 2014] we present indiscretion rate versus Speed of Advance, which at least is the right thing to do for the transit. Note the reclining of the curves in Fig. 5(a) indicating the limitation of SOA due to slowing down during snorting. Often indiscretion rate is presented as function of submerged speed rather that speed of advance.as in Fig. 5(b). Note the difference when snorting speed is a constant low value as in mode 2. Apart from giving a more flattering value for IR, the rationale could be that submerged speed is the tactical speed used by the commanding officer while the snorting time is subtracted from the operational time and a lower snorting speed decreases snorting time. We will argue that this argument will not stand in case of recovery on AIP.

Now we can present the range on fuel as function of SOA, Fig. 6(a) showing that to get from A to B it is best to sail in to mode 1, i.e. not slowing down during snorting. Perhaps coming as a surprise a side effect of using Li-ion batteries is an increase in range. The reason of course is the lower indiscretion rate made possible by the lower cycle losses. The further reduction of IR by adding a diesel engine is combined with a larger battery and thus a larger boat. The net effect is that range will then be slightly reduced but still larger than the smaller boat with lead acid cells. Fuel on board has not been changed for all options. Range sometimes is presented as function of submerged speed giving a false impression that mode 2 will result in a larger range: see Fig. 6(b). But slowing down during snorting makes the trip taking longer so in the end more fuel is used. Nevertheless there are practical reasons to snort at a lower speed of e.g. 6 kn. From Fig. 6(b) a range of 10 000 nm for a submerged speed of 10 kn and snorting at 6 kn could be accepted as a requirement for the benchmark 2700 ton submarine with lead acid batteries and 3 DG sets. Fig. 7 shows that this will result in an SOA of approx. 9.3 kn, almost the same for all cases.



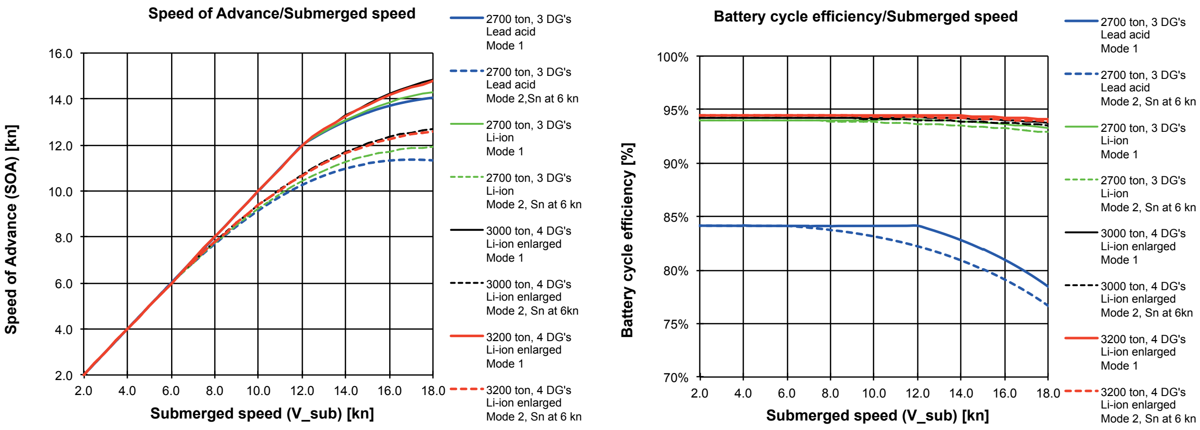
(a) (b)

Fig. 5 Indiscretion rate and effect of Li-ion batteries as well as increasing charging power (4th DG set), as function of (a) SOA and (b) submerged speed



(a) (b)

Fig. 6 Range on fuel (a) as function of SOA, showing that Mode 1 is the most fuel efficient and (b) as function of submerged speed showing that Mode 2 seems to give a larger range, which is misleading



(a) (b)

Fig. 7 (a) Speed of advance as function of submerged speed showing difference between mode 1 and 2 in slowing down the boat due to speed reduction during snorting (b) Battery cyclic losses for lead acid and Li-ion batteries compared

AIP Submarines: Overview of Options

A comprehensive study was carried out into the operational performance data of five AIP options based on data from [Prins, 2020] and detailed in Table 4. The "off-the-shelf" options (CCSt and H2/MH FC) are in blue lettering while the not available CCD and possible future FC options are in grey. For all options both a large and small AIP power was installed, approximately giving the boat a 9 kn or 4 kn balance speed. The smaller AIP plants got a modest combined weight for fuel and oxidant to be used in the patrol area, nevertheless requiring a larger boat of around 3000 ton. The larger AIP plants were given a larger budget for fuel and oxidant requiring a further increase of submerged displacement to around 3200 ton.

For all options the same budget for fuel and oxidant in the patrol area (i.e. 110 ton for the large AIP plants and 65 ton for the smaller ones) was stipulated. However due to the weight of the metal hydride used as carrier for the hydrogen, the hydrogen fuel celled boat falls short in performance. Whilst the LOX and H_2 is carried outboard and its volume is small for such a boat, perhaps space for a larger weight budget could be found. Of course this could result in a weight critical boat.

		Closed Cycle Diesel		Closed Cycle Stirling		Hydrogen Fuel Cell Metal Hydryde		Hydrogen Fuel Cell Carbon		Reformer FC	
Submerged displacement	ton	**3200**	**3000**	**3200**	**3000**	**3200**	**3000**	**3200**	**3000**	**3200**	**3000**
Nr of units		*2*	*2*	*10*	*4*	*6*	*8*	*6*	*8*	*2*	*2*
Installed power basic unit	kW	*400*	*150*	*75*	*75*	*120*	*34*	*120*	*34*	*350*	*140*
Total installed power	kW	800	300	750	300	720	272	720	272	700	280
Efficiency		*40%*	*40%*	*30%*	*30%*	*55%*	*55%*	*55%*	*55%*	*50%*	*50%*
sfc (F76 or H2)	g/kWh	*209*	*209*	*279*	*279*	*55*	*55*	*55*	*55*	*167*	*167*
Stoichiometric ratio		*3.40*	*3.40*	*3.40*	*3.40*	*8.0*	*8.0*	*8.0*	*8.0*	*3.40*	*3.40*
sLOXc	g/kWh	*712*	*712*	*949*	*949*	*436*	*436*	*436*	*436*	*569*	*569*
Electrical unit power	kWe	*380*	*143*	*71*	*71*	*120*	*34*	*120*	*34*	*350*	*140*
Total electric power	kWe	760	285	713	285	720	272	720	272	700	280
Auxiliary power/unit	kWe	*28*	*10.5*	*3.75*	*3.75*	*3.6*	*1.02*	*3.6*	*1.02*	*17.5*	*7*
Total auxiliary power AIP	kWe	56	21	37.5	15	21.6	8.16	21.6	8.16	35	14
Useful electric power	kWe	704	264	675	270	698	264	698	264	665	266
Balance speed	kn	9.5	4.5	9.2	4.7	9.4	4.5	9.4	4.5	9.2	4.3
Total Fuel (F76)	ton	224	214	225	215	200	200	200	200	225	215
Fuel for transit (F76)	ton	**200**	**200**	**200**	**200**	**200**	**200**	**200**	**200**	**200**	**200**
Fuel for AIP (F76)	ton	*24*	*14*	*25*	*15*					*25*	*15*
Fuel for AIP (H2)	ton					*1.4*	*0.8*	*3.8*	*2.2*		
Packaging fuel (H2 only)	ton					*98*	*58*	*76*	*45*		
Argon (CCD only)	ton	*4.1*	*2.4*								
Oxidant for AIP (LOX)	ton	*82*	*48*	*85*	*50*	*11*	*6*	*30*	*18*	*85*	*50*
Total fuel and oxidant for AIP		110	65	110	65	110	65	110	65	110	65
Total Fuel & Oxidant	ton	310	265	310	265	310	265	310	265	310	265

Table 4 Details of AIP options

AIP Submarine with Closed Cycle Diesel and Stirling Engine

As argued a measure of agility for an AIP submarine is the distance covered on LOX in the patrol area and the mean submerged speed during the patrol. Therefore Fig. 8 presents the range on LOX versus MSS for the 4 possible modes of operation introduced in Fig. 3. Next to the existing Closed Cycle Stirling (CCSt) plant the now abandoned Closed Cycle Diesel (CCD) is shown in the background.

First of all for both CCSt and CCD Mode 1 results in the largest range and not Mode 0. This may come as a surprise since the on-off operation of Mode 1 suffers battery cycle losses and the continuous operation of Mode 0 not. However the influence of the AIP related auxiliary power is important and the advantage of mode 1 is that this parasitic power also is switched on/off. Another factor is that mode 0 suffers from increasing sfc at part load and fuel consumption of course is tied to LOX consumption.

Mode 2, same as for snorting, shows a limiting MSS, of course caused by the submarine slowing down to 2 kn during recovery. Same as for range on fuel, if one wants to go from A to B in the patrol area Mode 1 is best, i.e. no slowing down during recovery. As explained mode 3 (AIP is 'on' during high submerged speeds, alternating with recovery on lower speeds) is essentially only possible for AIP and not for DG operation. The price of keeping the AIP continuously 'on' at full power is a lower range as shown in Fig. 8. There is however a case for Mode 3 as we will see when discussing recovery rate.

The choice between a small and a large AIP plant power is shown as a huge difference in extent of possible Mean Submerged speed between Fig. 8 (a) and (b). In fact limiting the MSS to around 4 kn prevents the submarine to reach optimum range and forces it always to be in the speed range where auxiliary loads dominate the picture and where to obtain maximum range the boat must accelerate instead of decelerate. Since size of AIP power was coupled with amount of LOX stored, also the range of the small AIP plants is considerably less. It could be questioned whether the AIP boat with small power/storage are military credible, proving that if one invests in AIP it must have a certain size to be useful.

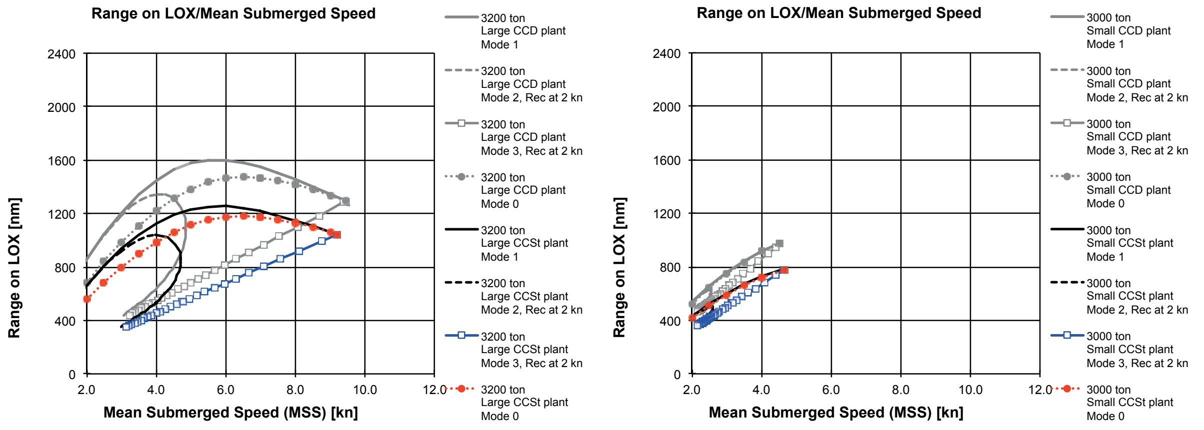
Finally it is a pity that development of the CCD has stopped: the diesel has a much better sfc and thus associated LOX consumption and is also much easier to scale up in power. So both in terms of range and balance speed, the two components of "agility" it is superior to the Stirling machine.

When plotting Recovery Rate as function of MSS, Fig. 9, Mode 2 exhibits a reclining curve (same as IR for snorting, refer to Fig. 5(a)). Mode 0 is given arbitrarily the value RR=100% since the AIP is always on (but one could also defend that RR=0% since there is no recovery). More important RR is lowest for Mode 3, i.e. when the AIP is kept running also during dashes in the high speed range above the balance speed. The reason is logical: the AIP then acts as a negative auxiliary load causing less discharge of the battery, which can then be recharged faster when speed is low again. However as we have seen it will cost LOX and therefore the penalty is a loss of range.

The effect of plant size, Fig. 9(a) versus (b) again is the extent of MSS, limited by the smaller plant during the whole mission to essentially lower speeds. The reclining slope of RR for mode 2 and the negative slope or mode 3 in Fig. 9 at first seems puzzling but becomes clear when plotting RR as function of submerged speed, Fig. 10. Then the excursions into the higher speeds are shown better, although the figures gives the false impression that these speeds can be sustained for a long period.

Finally the RR is the factor that transforms the submerged speed, which is important to the commanding officer as a tactical speed on a short time scale to the Mean Submerged Speed, i.e. the speed that can be sustained for a longer period during the patrol, see Fig. 11.

The plots for recovery rate and MSS, Fig. 9, Fig. 10 and Fig. 11 almost coincide for CCD and CCSt as shown, but this is also true for the Fuel Cell options: the behaviour is almost completely determined by the value of the AIP power.



(a) (b)

Fig. 8 Range on LOX of Closed Cycle Stirling compared to Closed Cycle Diesel (in grey) as function of Mean Submerged Speed, (a) for a large plant and LOX storage and (b) for a small plant and modest LOX storage

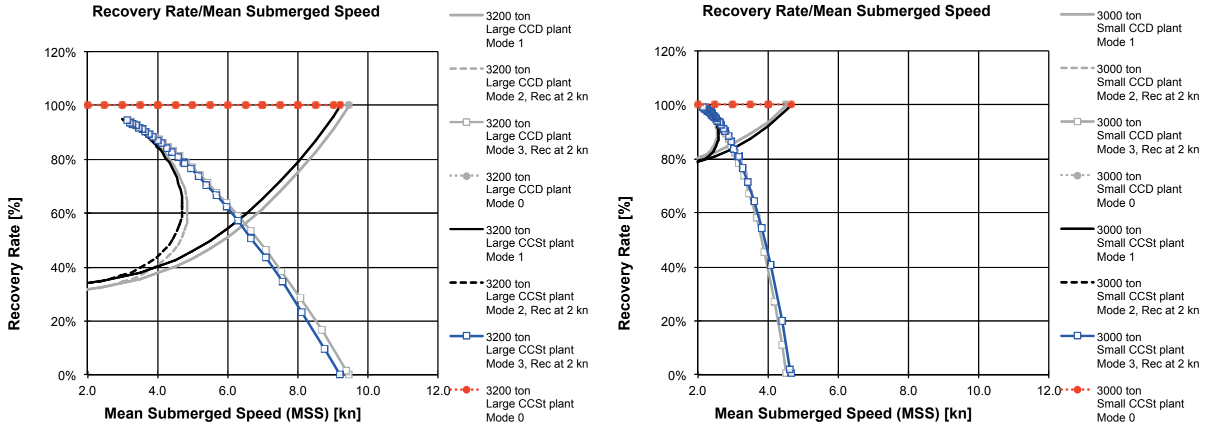


Fig. 9 Recovery Rate as function of Mean Submerged Speed, a) for a large plant and LOX storage and (b) for a small plant and modest LOX storage (almost the same for al AIP options)

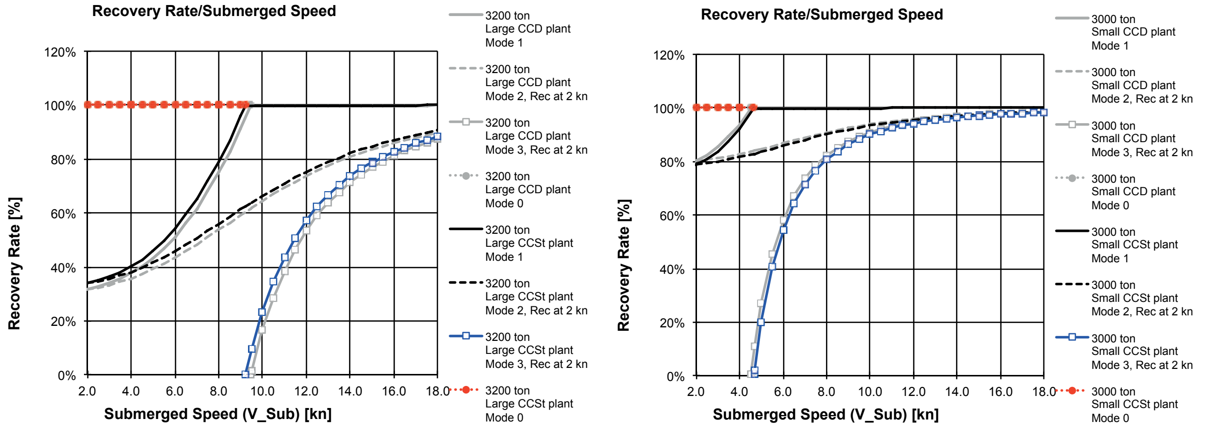


Fig. 10 Recovery Rate as function of submerged speed, (a) for a large plant and LOX storage and (b) for a small plant and modest LOX storage (almost the same for al AIP options)

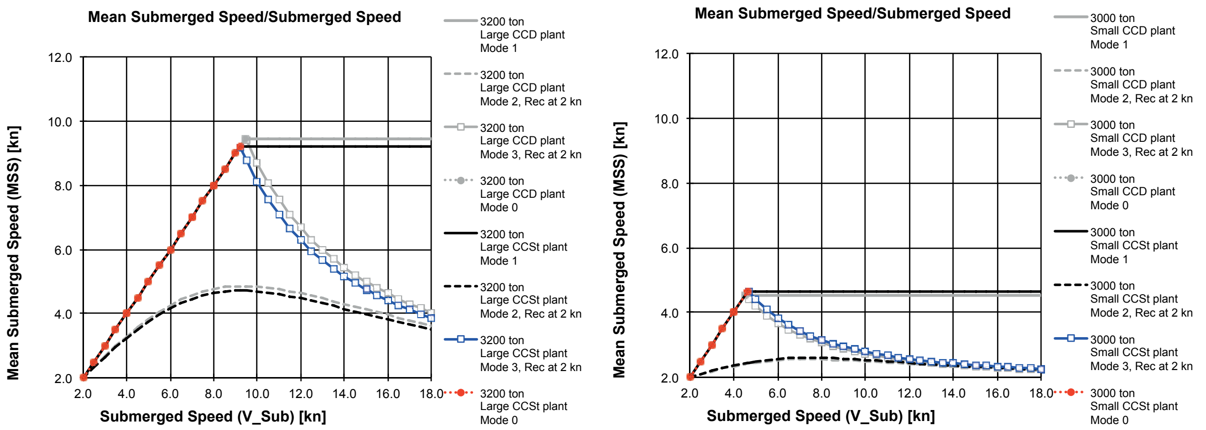


Fig. 11 Speed Of Advance as function of submerged speed, (a) for a large plant and LOX storage and (b) for a small plant and modest LOX storage (almost the same for al AIP options)

AIP Submarine with PEMFC and H_2 Storage or Reformer

Next to the Stirling installation the PEM Fuel cell running on H_2 is the other proven system. Due to the heavy weight of metal hydride used for storing the H_2 it is difficult to carry a large volume of LOX. This limits the range severely: see Fig. 12. This result may be too pessimistic since the volume-wise more could be carried. Actually in Fig. 2 for this AIP option twice the volume is drawn and when the total weight budget for LOX + H_2 + storage could be doubled as well the range on LOX would go up proportionally. The heavy weight of metal hydride also is somewhat counteracted by placing the cannisters outboard where they add to the submerged displacement. If located low they can act as ballast and even help the lack of weight of future Li-ion batteries. LOX can be located in- or outboard, depending on safety philosophy. The handicap of heavy storage of hydrogen could benefit from carbon based storage [Prins, 2020], where a promised 5% weight percentage of H_2 could improve submerged range substantially, see grey lines in Fig. 12 and comparing to Fig. 8, could compete in range with the Stirling option.

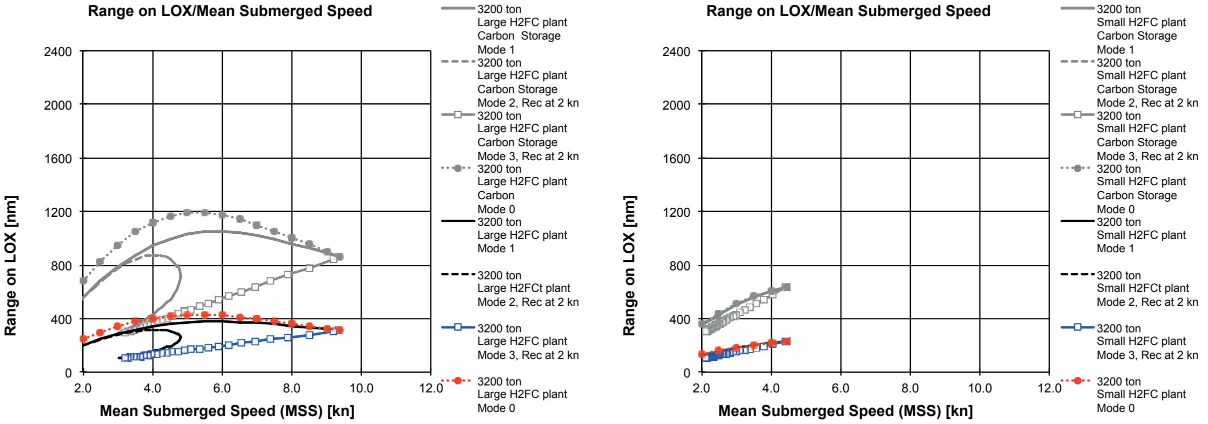


Fig. 12 Range on LOX of Fuel Cell operating on Hydrogen stored in Metal Hydride compared to Fuel cell with Hydrogen stored in Carbon Nano Structures (in grey) as function of Mean Submerged Speed, (a) for a large plant and LOX storage and (b) for a small plant and modest LOX storage

The limited range of the hydrogen PEM FC could also be solved with a fuel cell and a reformer so that like the Stirling engine the fuel cell can use F76 as a fuel. But that introduces other difficulties. First like the CCSt (and CCD) also CO_2 is produced (the PEM cell only produces water). Also a reformer will be very sensitive to sulphur content in the fuel and last but least the dynamics of the reformer will be slow [van Oosten, 2006] but in case of a submarine there is the battery to absorb the load variations. In future there may be a SOFC with internal reforming. These will also be slow in load response but its capability to handle F76 seems better assured. Anyway the alternative of a fuel cell with internal or external reforming is considered *not* to be an off-the-shelf solution and therefore is shown in grey in Fig. 13. Nevertheless the RefFC in terms of range comes out best of all options, so development should be encouraged.

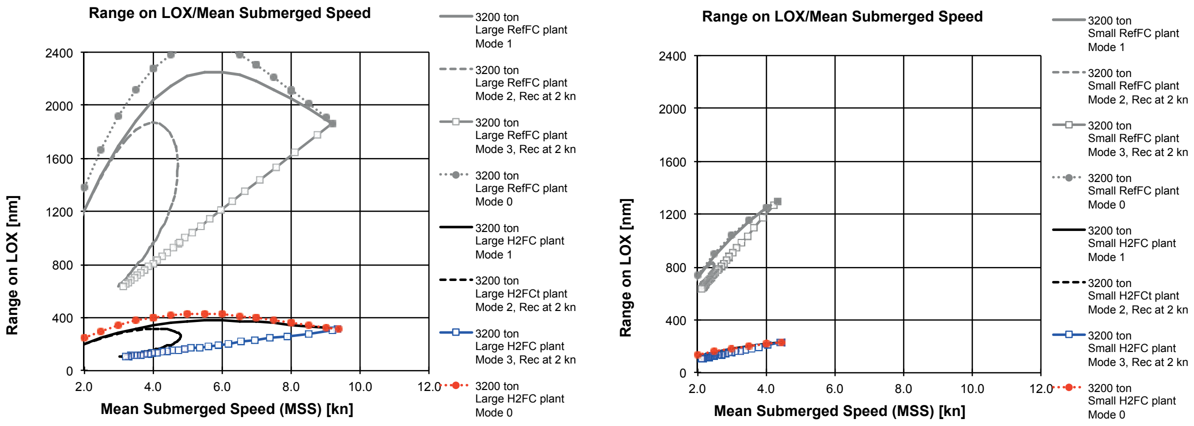


Fig. 13 Range on LOX of Fuel Cell operating on Hydrogen compared to Fuel cell with F76 reformer (in grey) as function of Mean Submerged Speed, (a) for a large plant and LOX storage and (b) for a small plant and modest LOX storage

It is remarkable that for the Fuel Cell options Mode 0 gives the highest range as opposed to Mode 1 for the CCSt and CCD. The reason is that auxiliary power, in particular for the PEMFC, was assumed to be lower than for de Closed Cycle options. And thus the advantage of Mode 1 is not only switching off the AIP plant but also that its auxiliary load is less for the fuel cells. But perhaps more important is the fact that efficiency of the fuel cell becomes better at part load: we assumed 55 % at full load, rising to 68% at 30% load.

5. Conclusion

The paper has looked with an open mind at new technologies for the conventional submarine - with and without AIP - that might improve stealth in the patrol area without loosing agility.

The Lithium-ion battery promises a quantum leap in energy capacity and charging rate but on inspection the increase in energy density (volume basis) is as yet not impressive, contrary to the specific energy (mass basis). But the latter for the submarine might be a disadvantage since batteries also have a function as ballast and a stability problem may enter the design problem. Also there is a safety issue with respect to fire. But putting these objections aside the combination of even a modest energy storage increase on board and the opportunity to increase charging power could raise the underwater range on battery and lower the indiscretion rate, in particular when one is prepared to enlarge the boat (same as required for AIP) to make room for larger batteries and diesel generator sets. This would enhance the military value of the boat without going into the complications of AIP.

AIP essentially is a hybrid solution that is betting on two horses: on the one hand there still are the battery and DG sets, but on the other hand the AIP plant and necessary oxidant in the form of LOX and possibly hydrogen as a fuel have to be integrated into the submarine. An AIP boat therefore is essentially larger and definitely more complex. It is shown in the paper that if the available space and weight for the required size of plant and storage capacity is insufficient the result might be a submarine that has a low military credibility. Then one could question whether it would perhaps be better not to opt for the complexity of AIP and to bet on a future breakthrough of the Li-ion battery.

In order to answer these sort of questions a method is required to analyse the operations and key performance parameters that characterize agility. When looking for key performance parameters one stumbles over old discussions: "endurance or range" and "Speed of Advance or submerged speed". General wisdom has it that range and SOA determine transit performance while endurance and submerged speed are important in theatre. In the paper it is argued that since SOA mathematically is a Mean Submerged Speed (MSS) it characterises the fluctuations between dashes of high submerged speed and recovery at low speed. The MSS for a conventional submarine, and even more so for an AIP submarine, is essentially low and this represents the Achilles heel of the non-nuclear submarine. But only by showing this weakness it can be improved. The important difference between the AIP and non-AIP boat is that the latter is vulnerable during snorting while the former is fully operational during recovery.

Mean submerged speed expresses the speed range in which the boat can sustainably run for longer times in the patrol area. Its maximum value is the balance speed. For conventional snorting that is around 12 kn, but for small AIP plants it may be very (if not too) low. A military credible submarine must have a balance speed of at least 8 to 10 kn. That requires a certain AIP power and will also result in high but at least useful recovery rates.

Range on LOX and/or battery must have a relation with the size of the patrol area, which might be a square of 100 nm that must be traversed several times during the mission. Therefore an underwater range on LOX and/or batteries should be in the order of magnitude of e.g. 1200 to 1800 nm.

The combination of range and Mean Submerged Speed is a measure of agility as was shown for the existing AIP solutions based on Stirling engine or PEM Fuel Cells, which can be compared with the performance of a non-AIP boat having advanced Lithium-ion cells and future developments in hydrogen storage and reformer fuel cells.

The Closed Cycle Diesel, if available could give a good range and balance speed. The Stirling option can have a credible submerged range but the scalability of power of the Stirling engine makes a sufficient balance speed problematic. The PEM Fuel cell can provide sufficient power but has a storage weight problem, which limits the range and tends to cut weight for fuel, diesel engines and pressure hull, thereby impairing the ocean-going capabilities. Storage of hydrogen in carbon nano-structures could solve this problem. The fuel cell with internal or external reformer literary could be a dream solution. The choice at the moment is not easy to make and the paper intents to support the debate.

References

[Klein Woud, 2019] J. Klein Woud, D. Stapersma; "Marine Engineering, Design of Propulsion and Electric Power Generation Systems"; Revised edition, Witherby, Livingston Scotland 2019, ISBN 1-85609-849-9

[van de Mheen, 2014]. R.J van de Mheen, I. Whithelegg; "A comparison of energy storage methods for conventional diesel-electric submarines" 12th Int. Nav. Eng. Conf. (INEC 2014), Amsterdam May 2014, IMarEst,

[van Oosten, 2006] B.T.W. van Oosten, D. Stapersma, I.P. Barendregt, J. Klein Woud.; "Dynamic simulation of a fuel cell with reformer"; 8th Int. Nav. Eng. Conf./World Maritime Technical Congress (INEC/WMTC 2006), London May 2006, IMarEst

[Prins, 1988] C.A. Prins, A.A. Ham; "In search of air independence; Maritime Defence"; June 1988

[Prins, 1990] C.A. Prins, D. Stapersma; "Atmosphere Independent Propulsion (AIP) for ocean going diesel electric submarines"; Submarine Symposium U 90, Stockholm May 1990

[Prins, 2020] C.A. Prins, D. Stapersma, "AIP for Ocean Going Submarines: off-the-shelf or promise", INEC 2020

Glossary of Terms

AIP	Air Independent Propulsion (various systems)
AUV	Autonomous Underwater Vehicle
CCD	Closed Cycle Diesel
CCSt	Closed Cycle Stirling
COI	Contact of Interest
DOD	Depth of Discharge
FC	Fuel Cell
H2FC	Hydrogen Fuel Cell
IR	Indiscretion Rate
ISR	Intelligence, Surveillance and Reconnaissance
LOX	Liquid Oxygen
MEM	Main Electric Motor
MSS	Mean Submerged Speed
PD	Periscope Depth
PEMFC	Proton Exchange Membrane Fuel Cell
RefFC	Fuel cell with internal or external reformer
RR	Recovery Rate
sfc	Specific Fuel Consumption
SF	Special Forces
SOA	Speed of Advance
SOFC	Solid Oxide Fuel Cell
SubSp	Submerged speed (speed during discharge of battery)
UUV	Umbilical Underwater Vehicle

Appendix I: Assumptions for Reference Boat and AIP and enlarged Battery Versions

- Submerged displacement is 88% of envelope displacement
- Delivered power coefficient Cd[1]= 0.016 w.r.t. envelope displacement
- Shaft losses: constant torque loss 4 kNm at deep and 2 kNm at snorting depth
- MEM power installed 4200 kW with nominal efficiency of 94%, decreasing at part load
- Auxiliary load normal operation 180 kW, survival operation 90 kW
- Extra auxiliary load during snorting 35 kW
- Extra auxiliary load during AIP per unit depending on type of AIP, see Table 4
- Battery at 50% DOD having nominal voltage of 422 V and with internal resistance of 8.9 mOhm for lead acid battery and 849 V resp 3.4 mOhm for Li-ion
- Electrical cable losses included (MEM armature 1 mOhm, battery 1 mOhm, generators 0.5 mOhm)
- DE unit mechanical power 1300 kW with nominal sfc = 225 g/kWh, always running full power or off
- AIP unit mechanical power and nominal sfc depending on type of AIP, see Table 4; sfc increasing at part load for CCD and CCSt but increasing for FC
- Nr of DG: see Table 3
- Nr of AIP chargers: see Table 4
- DG and AIP generator efficiency 95%
- LOX consumption 3.4 times F76 consumption and 8 times H2 consumption
- Fuel 220 ton, LOX + Fuel for AIP 110 ton (*for H2 incl. M Hydride mass*), both 95% usable
- Battery type and capacity: see Table 4

Appendix II: Analysis Tools

The following tools were used for the analysis:

SUBRANGE

- Analysis of snorting/submerged operation (DG's on/off) assuming not too large variations of battery charge around some nominal DOD (Mode 1 & 2)
- Buffering (Mode 0) is not yet included as it is in practice confined to surface operation
- Calculation of range and endurance on F76 as well as indiscretion rate (IR) and speed of advance (SOA)

SUBRATE

- Analysis of recovery/submerged operation (AIP's on/off) assuming not too large variations of battery charge around some nominal DOD (Mode 1&2)
- Also analysis of operational modes where AIP is continuously on and AIP power may be controlled to keep battery charged as far as possible (mode 0 and 3)
- Calculation of range and endurance on LOX as well as submerged recovery rate (SRR) and mean submerged speed (MSS)

SUBTIME

- Analysis of submerged discharging of batteries in three steps to allow for non-linear behaviour as function of DOD

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[1] Definition according to chapter 3 of [Klein Woud, 2019]