# AUXILIARY PROPULSION MOTOR DRIVES IN WARSHIPS

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**Synopsis**

Increasingly warships such as frigates and Offshore Patrol Vessels (OPV) are being used at slow-speeds either in constabulary duties or as part of a "poise and persistence without commitment" role to support other military activities. When operating in this way for long periods the main engine (ME) can be deleteriously affected and may require occasional loading-up to avoid coking etc. To avoid this, auxiliary motors are often provided to allow main engines to be rested to avoid maintenance related running hours. Sizing the motor is a trade-off between parameters such as: available Diesel Generator (DG) set power, together with the operational needs of the vessel, the fuel consumption, and emissions. This paper explores the solution space for the 90m Venator frigate design by studying a range of motors and converters of different ratings to see how these parameters are affected and to identify those which are most important to the ship's roles.

Military issues such as the crash-stop, lower noise, and heat signatures, loiter with persistence and redundancy are also explored together the vulnerability benefits. Operating in the littoral with a motor drive leads to less noise from main engines and gearboxes and makes better use of the ship's DG sets which can be acoustically isolated.

The upkeep benefits and the greater range of reversionary modes for propulsion should individual equipment, such as the controllable pitch propellers (CPP) are also addressed.

## 1. Introduction

The 90m frigate and Offshore Patrol Vessels (OPV) market is a large and growing business area which has large number of clients and potential shipyards and designers. Navies need whole-ship design solutions which meet their operational needs in a cost-effective flexible manner, Johnson, J et al., 2017, through the use of platforms which match their personnel skill-base, operating tempo (i.e. days at sea) and infrastructure arrangements (i.e. engine support and in-country technical know-how).

Since the widespread introduction of electric propulsion in the 1970's most notably with the Queen Elizabeth II liner, (Bolton, 1971) , a wide range of machinery equipment choices allow a broad choice of power and propulsion systems for a given warship and its specified duties. Recent technological opportunities arise with reliable and affordable variable speed drives (VSD). These are explored with the 90m Venator frigate design, (Kimber 2008).

Hybrid designs offer better propeller performance at lower speeds but there are potential issues with torque pull-out, ship dynamic performance in electric motor mode and the matching of the motor to the rest of the propulsion system to get a viable solution.

The set of performance issues is best addressed as the system design stage. This is explored here to identify key decision-based features so that the Power & propulsion (P&P) system selection can be analysed, and the appropriate outputs used to allow the best-balanced design to be identified

The best solution will be linked to the need for a good match with the ship's operating profile, its fuel economy, and the need to design for an appropriate level of survivability. These considerations make it necessary to conduct a thorough analysis of the in-service behaviours of a range of system designs.

## 2. Diesel Mechanical

The traditional design for OPV and corvette/frigate size vessels has been the use of Combined Diesel and Diesel (CODAD) whereby two or more CPP are each driven by one or more ME. As these ships increasingly have a constabulary and information gathering role, the trend is for more poise and loiter type operations. This can lead

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to long periods at low loads on the ME. For this reason, auxiliary propulsion is now increasingly fitted to alleviate this.

## 3. Hybrid Solutions

The UK Type 23 frigate is one of the first examples of electro-mechanical hybrid propulsion (McDougal, 1989). The design is specifically driven by Anti-Submarine Warfare (ASW) requirements where there is a need for quiet operations at slow to medium speeds provide by a propeller shaft-mounted propulsion motor (SPM) combined with the need for an immediate sprint capability provided by a GT engine.

More recently there has been a greater focus on fuel economy, both for longer distances between re-fuelling but also to save on through life costs and to offer better exhaust gas emissions as a government owned vessel.

Buckingham, 2013, demonstrates the economy of hybrid systems for the UK RFA Tidespring class, both for fuel economy and reduced engine running hours, together with the ability to have four power generators and four independent means for driving the two propellers. These naval auxiliaries also demonstrate that 2MW PTI hybrid machines are feasible in a tanker, but such a motor rating is likely to be too high in a warship due to limited space for such a machine.

In 2015, the USN decided to fit motor drives to its *Arleigh Burke* class. However, the cost of the retrofit program and other factors, such as the increased load on the three GT alternators (GTA), has led them to curtail this program (Rogoway, 2018). GTA are much less efficient that DG sets and there are usually four generating sets in most RN war ships. Consequently, fuel savings may have been less than originally anticipated and the ship is more vulnerable to a total electrical failure (TLF) (i.e. a blackout) if two GTA are operating near to full load. This coupled with the higher average patrol speed of this class, above 10 knots, makes for a thin margin for fuel savings. This situation may have been possibly averted if more P&P system studies had been undertaken to support the original decision.

Couch & Fisher, 2016, describe the design methodology for achieving the hybrid P&P design and outline its operating envelop and inherent flexibility. Simmonds et al, (2016 & 2017) explains that to achieve a robust hybrid design where there are many changes from one set-up to another requires a great deal of design analysis and integration which may require considerable insight and effort at an early design stage.

Newman & Simmonds, 2018, showed how a hybrid design, i.e. with PTI and PTO facilities, comprising a gearbox-mounted 1MW machine per shaftline in a 110m frigate, can reduce the total onboard installed prime movers, their ancillaries, and uptakes and downtake volume demands. In addition to saving fuel, such designs also provide increased resilience, flexibility, and availability. In this case, the fuel savings were only about 2% and so the justification in this case may be one of saved CAPEX rather than OPEX with the opportunity for a smaller machinery space. In a large frigate with four main propulsion engines, arguably there is already sufficient availability of propulsion power so the case for an auxiliary motor is more difficult to make.

Where the motor is provided as a stand-alone PTI drive with no assist mode (i.e. the motor can operate with the ME) and no PTO facility in a smaller ship, this poses the question of how the motor size is to be identified and justified. The remainder of this paper seeks to explore the issues so that designers can consider them for their own new designs.

## 4. Ship Operations

For modern frigates, it is important to have the ability to operate for long periods at slow steady speeds appropriate to the sea conditions, with low noise. The adoption of electric drives for this purpose may lead to lower fuel consumption, though not important at low speeds, and does not involve the ME operating at very low loads.

Therefore, a good hybrid solution allows good speed of advance without excessive underwater radiated noise (URN) and is a match to the operating profile.

So how is one to design and down-select an auxiliary drive which seeks to meet all such needs in a cost-effective manner? Clearly this is not possible: the propulsion system like the ship will be a balanced design where no one facet is optimised but function, performance, stealth, vulnerability, ship impact, reliability, safety, and cost are all tolerable and workable. To achieve such a solution requires synthesis and analysis and then the application of a decision-making process, such as that used for the Type 26 by McIntyre, 2012, but first a ship is required to serve as an example.

## 5. Ship Basis

The 90m Venator-frigate (Kimber, 2008) design was introduced as part of the set of Venator studies to identify the kind of platform that would suit local and global deployments.

| **Parameter** | **Value** |
|---|---|
| Length overall | 93.25m |
| Length, waterline | 90.0m |
| Beam, moulded | 15.12m |
| Design Moulded Draught | 3.95m |
| Design Displacement | 2,680 tonnes |
| Scantling Displacement | 3,039 tonnes |
| Maximum contracted speed | 24+ knots |
| Ship's electrical load (SEL)<br>Non-propulsion | 1,000kWe |
| Baseline Power & Propulsion | CODAD propellers |
| DE gensets | 3 x 1650 kWb<br>MTU 12V4000M53B, |
| Main Propulsion | 2 x 9,100kW diesel engines<br>MTU20V8000 |
| Propellers | 2 x 3.0m diameter, PD=1.2; BAR=0.7 |

**Table 1. Ship's Main Particulars**

The ship's assumed time-speed operating speed profile is shown in. Figure 1. This profile will vary slightly at higher sea states as the increasing resistance leads to speed loss at the top end. The extra resistance due to hullform, wind and wave at all sea states is based on the Holtrop & Mennen (1982) method.

Using the BMT proprietary marine P&P analysis tool, Ptool, (Buckingham, 2002) the baseline design and a set of P&P options have been modelled to show the loading and efficiency at each point in the P&P system between the power into the sea water (SW) and the energy extracted from the fuel oil.

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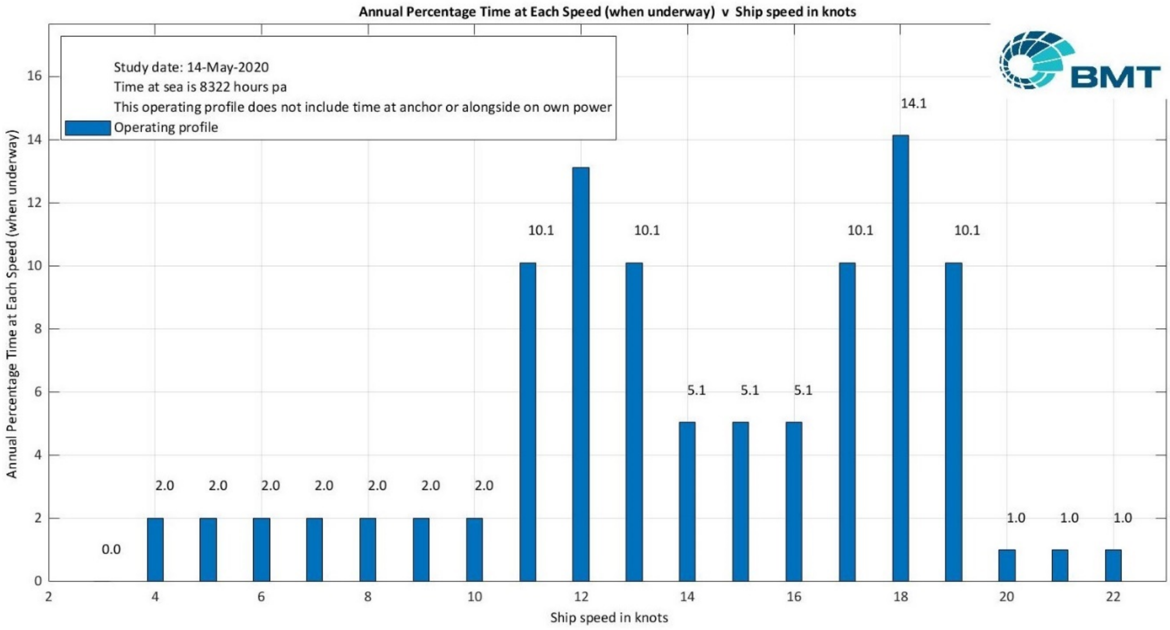


**Figure 1. Speed-Time Operating profile**

## 6. Study Set

### *6.1 Baseline Design*

As shown in Table 1, the baseline diesel mechanical design comprises two 9,1000kWb main engines and four 1650kWb DG sets. The design can operate with twin shafts at all speeds or with a trailing shaft so that the main engine loading is maintained above the lowest minimum continuous loads for a greater part of the speed range.

### *6.2 Hybrid Designs*

The set of hybrid designs comprises the same two ME with two auxiliary motors, in the range 230, 630 and 1,000KWb. The motors the propeller shafts through the reduction gearbox. It is assumed there is no minimum allowable continuous shaft speed as the shaft bearings are supplied pressurised lubricating oil.

Whilst there are numerous frigates and other combatants which have motor drive for lower speeds for loiter and low noise propulsion purposes, there are few, if any, which employ the same electrical machine for PTO purposes. Buckingham, 2017, and Newman & Simonds, 2018, considered the benefits of such hybrid options.

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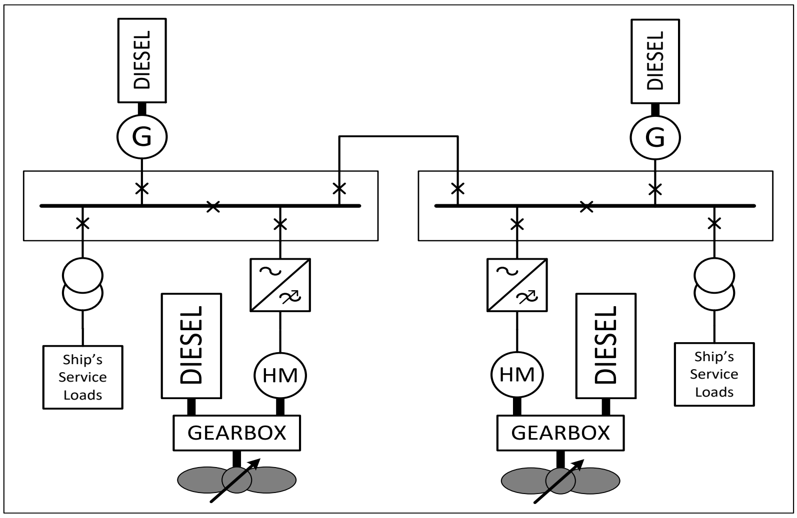


**Figure 2. Diagrammatic of the Hybrid Design**

Figure 2 shows how the two main engines driven into reduction gearboxes which supply power to the CPP and the PTI motor, shown as HM.

### *6.3 1500: Baseline mechanical drive*

The baseline frigate design is described in Table 1.

| **Option** | **Transmission** |
| --- | --- |
| 1500 - Two main engines - baseline | 2 x reduction gearbox: 1150 rpm to 300 rpm |
| 7802: Hybrid design | 2 x reduction gearboxes each with a 230kWb motor |
| 7806: Hybrid design | 2 x reduction gearboxes each with a 630kWb motor |
| 7810: Hybrid design | 2 x reduction gearboxes each with a 1,000kWb motor |

**Table 2. Summary of Power & Propulsion Design Solutions**

Table 2 gives a summary of the set of P&P solutions which are used in this paper to demonstrate the different design features.

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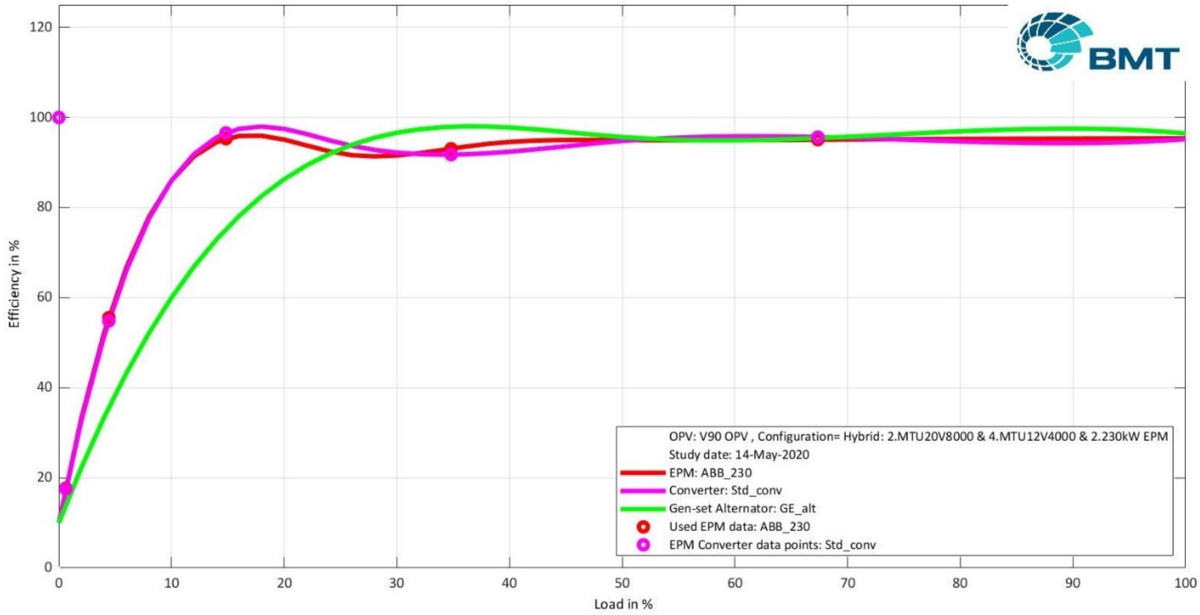


**Figure 3. Motor, Converter & Alternator Efficiencies**

Almost all equipment has low efficiency at low loads. Figure 3 shows the generic efficiency characteristics for the set of motors, converters and alternator used in this study. Due to their high efficiency at high loads, indicating low losses, their efficiency only falls away when the load is below 25%.

### *6.4 Comparisons*

The baseline design and the three motor options are compared for some of the principal operating parameters:

a. Shaft speed;
b. Propeller efficiency.

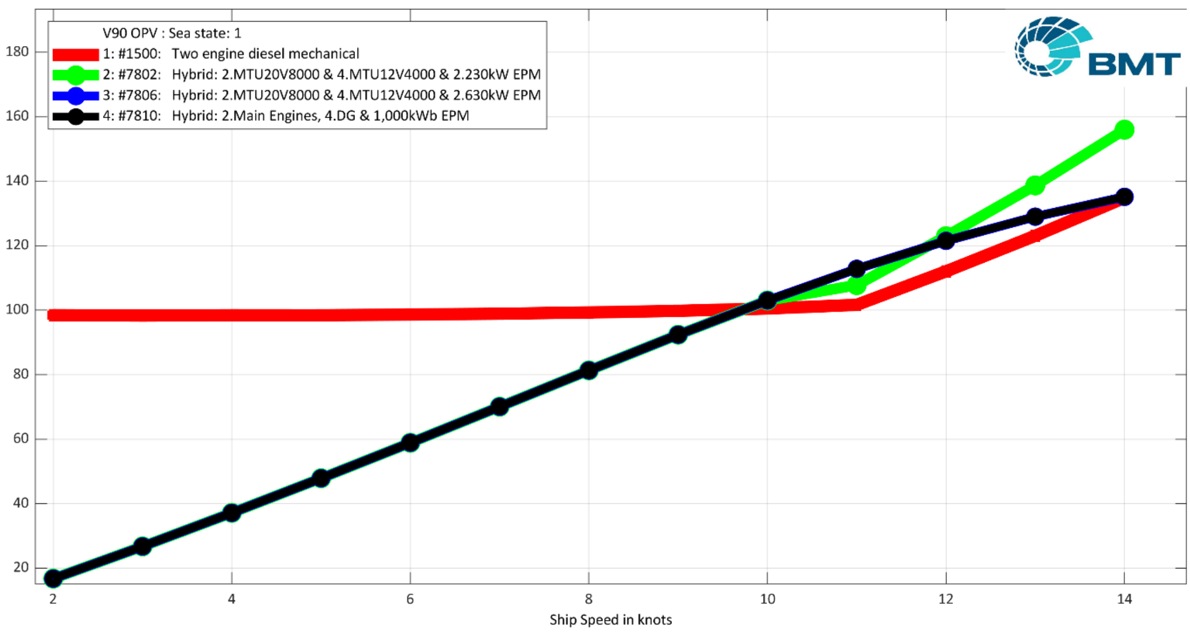


**Figure 4.Propeller Shaft Speed Comparison**

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Figure 4 shows how the propeller shaft speed in the motor options increases steadily from near zero, whereas the diesel engine option starts near 100rpm. The 230kW motor option operates at single shaft drive with a free trailing shaft, once the motor power limit is reached, hence the drive shaft speed is higher than the twin main engine drive in the baseline design.

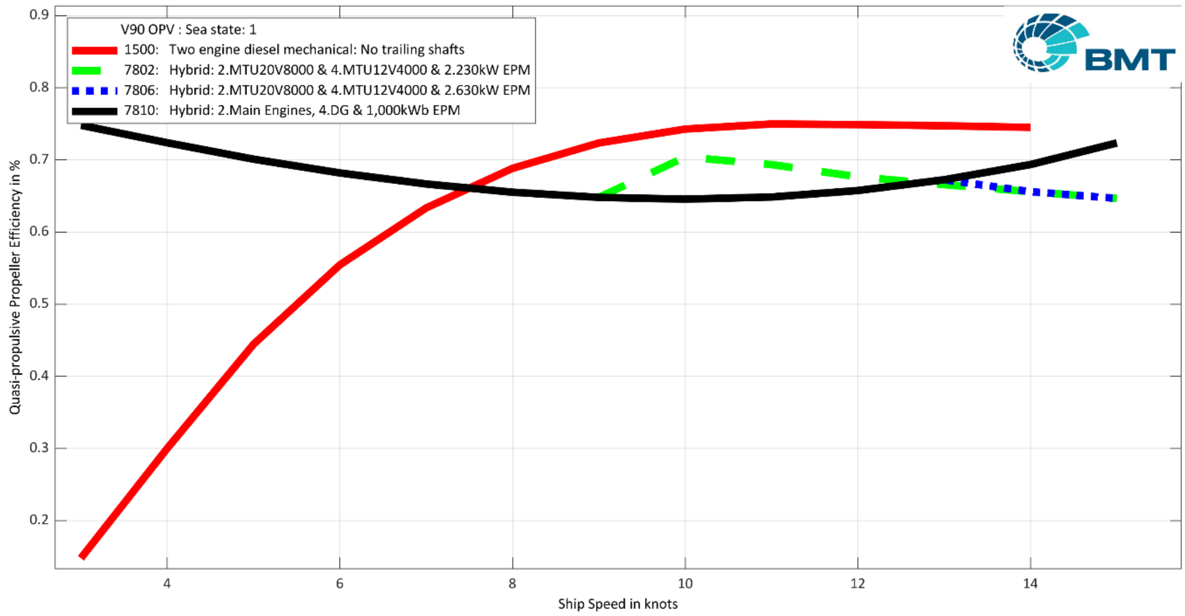


**Figure 5. Quasi Propulsive Coefficient Comparison**

Figure 5 shows how the motor options allow a better QPC by operating at a higher pitch at the slower speeds. Where the motors are then replaced by a single trailing shaft, this effect is largely valid up to 8 knots, depending on the motor size.

*Trailing Shafts*

The propulsion loading when running on one driven shaft with the other shaft either locked or free trailing was compared to the loading when running on two shafts. As this situation may occur when no motor drives are fitted it is of interest to identify the potential for additional power and fuel consumption increases.

The set of propulsion cases was considered for a ship speed of 7 knots. Table 3 shows the loading for the baseline case of twin propulsion shafts.

The free shaft case has a single drive shaft with the other one free to rotate in the flow passing over the undriven propeller. At slow speeds, typically up between 3 and 5 knots, (UK MoD MAP 01-97), the free propeller does not move due to the stiction in the transmission line. This is a measure of the required breakaway torque when sizing motors and effectively defined the minimum motor rating. The propulsion load is 15% higher but the additional load may allow for longer periods on the main engines, before a higher load is required to de-coke the engine.

The locked shaft case is where the non-driven shaft is locked stationary. This may be due to damage to the shaft. In this case, the ship's resistance and the propulsion load are higher .

In all such cases, the load on the main engine is below 5% which is about half the lowest continuous allowable load. For such reasons, motors are considered for ships that need to loiter at slow speed for long durations.

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| | | Free shaft case | | Locked Shaft Case | |
|---|---|---|---|---|---|
| For 7 knots | **Twin Shaft** | **Single driving Shaft** | **Free Shaft** | **Single driving Shaft** | **Locked shaft** |
| Torque load in kNm | 7 | 16 | 0 | 38 | 24 |
| Rotation speed in rpm | 99 | 100 | 58 | 103 | 0 |
| Drag force in kN | 0 | 0 | 7 | 0 | 32 |
| Total Delivered Power in kW | 150 | 172 | 0 | 409 | 0 |

**Table 3. Trailing Shaft Propulsion Loads**

## 7. Design Considerations

The main considerations when selecting the size of the auxiliary motor are listed below:

a. Minimum torque to breakout of stiction;
b. Fuel Consumption;
c. Safe to manoeuvre thrust and power;
d. Design for slower propeller speeds
e. Design for slow cruise;
f. Design for safe return to port;
g. Design as reversionary propulsion;
h. Design for Stealth;
i. Design for Lowest Main Engine Load.

*These are each addressed below.*

### *7.1 Minimum torque to breakout of stiction*

As Boughner, 2012, makes clear in the selection of the electric motors for the USS Makin Island,(LHD), it is necessary to ensure the motors can overcome the breakaway torque requirement and start a stopped shaft. Although the referenced inertia of the gearbox and main shaft line and propeller are to be overcome, it is the stiction in the seals and bearings that may have the greatest load at zero speed. The size of the stationary load can vary with the alignment of the shaft and the fit and temperature of the bearings and seals. Consequently, a conservative approach is always taken, and this affects the mapping of the motor torque-speed characteristic to the static and dynamic loading of the whole transmission

| **Parameter** | **Value** | **Comments** |
|---|---|---|
| Propeller inertia | 9,962 kg.m² | |
| Shaftline inertia (two sections) | 44+76.0=120 kg.m² | Two shafts 30m overall |
| Gearbox main gear wheel | 1,408 kg.m² | |

**Table 4. Shaftline Inertias**

### *7.2 Fuel Consumption*

It may be assumed that the installation of motors for slow speed operations is to save fuel. However, the electrical and mechanical losses from the DG set engine through to the motor shaft and thence to the propeller shaft can exceed the relatively poor Sfc of the ME at low speeds and loads.

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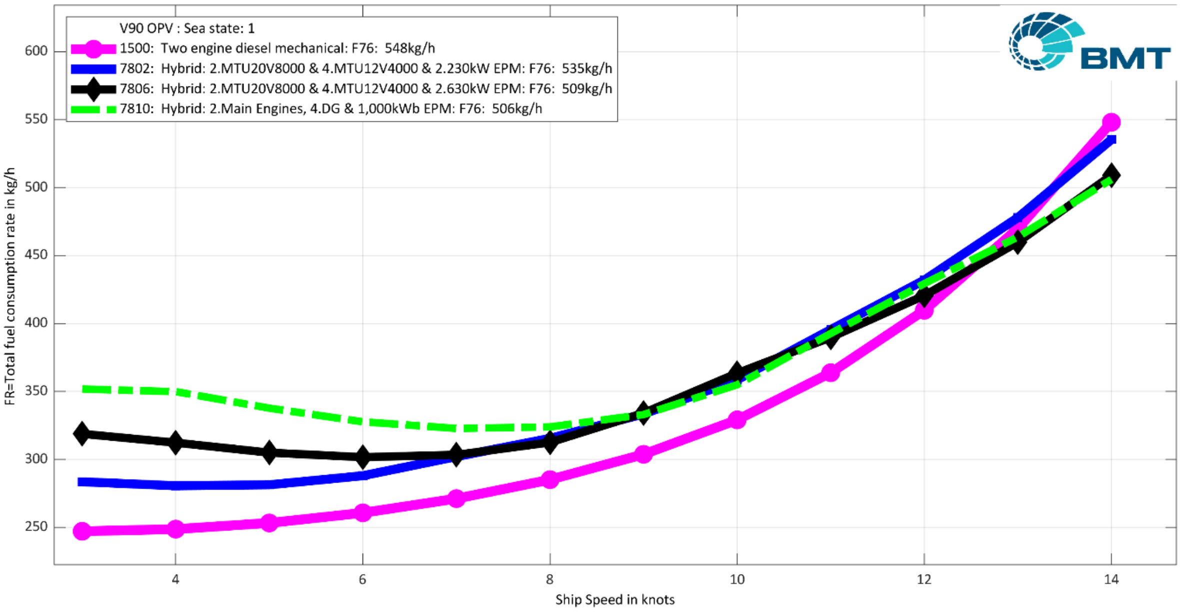


**Figure 6. Comparison of Fuel Consumption**

Figure 6 provides a comparison of the fuel consumption for the options including the power to the SEL. The figure shows the baseline mechanical option offers the lowest total fuel consumption compared to the three motor options. However, this option can only operate at such low loads for a limited period (perhaps up to 1 hour), before the ME is to be de-cocked by increasing speed and engine load for a period of time. This may then require an inconvenient a change of ship speed.

### *7.3 Safe to manoeuvre thrust and power*

A vessel is to be able to manoeuvre when in steerage so that it can stop within the maximum allowable IMO crash stop distance of 13 ship lengths. If underway on motor drive, it was considered whether the motors were able to manage this alone, albeit at slow speeds. When one considers that ships operate at slow speeds, in confined waters in the company of other ships, the capability to stop becomes a more important consideration.

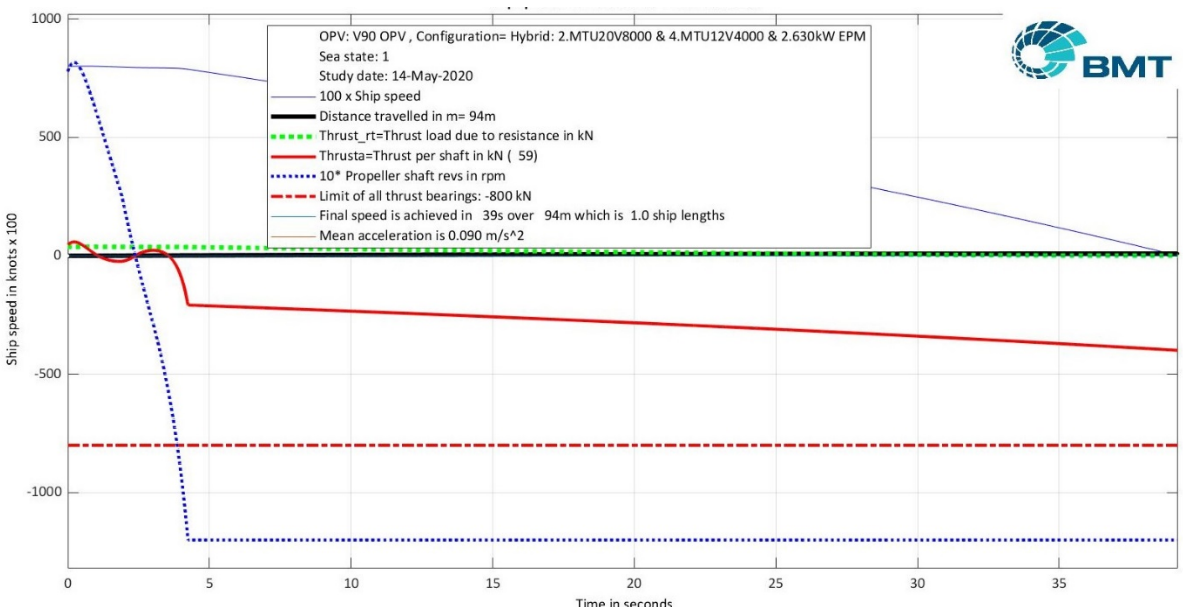


**Figure 7. Simplified Crash Stop Assessment for 630kW Auxiliary Motor Design**

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Figure 7 shows the crash stop sequence for various propulsion parameters for the 630kW motor design. Travelling at 8 knots it comes to rest within 1 ship length.

Although this ship has CPP which provide a very effective means of providing astern thrust, here it is assumed the motor is not configured to operate with the variable reversible pitch of the CPP and the propeller is at full pitch.

The crash stop studies have assumed the ship is underway on maximum motor speed and a crash stop is instigated. The inertias of the shaftline and the ship's hull are modelled, and a first order lag is applied to the torque demand on the motor. The speed of the reverse propeller speed is limited to 50% of maximum revs to limit the loading on the thrust block.

Table 5 show that all three motors solutions provide sufficient astern thrust to bring the ship to rest well within IMO requirements.

| **Motor Rating** | **Max Speed on motor** | **Stopping Distance & Time** |
|---|---|---|
| 230kW | 6 knots | 0.6 Ship Lengths in 28s |
| 630kW | 8.0 knots | 1.0 ships lengths in 39s |
| 1,000kW | 9.2 knots | 1.4 ship lengths in 46s |

**Table 5. Crash Stop Performance**

It is important therefore to understand that when manoeuvring in confined waters, maximum braking power and thrust is associated with the applied machinery's maximum installed power. Therefore, main machinery is ideally to be used for such situations.

### *7.4 Design for slower propeller speeds*

An motor should provide thrust so that the main engine loading avoids the lower corner of the diesel engine combinator curve as shown in Figure 8. The propeller speed is raised to avoid the minimum allowable continuous speed for the main engine. This requires the propeller blade angle to be finer to provide the required low thrust. This can lead to tip vortices and noise, and although the power demand is low, the engine load is below 25% which means that its Sfc is in a range which is not understood and is poorly defined.

Figure 8 also shows that even with single shaft operations, with a free trailing shaft, the engine load is significantly below the engine supplier's lower allowable continuous limit indicated by the red dashed line. If operating below this load, the engine is to be loaded up, and thus the ship speed is to be increased, so that a large number of potential issues due to cold combustion do not damage the engine. As Mensch, 2014, identifies, this can range from engine wear due to poor lubrication, incomplete combustion, condensation of combustion products on liners, etc.

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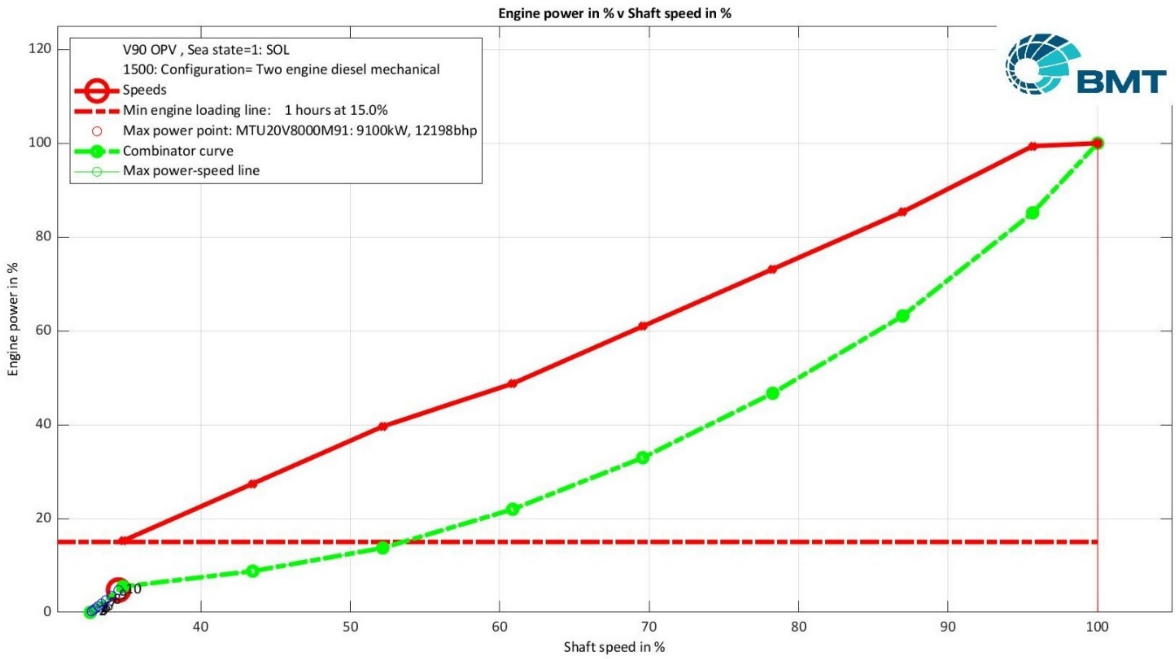


**Figure 8. Main Engine Power-Speed Characteristic**

### *7.5 Design for Slow Cruise*

To slow cruise with manoeuvring control, there needs to be sufficient water speed over the rudders and the power demand from the motors is to not be a controlling factor on the power available from the DG sets. Ideally, there is to be every confidence in the prediction in both the ship's resistance and the electrical load chart (for the principal climatic operations) so that the anticipated slow cruise motor and SEL loads matches the selection of the DG sets so that they are loaded between 65% and 85%, and so that only two need be running.

However, the motor torque-speed characteristic is key to ensuring that the desired performance is achieved.

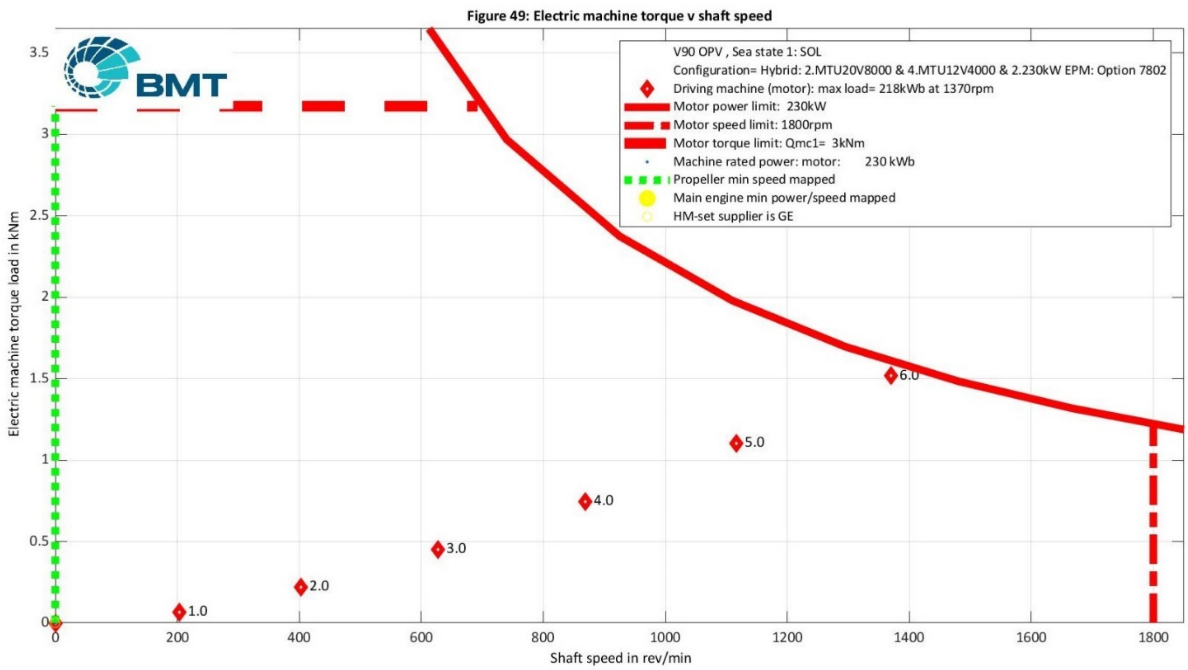


**Figure 9. Motor torque-speed characteristic**


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Figure 9 shows the ship speed range of the 230kW motor to be up to 6 knots where it is running at 1,370rpm. When the motor drive is discontinued at higher ship speeds, there may be a need for the motor to be clutched out to avoid over-speed condition in the un-excited mode. The motor PTI gear ratio to the main shaft is to consider the match of the motor characteristic to the range of propeller loads. This might be for the motor to drive the ship on a single shaft in reversionary and emergency modes and should the CPP pitch angles be frozen.

### *7.6 Design for safe-return-to-port*

Whist the IMO requirements for safe-return-to-port (SRTP), (IMO, 2009) do not necessarily apply to warships, the concept of damage control and surviving fire or flood damage to the machinery spaces is of great interest to the design of a warship. The SRTP requirements state that the ship's design is to:

a. Allow the ship to remain manoeuvrable and keep position even under unfavourable weather conditions;
b. Permit the ship to reach at least 7 knots in the prescribed normal weather conditions.

Additionally, there is to be at least 50% propulsion capacity should one Main Machinery Space (MMS) be lost to fire or flood.

Whilst clearly a baseline design with separate main machinery spaces and no motor would allow the design to meet the IMO requirements , the additional of a PTI motor to each shaftline provides an additional shaftline prime mover and greater availability to drive each shaftline. The main engines in each MMS would have separate LO and FO systems to meet the SRTP requirement for Essential auxiliary systems (e.g. compressed air, oil, fuel, lubrication oil, cooling water, ventilation, fuel storage and supply systems etc.) to remain operational.

However, ships have suffered common mode failures due to the same failure mode occurring in each MMS. The Viking Sky experience difficulties like this with low LO levels, (AIBN, 2019). Having separate propulsion drives (i.e. electrical and mechanical) on each shaftline improves propulsion availability, especially as DG sets typically have their own LO sump and FO Ready-Use (RU) day tanks.

An auxiliary motor drive may thus address the kinds of common mode failures where the ship is holed due to hitting a submerged object which then damages the hull and leads to flooding one or both MMS. Past examples are HMS Nottingham, (Groom, 2003) and HMS Brazen, 1994. If the motor can be located above the shaftline, it may then be able to drive the gearbox and shaftline when the main engine is out of action (i.e. due to SW in its LO and or FO lines for example).

*Normal Conditions*
To achieve 7 knots on one shaftline in sea state 1, Venator-90 requires an 409kW motor with the other shaft locked. The slow speed high torque situation also requires the motor rating and the gearing reduction ratio to be considered. If the shaft in the damaged MMS can be allowed to freely rotate, then the permissible motor rating would be lower.

*Unfavourable Conditions*
When addressing unfavourable weather conditions, the ability to steer and manoeuvre when one shaftline is lost, and presumably locked, is clearly much reduced especially in sea state 4 and above and the best speed to be expected is likely to be 7 knots. This would also be considered the minimum speed required for effective operation of the rudders.

For this ship, the motor rating to overcome the additional resistance of a locked trailing shaft and to provide the power for 7 knots speed would need to be 200kW. However as for normal conditions, the speed-torque characteristic would be a key consideration.

Depending on the motor location , a motor with suitable Ingress Protection (IP) rating may be able to operate longer in a flooded compartment than the main engine. This would particularly the case if it were driving into a gearbox with a PTI vertical offset arrangement. In such cases it is conceivable that the motor rating would be delivered by two motor to balance the gearbox loading.

### *7.7 Design as Reversionary Propulsion*

A motor drive may be is designed so it is specifically to be able to operate when main engines are not available due to common mode failure. This may be a limited flood into the engine room which has contaminated the main engine LO systems or a fire on the engine due to a fuel spill, etc, all events which have occurred through fate and misadventure. Such a feature would be specifically of value in ships with two main engines, be they separated or in one compartment.

For the motor to be ready to drive the shaftline with the main engine on the other shaftline, it would be best sized to allow the ship to operate as with the SRTP condition, in a range of sea states with a minimum safe speed of 7 knots or so. The motor is best sized so that it can be used to reduce the drag of the propeller it is driving so that best advantage is gained from the main engine.

### *7.8 Design for Stealth*

A ship whose main engine is operating on or near its lowest continuous operating speed will be running lightly loaded with a propeller at a very fine blade pitch. This leads to cavitation and an increased URN signature although the light loading means it is unlikely that the propeller will be damaged. Most noise data from PNA, Lewis, 1988, such as Burchill, does not adequately cover the prediction of URN in such off-design situations.

However, Figure 10 show that the propeller pitch is not anywhere near full until the ship reaches 11 knots.

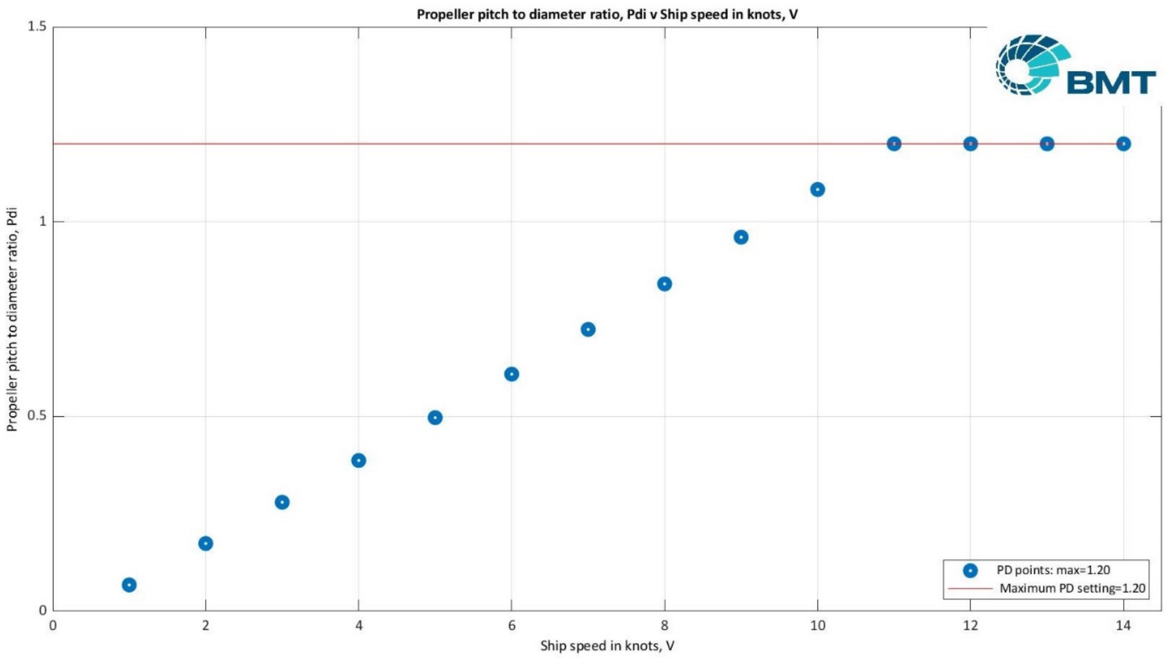


**Figure 10. Baseline mechanical drive. Propeller Blade Pitch Diameter Ratio**

### *7.9 Design for Lowest Main Engine Load*

As shown in the trailing shaft section, the single drive main engine is loaded at 5% or lower at 7 knots and if the vessel is operate for long periods of time at this speed, then motors are advised to avoid the need for speeding up to clear the ME and allow them to reach a better operating temperature.

## 8. Motor Assist

### *8.1 Motor Assist to Zero Drag of Trailing Shaft*

When the rating of both motors has been exceeded, the propulsion configuration moves to single-shaft main engine drive. The non-driven shaft is trailing freely if the water flow forces can overcome the inherent stiction in the shaftline. This usually happen at 4 to 6 knots. Once overcome, documented experience indicates that the shaft may rotate at 70% of the equivalent twin drive arrangement (MAP 01-097). The additional resistance, if this is the case, is a few percent of the ship's resistance but if a motor is provided this could be used to speed up the trailing shaft speed and zero its resistance. These studies showed that the fuel saving is 1 to 2% at 15 knots, lower with decreasing speeds. So, the benefit may not be on fuel consumption, but any noise and vibration from poor flow over a non-driven trailing shaft can be mitigated. The motor will also assure that the shaftline minimum speed for lubricating purposes is achieved.

A design where the motor is to offer propulsive power in an AND mode, above the twin motor speed limit may require a different gearbox ratio between the motor and the propeller shaft so that the motor has a bigger ship-speed range.

### *8.2 Motor Power Assist*

If the motor is used at its full rating to turn the training shaft faster and add thrust, there is little or no fuel consumption benefit as the power and this, thrust, down the motor shaft has a worse "fuel to thrust efficiency" than the direct diesel mechanical drive.

This situation can be different if the main engine is a GT engine which has a much worse Sfc at low loads. The Type 23 can operate the SPM to provide sided-boost, when the other shaft is GT engine driven.

## 9. Conclusions

This study has explored the use of auxiliary electric propulsion in a 90m frigate with two ME. The paper considers the issues when operating with a free and locked trailing shaft at slow speeds before addressing a range of issues relating to the choice of the power rating of an auxiliary motor.

The electric motor range is considered for speeds up to 14 knots and power ratings up to 1,000kW. The main reason for justifying the introduction of an auxiliary motor is to reduce the hours on ME at very low loads. Such operating conditions can lead to cold combustion and other damage and incur maintenance hours too.

In this study, it is indicated that the motor solutions do not save much fuel, but the balance would depend on how closely loaded the DG sets are to their optimal loading conditions. Where the loading of the ME is below 25% which is below the range for which manufacturers give data, and as the ship speeds are slow, the fuel differences are relatively small. It is also likely that a wide range of polluting emissions for ships are improved with an auxiliary motor so that ME need not be used in harbour. Crash stop assessments here have shown such motors can allow stopping in IMO required distances,

Warship survivability considerations indicate that motors which are located above the propeller shaftline may offer reversionary propulsion should the ME in that compartment be damaged by fire or flood.

If a motor can be rated to provide suitable propulsion at 7 knots and meet the IMO safe return to port requirement in their spirit, though not necessarily their exact regulations, then this too offers an increased measure of improved survivability.

The direct comparison of the propulsion performance at each speed has allowed the different solutions to be compared, but the challenge of identifying the right rating will probably be unique to the individual warship and its own set of requirements for propulsion and survivability. Motors will generally offer a reduced URN acoustic signature, and where this is required, a SPM is likely to be considered with a higher power range for quiet speed up to cavitation inception speed (CIS) of the propeller.

Only by considering each of the issues stated above, can a robust case be made for the justification of an auxiliary motor in the first place, and then a logical path of assessment to decide what rating it is to be.

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