PROPULSION OF ASW VESSELS

BY

C. M. Plumb, B.Sc., C.Eng., M.I.Mech.E., M.I.Mar.E., R.C.N.C.
(late of University College London)

This Crown Copyright paper was presented by the author at the Royal Institution of Naval Architects Symposium on Anti-Submarine Warfare held in London in May 1987, and is printed with their agreement.

ABSTRACT

There are many factors that must be considered during the process leading to the selection of a propulsion system. Two that are particularly important when the ship is an ASW vessel are the operating pattern of the ship and its noise signature. The types of propulsion systems in use these days and those that could be employed in the future are examined, especially as they affect the noise signature and are affected by the required operating pattern.

FACTORS AFFECTING PROPULSION SYSTEM SELECTION

When considering the selection of a warship propulsion system, there are many aspects that must be examined. In a design, it is unlikely that all aspects can be satisfied to the ultimate degree but an aim can be to provide adequate levels of all the major aspects.

Two particular features stand out as being important when considering the propulsion of an ASW vessel and these will be discussed first. They are the operating pattern of the ship and the whole question of underwater noise.

Operating Pattern

The starting point must be to decide what task or tasks the ASW ship is to perform. It could be part of a force that is to protect a single, high-value ship, or a merchant convoy, or a naval task force. In any of these cases, the best protection may be:

(*a*) To detect and destroy any enemy submarine that enters the sea area within which the ship or ships to be protected may operate.

(*b*) To detect and destroy any enemy submarine that comes close enough to pose a direct threat on the ship or ships to be protected.

(*c*) To make use of natural choke points (e.g. the Greenland-Iceland-U.K. gap) and form an ASW barrier across which enemy submarines must pass before they can endanger the ship or ships to be protected.

In each of these cases there could be different operating patterns employed depending on the ship sensors used and the geographic area.

The sensors most frequently used in the ASW environment are passive and active sonars. In the subsequent section on underwater noise, more will be said on these sonars, but as far as the operating pattern is concerned, a Towed Array (TA) passive sonar imposes important constraints on the ship's propulsion system. The array can be very long and to deploy and recover it can take a considerable length of time. The performance of the array can be adversely affected at higher ship speeds and so there can be significant periods where the ship is operating at just a few knots. In such periods the ship must minimize its underwater noise signature. This low operating speed immediately raises an operational dilemma as the ASW protection will be moving at a slow speed while the ship or ships to be protected may need to travel much faster for other reasons. The TA ship, if it is to keep up with the ships to be protected, could adopt an operating profile where it listens on the TA and, once it has been established that no enemy submarines are in the area of interest, it then travels at high speed to a new location, where again it listens on the TA. As the TA imposes a considerable drag at high ship speeds and may even have to be strengthened if ship speed limitations are not to be imposed, there could be an advantage if the TA can be recovered on board prior to the sprint. However, it is a matter of trade-off, whether the time taken to recover and redeploy the TA outweighs any speed restriction and the additional power and fuel consumed if the TA is streamed at high speed. Even if the TA is towed at high speed, there will be a time delay while it settles before the array can be used at the new location. Low ship speeds during TA operations imply low propulsion power levels, while high speed sprints, especially if dragging an array, imply high propulsion power levels. The range of powers achievable with a propulsion fit can be a limiting factor in a ship design and the TA operating pattern can exacerbate this.

As the winches and other handling gear needed to stow a TA on a ship are large and expensive, there can be a case for the ASW ship not being fitted with any way of storing the TA. In such an arrangement, the array is clipped on the vessel when needed and removed at other times. However, the array must be handled by some method and so a saving on the warship by this approach may be expensive when considering the additional support ships needed to carry the TA when it is not clipped to the ASW ship. In addition, there will be occasions when the warship is dragging the TA to a point where it can be passed to another ship and these times will limit the operational flexibility of the warship, not to mention the additional fuel consumed in the process.

It may be an advantage to run the TA at a slightly higher speed, thereby causing some loss in sonar range, but at the gain of a greater area covered per unit time. This tactic may avoid sprint and drift while still allowing the ships to be protected to proceed at a satisfactory speed.

When setting an ASW barrier across a geographic choke point, consideration must be given to the various environmental conditions that prevail; and there could be a trade-off between the ship's speed and the absolute sonar detection performance which results in the most effective barrier being when the sonar is being towed at a speed that does cause some interference.

As if the effects described so far are not enough, there is the added problem that the sonar performance is not uniform in all directions. The towing ship and the very shape of the array itself mean that the poorest performance is in front and behind the ship with the greatest performance on the beam of the array. As long arrays take a significant time to settle after a manoeuvre and the array must be reasonably straight before an adequate performance is achieved, the TA ship cannot change course frequently to cover blind arcs. This problem can be overcome by employing appropriate numbers of ASW units, disposed in a way to achieve the required coverage.

There is considerable activity by major navies to quieten their submarines and so there will come a time when passive detection will only give modest notice of a submarine's presence. Active sonar in these cases could be employed even though its use must alert the submarine of the ASW vessel's whereabouts. As there are many potential methods of establishing a surface ship's location, the additional information given by an active sonar may or may not be important. The use of active sonar does have noise implications on the ship's propulsion system and it does involve the ship operating at certain speeds, but the impact on the propulsion system design is, on the whole, less than that of the TA.

The tasks described have implied that the ASW ships are often operating at some distance from a main force. As the noise generated by friendly ships can impede submarine detection, this independence has advantages. This then raises the question, how long should a ship operate independently? One factor is the supply of fuel. There is a trade-off between the efficiency of the propulsion system and the fuel stowage. The more general factors to consider when selecting a propulsion system will be mentioned later. There is a range of efficiencies offered by the various possible propulsion systems, but selection of the most efficient system, while an advantage for independent operations, may have serious drawbacks in other areas of the design.

The operating patterns and tactics described above can be modified, depending on whether the ship is operating during peacetime, tension or war. Again, this raises more general questions on propulsion system selection, but it is a valid position to design a warship so that certain features are enhanced because they are important in peacetime, while still leaving those characteristics important for war at adequate levels. An example of this could appear in the area of the cost of ownership. As most warships, thankfully, spend the majority of their lives operating in peacetime conditions, the cost of ownership in these circumstances can be minimized by adopting certain operating patterns. If a war broke out, the cost of ownership, while still a consideration, could well slip down the priority table and the ship operated in a way that enhanced some war-like feature.

Underwater Noise

The sea contains many noise sources, both natural (marine life, weather effects) and man-made (shipping). These sources are variable in time and location and are not uniform across the frequency spectrum. Below about 1 Hz, noise levels are very high because of the low attenuation experienced in this frequency region. Between 1 Hz and 10 Hz, the level drops rapidly and the principal source is general turbulence in the sea. In the range 20 Hz to 500 Hz, the noise level varies little with frequency and is usually dominated by shipping noise. Above 500 Hz, the noise level drops rapidly again and is usually dictated by local weather effects. Thus a ship's sonar receives sound from many unwanted sources and these must be eliminated before the sound from a submarine can be identified.

Under ideal conditions sound energy can reach a sonar hundreds of miles from the source. However, ideal conditions seldom exist over very large areas and so the sound wave is modified and distorted in its passage; the greater the distance, the more likely some change is to occur. The factors that contribute to the sound wave modification and distortion are:

(*a*) Absorption. There are several processes that lead to the absorption of sound by seawater. Attenuation effects are particularly noticeable at high frequencies, though certain effects are responsible for losses at the lower frequencies too.

(*b*) Refraction. The velocity of sound in seawater varies significantly with pressure, temperature and salinity. Changes in velocity can diffract the waves and thereby distort the apparent direction of the source or mask from the sonar the existence of the source. The sea is far from uniform in terms of its temperature and its salinity level. Some variations are linked to geographic features and hence relatively stable while others change, for example, with the seasons.

(*c*) Reflections. These can occur at the sea surface, on the seabed or at boundaries between layers within the sea. The reflections off the seabed are affected by the condition of the seabed, the grazing angle of the incident wave and the frequency composition of the sound wave.

(*d*) Scatter. Foreign bodies within the sea can cause sound waves to be scattered.

The energy level of the noise signature and the more detailed characteristics can be important in ASW. Narrowband analysis of a ship's signature would show some sources that produce noise which has little variation about a mean, while other sources have pronounced peaks that extend over a very small frequency band. Noise can also be sensed over a wide frequency band (broadband analysis). Both types of analysis can be of importance in the ASW battle. The radiated noise varies from ship class to ship class and indeed from ship to ship of the same class. As such, the magnitude of any frequency 'spikes' and their disposition in the frequency spectrum, make narrowband analysis of signatures a vital part of classification of a noise source.

The noise signature of a vessel can degrade ASW performance by:

(*a*) Interference with the ship's own sonar.

(*b*) Interference with the sonars of other ships in the force.

(*c*) Giving the enemy notice of the ship's presence and thereby passing the initiative to the submarine.

At the early stages of the ASW ship design, a noise target must be set for the vessel. This target must reflect what sensor the ASW vessel is to use and this could include a margin for improvements that may be made during the life of the class of ship, how the ship is to operate, what threat the ship is likely to encounter, what characteristics the enemy is expected to incorporate in its submarines, and what performance the submarines are likely to achieve. Once set, this then forms the starting point for establishing features of the ship design.

The noise sources associated with a ship are the machinery, the propeller, and flow around the ship. At low ship speeds the machinery noise usually dominates the signature. The sources can be components out of balance, resonances or intermittent loads, e.g. combustion in a reciprocating engine, and useful information can be gained by monitoring on both broadband and narrowband sensors. Some noise sources can be reduced by good design and care over the manufacture of items but, even so, to reduce the noise source to a level that permits the target to be met may be excessively expensive or involve a long and risky development programme. Once generated, noise can be attenuated before it causes a problem in the open ocean. Noise from machinery can be transmitted to the sea by three paths. The path that dominates is not always obvious and it may need considerable investigation to establish the importance of each.

(*a*) Airborne. Noise energy from a machine can travel directly from the machine into the compartment and thence to the hull and sea. With air-breathing machines, there can be a noise path through the intake and exhaust ducts.

(*b*) Structure. Noise can pass through the mounting system to the ship's structure. There are additional paths that come within this category. Noise can pass through connecting pipework, cabling, duct walls and shafting.

(*c*) Fluid-borne. Many pieces of equipment must be supplied with fluid services and the noise can pass into the fluid and ultimately find its way into the sea, either directly through the fluid (in many cases the fluid is seawater) or by passing from the fluid into the ship's structure.

If very low ship underwater signatures are required, the importance of each path must be established. One technique that can be of help involves the use of the principle of reciprocity. Under certain conditions, an identical transfer function is obtained when the positions of the source and the receiver are interchanged. Thus a noise source in the sea can be detected at the machine and the noise paths investigated by disconnecting certain components in turn.

At higher ship speeds, noise, usually from the propeller first, followed by that generated around the hull and its appendages, becomes more important. Even once these noise sources predominate, there can still be noise 'spikes' caused by machinery, that can yield useful information when monitored on a narrowband analyser. Noise from the propeller can take three forms:

(*a*) Cavitation. Pressure varies in the region of the blades both as they rotate and at different ship speeds. Pressure levels can fall to a point where the water vapourizes. This state is short-lived and the bubble collapses, causing a noise.

(*b*) Singing. Discrete frequencies can be emitted from the propeller blades and these are thought to be resonance phenomena.

(*c*) Blade Rate. This is the noise generated in the region of the propeller as the pressure fluctuates in a cyclic manner. Even if pressure variations can be made to be small during steady state ship operations, higher variations may occur during ship manoeuvres. Blade rate noise is predominantly at the low frequency end of the spectrum.

Noise Reduction

Noise reduction involves costs and it possibly has other implications on the design of the ship. If it is possible to shut down equipment when the ship is to operate quietly, there could be the least impact on the ship design. In many cases it would impose undue operational penalties to do this and so measures have to be investigated to reduce the noise level emitted from running equipment. An assessment must be made on whether to reduce the noise at source and/or attenuate it during its path to the open ocean.

Some machinery is intrinsically quieter than others; for example, rotating machinery that experiences steady loads is likely to be quieter than reciprocating machinery that has cyclic impulsive loads. Within a complex machine, there may be a sub-component that is a significant noise source and by replacement or redesign, that sub-component can be improved from a noise viewpoint. With many pieces of equipment, there are only a few changes that can be made to improve balance, etc., and thereby reduce the noise signature, before a stage is reached where a major redesign is being undertaken. As a major change could lead to penalties in terms of development cost or loss of some other important characteristics (e.g. reliability), the point may come where all effort is directed to attenuating noise along its path to the open sea sensor.

A measure that is commonly taken is to mount the machinery. This can take the form of inserting resilient mounts between the machine and the ship foundations or by having two layers of resilient mounts with a large intermediate mass in between. In the latter case the aim is that there is a mismatch in stiffness in successive stages through the mounting arrangement so that they react independently. The intermediate mass should be as large as possible but practical considerations usually limit it to no more than the weight of the machine. The position of the resilient mounts and the structure of the intermediate mass are important if vibration modes are not to conflict with the mounting arrangements.

Most resilient mounting systems permit relative movement between the machine and the ship's structure. If this is the case any connections, such as pipework or, in the case of prime movers, output shafting, must have flexibility built into it. This flexibility, ideally, not only does not impede movement but also introduces attenuation along that potential noise path, though to combine these two functions—flexibility and attenuation—is not always possible. The greater the relative movement between a machine and the ship, the greater the technical problem. In the case of prime movers with high power and high speed output shafts, introducing adequate flexibility can be a significant problem that may impose space and weight penalties on the ship design.

If the airborne path is considered to be important, the machine can be housed in an acoustic enclosure. This is usually large enough to allow maintenance to be undertaken easily but major tasks may involve dismantling part of the enclosure. Self-contained ventilation and fire detection and fire-fighting systems can be incorporated. The enclosure does increase the overall space demand and there is less scope to overlap maintenance envelopes with adjacent machinery. Another measure that can be considered to reduce airborne noise is to close clad part or all of a machine. An operator will not be able to see malfunctions, such as leaks, quite so easily and cladding must be robust to withstand the rigours of removal for equipment maintenance and repair.

The location of the equipment in the ship can be an important factor. An equipment high in the ship is likely to have a longer and more tortuous path for the noise to find its way into the sea than equipment low in the ship. This in itself results in attenuation in most cases, though the extent of any overall reduction in noise energy depends on the detail of the design, with such effects as local resonances possibly cancelling some of the attenuation effects. Like other areas of noise reduction, the complete system (including the noise paths) needs to be examined, as design detail and the manufacture of the system are important when the precise attenuation patterns are involved.

Even once the noise energy has reached the outside of the hull, further noise reduction can be achieved by decoupling the hull from the sea. Acoustic tiles or the use of air emission systems are the common techniques used.

Measures that can delay cavitation noise being a serious problem, include designing the propeller to experience as low loadings as possible and making use of air, supplied from within the ship, to fill in the low pressure areas and hence prevent the water vapour bubbles collapsing (Agouti or Prairie). Pump jets have a duct shape that results in a gradual increase in static pressure between the duct inlet and the propulsor blading. This, together with care taken over the blade design, can lead to a delayed cavitation compared to that with an open propeller. There are several disadvantages associated with pump jets but probably the most important ones are that the system is heavier and more expensive.

Propeller singing is usually tackled by the appropriate shaping of blades and the use of materials that have suitable damping properties, though as the other properties of such materials are often less than ideal, they must be used with caution.

Care over the design of the propeller and the inflow into the propeller are important when trying to minimize the blade rate noise. Locating the propeller away from the hull and appendages helps to improve the flow in and around the propeller and hence avoids unnecessary pressure fluctuations. Clearly there is a trade-off here between noise reduction demands and those of other design parameters. Shrouding the propeller can be a useful feature when aiming to avoid a blade rate problem.

Maintaining a Quiet Ship

Once the measures that are necessary to achieve a ship with an appropriate underwater noise signature have been decided, the design can proceed. Care at this stage, and indeed during building, is important as an oversight can introduce a noise short. Such a short can, for example, consist of an inadequate clearance that results in a mount being shorted as the equipment moves in a seaway. During sea trials, the ship can be passed over a noise range and significant noise sources established and investigated to assess the implications of reducing them. As noise reduction measures can deteriorate with time (mounts can age or become contaminated for example) or noise shorts can accidently be introduced, the ship must return to the noise range at various times throughout its life, so that new sources of noise or increased noise levels can be identified and explored.

Other Factors Affecting Selection

Within this article, it is not possible to discuss in detail the various factors that must be considered during the selection of a propulsion system. A list of factors (in no particular order), which will carry a weighting that depends on the circumstances that prevail at the time of the design, is:

- performance
- weight demand
- space demand
- availability
- reliability
- maintainability
- ship signatures
- shock resistance
- costs

- the industrial base used by the Navy
- a resistance to change
- vulnerability
- manning

The words in the list cover a multitude of important aspects of design and a brief title can be misleading in terms of the full implications of adopting an approach to design. Many aspects interact with one another. By way of an example, consider the space implications of propulsion machinery in a SWATH design of ASW vessel.

Space demand can have a significant implication in the two important areas already discussed, viz. performance in the operating pattern and underwater noise. The propulsion machinery can be located in the hulls of the SWATH. The machinery then is in close proximity to the sea and in many cases, especially in small SWATH vessels, the hulls only offer a very confined space within which the machinery must be housed. This can limit the noise reduction measures that can be introduced and hence it can be difficult to achieve a very quiet ship. The diameter of the hull and the thickness of the strut can place a constraint on the type of prime mover and its output power. While preserving a small waterplane area, the ratio of thickness of the strut to the hull diameter (T/D in FIG. 1) can fall within a range of values. Gore[1] states that T/D is commonly in the range of 30–60%. Thin struts could lead to strength problems while a thick strut could significantly affect the hydrodynamic performance resulting in an excessive resistance at some or all ship speeds. There is however a further aspect that must be considered in this context. The vessel's power/speed curve can be modified by the introduction of bulges in the hull. An appropriate bulge could allow sufficient space within the hull to install an engine that would not be possible in a parallel section hull. A bulge could also be considered in a strut. Both these measures will alter the power/speed curve compared with a more conventional SWATH arrangement and it would be a matter of design consideration whether the penalties of higher resistance at some speeds and maybe the reduction of resistance at other speeds outweigh the opportunity to increase the installed power in the hulls.

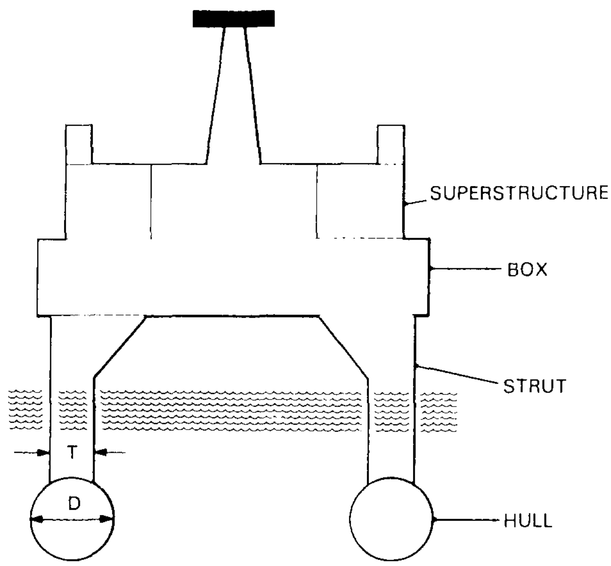

FIG. 1—SWATH NOMENCLATURE

Air-breathing prime movers in the hulls require ducting for both the air intakes and the exhaust uptakes. Ducting losses lead to performance losses and with gas turbines in particular, performance is very sensitive to duct losses. Duct losses depend on several factors such as the length and diameter of the ducting, the flow pattern of the gases and the bends. In general, ducts are longer in a SWATH than a monohull of the same displacement. This is because the draught of the SWATH is greater than in a monohull and, if ducts are led from one side of the vessel to the other (for reasons of having a single, off-centre funnel for example), the beam of a SWATH is greater. To avoid long exhaust ducts, the exhaust could terminate part way up the strut and discharge either outboard or in the space between the struts. If the former approach is adopted, care would need to be taken to avoid the exhaust presenting a major infra-red source, and if the latter approach is used, the passage of the plume along the underside of the box part of the SWATH or around the stern could lead to the need to use appropriate (and probably more expensive) materials or systems. In both cases the effect of the plume on any aircraft operations would need to be examined. It could be argued that it is unfair to compare a SWATH with a monohull of the same displacement as a SWATH will have a superior seakeeping performance. However, in a general discussion such as this, it is not possible to be more precise, when trade-offs in many design aspects not involved with the propulsion system are involved. The diameter of the ducts can influence and be influenced by the strut thickness (T). The number of bends in a SWATH duct arrangement may be greater than in a monohull to enable the exhausts to be led from a relatively wide hull to a relatively narrow strut. Thus the space requirement of the ducting can have an effect on the performance over the operating profile.

If machinery is located in the box (see FIG. 1), ducting losses can be made more modest but the problems associated with transmitting the power from the engines into the water increase. The use of bevel drive gearboxes can be considered. The powers transmitted through such an arrangement may be limited, especially if a low noise signature is required. The problem lies in designing the gears so that the various criteria that have evolved as being important in the design of parallel gears, including those believed to be important to produce quiet gearboxes, can be applied to bevel gears and in manufacturing the gears to a high accuracy. These difficulties can lead to the risk of an unacceptably high noise level from bevel gearing. Power could be transmitted through the strut by chain or belt drives. Noise and limitations on the powers that can be transmitted can again be a problem. Electric transmission can be attractive insofar as it can offer a relatively quiet transmission arrangement. As power required of the propulsion system rises, it may be necessary to consider more advanced concepts of electric motors, starting first with cooled motors (air and water) and leading possibly as far as considering superconducting motors. These more advanced concepts offer increasingly high power densities at the higher output power levels and thereby a higher power density within the hull of the SWATH. Machinery placed in the box does demand some services led from the hulls and the space in the box may be more sought after than in the hulls. These two aspects may result in a larger SWATH than otherwise and hence the likelihood of more power needed for a given speed. However, by placing the prime movers in the box, there can be fewer noise reduction measures applied to achieve a particular underwater noise signature and so this may, to an extent, counteract the other penalties on space demand. The overall efficiency of the propulsion system affects the space demand by virtue of the space demanded by the fuel storage.

This brief discussion on space demand in a SWATH is only intended as an illustration of the interaction between various factors in a propulsion system design, but it should be sufficient to reinforce the view that it is not practical to consider a characteristic in isolation when dealing with a complex piece of engineering such as a warship's propulsion system. The whole subject of selecting a propulsion system is covered in greater detail in a recent book[2].

OPTIONS OPEN TO THE DESIGNER

Again, a single article does not permit the full arguments to be considered so discussion will be mainly on the more common forms of propulsion systems, namely gas turbines and diesels transmitting power through gearing or electrical systems, with just a brief mention of oil fired steam. Even within this limitation, the discussion can only identify some important aspects without detailing all, but a list of references will hopefully allow the reader an introduction to more detailed cases when it is considered necessary to pursue the arguments.

Gas Turbines

With few exceptions gas turbines at sea have been derived from simple cycle aero engines. In terms of the two factors mentioned earlier as being important, viz. the underwater noise signature and the performance over the operating pattern of the ship, including the endurance at various ship speeds, the simple cycle gas turbine is a mixed blessing.

Noise

The continuous combustion process and the high rotational speeds, coupled with large numbers of blades on each rotor and stator, lead to a signature that tends to be biased to the higher frequencies and inherently devoid of noise 'spikes'. Several noise reduction techniques can be effective at attenuating the inherent signature. The auxiliary machinery needed to run the engine can introduce noise 'spikes' and resonances caused for example by ducting can introduce lower frequency noise, but both these areas can usually be dealt with effectively. Marine gas turbines are normally housed in modules which, among other things, provide an acoustic enclosure. The mounting arrangement of the module can allow resilient mounts to be incorporated, thereby attenuating the noise through that path.

Operating Pattern

The wide ship speed range necessary for the various tasks, together with the desire to have prolonged periods of operation independent of other units, makes it an advantage to have a propulsion system that is efficient over a wide power range. A modern marine simple cycle gas turbine has a peak thermal efficiency of about 35% at maximum power. However, the efficiency drops rapidly at part power so that by 25% of maximum power, the efficiency is around 20%. This can be seen in FIG. 2 where a specific fuel consumption against power curve is shown for a typical modern marine gas turbine. The efficiencies quoted do not include any losses due to ducting, losses experienced at elevated air intake temperatures or any transmission system losses, some of which are related to engine power. This poor part load efficiency has been an important consideration in many ship designs, with separate cruise and boost engines being fitted to enable engines to operate somewhere near their most efficient at the predominant ship operating speeds.

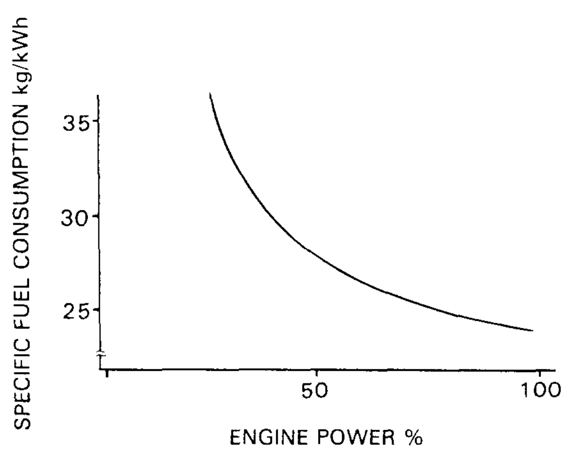

FIG. 2—SPECIFIC FUEL CONSUMPTION FOR A SIMPLE CYCLE MARINE GAS TURBINE

Improvements in the efficiency of simple cycle engines have been achieved over the years by appropriate increases in the pressure ratio across the compressor stage and increases in the turbine entry temperature. However, a law of diminishing returns applies and it is not expected that any significant further increases in efficiency can be expected. Any future improvement in the peak efficiency is likely to leave the same shape curve with a rapidly falling efficiency at part power.

There are two developments related to gas turbines which are aimed at improving the thermal efficiency and in particular the part load efficiency. While at most about 35% of the energy released by the fuel is usefully employed in a simple cycle gas turbine, almost all of the remaining 65% disappears up the uptake. The two new developments both aim to recover some of that energy. RACER is a system that was due to be fitted in the U.S. Navy's DDG51, ARLEIGH BURKE Class. A waste heat recovery boiler is located in the uptake of one of the four LM 2500 gas turbines. The steam produced by the boiler is fed into a turbine which drives into one of the propulsion gearboxes. The steam leaving the turbine is condensed and returned to the boiler. Several papers[3,4,5] have been written on this type of system.

The performance expected for such a system is:

(*a*) The peak efficiency will approach 45% and there will be only a modest fall in efficiency over a wide power range.

(*b*) About 30% additional power is available from the combined gas turbine plus RACER compared with the bare gas turbine.

These gains are not without penalty as there are demands in terms of a number of factors such as weight demand, space demand, maintenance load, etc.

The second main development is the advanced cycle gas turbine. A number of measures can be introduced into the cycle of a gas turbine which can enhance and modify the efficiency/power curve. One example of an advanced cycle is proposed by Rolls-Royce as a variant of the SM1A/SM1C range of simple cycle engines[6,7,8], but this programme is at a very much earlier stage than the RACER programme. The basic measures are to introduce an intercooler in the compressor (this reduces the work necessary in the later part of the compressor), a regenerator which transfers heat from the exhaust to the air prior to the combustion chamber (and so reduces the fuel needed to achieve the same temperature at the outlet of the combustion chamber), and finally a variable area nozzle prior to the power turbine (this enables a higher cycle temperature to be maintained over a wide power range, which results in a higher cycle efficiency and improves the heat transfer across the regenerator). This advanced cycle engine is expected to achieve a peak thermal efficiency approaching 45% and to have a reasonably flat efficiency curve over a wide output range. As such, its performance should be very similar to that achieved by the RACER system. Like the RACER plant, the advanced cycle gas turbine produces more power than the basic simple cycle engine from which it was derived.

While many factors must be considered during the selection of a propulsion plant for a future ASW vessel, it would appear that these two developments could be attractive contenders as they offer relatively low noise prime movers with relatively high thermal efficiencies over a wide range of ship speeds.

Diesel Engines

All diesel engines have a fairly constant thermal efficiency over the engine's power range, but the power turndown (maximum power to minimum power) is generally limited, as is the speed turndown. These two limitations can be important when trying to match a diesel to a ship that is required to operate over a wide speed range. For example, if certain conditions prevail, ASW operations may be conducted at around 20 knots while under other conditions there may be advantages in the ASW operations being conducted at a few knots. The type of diesel fitted in an ASW vessel is likely to have a speed turndown of about 3 to 1 and so if the diesel is sized to allow the ship to travel at 20 knots, the minimum speed on diesel power is 7 knots (assuming a constant speed reduction ratio in the transmission system and a fixed pitch propeller or a controllable pitch propeller that stays on the design pitch). 7 knots could be higher than the speed that allows full exploitation of the ASW capability under certain circumstances.

The three categories of diesel engine, low speed, medium speed and high speed, have no generally accepted definitions, but broadly low speed engines have output speeds that are compatible with propeller speeds, medium speed diesel engines have output speeds of several hundred revolutions per minute and high speed diesels are of 1000 revolutions per minute upwards. Low speed diesels have the highest thermal efficiency of the diesel types, with test engines reported to have a 50% peak thermal efficiency. This type of diesel has the highest power units and can burn the widest range of fuel grades, but the power/weight and the power/size ratios are low, compared both to other diesel types and to alternatives such as gas turbines. The low engine speeds coupled with the relative few cylinders often employed in low speed engines, results in a fairly high low-frequency noise signature. The size and weight of the engines present difficulties in introducing some forms of noise reduction and in any event, the attenuation of low-frequency noise is more difficult. The noise signature, the size and the weight are major disadvantages when considering the propulsion systems of likely ASW vessels.

While less efficient than low speed engines, the medium speed engines are still around the 45% area for thermal efficiency. The power/weight and power/size ratios are significantly higher than low speed engines, though still well short of current marine gas turbines. In the commercial sector there is considerable activity aimed at improving the thermal efficiency of medium speed engines and extending the range of fuel grades that they can burn. There are some who are convinced that medium speed engines can replace low speed engines as the mainstay of merchant vessel propulsion plants. As with low speed engines, it can be difficult to introduce sufficient noise reduction measures to produce an acceptable underwater noise signature in an ASW vessel, but the problems are less demanding than with the low speed engine.

The type of diesel engine most frequently found in warships is the high speed engine. Typically, it has a peak thermal efficiency of a little over 40% and has the most competitive power/weight and power/size ratios of the diesel types. The diesel engine is inherently noisier than a gas turbine, but the noise reduction measures that can be employed in conjunction with high speed engines, allow a high speed diesel to be part of the propulsion system of a very quiet ship. The diesel-electric propulsion system used in the Type 23 is quieter than some gas turbine options[9].

The diesel, as already mentioned, is more efficient than the simple cycle gas turbine and has a flatter efficiency curve over the power range. However, the high speed diesel shows no real advantage, in terms of thermal efficiency, over the RACER systems or the advanced cycle gas turbines that could be at sea in years to come. The waste heat from a diesel could be utilized to increase the overall efficiency but the waste heat is split between the exhaust (approximately 30%) which is relatively high grade heat and the cooling water (approximately 25%) which is relatively low grade heat and so recovery is more complex than in the gas turbine case.

Gearboxes

Because of the cyclic and tooth meshing nature of gearing, gearboxes are likely to produce a number of discrete frequency noise 'spikes'. There are several factors that have been suggested as being important when considering the noise produced by a gearbox, but universal agreement on the importance of each has yet to happen. The factors are:

(*a*) Gear tooth accuracy. The shape of the tooth and its surface finish are both important. Techniques to improve the process of cutting the shape, finishing the surface and measuring the final product, have helped to improve this aspect.

(*b*) Gear tooth configuration. When tooth contact is made and broken, sudden loadings can be imposed. Care over the number of contacts and the shape of the tooth at the point of initial and final contact can be important.

(*c*) Gear tooth loading. High loadings can result in various distortions within the gear train and this could lead to noise inducing situations.

(*d*) Gearcase structure. Support of the gear trains is important and distortion of the casing, due to loadings or thermal effects, can lead to additional noise.

In some designs, the gearbox is mounted on resilient mounts. Attaching the prime movers and the propeller shaft to a flexibly mounted gearbox can be tackled in several ways. The high rotational speeds of some types of prime mover, make the use of flexible couplings between the engine and gearbox a problem if a large relative movement between the two is to be possible. A way round this can be to mount both the prime mover and the gearbox on a common raft and then resiliently mount the raft. This reduces the relative movement between the two but still leaves the need for the propeller shaft to be attached to the gearbox. The propeller shaft must transfer the thrust from the propeller to the ship. Between the thrust block and the resiliently mounted gearbox there must be flexibility and this can be achieved by adequate separation of the two or by introducing a flexible coupling.

Electric Transmission

While electric transmission is generally heavier, less efficient and more costly than gearing, it does have some advantages including the potential for a low noise signature.[10] In fact some of the penalties may be relatively modest. For example, take the case of efficiency. A gearbox is generally around 98% efficient while an electric transmission system, which includes propeller speed control within the electric transmission system, is down to around 90%. However, this is a classic case where two different approaches to the same fundamental problem, cannot be compared by judging the performance in only one designed aspect. If the electric system consists of an a.c. generator and a.c. motor with propeller speed control effected by engine speed change (that is, the electrical system being used in a similar way to a gearbox), the efficiency is likely to be nearer 95%. However, in practice, once electric transmission is considered, it is often an overall advantage to the ship design if the propulsion system is integrated with the ship's electrical system. As the ship's electrical load demands a constant frequency, propeller speed control must be by a means other than varying the engine speed. This then results in a drop in the transmission efficiency. Even if the electrical transmission system does have a basic efficiency of around 90%, this does not necessarily lead to a significantly greater fuel usage than a gearbox alternative as the electrical system may allow individual prime movers to run nearer their peak efficiency for longer periods.

With the use of high power electric transmission, voltages must rise if acceptable current levels are to be employed. If integration of the ship's electrical system and the propulsion system is an aim, there can be a conflict over the desire to employ a standard voltage throughout the ship's electrical system (and this voltage to be common with other ships in the Navy to ensure commonality of equipment and spare parts), while the propulsion system demands a higher voltage for the high power application. There are options open to the designer to overcome difficulties, but each carries some penalty in other aspects of design. As 'quiet' ASW operations are conducted at relatively low ship speeds, the propulsion power demand for these operations is usually modest. Thus the philosophy of the Type 23 propulsion system emerges, that is electric drive only for the speeds where 'quiet' running is necessary and thereby the penalties associated with an electric transmission system are minimized.

Oil Fired Steam

While there are some oil fired steam warships used in ASW activities, they are generally old designs. Oil fired steam in new surface ships was abandoned by the Royal Navy almost 20 years ago for several reasons, which included the relatively poor efficiency of the plants. Modern marine oil fired steam plants could benefit from advances made in nuclear steam plant, power station steam plant and electronics and surveillance systems, to an extent where significantly higher efficiencies could be achieved. There are many factors that would need to be considered, but it is nevertheless unlikely that a modern steam plant in a warship would be more efficient than current simple cycle marine gas turbines. Certainly, compared with arrangements that have been discussed earlier which employ waste heat recovery with gas turbines or use diesel engines, the modern steam system would not compete favourably in terms of fuel consumption. Bearing in mind that a steam plant is also likely to be significantly heavier and larger than these competitors, further fuel penalties are incurred by the requirement for a larger ship.

Little is published on underwater noise of oil fired steam plant and so what can be said on its characteristics is limited. Many of the necessary pumps can be continuous flow devices and this coupled with high rotational speeds should bias the noise signature to the high frequency end of the spectrum. A possible low frequency source could be the boiler where large areas of plating etc. could resonate.

In Conclusion

While it has not been possible to discuss the subject in the detail that does it total justice, by exposing the arguments that are most likely to be raised when a designer is faced with selecting a propulsion system for an ASW vessel, it is hoped that some of the trade-offs and interactions have been illustrated. Each design will be different and the factors that prevail will vary; so only when the issues at the time are examined and a more detailed investigation conducted, can the broad picture painted here lead through many stages to a final design.

References

1. Gore, J. L.: SWATH ships; *Naval Engineers Journal*, vol. 97, no. 2, Feb. 1985, pp. 82–112.
2. Plumb, C. M.: *Warship propulsion system selection*; London, Institute of Marine Engineers, 1987.
3. Halkola, J. T., Campbell, A. H., and Jung, D.: RACER conceptual design; *A.S.M.E. Gas Turbine Conference, Phoenix, 1983*, paper no. 83-GT-50.
4. Halkola, J. T.: RACER—the contractor's view; *A.S.M.E. Gas Turbine Conference, Amsterdam, 1984*, paper no. 84-GT-101.

5. Donovan, M. R, and Mattson, W. S.: RACER—a design for maintainability; *Naval Engineers Journal*, vol. 97, no. 3, July 1985, pp. 139–146.
6. Bowen, T. L., and Groghan, D. A.: Advanced-cycle gas turbines for naval ship propulsion; *Naval Engineers Journal*, vol. 96, no. 3, May 1984, pp. 262–271.
7. Harry, N. J. F. V.: Marine Spey '86 update; *Journal of Naval Engineering,* vol. 30, no. 1, Dec. 1986, pp. 173–177.
8. Freeman, C. W. and Higson, A. J.: An intercooled regenerative marine Spey; *Institution of Mechanical Engineers Seminar on Alternative Gas Turbine Cycles, London, 7 May 1985*, paper no. 3.
9. Bryson, L.: The procurement of a warship; *Journal of Naval Engineering,* vol. 29, no. 2, Dec. 1985, pp. 226–263.
10. Firth, S. K.: Naval electrical propulsion systems; *Journal of Naval Engineering*, vol. 30, no. 2, June 1987, pp. 342–359.