MULTI-ENGINE SUBMARINE POWER SUPPLIES:
THE OPERATING CASE

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INTRODUCTION

For many years both conventional and nuclear submarines have used one, two or three diesel gensets to provide electrical power to recharge the submarine main batteries. However, many current gensets are based on older engine designs and more modern designs with their attendant advantages do not exist as products for submarine use. This paper seeks to explore the issues surrounding the use of up to four gensets with a modern diesel engine design to identify the benefits and shortfalls which may exist. The issues of ship impact, system reliability and product development will be considered. The performance assessments will be conducted with the BMT Vidar-36 submarine concept.
The diesel electric (SSK) submarine has become established as the leading capital platform for many of the world’s navies. In modern times they are increasingly asked to conduct a wider range of operations of longer and more distant duration: as a highly valuable asset they need to be able to spend the maximum time on patrol. To achieve this, the machinery needs to have a high availability and low upkeep burden.

The machinery in a submarine comprises a number of key elements: energy consumption; power generation; energy storage; propulsion drives and these have been addressed in a previous BMT paper in 2008 [Ref. 1]. This paper considers the issues relating to the use of diesel engines for power generation in more detail.

The most complex and hard worked equipment item onboard an SSK is the diesel engine generating set (genset) whose continuing good health and reliability is fundamental to the ability to transit and then conduct continuous operations once in the mission area. The current models which serve the world’s western navies are well-established designs which have been developed and improved through extensive usage.

**The Role of Diesel Engine Generators**

Although diesel engine generators are a mission critical feature of a submarine on patrol, they are notorious for being amongst the least reliable of onboard machinery. [Ref 2].

Although the development of the battery energy store and the electric propulsion elements have continued to be greatly developed through modern materials and solid-static electronics, respectively, the engine has an inherent vulnerability due to its arduous operation as a reciprocating engine when snorting. Although the engine technology continues to develop, such testing operating conditions are seldom the focus of mainstream development.

**Current SSK Arrangements**

The typical SSK has two or three gensets to allow for a high battery charge rate and to allow for a degree of redundancy. However often the increased number of units makes for a cramped arrangement which limits access for upkeep leading to the use of horizontal crankshaft removal in the Hedemora engines in the Australian Collins class [Ref 3]. The Australian Collins class is one of the few SSK with three gensets: this is largely driven by her extended periods away from her base port and the enduring need to ensure that there is always one genset available to allow for the ability to steam home.
Current Engines

Engine Range

However although the current range of world SSK gensets in western navies is confined to the following range of gensets:

<table>
<thead>
<tr>
<th>Engine Make &amp; Model</th>
<th>Power kW (bhP)</th>
<th>Speed rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTU 396: Surfaced</td>
<td>600 to 1350</td>
<td>1800</td>
</tr>
<tr>
<td>: Submerged</td>
<td>600 to 1250</td>
<td></td>
</tr>
<tr>
<td>Caterpillar 3512B</td>
<td>1070¹</td>
<td>1800</td>
</tr>
<tr>
<td>Pielstick PA4</td>
<td>590 to 2215</td>
<td>1500</td>
</tr>
<tr>
<td></td>
<td>(800 to 3000)</td>
<td></td>
</tr>
<tr>
<td>Paxman Valenta</td>
<td>1300</td>
<td>1800</td>
</tr>
<tr>
<td>Hedemora HV V18b/15Ub</td>
<td>1400 (1877)</td>
<td>1400</td>
</tr>
<tr>
<td>(VB210)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A210SM</td>
<td>1020 to 3400kW</td>
<td>1500</td>
</tr>
<tr>
<td>ASR1</td>
<td>1420</td>
<td>920</td>
</tr>
</tbody>
</table>

Table 1 - Submarine Snort Engines

The stated power ratings are estimates for normally aspirated operations.

Many of these engine models have also been used in fast ferry propulsion whose demand for fast acting engines which can respond reliably to sudden load demands makes for a robust design.

MTU 396

MTU have produced many diesel engines for submarines both with and without super-charging [Ref. 4]. Their current offering is 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 was introduced to submarines in 1982 and which has also been developed for a range of specialist applications in including low-magnetic applications.

Caterpillar

The Caterpillar 3512B is a well proven engine which is employed in the USN Virginia class of submarines. Following marine tests, in 1998 a more powerful version of the 3516B was introduced which had a longer stroke with 1864kW at 1600 rev/min. It is understood that it is not used as a snort engine.

¹ Estimated
Pielstick PA4

The 12 cylinder Pielstick PA4 engine is used on French submarines [Ref. 5] and those exported 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.

Hedemora

The Hedemora engines in the Collins class run at 1400 rpm [Ref. 6]. Slower speeds are usually associated with larger engines for the same power and this also usually means a larger engine as a whole which leads to volume constraints and issues with access and the removal of main parts.

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 the 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%.

Supercharging v Turbocharging

One of the challenges with a supercharged engine is the high exhaust temperatures experienced. When the Valenta was in development, temperatures of over 650°C were experienced. [Ref. 9]. Such temperatures make for expensive exhaust pipework materials and also make for larger cross-sectional areas due to the large volumetric flow. A supercharger design is also less fuel efficient than a turbocharger design.

In a turbocharger design, the addition of a turbine in the exhaust stream removes useful energy as work to drive the compressor. This is a more effective means of driving the compressor than in a supercharger design and it also reduces the exhaust gas temperatures with the benefits of smaller volumetric flow, smaller trunking and less need for exhaust gas spray insertion to reduce the exhaust gas infra-red signature.

Alternatives

Many of the current set of long-serving submarine engines run at speeds between 1600 and 1800 rev/min and are thus considered to be high speed engines but for today’s market there are many examples of even faster engines which may be more compact. It is those engines which are considered in due course.

Potential diesel engine replacements such as air-breathing solid oxide fuel cells in a hybrid arrangements are far from ready for sea and they do currently not offer the compact power density of the diesel engine (they are 50 times worse).

Current diesel engines have shown that they can be operated to achieve such requirements for most of the time. A modern replacement will need to be proven to be substantially better.

Engine Trends

Emissions Led

Future surface ship applications will need to meet IMO Tier III emissions measures and for many this will be achieved with secondary measures such as exhaust gas scrubbers to remove NOx and SOx. This will leave the engine designer more able to design for reduced fuel consumption and hence carbon dioxide emissions. Increasingly such improvements to fuel consumption are being achieved through double or sequential turbo-charging.

Although the greater trend towards the use of double turbo-charged diesel engines will allow for better trades between fuel consumption and emissions of engines as a whole, this trend will provide
more engines of a comparable design to the market leads of MTU and Pielstick who have led this
technology in the past and then applied them to submarine operations.

Hence it is possible that there will be a greater source of submarine capable gensets in the future
due to this very trend.

**Speed Led**

The ability to run diesel engines at speeds above 2,000 rpm has progressed greatly in the past 20
years: these could be used with a rectified supply to the batteries. As an example, Caterpillar now
offers engines which can operate in this speed range. Such engines have a high compression ratio
of 13 or over and if their Time Between Overhauls (TBO) is to be used as a measure of reliability,
their mean time between failures (MTBF) has also increased significantly over this period.

**General Trends in Engine Failures At Sea**

Using the wealth of operating data in the Japanese commercial fleet, in 2001 Kiriya [Ref. 2] showed
how there is a discernable set of trends when comparing data for the period 1982 to 1989 to that
recorded for the period 1990 to 1997. When all failure sources are considered, diesel engines
continue to dominate the burden of unplanned upkeep onboard when at sea.

The general MTBF of diesel engines has increased by almost 100%: increasing from 1,000 hours to
2,000 hours in the past 30 years. However after failure, the trend for the mean time to repair
(MTTR) was often becoming longer at 30 mins with combustion chamber related issues being the
worst going from 40 to 50 minutes. Such an observation is probably due to the increasingly
complex nature of the modern engine with its greater number of sensors, interfaces and electrical
devices all of which lead to a longer time to diagnose the issue and thus the MTTR. The effort
required to rectify the failure is likewise increasing from 10 to 14 man-hours per failure.

**Lessons For Submarines**

**MTTR**

Whilst there is not a direct read-across from commercial engine usage to submarine engine usage,
the lessons from the trends do indicate that the MTTR is a key aspect of Power and Propulsion
(P&P) System availability.

If the complexity of modern engines may mean that the MTTR will be longer it may also mean that
some engine failures may not be repairable at sea.

In both cases, it will be important for safety and operational reasons for a high proportion of
generating capacity to remain whilst the damaged engine is not available.

**Margin of Capacity**

The provision of power generation onboard a submarine is usually such that the necessary power to
the batteries whilst also supplying ship's services and propulsion when snorting can be met by the
gensets with one assumed to be inoperable. There is therefore a margin of capacity which
represents a surfeit that can be fully used at once due to the current limitations on the ship's lead
acid batteries. This margin is provided purely because of the critical nature of the role of the engine
and the perception of its inherent unreliability.

**MORE POWER SOURCES**

The use of smaller and more modern engines onboard a submarine would enable the current
benefits of the emerging engines to be implemented to the advantage of the submarine P&P system
as a whole. A set of four engines whose total power equals the maximum power that can be
absorbed by the energy storage whilst still supplying hotel and propulsion loads would in effect
have no excess capacity.
Graceful Degradation

A multiple genset design would represent a design which has a better ability to tolerate item failure as there would be a genuine scope for "graceful degradation" whereby a loss of one genset would allow a remaining, adequate, 75% capacity. The concept of the genuine use of a redundant system of elements has been thoroughly examined by Salter [Ref. 10]. Salter shows that systems where there are multiple items whose total capacity meets the top-line requirement, can be capable of accepting individual item losses with the overall capability continuing to be wholly adequate. Salter’s message is clear: it is important to consider a system wide graceful degradation as well as the necessary attention to individual item reliability. The battery energy store on a submarine is a good example of how a critical P&P system function is designed, by necessity, to have multiple elements any one of which can be bridged out if not fit for service.

Derating

Submarine models are typically rated below their open atmosphere rating when operating in snort conditions. As an example the MTU 12V 396 is rated at 1,200kWe for the TE54 designation [Ref. 11, pg 52] but when employed in the submarine version it is derated to 1,000kW on the surface and 900kW when snorting [Ref.4].

Although the current submarine engine models continue to operate reliably there now appears to be a situation due to modern technology whereby new entrants may enter this small but important market.

PERFORMANCE

The diesel engine is designed to supply the maximum electrical load budget at its maximum continuous rating (MCR) output or below with a margin, usually of the order of 10%.

The new replacements for the current set of engines will need to be able to withstand some exacting loads: they are likely to be thermally challenged by the testing requirements for a submarine power source. Such requirements are to be achieved with a high degree of reliability. Additionally such engines also need to be able to meet ever exacting emissions standards when operating in open atmosphere conditions and need to acquire an Engine International Air Pollution Prevention (EAIPP) certificate.

A submarine genset needs to be able to operate in a wide range of operating conditions:

- High back-pressure and low inlet pressures;
- Quick load acquisition;
- Good at accepting sharp air supply and load changes;
- Quick shut-down and secure arrangements;
- Open atmosphere and submerged conditions;
- Fast shut-down from full load;
- Shock rated.

Modern engines tend to have electronic control systems, advanced turbo-chargers and intercooler to allow for a better air charge. These features also permit the technical challenges to be addressed with more flexibility.

High Back-Pressure

The high exhaust gas back pressure due to snorting with the exhaust located 5m or so below the sea surface is an obvious challenge to the engine’s operations as are the reduced input air pressures. BMT have modelled the behaviour of diesel engines in these cases to identify the impact on the rated power and the specific fuel consumption (Sfc) (See Figures 1 and 2). Of greater concern is
the dynamic influence of the varying back-pressure and the dynamic instability this can cause to the turbo-charger behaviour.

Figure 1 - C18 Rated Power Variations

Figure 1 shows there is a significant loss of rated power with decreasing air supply pressure whilst an increase in the back-pressure has a less significant impact. Actual rated power figures would probably be worse than indicated here.

Low Inlet Pressures

BMT studies indicate that the reduced air inlet pressure to the engine is a more significant influence than the back-pressure as this leads to a reduced air charge to the combustion chamber and has a direct reduction on the rated power for reduced inlet pressures. In essence the impact of the lower inlet pressure is to reduce the benefit of the turbocharger such that the power rating tends towards the power of a non-turbo-charged engine.
Figure 2 - C18 Specific Fuel Consumption Variations

Figure 2 shows how the Sfc is most sensitive to the reduction in inlet air pressure with a low variation due to the changes to the exhaust gas back-pressure. The studies have found that the back-pressure can be tolerated up to a point when the turbo-charger effectively stalls.

Quick Load Acquisition

The submarine genset is expected to acquire full load within two minutes from a cold start. Although electrical pre-warming of LT, HT and LO lines will facilitate this, the engine itself has to be thermally tough and modern engines are designed with greater attention to thermal resilience through more advanced design methods.

Good At Accepting Sharp Air Supply And Load Changes

The engine can experience random and sustained fluctuations in air supply and exhaust transients due to the action of the sea state when snorting.

A modern electrical control system will allow the regulation of fuel to ensure a quality of supply from the generator to meet the STANAG 1008 requirements. Such regulation is required due to the transients seen in the exhaust and air inlet lines due to wave interaction with the air inlet and diesel exhaust. Higher speed engines running at 1800 rev/min have a lower inertia than slower designs and although they would tend to react quicker to an external influence, they too are more responsive to the electronic controls.

Quick Shut-Down And Secure Arrangements

Due to the need to avoid enemy detection, it is necessary for an engine to be shut down promptly at any time. The design of the engine needs to be able to handle the thermal soak that follows such a shut-down. The lighter inertia allows for the shaft rotation to be quickly reduced and the turbo-charger also acts to decelerate the motion of the pistons.
Open atmosphere and submerged conditions

The submarine engine needs to be able to cope with a wide range of external conditions: chiefly the need to be able to operate safely and reliably both in open and snorting conditions. Extended operations in high sea states needs to be specifically considered.

Shock Rated

The engine and specifically the engine block is to be designed for a shock environment even with the adoption of double resiliently mounted arrangements. Usually nodular (spheroidal) graphite cast iron particles are employed to provide a resilience to shock and this is becoming more common across the marine commercial diesel engine offering.

Summary

Modern engine developments such as electronic control and advanced turbo-charging techniques have made it easier to consider the performance merits of modern diesel engines for submarine genset applications.

SAFETY

In the past the supply of a safe genset was a matter for the procurement authority who would impose its own quality system and means for acceptance. Today the classification societies are now able to offer a suitable means of third party assessment for submarine equipment. In particular Germanischer Lloyd has a full set of submarine standards which include the requirements for submarine diesel generator sets. Such a trend has made it easier to adapt a standard genset for submarine use.

Due to electronic controls, modern diesel engines are capable of producing a steady power supply over a wider range of ambient intake and exhaust conditions than was possible with older models.

The engines can be “dead ship started” in the event of complete loss of electrical power. Battery power to the on-engine ancillaries and especially the governor is a key design feature. Hydraulic or other actuator back-ups will also be required for the operation of valves such as those for the exhaust hull valves.
MODERN SUBMARINE ENGINES

The study has identified a modern engine which would appear to suit the necessary conditions for operation a submarine genset. A wide range of high-speed engines were reviewed and amongst a number of possible candidates, the Caterpillar C18 [Ref. 12] was selected. The expected performance of four such engines was compared with the performance expected from two MTU 12V396SE84 gensets using information from Ref. 4 and BMT’s own assumptions and estimates.

<table>
<thead>
<tr>
<th>Feature</th>
<th>MTU 12V396SE84</th>
<th>Caterpillar C18</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number onboard</td>
<td>2</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Unit Weight</td>
<td>9.62 tonnes</td>
<td>4.66 tonnes</td>
<td></td>
</tr>
<tr>
<td>Unit Footprint</td>
<td>7m2</td>
<td>4m2</td>
<td></td>
</tr>
<tr>
<td>Unit Volume</td>
<td>18.65 cubes</td>
<td>6.23 cubes</td>
<td></td>
</tr>
<tr>
<td>Power density</td>
<td>53.61 kW/cube</td>
<td>88.25 kW/cube</td>
<td>63% benefit</td>
</tr>
<tr>
<td>Standard Sfc: surface (Open)</td>
<td>214 g/kWh</td>
<td>207 g/kWh</td>
<td>4.5% benefit</td>
</tr>
<tr>
<td>Standard Sfc: snorting</td>
<td>280 g/kWh</td>
<td>223 g/kWh</td>
<td>3.5% benefit</td>
</tr>
<tr>
<td>Unit Rated Power - Open</td>
<td>1,000 kW</td>
<td>550kW</td>
<td></td>
</tr>
<tr>
<td>Total installed power - Open</td>
<td>2000 kW</td>
<td>2,200kW</td>
<td></td>
</tr>
<tr>
<td>Total installed power - Snort</td>
<td>2 x 900kW = 1800kW</td>
<td>4 x 420kW = 1680kW</td>
<td>7% penalty</td>
</tr>
</tbody>
</table>

Onboard Total Genset

<table>
<thead>
<tr>
<th>Feature</th>
<th>MTU 12V396SE84</th>
<th>Caterpillar C18</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>19 tonnes</td>
<td>19 tonnes</td>
<td>Same</td>
</tr>
<tr>
<td>Footprint</td>
<td>14m2</td>
<td>16m2</td>
<td>14% penalty</td>
</tr>
<tr>
<td>Volume</td>
<td>37 cubes</td>
<td>25 cubes</td>
<td>32% benefit</td>
</tr>
<tr>
<td>Fuel for 20 days snort-transit</td>
<td>157 cubes</td>
<td>140 cubes</td>
<td>4.5% benefit</td>
</tr>
</tbody>
</table>

Fuel & Gensets

<table>
<thead>
<tr>
<th>Feature</th>
<th>MTU 12V396SE84</th>
<th>Caterpillar C18</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total volume:</td>
<td>194 cubes</td>
<td>190 cubes</td>
<td>2% benefit</td>
</tr>
<tr>
<td>Total weight</td>
<td>153 tonnes</td>
<td>159 tonnes</td>
<td>4% penalty</td>
</tr>
<tr>
<td>Estimated Time Between Overhauls (TBO)</td>
<td>7,247 hours 2</td>
<td>4,651 hours</td>
<td>Estimated</td>
</tr>
<tr>
<td>Estimated MTBF</td>
<td>14,494 hours 2</td>
<td>9,301 hours</td>
<td>MTBF is assumed to be twice the TBO</td>
</tr>
<tr>
<td>Calculated probability of all gensets failing in service</td>
<td>1.06e-03</td>
<td>6.4e-6</td>
<td>165 times less likely with the Cat C18</td>
</tr>
</tbody>
</table>

Table 2 - Engine Comparisons

Table 2 indicates how the C18 may offer benefits in terms of volume (ie due to power density) and the probability of power supply with small penalties in terms of a reduced installed snort power

2 BMT estimate
C18 Performance

BMT studies sought to identify the likely performance of the C18 when operated as a snort engine in an SSK environment (Figures 1 and 2). Without much of the detailed engine information necessary to portray an accurate prediction, the general trends were estimated to identify the impact on the rated power and the change to the $Sfc$ at the top rated power for changes in inlet air supply and gas exhaust back-pressures. This engine performance data was then used to assess the impact on platform operations.

PLATFORM

The Vidar-36 submarine design from BMT [Ref. 13] was considered as the platform for this assessment. BMT Defence Services developed the Vidar-36 through its Inspira™ process and it serves as a virtual technology test-bed for many methods and design ideas. The baseline Vidar design is a conventional SSK which comprises the following machinery features:

- A displacement of 3,600 tonnes to offer ocean-going performance;
- A brushless DC (active stator) propulsion motor rated at 5,300kW;
- Methanol-fuelled PEM fuel cell for submerged endurance;
- Liquid oxygen for submerged fuel combustion;
- Two 1200kW diesel engines installation for snort power generation.

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 theatre in a realistic timescale, transit speeds of over 10 knots are therefore to be expected. A reasonable future transit requirement would be over 3200nm range at over 12 knots for a mission of 70 days.

Vidar Mission Details

Once in theatre the submarine travels at four to five knots. The hotel load is assumed to be 150kW with a snort electrical load of 260kW. The snort transit range requirement is for 3,400nm (ie 6,800nm there and back). The endurance when snorting is a key performance criterion for a platform which may have to travel long distances to theatre. The operation of the Vidar with four Caterpillar C18 gensets in snort operations for battery recharge between submerged transits is presented below.

Figure 3 shows the anticipated range and patrol length performance on Submerged Transit Speed (STS) (y-axis) and snort speed (x-axis) for such an arrangement.
Figure 3: Range and Patrol Length Performance

Figure 3 shows how the provision of 176 tonnes fuel for a mission length of 40 days permits a range of 3,400 nm to be achieved if a 12 knot submerged transit speed is combined with a snort speed of 8 knots (red circle). The total patrol length is 68 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 question addressed by those in the operational analysis world [Ref. 14]. However a submarine build project requires such issues to be addressed in the early stages of design if the vessel is to be suitable for a range of operations and indeed if the appropriate number of vessels is to be built with the right set of properties as identified above.

The study has identified the set of patrols and mission durations and ranges for a range of submerged transit speeds. The snort speed has been fixed at 8 knots and snort periods in transit are not limited due to the lack of an active threat outside the mission theatre.

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 STS. The variation of range with these parameters is shown in Figure 4.
Figure 4: Range & Patrol Duration v Mission Duration

Figure 4 shows how the range (in red) increases with slower STS and shorter mission durations. The effect of reduced energy availability in the lead acid batteries is seen in the rapid falling away of range for the higher STS. Figure 4 also shows how the patrol duration lengths (in blue) decrease with increasing submerged transit speed.

Conclusions

The study has explored the scope for the use of more but smaller diesel engine generating sets to provide the power for submarine snorting and battery recharging.

The type of solution analysis presented here allows for an assessment of:

- The mix of engines and their sizes;
- The impact of the available fuel;
- The limitations of lead-acid batteries at higher submerged transit speeds;
- The mix of snort and submerged transit speeds in a patrol;
- The impact of mission profiles on maintenance period durations.

The information provided can allow decision makers to review the basis of operations and it can be used to form procurement and operational policy decisions. The right answer in terms of submarine design, fuel allowances and the number and mix of engines is to be derived from the operational and engineering analysis to realise a solution which meets national requirements.

SUMMARY

This paper has explored the scope for the use of more and smaller gensets in an SSK. The considerations for mission and patrol times as well as operational range have been reviewed and an example of the kind of analysis that could be employed has been demonstrated.
The BMT Vidar-36 submarine design has been used to demonstrate some of the impact on performance due to engine changes.

ACKNOWLEDGEMENTS

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REFERENCES