THE IMPACT OF THE GAS TURBINE ON THE DESIGN OF MAJOR SURFACE WARSHIPS

BY

S. J. PALMER, C.B., O.B.E., F.R.I.N.A.

(Deputy Director-General Ships and Head of the Royal Corps of Naval Constructors)

This Paper, the Parsons Memorial Lecture, was delivered by the Author to the Royal Institution of Naval Architects, by whose permission it is reproduced here.

The Parsons Memorial Lecture was instituted in 1935 and is delivered annually under the auspices of the Royal Society. The range of Sir Charles Parsons' activities was wide and included almost all branches of engineering and also optics. Each Memorial Lecture deals with one of the subjects in which his interests lay and in which his genius played a part.

Summary

In the last five years there has been a remarkable switch from steam turbines to gas turbines for the propulsion of the major surface warships which are being designed for the navies of the world. These gas turbines are generally based on aero engines which have been developed to a very high standard, usually at enormous cost, for the aircraft industry.

The use of these gas turbines has brought many new problems for the warship designer, particularly in the size of the downtakes and uptakes and in the great heat discharged from the funnel. These drawbacks have to be weighed against some remarkable improvements in ship availability and ship operation, and a reduction in engine-room complement and in through life cost.

This paper outlines the history of these developments and the bold decision by the Navy in 1967 to go for 100 per cent gas turbine propulsion for all its future warships. The results of that decision can now be evaluated as the first ships of the new gas turbine Navy are far enough advanced to enable a comparison to be made with existing steam turbine warships.

The effects on displacement, fuel consumption, layout, complement, upkeep, cost, and ship operation are discussed and it is shown that the advantages derived from the use of gas turbines decisively outweigh the disadvantages and that a significant advance has been made in the design of warships.

Introduction

When the *Turbinia* tore away from the warships of the day at Spithead in 1897, Charles Parsons showed in a dramatic way that a new propulsion plant of tremendous potential had arrived. Thereafter the Navy's ship and machinery designers were not slow to see the advantages of the steam turbine compared with the reciprocating engine, but they soon found that there were drawbacks as well as gains. While the steam turbine packed more power into a given weight and space, was quieter, caused less vibration and made engine-rooms better spaces for men to work in, it was also less economical at cruising speed, could not reverse, and required a much higher standard of quality control to achieve the same standard of reliability. So the change-over to steam turbines was slow and to some extent painful, and it was several decades before the majority of surface ships of the Royal Navy were driven by these engines.

That historic change to steam turbines is today closely paralleled by the current change to gas turbines by all the major navies, and it is taking place in about the same time scale of several decades between first going to sea and large scale adoption. As with the earlier change, there are tremendous advantages to be gained and many new problems, and this paper sets out to examine the impact of these on the design, the cost and the operation of major surface warships.

History of the Naval Gas Turbine

The aero gas turbine was developed by this country and others during the war, but it was not until the late 1940's that attempts were made to adapt this new form of propulsion for use in warships. Designers soon found that the marine problem is in many ways more taxing than the air one, since good engine efficiency is required over a wider range of power and a longer life is needed, yet at the same time having to work in a ship at sea brings in a host of new problems.

After using gas turbines in several designs of small fast craft, including MGB 2009, the first vessel in the world to be propelled by a gas turbine, the Royal Navy adopted a policy in the 1950's of using specially designed gas turbines as boost engines in classes of destroyers and frigates to augment the power of steam turbines for short periods at high power. It was the low specific weight of the gas turbine which made this an attractive policy, and as major warships operate for only short periods at high power it did not matter so much that the gas turbines had a relatively short life and poor fuel consumption. Later experience with these engines at sea showed that they were more rugged than the original lightweight 'racehorse' concept implied, and they have since come to be regarded as prime movers in their own right and not merely as boost engines. Experience also cast doubt on the wisdom of trying to maintain and repair gas turbines *in situ*, and in time the possibility of removing a defective engine and replacing it by a new or reconditioned engine came to be regarded as one of the major virtues of the gas turbine.

It also became apparent that the cost of developing a new gas turbine solely for naval purposes was very high and that the adaptation of an aircraft engine would be more cost effective. Aircraft gas turbines by the nature of their duty must be mechanically highly reliable in their own environment. This reliability is achieved by tremendous development effort and cost, which is justified because the potential market may run into thousands of engines. This development is also used to resolve manufacturing problems, so that engines can be produced economically even though subject to stringent quality control. Subsequent experience in service is built up rapidly by virtue of the large number of engines operating and their intensive usage in commercial operation. As a result, aircraft engines have lower specific weight and are more thoroughly proven than any industrial gas turbine suited for naval application. However, while aircraft gas turbines are thoroughly proven for use in aircraft, the effects of special conditions at sea cannot be accurately forecast, and must be evaluated by trials in a ship at sea. The most important of these special conditions are: running at sea level pressures and temperatures in a humid, salt-laden atmosphere; ship motion and transmitted hull vibrations; the aerodynamics of the air intake and exhaust ducts; the dynamics of the propeller and shafting, and the need to go astern.

In 1965, the Navy Department decided to convert H.M.S. *Exmouth* to an all gas turbine propulsion ship, using a marinized aero engine, the Rolls-Royce

Olympus, as the main propulsion unit and with Proteus engines for cruising. Experience from the very first sea trials showed that the plan was outstandingly successful and that the use of gas turbines brought a number of very important improvements in the performance and availability of the ship. A bold decision was then made in 1967 to go for one hundred per cent. gas turbine propulsion for all future surface warships. This important decision was taken early, and when other navies were still exploring the various options for propulsion plants, because the Royal Navy was then about to start on an ambitious programme for producing new classes of frigates, destroyers and cruisers, and there was no time to lose if this progamme was to be kept and if the opportunity of developing propulsion plants with the minimum number of different engines was to be seized.

For the last six years, the Navy's designers and their contractors have been toiling away producing their designs and models and mock-ups and building ships and manufacturing engines, and there has been a growing understanding of the accompanying problems and particularly of the extra space required for downtakes and uptakes, the need for well-shaped ducts which will not throw of eddies in the air flow into the engine, the great quantity of heat discharged from the funnel, and the need for absolute purity of the fuel. None of these was unforeseen but, as always in engineering, the cost and the complexity of the detailed design has turned out to be greater than was generally expected a few years ago. On the other hand, there has been a growing appreciation of the inherent advantages of present day gas turbines over all other forms of propulsion for surface warships.

The purpose of this paper is to examine the impact of the changes brought about by gas turbines on the design, operation, reliability, availability and cost of major warships, and then to attempt to weigh the advantages against the disadvantages. The paper is confined to warships for the Royal Navy although substantially the same arguments apply to all major surface warships.

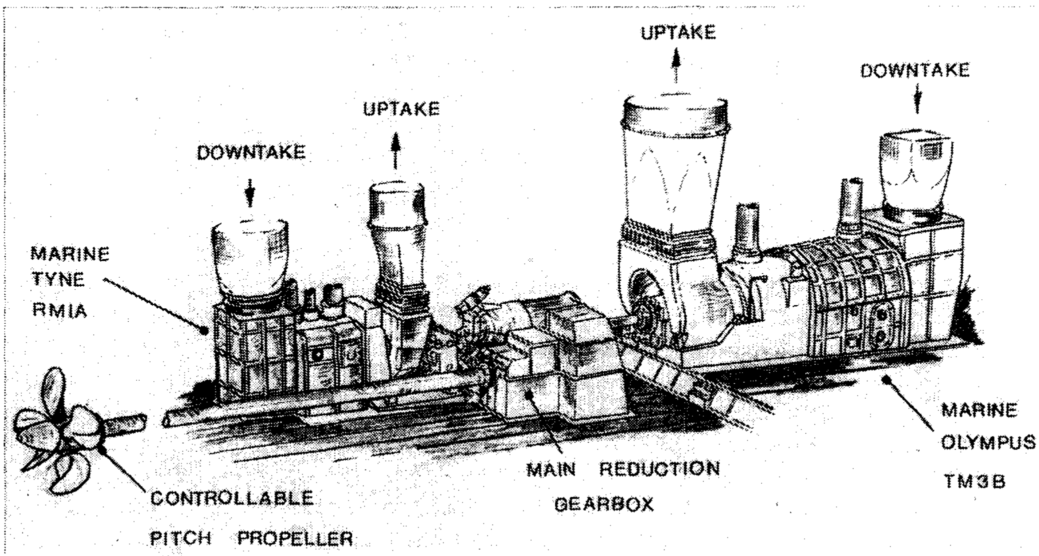

FIG. 1—OLYMPUS/TYNE PROPULSION PLANT

The Propulsion Plants in New Design R.N. Ships

A standard gas turbine propulsion plant has been developed for R.N. frigates and destroyers. This is a twin-shaft COGOG arrangement with one Rolls-Royce Olympus main engine and one Rolls-Royce Tyne cruise engine on each shaft. These drive Stone Manganese Marine controllable-pitch

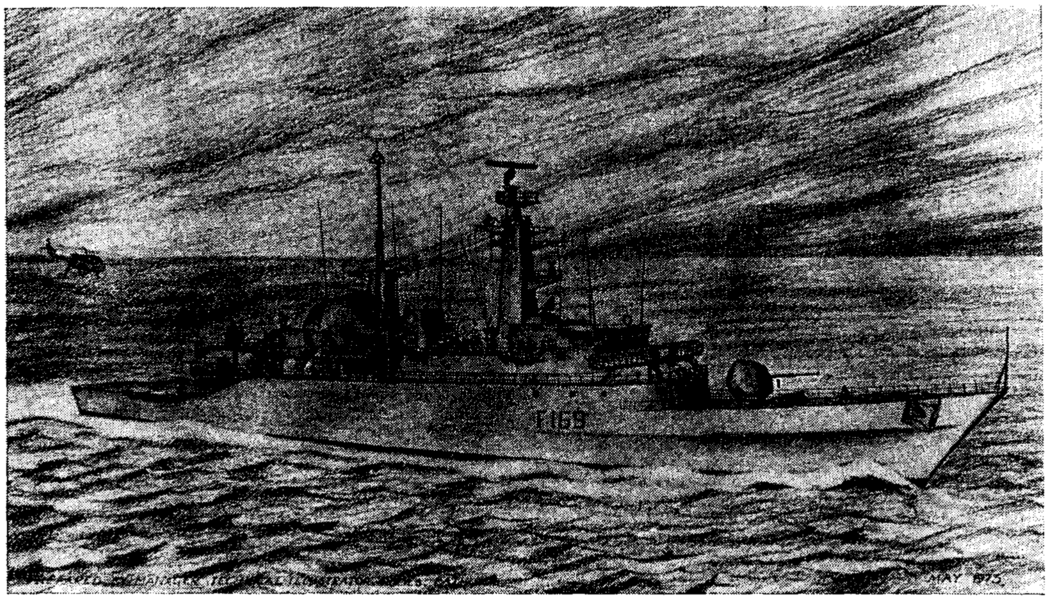

FIG. 2—ARTIST'S IMPRESSION OF H.M.S. 'AMAZON'

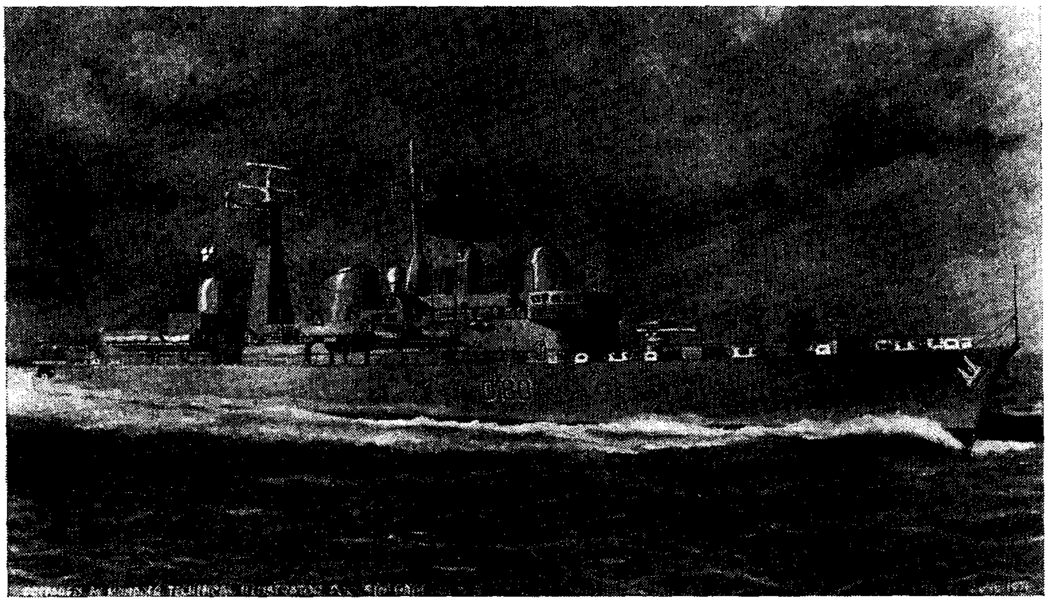

FIG. 3—ARTIST'S IMPRESSION OF H.M.S 'SHEFFIELD'

propellers through David Brown reduction gearing. Machinery controls are electronic and by Hawker Siddeley Dynamics Engineering. The layout has been published several times; its general appearance is shown in FIG. 1.

This plant is specified for the Type 21 frigates, eight of which have to date been ordered for the Royal Navy, and for the Type 42 destroyers, six of which have to date been ordered for the Royal Navy and two for the Argentine Navy. The lead ships are respectively H.M.S. *Amazon* (FIG. 2) being built by Vosper Thornycroft and H.M.S. *Sheffield* (FIG. 3) being built by Vickers, and these ships, which are the first custom-built all gas turbine major warships for the Royal Navy, are now nearing completion. An all Olympus gas turbine drive is specified for H.M.S. *Invincible*, the new through-deck cruiser, and combinations of Olympus and Tyne engines are being used for all other new surface warship designs now on our drawing boards.

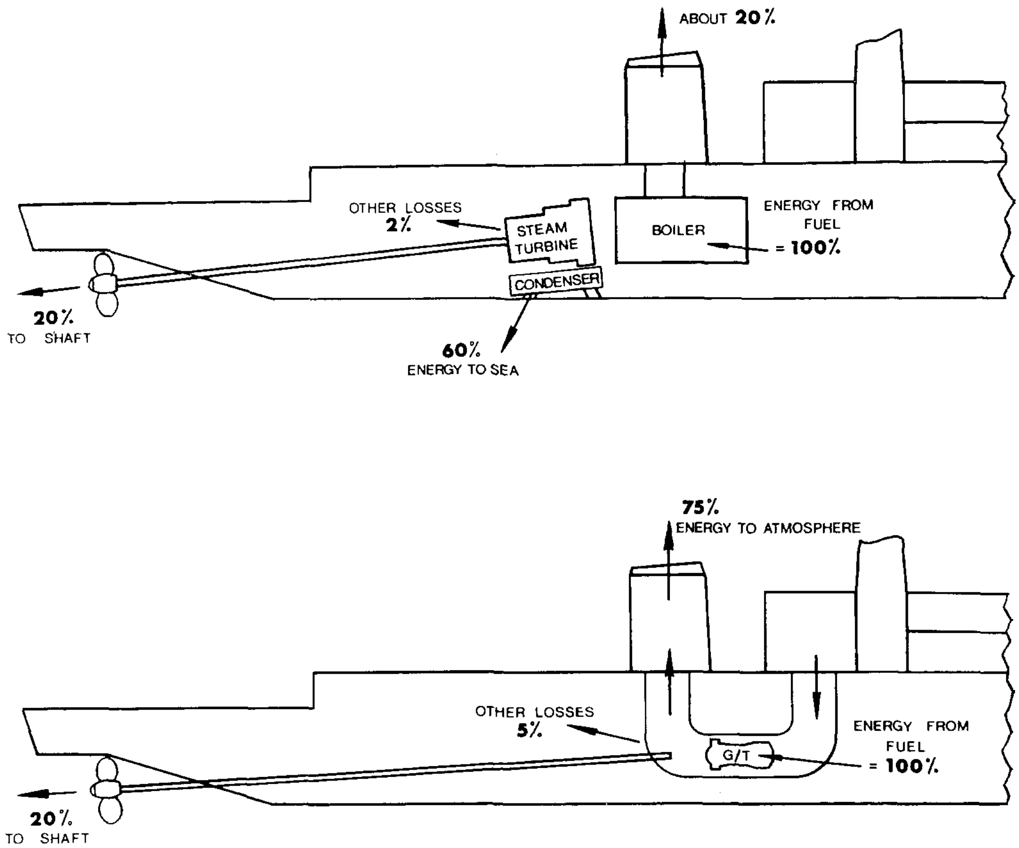

FIG. 4—HEAT CYCLE—STEAM AND GAS TURBINE

Some Features of these Propulsion Plants Compared with Contemporary Steam Plants

Propulsion Cycle

There is a fundamental difference between the steam and gas turbine propulsion systems currently in use for warships. The steam turbine works on a closed cycle, burning oil in the boiler furnace and rejecting some heat in funnel gases but most to the sea by way of the condenser circulating water. The gas turbine is an open cycle internal combustion engine where the air/gas products of combustion are used directly as the working fluid and all significant waste heat is rejected to atmosphere. The difference is illustrated in FIG. 4. The flow through the exhaust duct of the gas turbine carries away to the atmosphere about 75 per cent of the fuel energy, a job which is done very much more conveniently, at least for the naval architect, by the cooling water flowing through the condenser of a steam ship.

Although the temperature of the combustion zone in a boiler and in a gas turbine is of the same order, much more air is needed in the latter in order to reduce the internal temperature to what the turbine materials can stand, a function performed by the steam in a boiler. We thus find that, at the same power, gas turbines operating at the current gas temperatures require about three times the quantity of air required for boilers. The gas turbine exhaust temperature is also considerably higher. The discharge of large quantities of hot gas from the funnel is one of the less desirable characteristics of a gas turbine ship.

Size and weight

Each gas turbine is arranged as a module, complete with acoustic enclosures and essential auxiliaries. It is a compact, packaged power unit, needing only supplies of fuel, lubricating oil and compressed air for starting.

The power, weight and size of the turbine modules already fitted in R.N. ships are:

Olympus — 28000 s.h.p., 30 tonnes, 9·3 m × 3·0 m wide × 4·3 m high
Tyne — 4250 s.h.p., 15 tonnes, 5·5 m × 2·1 m wide × 2·5 m high

but many improvements are being made or are projected which will uprate the power of later models.

Modern marine steam plants of the same power as gas turbine plants based on these modules, and including gear boxes, shafting, propellers, downtakes and uptakes, would be about 15 per cent heavier and would require about the same space in a ship.

Another factor affecting ship design is the height of the centre of gravity of the plant. Here, perhaps rather surprisingly, there is little difference between steam and gas; this is because some heavy items of the steam plant, such as steam piping and turbo blowers, have to be relatively high in the ship.

Ducting

A gas turbine is very sensitive to irregularities in the flow of air and gases in the inlet and outlet, and the inlet in particular must be so shaped as to avoid producing eddies as these can lead to compressor blade failure.

The ducting must also be designed with a low resistance to air flow as the performance of a gas turbine is affected by the pressure drop; for example, an increase of one inch of water back pressure on the Olympus engine leads to a loss of power of about 100 h.p.

The exhaust duct has to cope with gas which initially might be at a temperature as high as 500°C, and which at full power travels at about 200 feet per second.

Controlling Changes in Plant Design

The Navy's decision to use two standard gas turbines for the propulsion of the present generation of surface warships was linked with another important policy: a decision to standardize the propulsion plant for ships of each class and not to allow minor variations from ship to ship. Such a policy is clearly essential when all the components are to be 'repaired by replacement'. Great care is therefore being taken to get the design of the lead ships right, even down to quite minor details, and then to document this very precisely and ensure that all follow-on ships are built to exactly the same pattern.

This policy was never followed with steam ships for the Royal Navy. With components coming from a number of different suppliers and connected together in the ship by numerous pipes which wound their way in three dimensions through the machinery spaces, there was a tendency to accept many variations from ship to ship and, to a considerable degree, each ship was custom-built and only the general arrangement drawings applied to all the ships of one class.

In recent years, we have also come to the conclusion that it pays to test the complete propulsion plant for a new class of ships in a shore test plant, as this greatly reduces the teething troubles which are inevitable with a first of class and reduces the number of design changes which have to be made later. Building and testing such a plant is no light undertaking as one can see by the shore installation at Ansty of one shaft set of machinery for H.M.S.

Invincible. This plant is currently in operation by Rolls-Royce. FIG. 5 shows the building during construction, and the scale of the project is illustrated by the gearbox standing outside before being installed.

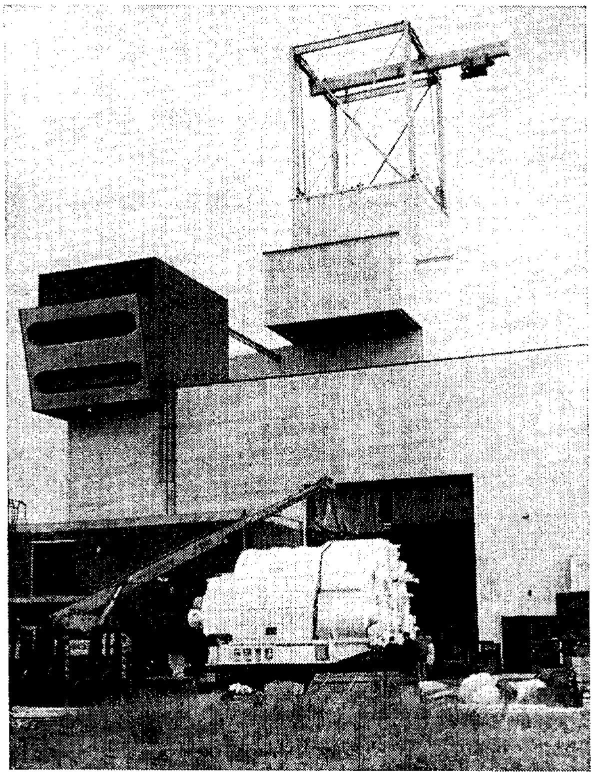

FIG 5—SHORE TEST SET AT ANSTY

Reliability

In the aircraft application, the reliability of the aviation gas turbine is extremely high but, of course, aircraft flights are at most of only a few hours duration after which the opportunity for checks and servicing and even replacement arises. In the case of ships, we are talking of mission durations of hundreds and sometimes thousands of hours; here the probability of a gas turbine engine failure of such severity as to require removal becomes significant. In current R.N. designs, as we have seen, we have got round this by fitting two engines on each of two shafts, one suitable for cruising and one for higher powers; thus, in the event of failure to an engine which is not repairable at sea, three good engines remain, of which, generally speaking, two will be adequate for most operational requirements.

Although the reliability of the gas turbines themselves is well established, there are many other factors which affect the reliability of the whole plant. These include the geometry of the downtakes and uptakes, thermal movements, stresses, vibrations, the control system, the shafting and propeller, and so on. Most of these can be checked out very effectively in the shore test plant, though even there the simulation of the propeller behaviour is difficult.

Life Factor

An aviation gas turbine is designed for operation in two conditions, the first at full power for take-off followed by the second, at about 80 per cent full power, for steady cruising. It is the operation at full power, and thus at high gas temperatures, that uses up the life of the engine, and the life at full power can be as little as 1/20th of that at cruising power. Like aircraft, warships spend little of their time at full power and there should be no difficulty in conserving the life of the Olympus gas turbine by slightly restricting the power at which it is usually run. The controls of the Tyne are set so that it cannot be run above the power at which a reasonably long life can be expected, and if higher powers are demanded the drive will be switched over to the Olympus. The Commanding Officers of our new R.N. ships will have to be aware of these points. If they are to avoid unnecessarily large overhaul bills they will have to think about conserving engine hours when they decide the speed at which their ships will run. Initially we expect to average three or four engines changes per ship per year, and this should improve to two or three changes per year as the mean achieved life improves.

Fuel Consumption

The specific fuel consumption of present-day gas turbines varies more sharply with the power than the fuel consumption of steam turbines and, if we move far away from the optimum, it rises considerably. However, at or near the optimum, the consumption with gas turbines is lower, possibly as much as 20 per cent., than can be achieved with steam plants designed to the restricted weight and space available in warships. It is usually possible to operate somewhere near these favourable conditions for gas turbines by fitting two engines per shaft.

The latest advanced technology gas turbines do even better for fuel consumption and it varies less steeply over the power range. It is unfortunate that their much higher initial cost and overhaul costs outweigh their saving in fuel. A point has now been reached where one can very nearly buy two Olympus gas turbines for the price of one advanced technology turbine and, for warships, at that price the latest is not the best.

Control

The integrated nature of the gas turbine facilitates remote control (that is, bridge control) and automation. As the response to demands for changes in power can be an extremely rapid change in gas generator speed, some degree of automation in control is desirable to avoid harmful effects on the plant from operator error. A notable instance of the rapid response of the gas turbine is that it can attain full power from cold in about two minutes.

Cost

It would be appropriate here, if it were possible, to consider the cost of producing and installing in a ship a complete main propulsion system plus the associated auxiliary machinery systems. With the gas turbine system would be included the turbines, downtakes, uptakes, gearing, propellers and machinery controls, and with the auxiliary machinery would be included electric generators, air-conditioning plant, distilling plant and air compressors. The steam plant would include boilers and all associated systems and auxiliaries that do the same jobs as have been taken for the gas turbine plant.

Unfortunately there are no reliable figures to compare the cost of one with the other because no one, to the author's knowledge, has ordered steam plant and gas turbine plant to meet precisely the same requirements. The best that the Ministry of Defence has been able to do is to ask the design staff and technical costings staff to estimate how the costs would compare; these estimates indicate that the steam plant might be up to 10 per cent cheaper.

There is an additional cost with the gas turbine plant to allow a policy of 'repair by replacement' or 'upkeep by exchange'. Each gas turbine module has a gas turbine change unit, which is the basic aero unit modified for marine use, and it is this unit which is removed for overhaul ashore. To support the upkeep by exchange policy, a number of spare change units must be held; these contribute to a higher initial capital cost than would be incurred with conventional steam plant, the amount extra being within 10 per cent. of the total cost of the complete propulsion plant. Nevertheless, as will be seen later, there is little doubt that the total through life cost, including the cost of engine-room staffs, will be lower with gas turbines than with steam turbines.

Effect on Ship Design

Let us now examine the effect on the overall design of warships of fitting gas turbines instead of steam turbines. Notice first that the new naval policy of adopting two standard gas turbine engines brings a fundamental change from past practice where steam plant was designed to suit each individual class of ship. With the new gas turbine policy, the engines are developed before the ship and must be used like building blocks to make up the power required.

Number of Engines and Reliability

The choice of which engines and how many depends not only on the top speed and the cruising speed but also on the ship's operating pattern and on the overall propulsion system reliability required. Reliability is time dependent and for the mission times and likely operating profiles of our new ships, a multi-engine fit is necessary. With the four engines being fitted in current R.N. designs, it is confidently expected that the operating standards being aimed at will be met and that a marked improvement over the reliability of current steam plants for surface warships will be achieved.

Speed, Fuel Consumption and Flexibility

Probably the main effect of the introduction of Parsons' steam turbine was to raise the operational speeds of fleets from under 20 knots to nearly 30 knots, a dramatic increase. The gas turbine, however, is unlikely to lead to any increase in the top speed of current major warships in average sea states, if only because in practical terms 30 knots is a sort of speed barrier for monohull, displacement ships over about 3000 tons if a reasonable balance is to be kept between the weight and space assigned to propulsion and other things, such as weapons systems. It is true that efforts are being made to surmount this barrier with hydrofoils, surface effect ships, small waterplane area twin-hulled ships and other new types, but these are as yet insufficiently developed to be discussed here.

With the gas turbine, changes of speed may be made quickly at very short notice, and the consumption of fuel is much affected by the point in the engine power range at which the engines are run. With the Olympus/Tyne combination, the maximum sensible cruising speed is limited by the power available from the Tyne engines because the fuel consumption of the Olympus engine is relatively high at part load making it an expensive engine to run outside the higher speed range for which it is designed.

With the Tyne at or near full load, the specific fuel consumption is about 0·5 lb./s.h.p.-hour. When allowance is made for the separate auxiliary load, the consumption can rise to nearly 1 lb./s.h.p.-hour; this is generally about 20 per cent better than the overall fuel consumption of a steam plant at cruising speed.

The ability to start gas turbines in a few minutes enables the ship to remain at a few minutes notice during most of its running life, and to run on cruising engines with the other engines immediately available for starting. Thus with gas turbines, 'steaming' can be economical while maintaining the ability to increase to full power in a few minutes.

Downtakes, Uptakes and Superstructure

The downtakes and uptakes have a big influence upon the ship design. With the Olympus engine, a cross-sectional area of about 6 square metres is required for the inlet trunk and for the exhaust trunk, and this is sufficient for hoisting the gas turbine generator out of the ship, through the downtake trunk. This trunk must of course be vertical if it is to double as a removal route. Both downtakes and uptakes need thermal lagging where they pass through habitable spaces, the former to reduce the heat loss from the ship into the cold turbine air supply and the latter to prevent excessive heat from the hot exhaust finding its way into the ship. Acoustic lagging is also required to reduce the amount of flow noise which finds its way into the ship.

It is necessary to put the downtakes where there is little chance of drawing down any of the exhaust efflux as this would cause a drop in performance due to the high intake temperature and to fouling and corrosion of the gas turbine compressor blades from carbon and sulphur products.

The downtakes and uptakes make heavy demands on space in the superstructure, particularly as extra space is required to protect the openings from spray and salt water. Because the high temperatures in the gas turbine make the blading very susceptible to salt corrosion, the inlets are faced aft and spray eliminators are fitted to reduce the amount of sea-water entering the intakes. For an Olympus turbine, these spray eliminators add about 40 cubic metres to the volume of the intake, this high in the ship and near amidships where space is at a premium. If there is a need to reduce airborne noise or the noise level at exposed command positions, the intakes and possibly exhausts as well have to be enlarged yet again to accommodate silencers which, besides being bulky, are by no means negligible in weight. All in all, when gas turbines are placed well down in a ship the ducting sadly reduces the extent to which the compactness and lightness of the engines themselves can be exploited.

The exhaust gases from gas turbines are at a much higher temperature than those from steam plant, and it may be necessary to site some aerials and equipment where they are not likely to be in the hotter parts of the efflux. This can influence the layout of the masts and aerials and the design of the funnel. All this underlines the need for very careful design of the upperworks, and wind tunnel experiments are needed to determine the path and temperature of the funnel efflux at different ship and wind speeds. FIG. 6 shows a typical experiment of this sort with a model of H.M.S. *Amazon*.

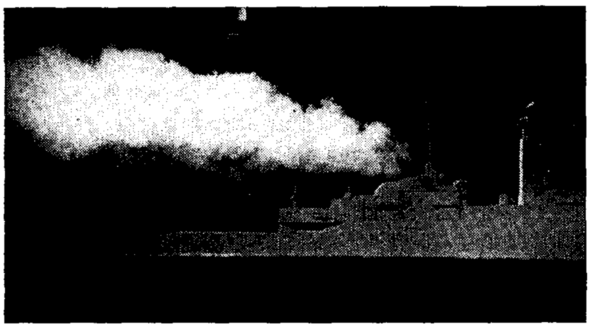

FIG. 6—H.M.S. 'AMAZON'—WIND TUNNEL TESTS

Engine-room Complement

The steam plants developed after the War for the Royal Navy were in many respects highly successful, but with separate turbines, boilers and auxiliaries they required a number of watchkeepers, and with three watches this added considerably to the ship's complement. These men were also needed for on-board maintenance because only in this way could an acceptable standard of ship availability be obtained. By its nature, steam plant has largely to be repaired *in situ* and hot and dirty work it is too, with pipe lagging, leaky joints and wet bilges to add to the discomfort.

With the gas turbine plants in current R.N. designs, the amount of onboard maintenance should be significantly less, particularly as the upkeep policy for the auxiliary machinery is to exchange a defective unit for a new or reconditioned one, as with the gas turbine change units.

The multi-engine fit will allow running hours on individual engines to be husbanded so that the time at which each engine will achieve its planned life may be made to coincide with a scheduled ship maintenance period. The ships are being designed so that turbine change units and auxiliaries can be exchanged within 48 hours with the minimum of outside help, and adequate access routes are fitted to make this possible. FIG. 7 illustrates these removal routes in H.M.S. *Sheffield*.

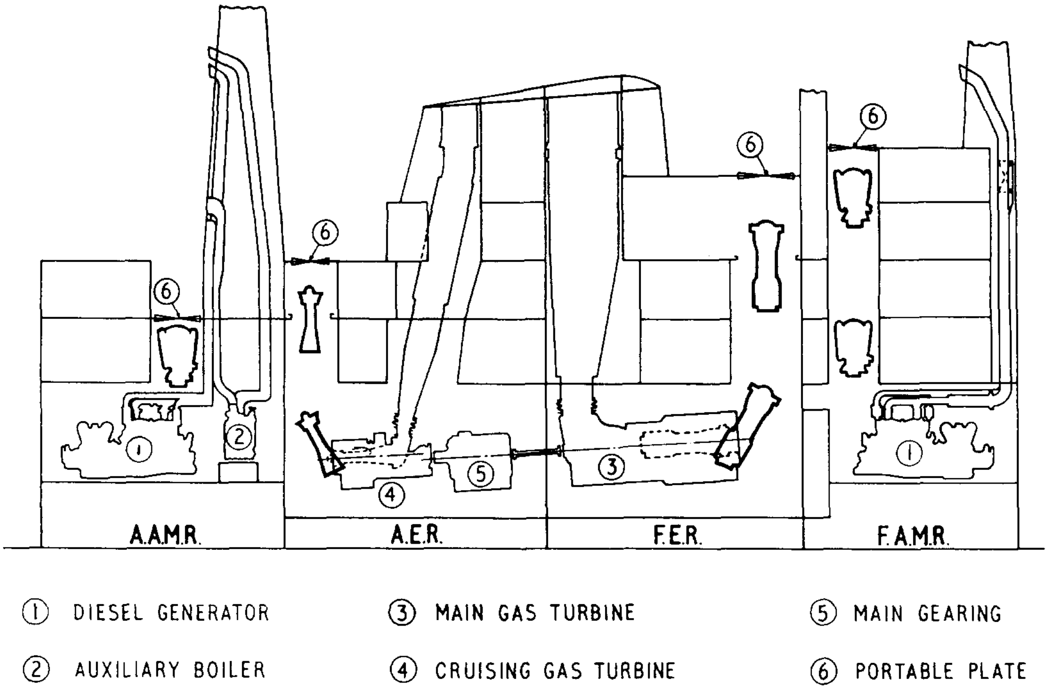

FIG. 7—H.M.S. 'SHEFFIELD'—REMOVAL ROUTES

The gas turbine plant can also be controlled by systems which lend themselves to bridge control and reduce the number of operators required below. In new design R.N. frigates, the reduction in engine-room complement due to having gas turbines is estimated to be at least 17 men. In addition, each man needs the services of about $\frac{1}{8}$th of another man, so the total saving would be about 20 men. These reductions in manning have an effect on the size of the ship and the capital cost, and an even greater effect on the through life cost.

Perhaps as important is what is being done for the men who work in the machinery spaces. The history of steam is one of endless hard work for the men looking after it, much of it under hot, oily, unpleasant conditions. By contrast, the artificer of a gas turbine ship should cease to feel at a disadvantage compared with, say, an electronics technician. He will become more a white coated diagnostician, and his job will offer wider scope for intellectual satisfaction than would be possible when running steam plants. Satisfactory recruiting these days depends perhaps as much upon such factors as it does on pay, leave and other service conditions. It is the opinion of many senior engineer officers in the Navy that in time the manning of a steam-driven fleet might have become extremely difficult due to the unattractive working conditions down below.

Machinery Controls

In days of sail, ships' captains and their sailing masters used to control the ship from a position as far aft as possible, where they could command the best view of the ship and her sails and could evaluate the forces of sea and wind acting upon them. It was also a useful position from which to monitor the performance of the crew and to issue orders to bring about changes in course and speed.

With the advent of steam, with no sails to be viewed from aft, the command naturally moved to the present bridge position, high up near amidships, to get a better perspective of the whole ship and to be nearer the centre of rotation for manoeuvring. The propulsion plant and the men operating it were now below decks, and the control link from the bridge was by means of voice pipe or mechanical indicators.

In time, damage control measures and the growing number of main propulsion and auxiliary machinery variables which needed to be controlled with precision led to the development of what was called a machinery control room adjacent to the machinery spaces; now in our latest ships other functions, such as the control of electrical distribution systems, have been incorporated in the same compartment and it has been renamed the ship control centre.

The advent of the gas turbine plant has had two effects in the machinery control field:

(*a*) it has led to a substantial reduction in the number of parameters to be controlled. A gas turbine plant has probably less than 25 per cent of the number of controllable variables in an equivalent steam plant.

(*b*) there is a very marked reduction in the time of response in the control loops.

These two factors have made the machinery control problem in modern warships particularly suitable for resolution by electronic control techniques, which can be designed to take full advantage of the quick response inherent in a gas turbine propulsion system. Although the design of the control system is complex, its operation is simple and it is possible to achieve complete control over both forward and astern motions of the ship by moving just one lever, a lever which controls both the power generated by the gas turbine and the angle of incidence of the controllable-pitch propeller simultaneously.

The wheel has now, as it were, turned a full circle, and we are back at a position where it is possible once again to place the forces moving the ship directly under the control of the men responsible for her navigation and safety. Future trends will, the author is sure, reinforce this move towards a 'pilot's cockpit' approach to the bridge in modern warships and the ship control centre will increasingly tend towards machinery surveillance and condition monitoring.

Transmission and Gearing

Gas turbines are not reversible and the requirement to go astern adds to the complexity and requires either a reversing gearbox or a reversible pitch propeller. A reversing gearbox to transmit the power required is large and heavy, and a controllable pitch propeller, with its much simpler gearbox, takes up less weight and space, but the control system is more complex.

A balance of these factors, together with reliability, has to be made in each new ship design, and this has led to the adoption of controllable-pitch propellers in the new R.N. frigates and destroyers, where space is severely restricted.

A further balance has to be struck in deciding the speeds of rotation of the power gas turbines and propellers. The greater the ratio of these speeds the bigger and heavier the gearbox will be. There is generally an advantage in being able to keep propelling machinery as far aft as possible, but this positioning is restricted by a large gearbox. Also, fast turning propellers make more noise than slow ones, but slow propellers are large and there are limits to the diameter that can be accommodated under a ship's stern without protruding too far below the keel. The running speed of an economically sized power turbine disc of a gas turbine is about 5000 r.p.m. and suitable r.p.m. for a quiet propeller would be about 150. The gearing to meet both conditions would however be too big and heavy, and in practice the speeds are adjusted to make a sensible compromise.

Electrical Power Generation and Auxiliary Machinery

Undoubtedly the most reliable way of producing electrical power in a warship is by means of turbo-generators, and these have been developed over the years to give very long periods of trouble-free operation regardless of the loading upon them. Since gas turbine ships have no suitable steam supplies, this form of generation is no longer available, and the choice is narrowed to Diesels or gas turbines. Gas turbines of the relatively small powers required do not yet command a large enough market in this country to ensure their development to the standard of reliability required. Diesels, though reliable and economical, are large, heavy, noisy and expensive on maintenance and, moreover, they are intolerant to light loading.

After careful analysis, the Navy has decided that at present the advantage lies with Diesels, and that power generation in R.N. ships will be by a standard range of Diesel engines currently covering a range of outputs from 250 kW to 1750 kW. Thus the Navy's 'all gas turbine policy' means the end of the steam era in surface warships but not the end of Diesels.

In view of its many known disadvantages such as mess, heat, lagging and heavy maintenance, serious consideration was given to eliminating all steam from our gas turbine ships. It was, however, decided in the end that steam offered overwhelming advantages for three specific purposes, namely the manufacture of fresh water, the heating of compartments and the heating of domestic water. Automatic domestic boilers have therefore been incorporated for these tasks. All other auxiliary machinery is electrically driven except for some pumps for the main propulsion which are gear driven from the main gearboxes.

Fuel Stowage

Gas turbines suffer considerable reduction of running life unless they are supplied with very clean distillate fuel which, in the Royal Navy, means clean diesel fuel. Unfortunately diesel oil has some affinity for water and ships live in a marine atmosphere and are supplied with fuel which has a real risk of being contaminated by sea water when it is delivered. Significant quantities of water are released from water saturated fuel when it cools, and so small quantities of sea water must be expected to exist as free water in the fuel. This free salt water will corrode steel storage tanks unless they are properly protected.

The corrosion often occurs as pitting of the bottom structure and other horizontal surfaces and is, of course, more rapid and more widespread if some form of sea-water ballasting is operated. This corrosion provides a further source of contamination of fuel and an uneven tank surface which itself is more difficult to clean. If tanks are uncoated, we face the through life cost and docking times involved in carrying out sufficiently frequent and detailed survey and repair to ensure that the somewhat indiscriminate corrosive attack does not affect operational service, particularly in the later life of the vessel.

In considering surface coatings for protection of these tanks, the Royal Navy has drawn on its experience in developing coatings for aviation fuel tanks, and has adopted a system based on an expoxy resin which is applied over surfaces which have been abrasive blasted to a white metal finish. Such a coating should have a life of over ten years with a limited amount of touching up. This system has been developed to the Navy's own specification and is suitable for both aviation and diesel fuel stowage.

For reasons of stability and more pressing demands for space higher in the ship, a considerable proportion of fuel in warships has in the past been stowed in double bottom type stowages. The ship designer is now being forced to give greater consideration to storing fuel in spaces which are more convenient for carrying out the exacting processes of preparation and coating with a high duty composition. In the meantime, a proportion of the fuel stowage in some current designs is in tanks of shallow depth and the internal complexity is such that they call for very detailed planning and production effort on the part of the builders if the required preparation and coating standards are to be achieved.

Noise

The gas turbine units can very largely be isolated from the hull and there need be very little low frequency water-borne noise. There is a high-frequency air-borne noise problem but this is easier to combat, and it can be reduced by enclosing the gas turbine modules in sound-insulated casings and by careful design of inlet and exhaust trunking. Both downtake and uptake trunks need acoustic lagging to reduce the amount of air-flow noise which finds its way into the ship. In practice, the noise levels in the gas turbine rooms and elsewhere in the ship have been found to be much lower than was feared at one time.

Ship Size, Displacement and Procurement Cost

The features of the gas turbine plant which affect the size and displacement of a warship are the power and number of engines, the ducting, the fuel, the complement and the auxiliary power.

By carrying through design studies based on the Type 42 destroyer, it has been found that if the R.N. were to revert to steam machinery and still meet the specified requirements for this design then the displacement would have to be increased by about 250 tons. This increase is made up of an additional 100 tons for steam machinery and auxiliaries, 60 tons for more fuel, 50 tons for the additional accommodation and 40 tons more for structure required for fuel and machinery.

The larger steam-driven destroyer might be very slightly cheaper to buy. Expressed as percentages of the cost of the propulsion and auxiliary machinery systems, the steam machinery would, according to our estimates, be about 10 per cent. cheaper but the 50 tons for extra accommodation and the 40 tons for extra structure would cost 7 per cent. more. Thus the steam version of such a destroyer might be cheaper by about three per cent. of the cost of the machinery. If equipped with weapons similar to those in the Type 42 destroyer, this would be approaching one per cent. of the total cost of the ship.

Upkeep

The upkeep of naval ships involves maintenance at sea by ship's staff, maintenance alongside by ships' staff assisted by naval shore-based repair teams, and refitting by civilian labour in the Royal Dockyards. Over the whole life of a warship, the cost of all these upkeep operations is usually in excess of the initial procurement cost.

With gas turbine ships, all these upkeep operations will be much cleaner than with their steam-propelled sisters due to the absence of lagged steam pipes and main boilers. With more of the work of machinery repair taking place in shore workshops and less *in situ* afloat, there will also be a change of emphasis in the work that is done on board which will, to a much greater extent, be the removal and replacement of machinery followed by its setting to work and testing and tuning.

The policy of upkeep by exchange coupled with greater standardization of machinery units will allow line overhauls ashore with properly set-up facilities, tools and procedures. Line overhauls have many advantages, including continuity of like work, greater expertise and improved reliability after overhaul, and also a saving in the cost of providing facilities because these need not be duplicated in several places.

It is expected that the time and money spent on the upkeep of gas turbine ships will be significantly less than on steam turbine ships, possibly by 5 per cent. or more, and that the frequent delays experienced with *in situ* refitting of steam machinery, in an environment considerably short of the ideal, will be reduced.

Industrial Base

One of the problems of present day steam machinery for surface warships is the difficulty of ensuring adequate quality control over the design and production of the plant and over the installation of the many sub-systems and components. This problem has been tackled successfully by the specialist firms in this country producing steam plants for our nuclear submarines but the sections of industry dealing with surface warship steam plants, faced as they are with a declining market for their products, are finding it increasingly difficult to achieve the high degree of co-ordination which is needed in the evolution of a plant which, by its nature, requires inputs from so many subcontractors.

On the other hand, the aero gas turbine industry is highly integrated and the standards and techniques of that industry are specifically aimed at providing a very high degree of reliability. The marinized gas turbines are supported from the same industrial base and are sufficiently similar to their aero-parents to use the same standards and techniques, and thus to reap the same benefits of reliability.

Through Life Cost

In the last few years, the costs of ships upkeep have risen so much that the Navy has become more aware of the total commitment over the whole life of the ship. The initial procurement cost of a warship is usually only about 25 per cent. of the total through-life cost, the other main contributors being operating costs 25 per cent., maintenance 32 per cent., and complement 18 per cent. This proves, what every designer knows instinctively, that it is often worthwhile to pay more at the procurement stage for features which will save heavier charges later on or reduce the number of men needed to run the ship.

When practicable, through life costs are now taken into account when making important design decisions, and such an analysis brings out another argument in favour of gas turbines compared with steam turbines. In the past, there was a good deal of uncertainty about the money that would have to be spent on the upkeep of steam machinery; gas turbines, however, will be maintained by a process of exchange by repaired units, and the reliability and the frequency of exchange have been much studied so that a good deal of data to judge the through-life costs of the new propulsion plant is now held.

Expressing all figures as percentages of the cost of producing and installing one complete steam plant plus auxiliaries, the following TABLE gives a balance sheet comparing the estimates of the cost of a gas turbine plant with that of an equivalent steam turbine plant, omitting all items where there is no identifiable cost difference:

TABLE I—*Breakdown of the through life cost of a gas turbine ship showing the difference in cost of items expressed as a percentage of the cost of production and installation of one complete steam plant and auxiliaries*

Item	*Difference in cost as percentage of cost of one steam plant*
Producing and installing the complete propulsion plant plus trunking, gearing, propellers, machinery controls, electric generators, air conditioning plant, distilling plant, and air compressors	+10%
Other ship procurement costs, the displacement and accommodation being reduced as described earlier	− 7%
Extra engines to implement the 'upkeep by exchange' policy	+10%
Saving in fuel consumption over 20 years	− 5%
Saving due to reduction of ship's complement over 20 years	−40%
Saving in upkeep costs over 20 years	− 5%

This shows a net reduction equal to 37 per cent. of the procurement and installation cost of a steam plant. This would normally mean a reduction of about two per cent. of the through life cost of a destroyer or frigate.

Ship Availability

When one of these new ships is in service and a machine or equipment becomes defective, a decision will have to be made either to remove it and replace it by a new or reconditioned item or to repair it onboard. With good removal routes built into the ship and with a ready supply of reconditioned items, it should be comparatively simple and quick to remove and replace. For failures which are identified as being within the capacity of the ship's staff to repair, suitable assemblies and components will be supplied as onboard spares for repair by exchange, and again this should reduce the downtime for corrective maintenance.

Provided that the correct logistic support is in the right place at the right time (and a considerable effort is being put in to make sure that it will be), the net result of this policy will be a big improvement in the time the ship is available for service. The adoption of this large scale procedure for repair by replacement depended on the decision to use gas turbines and thus remove the biggest and most time consuming part of a ship's maintenance load. There is no doubt about the value of this tremendous change in naval upkeep policy and no doubt that with this new policy the Navy will be able to spend more time at sea. The indications are that with reduced times for refitting and with reduced downtime for replacing defective items in between refits, the operational availability of ships will be at least ten per cent. greater than it has been with steam ships. However, this advantage may not be reached at once as some initial teething troubles with the new plants must be expected.

Standardizing on a small range of gas turbines should also, in time, ease the problem of training personnel and lead to improved operation and maintenance at sea.

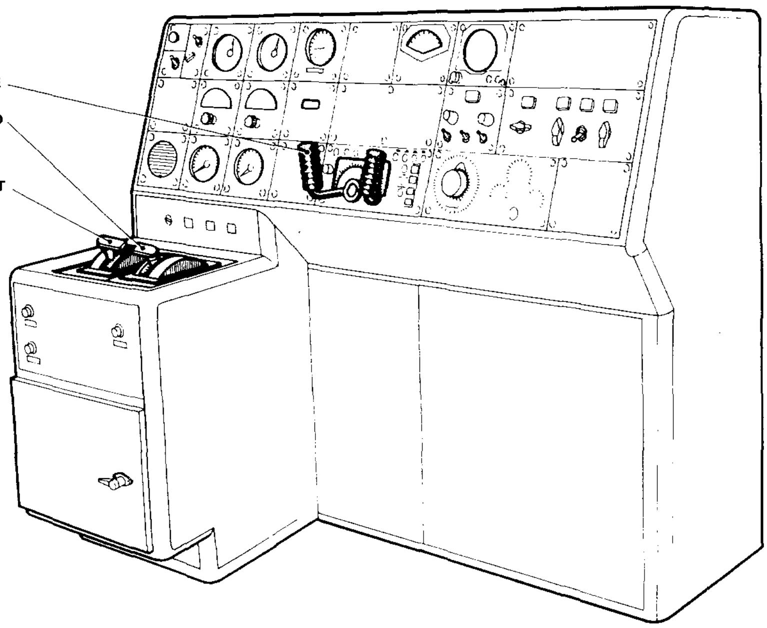

FIG. 8—H.M.S. 'SHEFFIELD'—BRIDGE CONTROL CONSOLE

Ship Operation

Here the advantage of the gas turbine is considerable because of the ease of control of the propulsion plant from the bridge, the quick start from cold and the quick reaction of the plant. FIG. 8 shows the Bridge Machinery Control Unit fitted in H.M.S. *Sheffield.* This console has been designed to provide simple one-man control of the ship's speed and course from the bridge. The steering handle controls the movement of the rudder and the two levers on the operator's left control the revolutions per minute and the pitch setting of the propellers. When the ship is at rest, these levers are set at a zero thrust position, which sets the propeller blades at zero pitch. When the levers are moved forward the propeller pitch is increased and the revolutions per minute are increased until the ship is at full ahead speed. Moving the levers backwards from the zero thrust position drives the ship astern. Thus the Officer of the Watch now has available a much more flexible plant which he may readily control himself without intermediaries, and this should give a higher standard of ship handling and save manpower.

The ability to start immediately from cold gives great advantage against the unexpected emergency, be it weather, war or mission, and it allows a prudent anchor watch to be kept in bad weather without wasting fuel or watchkeepers. No longer will it be necessary for the engineers to go below to flash up hours before sailing and, since the main propulsion plant can be lit up and shut down quickly, there should be more nights at home for the crew.

The choice of ship speed with a gas turbine plant will not be such a simple business as it was with steam, where a simple graph of fuel consumption against speed was all that had to be considered. Now there will be a choice of which engine to use and the problem of shorter life with higher power. Speeds of advance will have to be tailored more carefully to engine requirements and a difference of one knot may make a big jump in fuel consumption. It is possible that single shaft running, with a feathered propeller on the other shaft, may be adopted to conserve engine hours.

The gas turbine change units can be transported by air and this, with the ability to change main engines in 48 hours, reduces the need for overseas bases, except for an airfield and a crane and even these are not required if the ship can rendezvous with a suitably equipped support vessel.

Rapid start, rapid changes of power and rapid engine replacement give the naval planner the flexibility to keep his fleet at short notice for sea and for full power without wasting fuel or men, and with less time needed for machinery maintenance on board.

Summary of the Advantages and Disadvantages of Gas and Steam Turbines

It is not easy to assess the relative merits of these two propulsion plants when not all the advantages or disadvantages lie with either one and different features have different values. For example, how does one compare the advantage of the steam turbine in discharging comparatively little heat from the funnel with the better working conditions for engine-room personnel in gas turbine ships?

However, by giving merit and worth factors to each of the several features discussed, the total impact of the gas turbine on the design of major warships may be weighed and assessed.

TABLE II—*Comparison of gas turbine and steam turbine ships*

Feature	*Advantage factor*	*Worth factor*	*Product*
Downtakes, uptakes, superstructure	−3	2	−6
Auxiliary power	−1	1	−1
Arrangements for going astern	−1	1	−1
E.R. complement and conditions	2	1	2
Through life cost	1	2	2
Ship availability	2	3	6
Ship operation and control	2	3	6
Industrial base	3	1	3
Overall assessment			POSITIVE

Referring to TABLE II, in the first column are the main features which, in the author's view, affect the comparison of warships with gas turbines and with steam turbines, omitting all those features for which there is little to choose between the two forms of propulsion machinery. In the second column, advantage factors of 3, 2, or 1 are awarded if the gas turbine ship has a distinct, a moderate, or a slight advantage, and −3, −2, or −1 are awarded if the steam turbine ship has a distinct, a moderate, or a slight advantage. In the third column, worth factors of 1, 2, or 3 are allocated depending on what is judged to be the relative worth of these features to the Navy.

In column four, the figures in columns two and three are multiplied and then added to give an overall assessment. Rough justice indeed, and many would argue with the details although none, it is hoped, would argue with the positive sign of the overall assessment which indicates that the move to gas turbines really has affected an improvement in the Navy.

Finally, the author explains why the Navy preferred gas turbines to two other forms of propulsion plant, namely Diesel and nuclear.

Comparison of Diesel Engines with Gas Turbines for Surface Warships

Diesel engines have a significantly lower fuel consumption than gas turbines, particularly at part load, but in the powers required for warships they are very much bigger and very much heavier; in fact, the weight per horse-power of a modern medium speed Diesel can be between five and ten times that of a gas turbine. In other words, high power Diesels are efficient but heavy and bulky and, as they cannot easily be lifted out, the onboard maintenance is greater, which is something to be avoided.

A comparison between the Type 42 design and an all Diesel design with similar operational capability shewed that the Diesel machinery and fuel would weigh about 250 tons more and the machinery space would need to be about 20 feet longer.

The choice between gas turbines and Diesels for cruising is more finely drawn and the latter are particularly attractive for their low fuel consumption and their greater tolerance of salt ingestion. After careful consideration, the Royal Navy has decided in favour of gas turbines to avoid the small increase in ship length and displacement and the considerable increase in onboard maintenance which Diesels in this range of power would have required; some other Navies have chosen Diesels and there are good arguments for both choices.

Comparison of Nuclear Propulsion with Gas Turbines for Surface Warships

A nuclear ship to meet the same Staff Requirements as a modern frigate or destroyer would have to be considerably larger to house present day designs of reactors and steam plant. The initial cost and upkeep costs would also be very much greater, but operating costs might be very similar with the current prices of petroleum and nuclear fuel. In short, at the present time a nuclear ship of this type would not be cost effective.

There are growing signs that the world's oil reserves are now reaching a stage where new field discoveries are being outstripped by the rising demand, and this single factor is the greatest threat to the future prospects for marine gas turbines. It appears that this threat is not likely to produce any dramatic effect before the end of this century, and when it comes man will, presumably, have to supplement the use of fossil fuel engines with nuclear machines.

FIG. 9 represents the rise and fall of ship propulsors. The fate which befell earlier forms of prime movers for warships will one day close the innings of the gas turbine, but until that happens it should reign supreme for several decades.

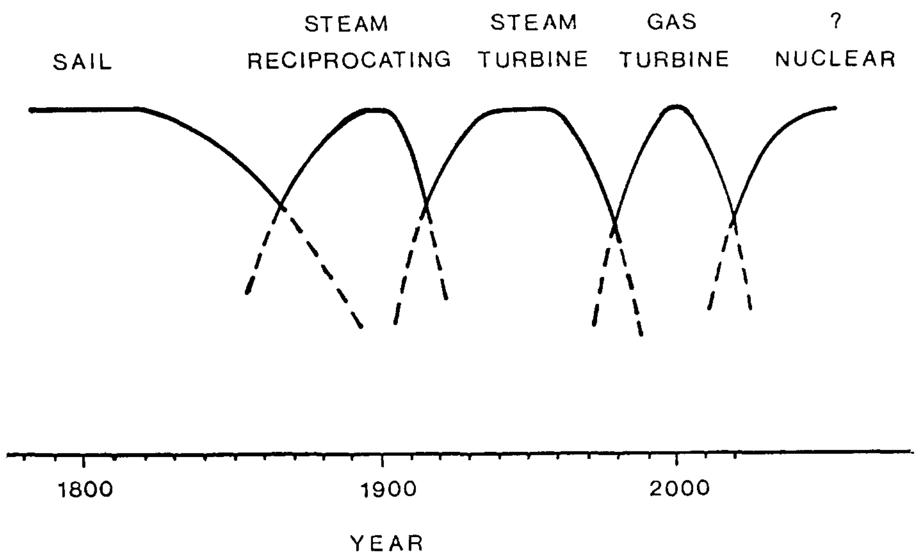

FIG. 9—PRIME MOVERS FOR SURFACE WARSHIP PROPULSION

Conclusion

What we are now witnessing is the debut of a new generation of marinized gas turbines. Fitting these turbines in major warships has thrown up problems in the size of the uptakes and downtakes, the heat and volume of exhaust gases, and so on, but there is no doubt in my mind that these are outweighed by the considerable improvements they bring to the design and operation of these ships.

With experience, as gas turbine temperatures are up-rated and new techniques are developed, many more improvements will no doubt be found to steadily tip the balance which has been drawn in this article further in favour of this new form of propulsion.

It is concluded, therefore, that the reign of the steam turbine as the prime mover of the world's navies is now ending and that we are in the throes of another revolution in ship propulsion, and that by the end of this century most major surface warships will be driven by gas turbines, and that because of this their complements will be reduced, their availability will be improved, their performance will be better and their through-life costs will be less.