SUBMARINE POWER AND PROPULSION: BALANCING THE ENERGY ELEMENTS

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SUMMARY

The challenge for designers of submarines with an ocean going capability is to achieve a power and propulsion system design which allows the ambitious transit distances to be achieved whilst still allowing for stealthy operations in the mission area. Using the BMT concept submarine design, Vidar-36, this paper shows the consequences of changes to the size of the main battery, the main engine, embarked fuel and the AIP capability within prescribed limits.

The way in which the different combinations of these energy elements affect the operating parameters, such as the achievable range, for a range of snort and submerged speeds is shown.

The performance benefits of modern batteries and modern diesel-engined generating sets (DG sets) are also explored. This information will also allow those who set platform requirements to better appreciate the conflicting challenges which need to be overcome to achieve a balanced submarine design.

CONTEXT

Scope

If diesel electric (SSK) submarines are to conduct operations of longer and more distant duration they will need to be able to go faster during the transit to allow the maximum time on mission. To achieve this, the power and propulsion machinery needs to have the right design parameters to allow operations within the prescribed operating envelope together with a high availability and low upkeep burden.

The machinery in a submarine comprises a number of key energy elements: energy consumption; power generation; energy storage; propulsion drives and these have been addressed in previous BMT papers in 2008 [Ref. 1] and 2010 [Ref 2)]. This paper considers the subtle issues and consequences relating to the variation of these different elements.

Current SSK Arrangements

The typical modern SSK has two gensets to allow for a high battery charge rate and to allow for a degree of redundancy. In a cramped arrangement there is limited access for upkeep. In the Australian Collins class this led to the use of horizontal crankshaft removal in the Hedemora engines [Ref 3]. The Collins class is one of the few SSK with three gensets: apart from redundancy and the need for a compact genset arrangement to avoid increasing the submarine length, the provision of three sets supports the enduring need to ensure that there is always one genset available to allow for battery recharge.

Current Engines

Engine Range

In modern Western submarines, the DG sets principally employ the following engines

Engine Make	Power	Speed

& Model	kW (bhP)	rpm
MTU 396: Surfaced : Submerged	600 to 1350 600 to 1250	1800
Pielstick PA4	590 to 2215 (800 to 3000)	1500
Paxman Valenta	1300	1800

Table 1 - Submarine Snort Engines

The stated power ratings are estimates for normally aspirated operations. When operating in the snort condition, their rating will typically be reduced by 25% from their surface ship rating. As an example the MTU 12V 396TE54 is rated at 1,200kWe for the surface ship TE54 designation [Ref. 4, pg 52] but when employed in the submarine version it is derated to 1,000kW on the surface and 900kW when snorting [Ref.5].

MTU 396

MTU have produced many diesel engines for submarines both with and without super-charging [Ref. 5]. For many years their offering has been the 396 which has been available with a turbo-charger design since the 1980's after MTU had a public test-bed demonstration of its performance in 1982. Over 210 MTU 396 gensets are in use in SSK applications. They come from a broad pedigree which has also been developed for a range of specialist marine applications including low-magnetic applications.

Pielstick PA4

The 12 cylinder Pielstick PA4 engine is used on French submarines [Ref. 6] and those exported from France to other navies. The best known models are the PA4-185 and the 200-VG models. The PA4 engines are fitted with a variable geometry combustion chamber and are now supported by MAN.

Paxman Valenta

Paxman engines have been on UK submarines since the U and V class of World War II. The last design to enter service before Paxman was acquired by MAN Diesels was the Valenta 16SZ which has a mechanically-driven super-charger on HMS Upholder [Ref. 7 and 8] , now HMCS Victoria, and the remainder of that class. The design is reviewed in some detail by Sessions et al [Ref. 9]. His paper shows how supercharging both increases the rated power of a naturally aspirated engine and lowers the specific fuel consumption (Sfc) by over 20%. Mann reported on this aspect and the issues with snorting [Ref 10].

MTU 12V4000U83

In 2011 MTU announced their concept design for a new submarine engine; the submarine version of the 12V4000, the U83 would be rated at 1300kWb. The expected performance of the new engine was compared with the performance expected from two MTU 12V396SE84 gensets using information from Ref. 5 and due to a lack of some information, BMT's own assumptions and estimates.

Feature	MTU 16V396SE84	MTU 12V4000U83[1]	Comments[2]
Rated snort power	1,200kW	1,300 kW	8.3% benefit
Length – DG set	4.94m	4.58m	7% benefit
Length - Engine	3.320m	2.52m	7% benefit
Width	1.60m	1.55m	3% benefit
Height	2.85m	2.60m	9% benefit
Weight – Engine	8,800kg	9,737kg	11% worse
Weight – DG set	13,050 kg	13,987 kg	7% worse
Unit Footprint	7.9m2	7.1m2	10% benefit
Unit Volume	22.5 cubes	18.5 cubes	18% benefit
Power density	53.3 kW/cube	70.4 kW/cube	32% benefit
Standard Sfc: surface (Open)	214 g/kWh	205 g/kWh	4.2% benefit
Standard Sfc: snorting	280 g/kWh [3]	2683 g/kWh3	4.2% benefit

Table 2 - Engine Comparisons

Table 2 indicates the potential benefits of the new engine in terms of volume (i.e. due to power density).

Platform

The BMT Vidar-36 submarine design [Refs. 11 & 12] is the platform for this assessment. BMT Defence Services developed the Vidar-36 through its Inspira™ process and the design serves as a virtual technology test-bed for many methods and design ideas. The baseline Vidar-36 design is a conventional SSK which comprises the following machinery features

- A displacement of 3,600 tonnes with tankage for 176 tonnes of burnable fuel;
- A brushless DC (active stator) propulsion motor rated at 5,300kW;
- A 7m long AIP plug methanol-fuelled, liquid oxygen supplied PEM fuel cell for a submerged endurance of 14 to 28 days (21 standard);
- Two 1200kW diesel engines (i.e. two MTU 16V396SE84(L)) installation for snort power generation;
- Top sprint speed of 20 knots.

Range

The key operating requirement is range, where this figure is taken to mean the furthest distance from port possible at the standard operating conditions. A long range will permit operations far from base-port, as well as extended duration in the mission area once the submarine has arrived. The transit to the theatre will use snorting and batteries to avoid

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1 Estimated from given 12V4000M23S data

2. Comments show the benefits of the 4000 over the 396.

3 BMT estimates

depleting the AIP's fuels and oxidant. This assumes that a surface transit cannot be undertaken due to the surface threat.

Self-noise and indiscretion on such occasions is still critical but to arrive in the mission area in a realistic timescale, transit speeds of over 10 knots are therefore to be expected. A reasonable future transit requirement, the standard operating conditions, would be a range of over 3,000nm at 11 knots submerged transit speed with 6 knots snort speed. This is to achieve a patrol duration of ~60 days.

Vidar Mission Details

Once in mission area, the submarine travels at four to five knots. The hotel load is assumed to be 150kW with a snort electrical load of 260kW. The endurance when snorting is a key performance criterion for a platform which may have to travel long distances to the mission area. The operation of the Vidar-36 in snort operations for battery recharge between submerged transits is presented below. Figure 1 shows the anticipated range (i.e., or half-range) and patrol duration performance on submerged transit speed (y-axis) and snort speed (x-axis) for such an arrangement.

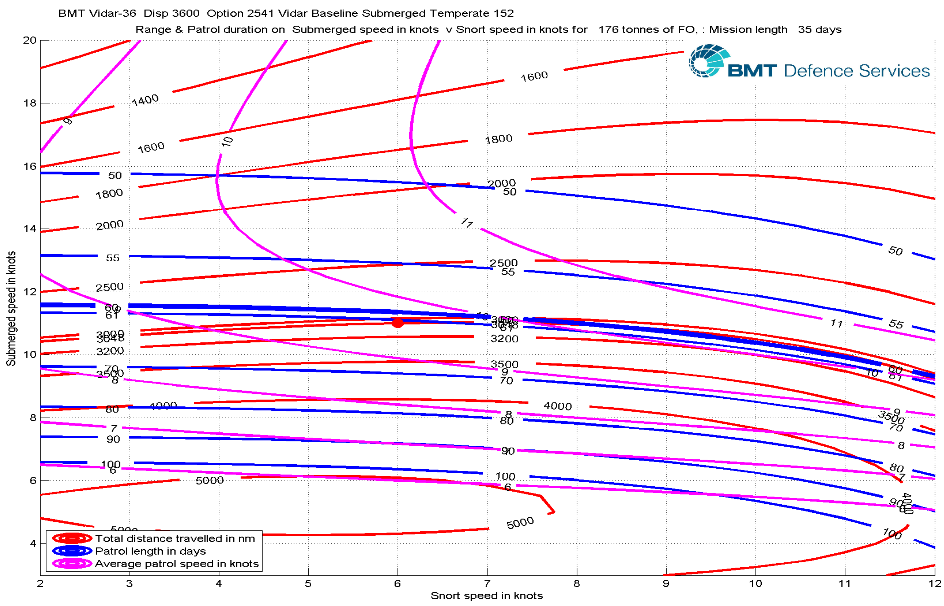

Figure 1: Range and Patrol Length Performance

Figure 1 shows how the provision of 176 tonnes burnable fuel permits a range of 3,048 nm to be achieved at the standard operating conditions shown as a red circle. The total patrol length is 61 days (blue lines).

TRANSIT SPEED V MISSION DURATION

Requirements

To be able to operate at ranges far from the home port, and to stay on mission for the longest possible time is a standard challenge addressed by those in the operational analysis world [Ref. 13]. However such issues need to be addressed in the early stages of design if the vessel is to be suitable for such operations and indeed if the designed operating tempo is to be balanced with the intended number of vessels.

This study has identified the achievable range for a range of submerged transit speeds and mission durations. In this case, the snort speed has been fixed at 6 knots and the duration of snort periods in transit are not limited due to the lack of an active threat outside the mission area.

Range and Patrol Duration

For the total amount of available fuel burn, the range of the submarine can be deduced from the mission duration and the submerged transit speed. The variation of range with these parameters is shown in Figure 2.

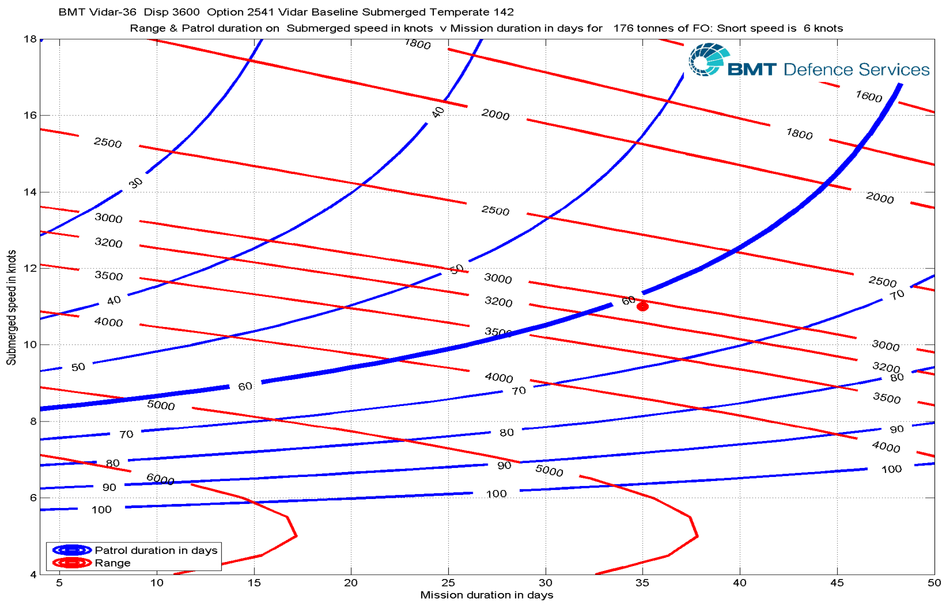

Figure 2: Range & Patrol Duration v Mission Duration

Figure 2 shows how the range (in red) increases with slower submerged transit speed and shorter mission durations. The effect of the square resistance curve is seen in the rapid falling away of the range distance for the higher submerged transit speed. Figure 2 also shows how the patrol duration lengths (in blue) decrease with increasing submerged transit speed.

The red dot shows the design point of 11 knots submerged for 35 days which gives a patrol duration of ~60days and a range of ~3000 nm.

DESIGN VARIATIONS

BMT sought to explore the impact of changes to the design of the submarine in terms of:

a. Changes to the length of the AIP plug,

b. Trades between the number of batteries and the fuel stored onboard.

c. The use of lithium ion batteries instead of standard lead acid units;

d. And the adoption of a modern DG set.

AIP PLUG AND FUEL/BATTERY TRADES

The length of the AIP plug is 7m in the baseline. This was varied between 5m and 9m to identify the impact on range from the change to resistance.

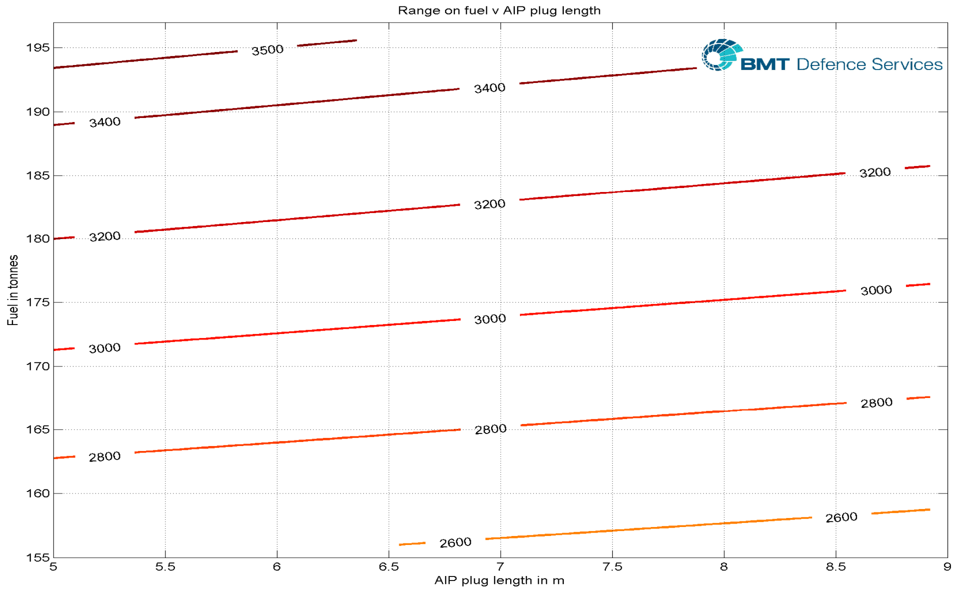

Figure 3: Range on Fuel v AIP plug length

Figure 3 shows how the 2m variation in AIP plug length has a 2% impact on the range of the submarine's operations compared to the +/- 20 % change in batteries/fuel which has a +/- 14% impact.

If 2m of the AIP plug is set aside for additional fuel storage with the remaining 5m retained for a reduced AIP fit, the standard AIP capacity falls to 15 days but the extra fuel provides a 7% increase to the submarine's range.

LITHIUM ION BATTERIES

The Gaia 500Ah lithium ion cell being developed by LTC is provided in modules of 23 cells (Ref 14) . The module is 1450mm high by 500mm x 290mm and weighs ~385kg. It stores 40kWh of usable energy with a maximum continuous current of 320A at a voltage of 82.8V.

The baseline Vidar-36 design has 600 lead acid cells each rated at 8800Ah. These are arranged in two strings each of 300 cells to yield a usable voltage of over 700 Volts. Due to the limitation in the rated current of the lithium ion battery module and also to take advantage of its significant voltage, the 330 lithium ion modules are arranged in 33 strings of ten with a system voltage of 828V.

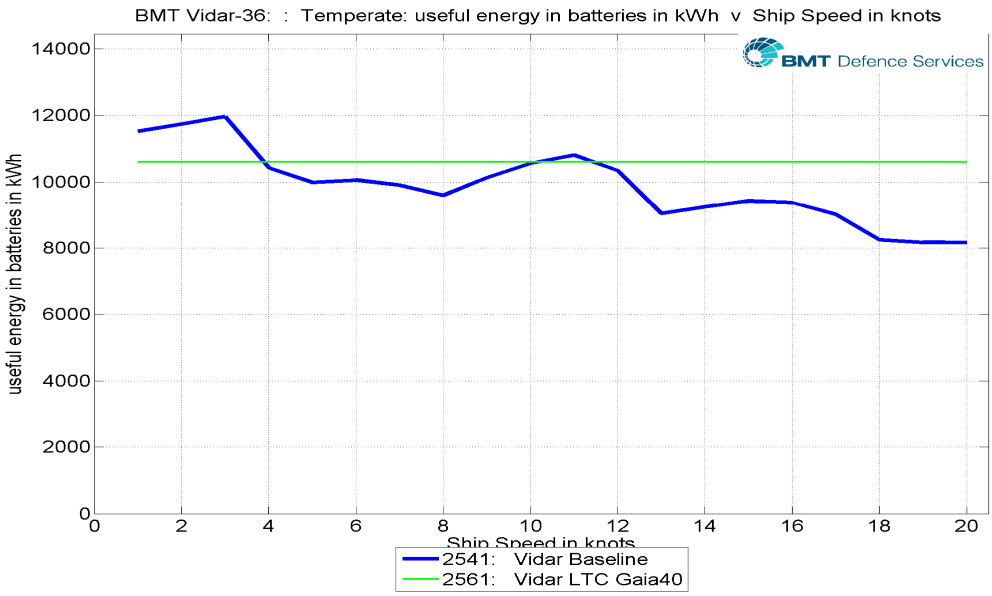

Figure 4: Useful Energy Stored in Ship's Battery

The lead acid battery is limited in the energy it can supply when delivering high current, i.e. high power at high submarine speeds; it is able to deliver more energy with lower currents.

To ensure the lithium-ion battery fit has the same energy delivery at all submarine speeds, it is matched to the lead acid battery at the lower ship speed as shown in Figure 4. This is better demonstrated in Figure 5 which shows the same discharge duration at low powers but a significantly higher duration at higher powers.

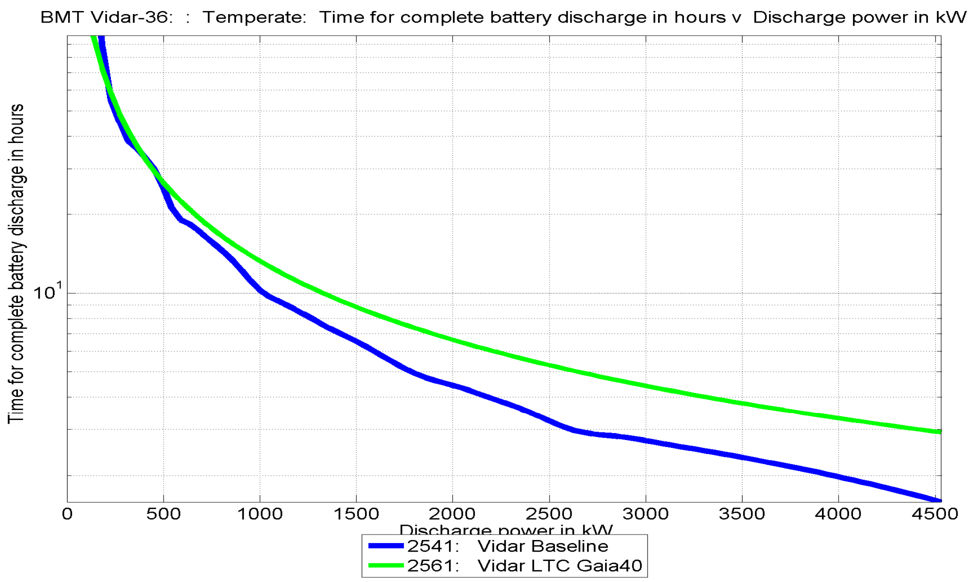

Figure 5: Time for Complete Battery Discharge in Hours

This extended battery capacity at higher speeds does not affect the range of the submarine which is defined by the original energy stored onboard when leaving port, i.e. the amount of usable fuel. Neither does this improved battery allow for the limits of indiscretion ratio to be altered as the ratio between time submerged and time to snort is the same for a given speed, the rate of energy consumption and the rate of battery re-charge are not changed.

However the ability to stay submerged for longer periods of time with a larger battery charge and with a greater scope to go at full speed for longer is a major operational and tactical benefit. The lithium ion batteries provide extra energy and therefore the potential for increased time and/or speed and travel distance between snorts.

This extra time is translated into significant range benefits at higher speeds as shown in Figure 6. At 20 knots, the baseline distance of 36nm is increased to ~50nm.

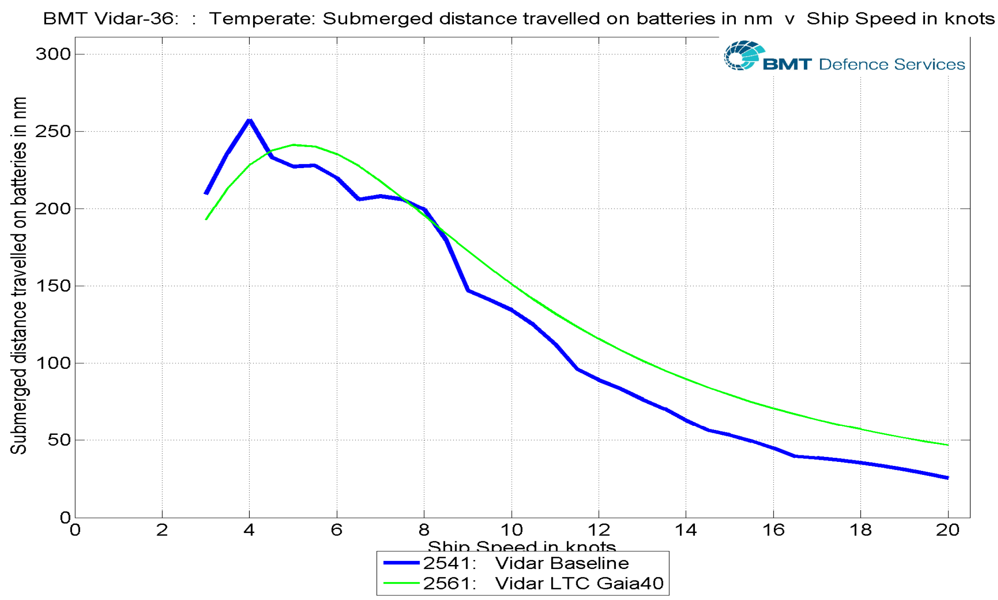

Figure 6: Submerged distance v ship speed

Figure 7 shows how the use a greater part of the stored battery energy can lead to longer snort times to fully recharge the battery. However in practice the larger and more flexible battery capacity gives the submarine commander more options on when to charge and for how long: he has less range anxiety!

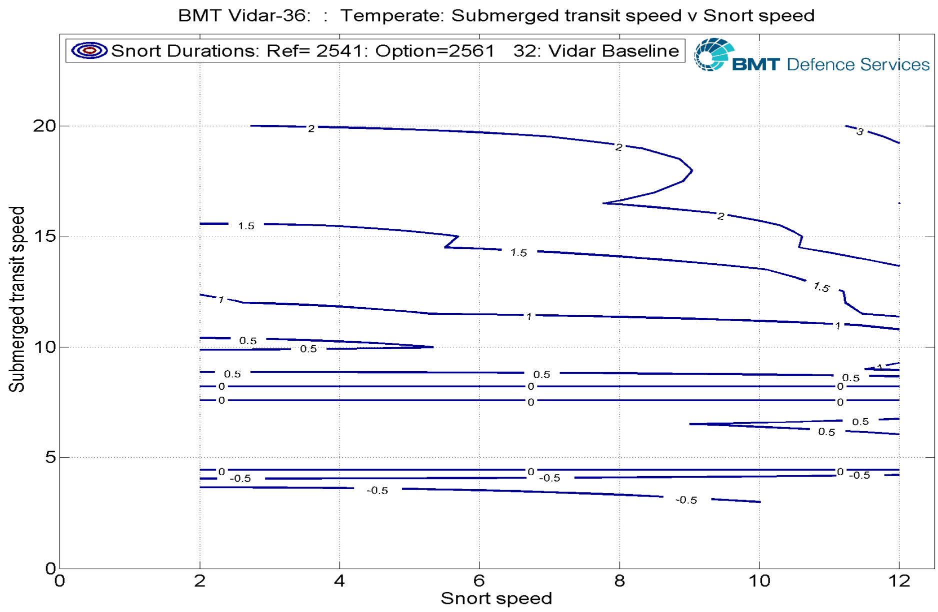

Figure 7: Increased Snort Time v Snort Speed

MODERN DG SET

Figure 8 shows the increased range offered by a DG set with the more powerful and more efficient MTU12V4000U83 engine.

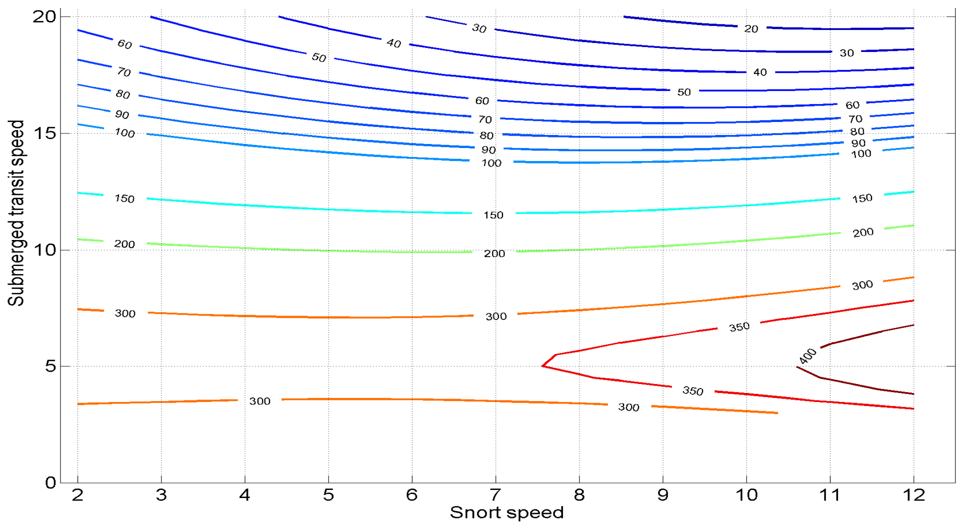

Figure 8: Range increase with MTU12V4000U83

Figure 8 shows how the new engine with its better Sfc allows the fuel to take the submarine further. The greater rated engine power allows the batteries to be re-charged more quickly with an IDR benefit of 3% at the standard operating condition.

CONCLUSIONS

The study has used the BMT Vidar-36 submarine design to explore the consequences of the use of different AIP plug sizes and a mix of battery and fuel provision as well as the use of lithium ion batteries and modern DG sets.

The considerations for mission and patrol times as well as operational range have been reviewed and the method of analysis has been demonstrated.

The changes to the AIP plug sizes had a small (2%) impact on submarine resistance and powering but the achievable operating range is sensitive to changes in DG set designs and the fuel provisions.

Lithium ion batteries offer a significant benefit in terms of the allowable times between battery re-charge and also allow for longer periods at top speed. A modern more efficient and more powerful engine provides a greater range and shorter snort times.

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