WARSHIP PROPULSION SYSTEM SELECTION

BY

COMMANDER S. P. C. WESTWOOD, B.SC., C.ENG., M.I.MAR.E., R.N.
J. SPENCER, B.SC., R.C.N.C.
(Sea Systems Controllerate)

AND

R. R. SIMPSON, M.SC., C.ENG., M.I.MAR.E.
(YARD, Ltd.)

This article was presented as a paper at the Institute of Marine Engineers' Centenary Year Conference, 'Past, Present and Future Engineering in the Royal Navy', at the Royal Naval Engineering College, Manadon, on 6 September 1989. It is printed here with the ready agreement of the Institute.

ABSTRACT

It is likely that the quality of fuels available in the future will deteriorate, the manpower resources available both for watchkeeping and maintaining machinery at sea and for supporting activities ashore will reduce and the targets to be met with respect to underwater noise and IR signature will become more stringent. These factors, together with the changing perceptions of the main mode of operation of future classes of ships will greatly affect the choice of propulsion machinery.

Costs, both unit production costs and, more importantly, through-life costs, have an ever-increasing influence on new designs of ship, and the propulsion system must provide an economical solution to the operational requirements. New concepts in machinery development are discussed, together with trends in engine/propulsion efficiency, energy recovery, automation, condition monitoring, reduction in manning levels and increased equipment reliability and system availability, in order to achieve the Staff Requirement within the budget.

Introduction

Modern warships are sophisticated vessels. The complexity of their conception, design, build and commissioning has been compared with elements of the U.S. space programme, but how and where do these designs start? This article attempts to gather together and discuss some of the many factors and considerations which influence the choice of main propulsion machinery and major auxiliaries for Royal Navy frigates and destroyers. This size of vessel has been chosen as being most representative of 'the general case' but many of the factors will be equally relevant to specialist craft such as minesweepers. Submarine propulsion machinery will not be discussed.

A warship's propulsion machinery obviously has to be designed to enable the ship to perform her wartime role; this factor may thus be considered the most important and worthy of considerable discussion. However, before discussing what specific role a warship is designed to carry out in wartime, it is perhaps necessary to examine briefly why a ship, *per se*, is required at all, indeed why a Royal Navy, or why any Armed Forces.

Taking as a simplistic premise that the purpose of the Armed Forces is to protect the United Kingdom from external threat it must be assumed that it is just as important to protect the 'way of life' as it is the land mass itself—i.e. the jobs, and hence the industries are of prime importance. In protecting the United Kingdom would it be acceptable to procure all defence equipment abroad thereby reducing or even exterminating large sections of U.K. industrial capability? It may be that trade agreements and exchange agreements or other political considerations lead to the specification of foreign equipment being used but conversely other political considerations may constrain designers to use U.K. equipment where there is better or cheaper equipment available elsewhere. Likewise national politics may have some influence; industry in areas of high unemployment and other 'prestige industries' may not be allowed to founder but the increased emphasis placed by the Ministry of Defence on competition is making this factor less likely to be relevant. However, although lame ducks are unlikely to be nurtured, some with a slight limp may continue to be supported. These two factors are not appropriate for any deeper analysis in this paper but suffice it to say that international and national politics are both factors which will influence the design and procurement of British warships and hence the choice of propulsion machinery.

Accepting the fact that a warship is necessary and returning to the premise that a major factor in the choice and design of its propulsion machinery must be its ability to carry out its wartime role, it is necessary to consider how, and importantly when, this role is specified.

The timescale from the first conception of a 'Requirement' to the commissioning of the first ship of the class can be some 12 to 15 years. When framing the role that the ship will be required to carry out, other than in the broadest of terms such as 'Anti-submarine' or 'Anti-surface', the Naval Staffs will want to be aware not only of what is technologically feasible at the time of stating the requirement but also of what can confidently be expected to be feasible at some considerable time in the future when the decision to order the ship will be made. This crystal ball gazing is necessary to ensure that, in a time of swiftly advancing technology, a warship is not obsolete by the time she is built. There needs to be therefore a continuing dialogue between the 'Operational Requirements' Staffs and the Procurement Executive right from the beginnings of the germination of the 'Requirement' and throughout the subsequent design stages. Factors identified here that ultimately affect the choice of propulsion machinery are therefore 'technological developments', existing and anticipated, and the long timescale concerned which inevitably leaves open the possibility of a change in specification to accommodate a change in the threat occurring during that timescale. Thus even the apparently simple statement of the required wartime role is not such an easily definable target for the platform designer to aim at, but a constantly moving one. However, the initial 'Statement of Requirement' must be considered as the prime factor which will start the conceptual design process which will then generate the many other factors to be considered. (FIG. 1).

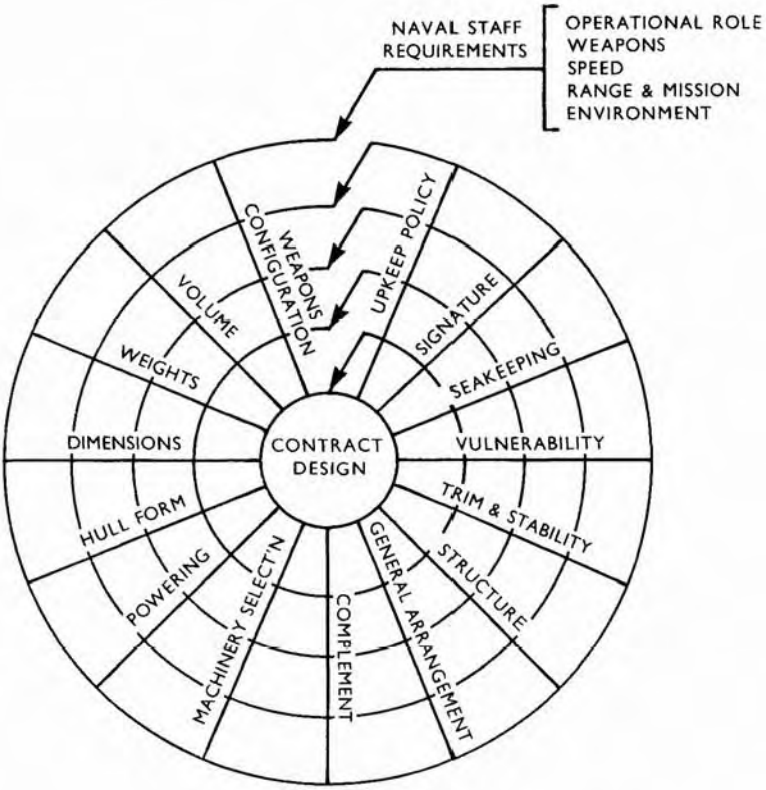

FIG. 1—SHIP DESIGN SPIRAL FOR WARSHIPS

The many factors shown in the figure are interdependent and interlinking to a far greater extent that can be shown clearly on this simple diagram, but it is suggested at this stage that the choice of propulsion package can be arrived at from consideration of the factors shown, after a few excursions around an iterative loop.

A factor not shown in the diagram and one which is becoming more and more of overriding importance is, of course, cost.

Cost impinges directly on virtually every other factor to be considered; not only is it a major factor itself in, for example, the decision between 'Propulsion fit A' and 'Propulsion fit B' which have identical performance, but it has a significant influence on the majority of other factors to be considered. For example, is it absolutely essential to specify an endurance of 9,000 nautical miles at 20 knots? Would 8,000 nautical miles at 18 knots suffice? Is a maximum speed of 30 knots really necessary? Would 29 knots do? Grouping some of the major factors from FIG. 1 illustrates this in FIG. 2.

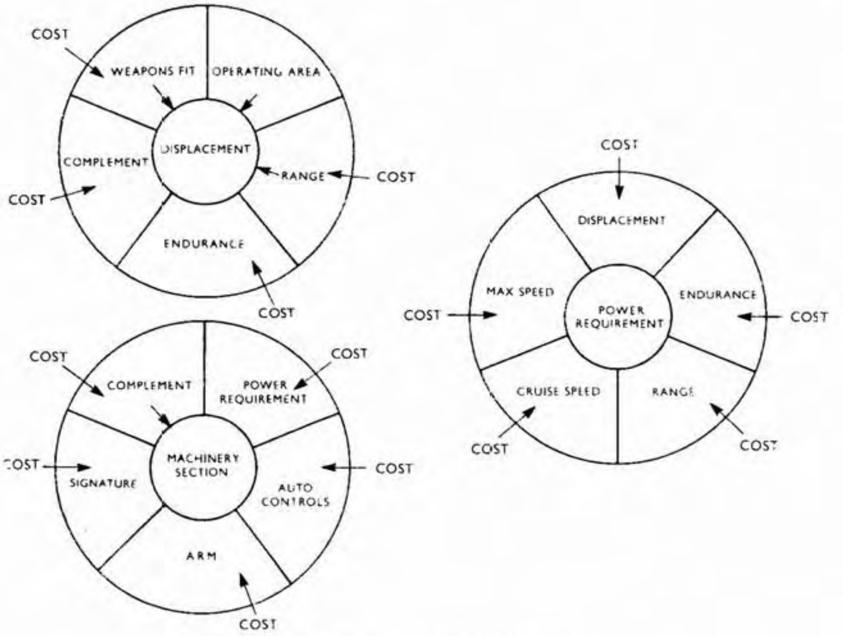

FIG. 2—COST AFFECTS EVERYTHING

The factor of cost can thus be considered the other main factor, alongside wartime role, which guides the designer down his path towards a choice of propulsion machinery. There is another major factor however, and that is the Secondary Role. Warships spend the vast majority of their time not at war, and the secondary or peacetime role inevitably imposes the need for different operating patterns and different armaments etc. It is a subject worthy of much debate to examine how much the optimum solution of the machinery requirement for the wartime role should be compromised by the requirements of the secondary role.

Take for example the basic difference in operating pattern for a frigate in her wartime role, which is to hunt and destroy submarines (an ASW frigate), and in her peacetime or 'tension' role which can be described as 'General Purpose'. FIG. 3 considers only one factor, that of operating speed, and the percentage of time spent at that speed.

These profiles will almost certainly lead to two different machinery fits to optimize such other factors as unit production cost (UPC) and through-life costs (TLC), etc., and, whereas the different roles can be accommodated to a large extent in the weapons fit by such concepts as 'Fitted for but not with' or 'Fitted to receive', such measures are not possible for main propulsion machinery or major auxiliaries. Similar profiles exist for energy generation, and are discussed later.

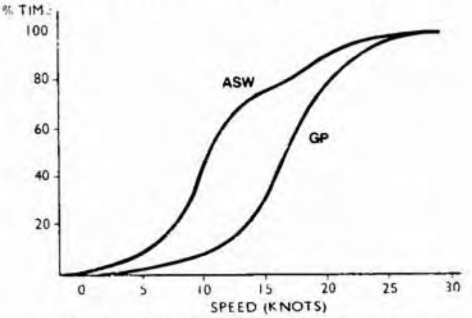

FIG. 3—TYPICAL OPERATING PROFILES

FACTORS AFFECTING SELECTION

Costs

The principal costs associated with marine engineering aspects of a warship design are defined as the UPC (the cost of purchase and installation of equipments) and the TLC (UPC plus fuel and support costs). Development costs for individual equipments are often separated as the degree of amortization for a particular project can distort the picture unrealistically. Manning costs are addressed later in the article.

TABLE I—*Cost comparison (£M)*

	COGAG	*CODAG*	*CODAD*	*CODLAG*	*Steam*
UPC	17	15	13	15	17
TLC	54	45	36	46	57

COGAG: combined gas and gas
CODAG: combined diesel and gas
CODAD: combined diesel and diesel
CODLAG: combined diesel electric and gas

A cost comparison for some of the machinery options available for a typical frigate is given in TABLE I. This assumes a 25 year life, and fuel at £200 per tonne at ship. The proportional contribution of UPC, fuel and support to TLC is fairly consistent between the options, and is shown in TABLE II.

TABLE II—*Through-life cost distribution*

Cost Element	*Contribution*
UPC	30%
Fuel	50%
Support	20%

Examination of TABLE I would seem to indicate only one possible solution on cost grounds—i.e. all diesel engines. However, part of the conundrum facing the marine engineering designer is that diesel engines are not always suitable for ship propulsion, total weight and volume being only one of the problems. Underwater noise signature is another and is addressed later in the article.

On the other hand gas turbines, which offer high specific power outputs, are more costly to purchase and maintain, and generally exhibit higher specific fuel consumption.

The following sections examine how fuel and support costs may be reduced by selecting machinery to suit the operating profiles and refit cycles; the method outlined applies whatever other constraints are placed upon the choice of machinery. More elements of the conundrum will emerge!

Fuel Cost Reduction

Propeller efficiency, at around 65%, represents a considerable waste of fuel. However, designers have strived for many years to improve this situation and the marine engineer has little opportunity to improve matters by selection. Controllable Pitch Propellers (CPPs) can lead to heavier shafts, larger outboard bearing brackets and hence to increased hull losses; but other losses, such as those within gearing and transmissions, are very low and offer little scope for significant improvement.

The main area where the choice can make an enormous difference is that of prime movers. Typical specific fuel consumptions (sfc) for open cycle gas turbines, intercooled regenerative (ICR) gas turbines, and medium speed diesel engines, are shown in FIG. 4.

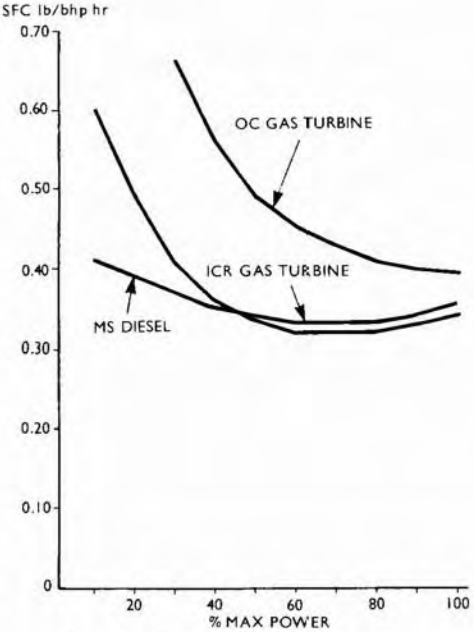

FIG. 4—SPECIFIC FUEL CONSUMPTIONS
ICR: intercooled regenerative
MS: medium speed
OC: open cycle

Open cycle gas turbines are seen to be particularly thirsty. Whilst the ICR gas turbine will match diesel engines at higher powers, below 40% full power they too show a marked loss of efficiency. In turn, diesel engines, whilst displaying a flatter sfc charactericstic, are often unhappy when operating for lengthy periods at less than 40% full load.

The trick would seem to be, whatever the prime mover, to operate at powers above 40% full power for as large a proportion of operating time as possible.

Another essential consideration is that of energy generation. Throughout its life a warship will develop a large quantity of energy, perhaps 500,000 MW hours, whether it be for propulsion or the generation of electricity. Unlike the power station, the power levels at which this energy is generated are very disparate. At maximum speed a frigate may generate 40 MW. At 6 knots, 1½ MW (including ship's services) may suffice. How then can the marine engineering designer minimize fuel consumption by obeying the 40% rule?

It is an established principle that the power/speed relationship is a cube law (approximately). Combining this with each of the operating profiles in FIG. 3 gives the distribution of power levels at which energy is generated. Typical results are illustrated in FIGS. 5 and 6.

Examination shows a wide variation, partly dependent upon ship's role, but with dominant features. In the anti-submarine warfare (ASW) role (FIG. 5) some 40% of total energy generated (TEG) is at less than 10% of total installed power (TIP), and 70% TEG is at less than 30% TIP. In the general purpose (GP) role (FIG. 6) somewhat higher powers prevail, with less than 5% TEG at less than 10% TIP, but 75% TEG at between 10% and 40% TIP. In both cases an uncomfortably large proportion of energy is generated at less than 40% TIP.

FIG. 5—ASW FRIGATE ENERGY CONSUMPTION (PROPULSION AND AUXILIARY LOAD), ASSUMING 1 MW AUXILIARY LOAD, 3000 HOURS/YEAR
TEG: total energy generated
TIP: total installed power

FIG. 6—GP FRIGATE ENERGY CONSUMPTION (PROPULSION AND AUXILIARY LOAD)

Fuel consumption is minimized by offering a considerable degree of flexibility in the choice of prime mover combination available to the operator. The British COGOG arrangement, with two 20 MW Olympus engines and two 4.5 MW Tyne engines was an early attempt. Whilst this may look expensive now when judged against modern alternatives, the choice of prime mover was governed by other considerations at a time when fuel was relatively cheap. The concept though would seem to be a sound one.

In a more modern arrangement, with the Tyne engines replaced by fuel-efficient diesel engines or ICR gas tubines of a similar rating, fuel efficiency would be improved dramatically, particularly in the GP role. In the ASW role, the CODLAG arrangement of the Type 23 frigate, with four 1.3 MW DGs supplying two 1.5 MW electric motors for propulsion, as well as ship service loads, is particularly flexible and fuel-efficient.

Once again the balancing act continues. To select a propulsion plant that will be equally efficient in both GP and ASW roles would require an increase in the number of prime movers in order to stay within the 40% rule. And space also costs money!

Support Costs

The two main issues here are unit overhaul costs and frequency of overhaul; the latter can also be sub-divided into infrastructure costs and loss of utilization of the prime asset. The cost breakdown in TABLE II attributed only 20% to support; this covers only the unit overhaul costs. The other issues are also addressed here.

On a per unit of installed power basis, the cost of overhauling an open cycle gas turbine every 5,000 hours is calculated to be about four times that of a diesel engine requiring major overhauls every 12,000 hours. It is estimated that an ICR gas turbine, with 25,000 hour life, would cost a similar amount to overhaul. On overhaul cost grounds diesel engines would appear to win hands down, there being no 25,000 hour gas turbines on the market at the moment.

Whilst the infrastructure and asset down-time costs have not been calculated it is clear that very large sums of money are involved in this aspect of support; the Royal Dockyards at Devonport and Rosyth alone employ some 15,000 people. That number though is small in comparison with those employed in the past and, whilst the reduction in numbers of ships in the Fleet has been a major influence, the success of the design engineers of all disciplines in reducing maintenance and overhaul frequency and down-time has also had a marked effect. There is though still room for improvement.

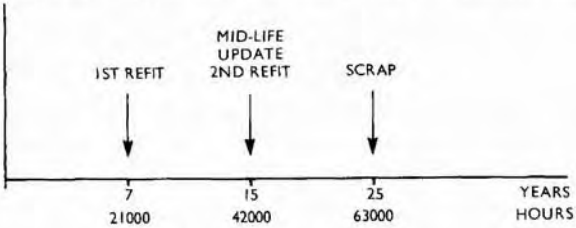

FIG. 7—UPKEEP CYCLE

If one takes the hypothetical case of a warship operating 3,000 hours per year, with refits every seven years, the upkeep cycle would be similar to that shown in FIG. 7. If that warship were to be equipped with a twin-shaft COGAG/CODAG propulsion system, the estimated operating hours for each engine over the seven year period are as shown in TABLE III. The operating hours associated with a ten year refit cycle are also shown.

TABLE III—*Operating hours between major refits (3000 hr/year; GP profile; geared drive; both shafts turning)*

	7 yr Cycle	*10 yr Cycle*
Boost Engines 25%	5,250	7,500
Cruise Engines (85%)	17,850	26,500

Installing engines with such life

spans would reduce overhaul frequency to refit periodicity; these life spans are well within the grasp of their designers now, and must represent an immediate goal as the marine engineer's contribution to increased warship availability and utilization, reduced infrastructure costs, and reduced support costs.

Availability, Reliability, Maintainability (ARM)

Future warships will be expected to spend more time at sea than the current generation of ships and hence will have to have a higher availability. This means in turn that all the components and systems installed in the ship must be reliable and require the minimum time to maintain.

The difference between reliability and availability can be illustrated by an example relating to the choice of propulsion engine. A twin engine installation is less reliable than single engine fit because in the twin engine fit there is twice the chance of a failure occurring in one engine. However, the availability of propulsion power is higher in the twin engine fit because a single engine failure will not result in a total loss of power.

In order to achieve a high availability propulsion system it is necessary to consider reliability and maintainability early in the concept design phase and to use the results from such studies as one of the criteria on which to compare alternative machinery schemes. These studies should include comparisons of the frequency and cost of scheduled maintenance associated with each of the schemes, whether the maintenance is carried out at sea, in harbour or ashore, and the ship downtime caused by the maintenance. To illustrate the type of arguments that must be considered, a comparison between gas turbines and diesel engines is given here:

(*a*) The gas generator in a gas turbine will have to be replaced at about 5000 operating hours. A major overhaul on a diesel engine is required at about 12000 hours.

(*b*) The ship downtime resulting from a gas generator change will only be several hours whereas the top overhaul for a diesel may require several days.

(*c*) The total cost associated with the gas generator change will be much greater than that associated with a diesel top overhaul because the gas generator must be returned to the manufacturer for refurbishment.

Without considering the cost a decision must be made as to whether it is more acceptable for the ship to be unavailable for frequent short periods or for longer but less frequent periods. It is important that the reliability studies are not confined simply to the major components of the propulsion train but that they incorporate also all the necessary supporting systems.

Targets should be set for the required levels of reliability and availability and statistical reliability data for system components obtained from data compiled from similar components in service. Whilst there is scope to assemble existing components into highly reliable and available systems, high component reliabilities must be achieved to minimize repair manhours and downtime. Failure effect analysis provides a structured method to determine the knock-on effects of a particular failure, which in itself may be of a trivial nature, but which may ultimately affect the overall mission. Numerate evaluations can be used to identify weak areas of the design and to provide confidence that the necessary ARM levels will be achieved.

The upkeep policy proposed for the ship must also be defined at an early stage in the design. An extensive repair by replacement policy will require more design effort to be expended on removal route arrangements rather than on the facilities required to maintain equipment *in situ*. The upkeep policy is also closely tied to the manning policy of the ship, but it should be noted that in the future there will be pressure to reduce shore support as well as ship crews. This means that simply shifting the maintenance load from ship to shore may not provide the best solution.

Machinery reliability and maintainability is the classic chicken and egg situation. Usually, in the limited timescale associated with ship and propulsion scheme design, reliability studies do not commence until a high level of machinery system detail is achieved. By this time many of the major decisions on equipment and systems have been taken and any shortfalls in ARM highlighted by the studies can only be corrected by the incorporation of additional facilities rather than by fundamental changes. The only remedy is for the designer and the reliability engineer to work together throughout the design to ensure that the requirements are effectively achieved.

Manning

The complement of a ship has an effect on the unit production cost in that each crew member requires accommodation and hotel services which, in turn result in a larger ship for the function it has to perform. However, by far the most significant factor is the effect which the size of complement has on the through-life cost of the ship.

This article is specifically concerned with propulsion aspects and the discussion is therefore limited to engineering personnel, although many of the arguments may be used on a whole ship basis.

If the engineer himself is assessed on the same basis as he would assess the machinery he operates and maintains the following would be the result:

(*a*) planned availability for operation 8 hours in any 24 hours;

(*b*) requires frequent shutdown during operational period for minor maintenance (meals, etc.);

(*c*) requires extensive, expensive initial programming (training);

(*d*) requires frequent refits ashore, scheduled and unscheduled (leave and sick);

(*e*) limited operational life (will not be on the same job for the life of the ship);

(*f*) very expensive to run in terms of fuel costs, support costs and index-linked leasing costs.

This impersonal look at engineers suggests that the fewer you have the better—until of course something breaks down.

The potential for cost savings by reducing the number of personnel on board has of course been recognized by commercial shipping lines for several years and has been reflected by the ever-decreasing seagoing engineering posts becoming available.

This reduction in manning has been taken to the extreme in a recent scheme proposed by the Japanese which comprises a convoy of unmanned merchant ships remotely controlled from a mother ship. The mother ship also accommodates a team of engineers who can be transferred, by helicopter, to any ship in the convoy which is malfunctioning. This concept, although technically possible today, does pose significant problems, and in any case would not be a viable solution for naval ships—or would it?

The engineering complement of a naval ship can be reduced in a variety of ways:

(*a*) A high degree of automation can be installed to release the engineering staff from routine watchkeeping and data logging tasks. The current generation of Integrated Machinery Control and Surveillance Systems (IMCAS) using VDU terminals can enable all machinery control and monitoring functions to be exercised from any terminal in the ship. This, coupled with automatic data logging and engineer's calls allows the machinery control room to be left unattended for considerable periods. Knowledge-based condition monitoring systems can predict the likelihood of a particular equipment or component failure, thus allowing ship's staff to plan maintenance rather than to perform emergency repairs as a result of a failure.

(*b*) Estimates of the effort required for scheduled and unscheduled maintenance can be used as one of the criteria on which the selection of a particular machinery scheme is based. The results of a recent study of this type are shown in TABLE IV. This shows the estimated non-commissioned engineering complement required for each of nine different machinery schemes based on current R.N. manning practices. The CODLOG / CODLAG scheme was chosen as a basis because it is similar to that used in the Type 23 frigate which has a known complement of 12 watchkeepers and 20 maintainers. The results indicate that manning, based on current naval policy, is not sensitive to machinery type. On the other hand manning is sensitive to the type of control and monitoring systems employed.

TABLE IV—*Non-commissioned engineering complement*

	Machinery Scheme	*Engineering Complement*
1	CODAG/CODOG	33
2	COGLAGL	31.5
3	CODLOG/CODLAG	32
4	gas turbine	32.5
5	steam	33
6	COGOG/COGAG	33
7	CODAD	33.5
8	CODLAD	33
9	2 diesels	33

(*c*) The traditional departmental boundaries between mechanical, electrical and weapons can be ignored. A single engineering department could cover the whole ship. The on-board technicians would have a broad training base and would be supported in specialist areas by the use of shore-based advice, on-board video information and knowledge-based diagnostic help.

(*d*) The equipment can be made so reliable and predictable that little scheduled and, perhaps more significantly, unscheduled maintenance is required when the ship is at sea.

The cost of manning a naval ship is perhaps the most significant factor affecting the overall through-life cost of the ship and any scheme which can reduce the complement is likely to show considerable through-life cost savings which far outweigh any increase in unit production cost caused by increased automation, etc.

Signatures

The propulsion machinery has a significant affect on two signatures, underwater noise and infra-red. Both these emissions can be used by hostile missiles or torpedoes to define their target and, as the sophistication of weapons increases, so the level of emission necessary for definition decreases.

Underwater Noise

The underwater noise signature of a modern warship is crucial to its success as an operational platform. Low underwater noise requirements have a fundamental impact on the way machinery, especially propulsion machinery, is selected and installed.

Recent warship designs have utilized a wide range of propulsion machinery installations with different acoustic characteristics but all designed for low underwater noise levels. These include variable speed, double mounted propulsion diesel installations with appropriate flexible drive shaft arrangements to accommodate relative movement between the engines and solidly mounted gearboxes and to reduce the transmission of engine vibration and noise via the gears to the hull. In some cases the gearboxes are also flexibly mounted to give a further reduction in transmission through the hull. A typical example of expected underwater noise radiated from a frigate propulsion diesel installation is shown in FIG. 8.

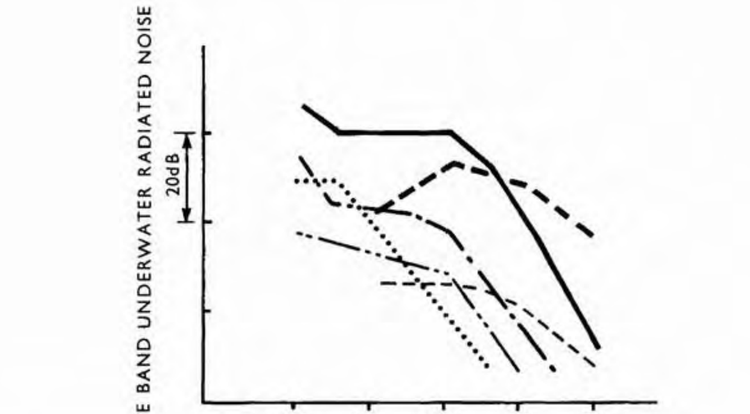

FIG. 8—TYPICAL EXAMPLES OF EXPECTED RADIATED NOISE FROM A FRIGATE PROPULSION DIESEL INSTALLATION

Similar noise reduction measures can be used in conjunction with gas turbine installations but, in general, the levels of underwater noise associated with gas turbines is less than that associated with diesel engines.

Diesel electric installations using double mounted diesel generators fitted in acoustic enclosures in conjunction with direct drive propulsion motors can achieve low levels of underwater noise radiation but great care must be taken to avoid significant propulsion motor excitation due to ripple on the electrical supplies.

Specification of a satisfactory acoustic design requires recognition of the significance of the non-mount paths including transmission of fluidborne noise to the sea via the machinery cooling system and excitation of the ship hull by airborne noise and by the engine exhaust systems.

Fluidborne noise generated by pump vibration and pulses in the flow can be reduced by the installation of flexible bellows pieces. The bellows accommodate the relative movement between flexibly mounted equipment and rigid pipework and also provide a form of flexible accumulator that can absorb the pressure pulses in the fluid. Avoiding short straight lengths of pipe between pumps and hull openings also helps to reduce the underwater radiated noise.

Excitation of the hull by airborne noise can be reduced by installing major noise sources within acoustic enclosures. This has the additional advantage of improving habitability within the machinery spaces.

Noise isolation devices may be restricted to purely passive devices such as rubber mounts, flexible pipe supports, rubber bellows and machinery enclosures. Additionally, active vibration, airborne and fluidborne noise cancellation techniques are being developed which may be used to further modify the signature in particular frequency ranges.

Propulsor selection is of vital importance in the case of a quiet ship. Controllable pitch propellers, operating at or near design pitch for quiet running, or fixed pitch propellers may be used. A variety of schemes have been developed to reduce propeller noise by introducing compressed air into the region of the propeller all of which provide improvements in noise under particular circumstances. The optimum selection of propeller depends on the type of machinery scheme installed but in all cases cavitation-free operation up to medium ship speeds and low cavitation noise under sprint conditions are primary requirements. Other variants, such as ducted propellers, are possible and may be desirable in certain operating scenarios.

Infra-Red Emissions

The most significant sources of infra-red emission are the hot engine exhaust pipes where they emerge from the funnel top and the exhaust plume itself.

Current generation warships incorporate cheesegraters at the exhaust pipe outlets; these devices, as these names suggest, comprise a series of slots cut in the exhaust pipe. The differential pressure between ambient air and the exhaust gases within the exhaust pipes draws ambient air into the exhaust through these slots to cool the platework at the funnel top.

If, however, infra-red emission must be reduced below that currently achievable using cheesegraters in order to reduce the chance of detection by more sophisticated missiles, then the temperature of the exhaust plume itself must be reduced. Several proposals for plume cooling devices have been developed in recent years. These devices are designed to dilute the hot exhaust gases with large quantities of ambient air before the plume leaves the funnel, but to date the effectiveness of such systems has not been tested at sea. Although not as strong as the engine exhaust plumes another source of infra-red emission is that from the hull, especially in way of the machinery spaces. In warm ambient temperatures the emission from this area is negligible but against a background of a cold sea the emission may be sufficient for detection.

Conclusions

The mechanical engineer is invariably faced with a number of often conflicting requirements to satisfy when designing a warship propulsion system. Some of the factors have been discussed in detail but the final design will always be a compromise in an attempt to give the optimum solution and it will require continuing dialogue between the operational staffs and the technical staffs.

Whilst fundamental methods of propulsion are unlikely to change significantly in the foreseeable future and a gradual development of current equipments seems the best that can be predicted, there is an increasing number of techniques available to assist in the development and assessment of proposed propulsion systems. These techniques, if used at an early stage in the concept design, can indicate through-life costs, reliability and various signatures; and pressure must be maintained to realize their undoubted potential for the development of propulsion systems which will offer reduced costs (both UPC and TLC), better ARM, lower signatures and smaller complements.