PROGRESS IN NAVAL MACHINERY DURING THE LAST THIRTY YEARS

BY

VICE-ADMIRAL SIR RAYMOND HAWKINS, K.C.B., M.I.MECH.E., M.I.MAR.E.
Chief of Naval Supplies and Transport and Vice-Controller

This Paper, the thirty-seventh Thomas Lowe Gray Lecture, was read by the Author before the Institution of Mechanical Engineers on 27th January, 1965, and is reproduced by permission of the Institution.

INTRODUCTION

In 1930, Engineer Vice-Admiral Sir Reginald Skelton, the Engineer-in-Chief of the Fleet, gave an account of naval engineering to the Institution of Mechanical Engineers in the third Thomas Lowe Gray Lecture.[1] He described the principal developments since the very earliest days of marine engineering and discussed the reasons for changes which have occurred from time to time. He was particularly interested in equipment that failed when first designed, but which later came back into vogue, and justified this on the grounds that 'it might assist us to view in a better perspective the significance and promise of marine advances and trends, this being particularly difficult because of the bewildering variety of marine engine types and designs available'. He said that this great variety sprang from the motives that had always existed during the application of mechanical power to the propulsion of ships. These were defined as: 'the generation and application of power in the most economical way with the means available; the design and production of machinery making a minimum demand on ship space and displacement; and, paramount in the case of marine installations depending for long periods on their own resources, the attainment of a design promising a proper standard of reliability and durability.' The relative significance of these motives was, of course, modified by individual considerations.

It is a very salutary experience to read Admiral Skelton's lecture in these days where progress is thought to be so rapid that bewilderment sometimes takes the place of reason. One realizes that the potential for bewilderment must then have been considerably greater than it is now, for it was the fundamental inventions and innovations of those days, and the 'motives' that prompted them, which set the scene for the developments of most of our machinery in use today. We are, to a large extent, the developers and appliers of the original thoughts and decisions of our forefathers. The situation is rivalled today by the problems facing us in nuclear propulsion, and we must hope that we also make adequate and timely decisions. It will no doubt require an exhausting period similar to the 'Battle of the Boilers' which took place in those not very far-off days.

Since those formative days of the last century, the very great advances in ship design have been described in detail in many papers. The immense increase in power within smaller spaces; reduction in marine engineering complements almost by orders of size; great increase of endurance; all have been the result of hard and painstaking trial and development. Admiral Skelton dealt with development from the earliest beam engines and flue boilers to the geared

---

[1] 'Progress in Marine Engineering', *Papers on Engineering Subjects*, No. 11.

turbine, and interwoven with most of the changes was the gradual improvement in materials and manufacturing methods which alone rendered the use of many of the new types practicable. In 1949, Vice-Admiral Sir John Kingcome extended the story of far-reaching improvements in detailed design.[2] In addition he discussed a new piece of equipment, the gas turbine, but even with this great invention it must be recalled that the principles had been well known for years. It was only the development of suitable materials that brought an end to the delay in its production.

The whole of this history is a slow but in total spectacular improvement in detailed design and materials to give improved component efficiencies, reduced weight and size, and to some extent improved reliability, although sometimes at the expense of durability. The predominant factors in ship design still include those 'motives' of earlier days, but in the 1949 Lecture the first reference was made to the rapidly increasing effect that new military requirements were having on ship design as a whole. These included resistance to underwater shock, improvement of damage control arrangements, improvement of the ability to operate for very long periods from the Tropics to the Arctic, with greater reliability and durability, and much improved living and working conditions for the crew. In addition, the revolution in naval weapons which was then beginning was also influencing ship machinery design. Underwater and above-water missiles were being designed with complex and extensive control equipment which required large power supplies and many other ancillary services for efficient operation; with them they brought the need for yet more military requirements in the ship itself. In 1957 Vice-Admiral Sir Frank Mason gave his Parsons Memorial Lecture,[3] and in bringing the story of development up-to-date, he introduced the additional requirements of silence, to meet the increasing tempo of underwater warfare, and automatic and remote control to counter nuclear attack. He summarized the naval machinery design problem in ten main requirements and emphasized that in the selection of a judicious compromise of these lies the artistry of design; this compromise varies for each class of ship as the emphasis is moved to meet a particular duty. It is relevant to this paper to restate these ten requirements:

Reliability
High endurance at cruising speed combined with a high top speed
Low weight
Small space, including height
Ease of operation
Ease of manufacture
Ease of maintenance
Resistance to shock
Silence of operation
Adaptability to automatic control

THE FLEET TODAY

All these demands for military characteristics, power, ancillary services, and special operating conditions have changed the designer's job from being primarily a problem of ship propulsion to one of designing a completely

---

[2] 'Marine Engineering in the Royal Navy', Vol. 3, No. 2.

[3] 'Naval Propulsion Engineering', Vol. 10, No. 2.

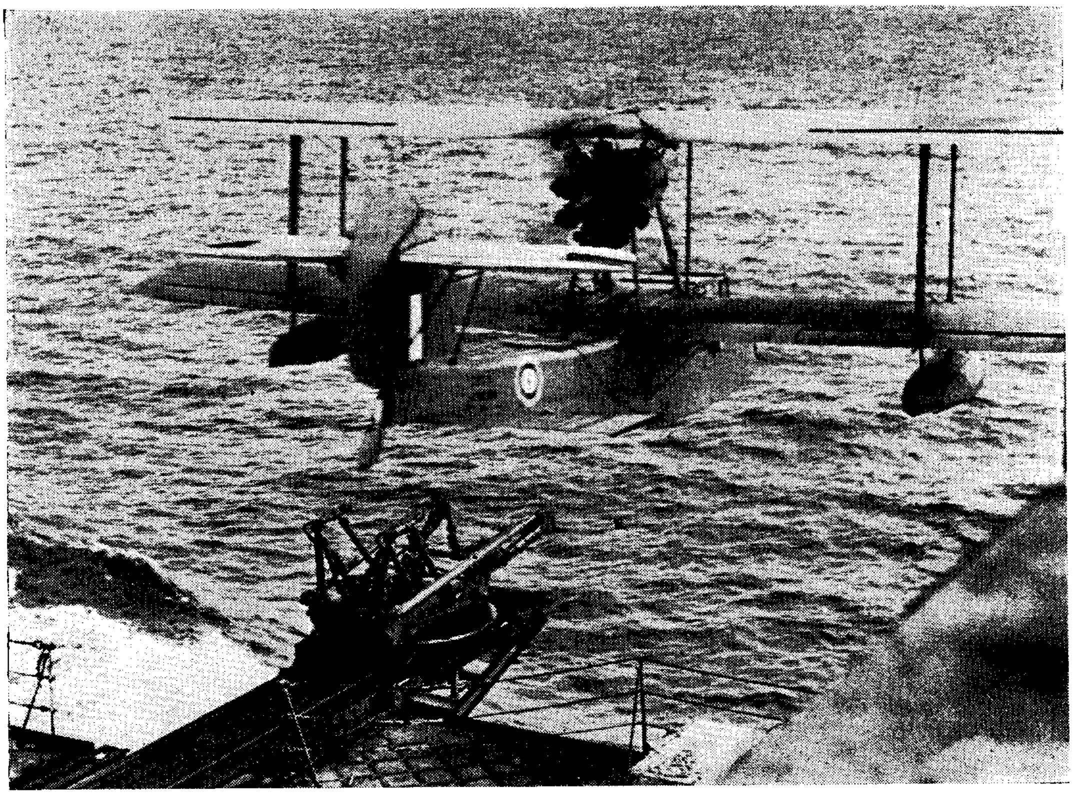

FIG. 1—AN EARLY CATAPULT LAUNCH OF A WALRUS SEAPLANE FROM H.M.S. *Edinburgh*

integrated ship installation which provides all these varied services. More than ever before, one can say that the weapon of today is the whole ship, which can only be designed if the purpose and use of the ship is clear. It is worthwhile to concentrate a little on this growth of ancillary and domestic equipment. First we must discuss what type of Navy we wish to have.

Our overseas bases are now very few, and we therefore require our ships to operate on their own for long periods away from shore support. Indeed, most of our ships spend part of a Commission in Home Waters and part of it East of Suez, and they must therefore be able to live in extremes of climate and weather. Their duties will include brushfire emergencies and aid to civil powers, tactical exercises and surveying and fishery protection, often carried out at short notice. Although these are called peace-time occupations, they are hard and onerous duties which call above all for instant readiness, reliability and durability. In addition, our ships must be equipped for the more sophisticated methods of warfare that could develop.

These world-wide commitments require us to operate a large variety of warships ranging from aircraft carriers to minesweepers. The aircraft carrier that is now being designed must be able to operate the present as well as the next generation of aircraft. These large, heavy and very costly weapons must be put into the air by catapult and recovered again by arresting gear. They must be maintained and serviced on board, and this requires workshops and highly skilled men with complicated test installations. For example, an expensive hydraulic installation must be fitted on board for testing aircraft systems, and the standards of cleanliness must be as stringent as those for the aircraft system itself. There must be starting air for aircraft, and low-pressure cooled air for the aircraft and pilot when they are under conditions of immediate readiness. Liquid oxygen of breathing purity must be provided, and large quantities of high-pressure air of clinical purity and dryness. A vast complex of radar and electronic equipment, requiring extensive cooling arrangements, is needed to control aircraft and to direct operations. Skilled crews must operate and maintain all this complicated equipment and they must be adequately supported in order to carry out this duty efficiently under difficult conditions. There must be air-conditioning to cope with climatic extremes and with wild heat from the powerful equipment on board, and increased refrigeration plant to cope with the change in messing arrangements (for frozen joints and vegetables are now being carried instead of carcasses and tinned vegetables). Chilled drinking water, laundries and all the paraphernalia of modern life must also be carried. These changes are not made merely to lap the modern sailor in luxury; the type of work to be done, the heavy usage, the need to improve the availability of all this equipment demands that living conditions for men on arduous duty and away from base for long periods fit them for their task. In the Andrew Laing Lecture[4] that I gave to the North East Coast Institution of Engineers and Shipbuilders in October 1964, there is a graph showing the rapid growth of installed electrical power in various types of ship. This sums up the growth of all these domestic and ancillary services in the modern ship, and illustrates the immensity of the design problem set by modern warfare.

In previous surveys of naval engineering, little mention has been made of the very specialized machinery which is concerned with the launch and recovery of aircraft which operate from ships. This fascinating subject is worthy of a complete paper of its own, but my lecture would not be complete without reference to the engineering problems that have been overcome during the amazing development of naval air warfare.

The desire to assist by external means the take-off and landing of aircraft is as old as powered flight itself, for the Wright brothers experimented with a rudimentary form of catapult to help their first aircraft into the air. The problem for the Navy has always been to reduce the take-off and landing run, so as to launch and recover, within the confines of a ship, aircraft of performance comparable to that of shore-based types. The minimum penalty to the aircraft itself is therefore vital and this is achieved by limiting the airborne fittings to hooks at airframe strong points, and building machinery into the ship to supply energy for launching and to destoy it for recovery.

To launch a modern aircraft from an aircraft carrier it is necessary to accelerate it to a speed of approximately 150 m.p.h. in a run of about 150 ft, and this requires an acceleration several times that of gravity. This acceleration is limited not only by aircraft strength, but more generally by the physiological effects on the men inside. For many years, the latter prevented full development of the assisted launch, but in the last twenty years, brave experiments have lifted this limitation by proving that the human body can withstand, for short periods, the forces produced by high acceleration.

Developments of catapults started at about the end of the First World War to enable spotting aircraft to be launched from cruisers and battleships while under way, a cordite-operated type catapult being used for this purpose (FIG. 1). With the introduction of the aircraft carrier, the basic requirement was for an aircraft to be capable of free take-off from the deck, and a catapult was not therefore a necessity. Assisted take-off was, however, extended to the carrier in the form of an accelerator which was used under special but infrequent conditions. This was a hydro-pneumatic type which was under continuing development for service in all our carriers until a few years after the Second World War. The introduction of the jet propelled aircraft then began to demand the use of a catapult for every take-off, and it became apparent that the hydro-pneumatic type had reached the end of its development possibilities, and a

---

[4] 'Post-War Developments in Naval Propulsion', Vol. 15, No. 3.

FIG. 2—A MORE RECENT LAUNCH OF A BUCCANEER AIRCRAFT FROM H.M.S. *Victorious*

new concept was required.

Today Britain leads the field in catapult technology and every aircraft carrier that operates modern fixed-wing aircraft is fitted with catapults of British design. These are slotted cylinder steam catapults,[5] invented by and developed under the direction of Commander C. C. Mitchell, O.B.E., B.Sc., R.N.V.R. The slotted cylinder principle is well known and was used by I. K. Brunel with very limited success in the early days of the Great Western Railway. In later days it was used by the Germans to launch their V1 missiles, but the development of the steam catapult has been its most successful application (FIG. 2). Many difficult problems were associated with this development. In particular, the catapult moving parts weighing about three tons had to be stopped at the end of launch in about five feet, and the cycle had to be repeated to launch aircraft at intervals measured in seconds. They were all overcome and present catapults operate very satisfactorily up to an equivalent of 25,000 h.p. As with all our equipment the rate of growth has shown the same pattern over recent years and this is illustrated in FIG. 3.

Another vital piece of flight deck machinery which required extensive development was the arresting gear. The first deck landing was carried out in H.M.S. *Furious* in 1917. It was a free run landing with no attempt to stop the aircraft by external means. This method was used with varying degrees of success until the 1930's, when arresting gear was first used in the Royal Navy in order to exploit the considerable development in aircraft performance then beginning to take place. The gear consists of a transverse wire stretched across the deck which engages a hook that is lowered from the after part of the aircraft. The wire is pulled out against a resistance exerted by a hydraulic ram through a wire rope and sheave system, thereby absorbing energy from the aircraft and reducing its landing run. The treatment accorded to the wire rope during this process is severe in the extreme and its life is relatively short. It is subjected

---

[5] 'The Steam Catapult', Vol. 6, No. 3, and 'A Steam Catapult Installation', Vol. 10, No. 2.

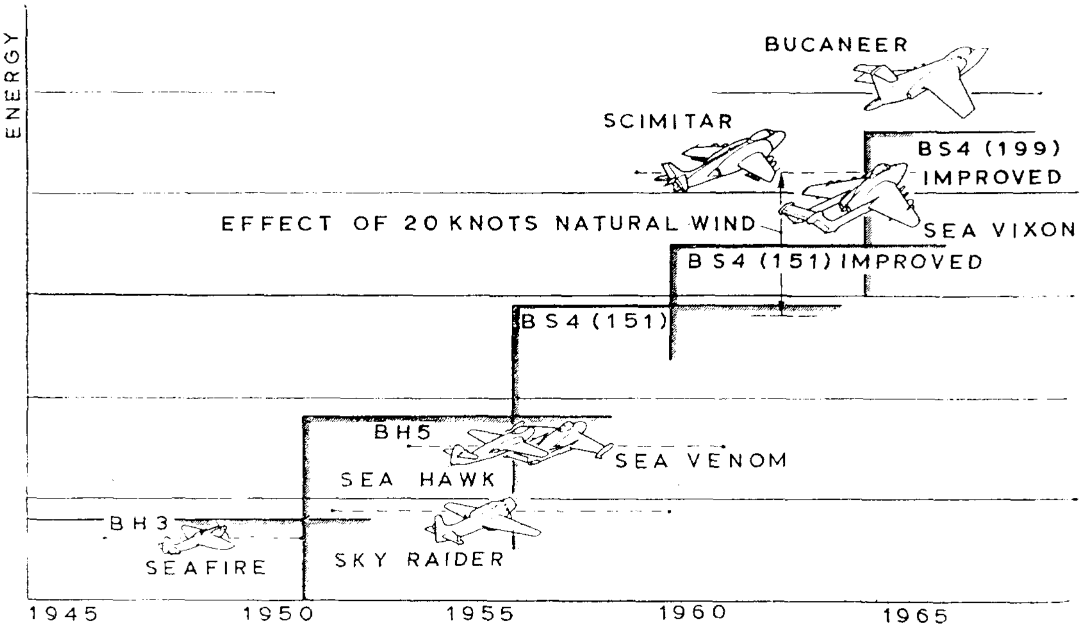

FIG. 3—DIAGRAM SHOWING INCREASE IN CATAPULT ENERGY

to very high impact loads, severe abrasion should the aircraft yaw at the moment of impact, high stressing due to bending round the narrow throat of the hook on the aircraft, and stress waves set up in the rope. The transverse portion is therefore made detachable. The remainder of the rope which is connected to the energy absorber has a much longer life, but the design problem is still severe and is increasing as the landing weight and speed of aircraft increase. An arresting gear of different arrangement and with considerable development potential was demonstrated publicly at the Royal Aircraft Establishment, Bedford, in August 1962. Two long thin cylinders are placed on either side of the runway, and the ends of the arresting wire rope are directly connected to a piston in each, so that the wire acts as a flexible piston rod. The cylinders are maintained full of water, and the energy of the aircraft landing is absorbed by the pistons expelling the water through small orifices in the cylinder walls as they are drawn along the cylinders. The spectacular result led to this device being called the 'Water Spray Arresting Gear'. This direct-acting type of gear has the advantage of simplicity, particularly for shore airfield use, where the water is lost, and where re-setting can be done in comparatively slow time. It is also being developed for possible use in aircraft carriers, if the problems associated with water recovery, rapid re-setting and marine atmospheric corrosion can be overcome.

Turning to our latest ships in service, the guided missile destroyers of the *County* Class, with their guided missile systems and gas turbine boost machinery, are now well known and in widespread operation. The effort and ingenuity required to design these modern warships with their missile equipment is immense, due not only to the novelty of the new weapons, but also to the difficulties already described of integrating the whole array into one operational unit. The G.M.D. design was really our first attempt at a completely new and revolutionary type of vessel, and the problems encountered during its design and building emphasize most forcibly the need for simplicity in the design of components and of the total system. Without this, reliability, durability and economy in both capital and running costs, which are needed as much now as when Admiral Skelton defined them, cannot be obtained. Simplicity is only achieved by spending money on the development of the whole design, both of individual units and their installation. It is money well spent for it is returned

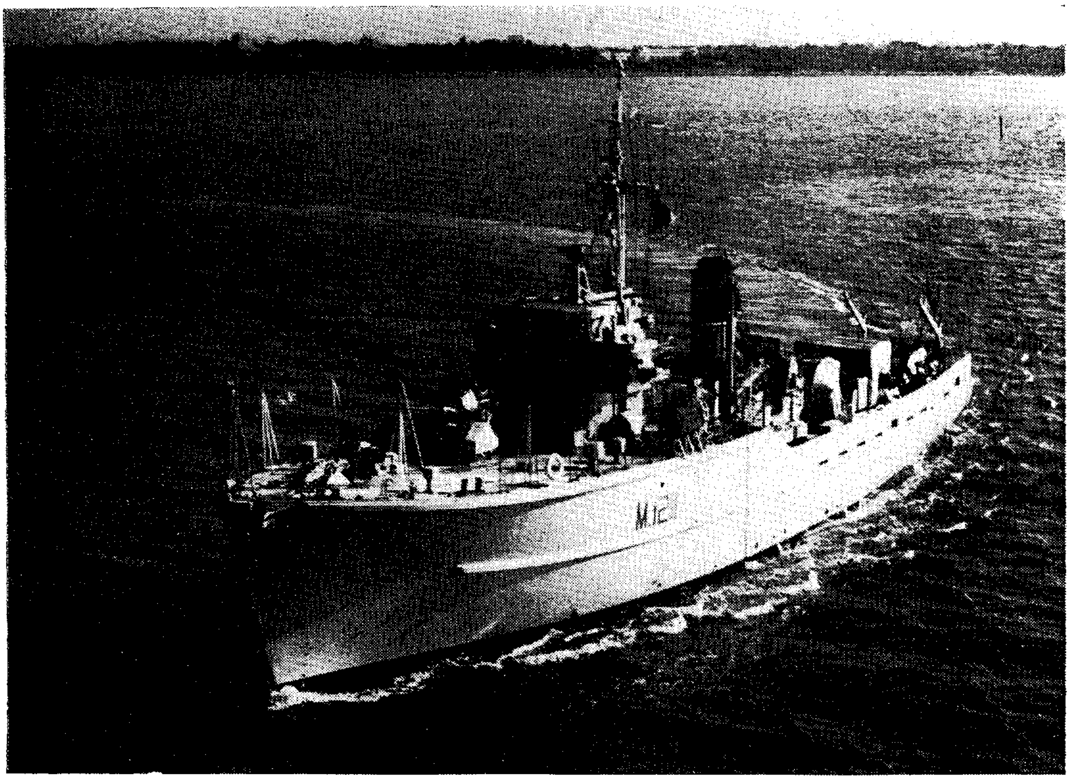

FIG. 4—H.M.S. *Houghton*—COASTAL MINESWEEPER

many times over by the resultant reduction of capital and running costs.

In the frigate group we have the *Leander* Class, the latest in the most successful line of development from the original Type 12 frigates, using Y.100 steam turbine machinery. This development from the first designs of the late 1940's involves a much increased capability, and a consequent growth in ancillary and domestic services. This has only been possible by much detailed design development, aimed at simplification of machinery and systems, to obtain increased output from the same overall space. This development work has been so successful that while providing the increased requirements, a reduction in total maintenance and better accessibility has also been achieved. The Diesel engined Type 41s and 61s represent another type of frigate of the same era. These are also extremely good runners, after working out early 'teething troubles', and although by no means modern in their machinery design, they have done much to clarify our latest philosophies on the design of Diesel installations. We also have the later *Ashanti* Class general purpose frigates which use gas turbine boost machinery of the same type as the G. M. D., but at lower power and with a single shaft.

Our submarines are now in the middle of great revolutionary change. The conventional boat has still a very active and important task but the nuclear submarine is an entirely new weapon. It means that those old dreams of almost unlimited movement in the oceans are brought nearer. Deep diving, very manœuvreable submarines, capable of high underwater speeds for long periods, are now an important feature of naval life, and there is still tremendous scope for the development of nuclear power plants for the future.

The smallest vessels are the minesweepers and fast patrol boats. These are both very specialized craft with their own military requirements. The minesweeper, with its need for low noise and magnetic signature, and the fast patrol boat, requiring high power with a high power-to-weight ratio, both set their own complex problems. The coastal minesweeper uses the Deltic Diesel

FIG. 5—H.M.S. *Brave Borderer*—FAST PATROL BOAT

and the *Brave* Class fast patrol boat uses the Proteus gas turbine. Both, which have been most successful designs, were world leaders when they went into service, and still are. They have certainly done much to influence modern naval design of small ships. These vessels are shown in FIGS. 4 and 5.

Another interesting new vessel is the Assault Ship, which is now building[6]. Apart from all the panoply of modern requirements, this vessel has the added complication of having to change its displacement in a very short time, in order to launch and recover its landing craft. This required detailed design work on a pumping-and-tankage system involving much computer work.

It will be clear, from this brief description of the complicated requirements for modern warships, that it is impossible to forecast the use to which specific types of machinery may be put in the future without reference to the functions of the ships that will be required and their method of use. Apart from any security aspect, the formulation of future operational requirements is difficult in these days of rapidly changing weapons and political policies. We can, however, briefly examine the particular assets of each type of installation, and this will allow some measure of prognostication.

STEAM INSTALLATIONS

There has been a steady, but over the years spectacular, improvement in component efficiencies. It is therefore easier to break away from excessive system complication, which was current some years ago in the interests of economy, and to concentrate on simple plants which are a better compromise between all the conflicting pressures. To these ends, the use of 'integrated' systems is being studied. This work is concerned with the matching of dynamic characteristics of individual components, thereby achieving more simple, self-regulating installations. Pure physical integration of components is a secondary consideration, but this may also have a part to play in the process.

---

[6] 'The Assault Ships', Vol. 15, No. 1.

The future of steam installations is frequently questioned, due to recent improvements in Diesel installations and the progress being made in the use of gas turbines. However, there is no doubt that the steam installation is the only plant at present suitable for our large ships of high horse-power; the upper power limit is determined only by the power absorption capabilities of the propeller, and by draught limitations. A steam installation also has considerable design flexibility in that the provision of ancillary and domestic services is comparatively simple, and cycle efficiency can be traded for weight and space to achieve an optimum design. Operational flexibility is also good over the whole power range, this being covered entirely by operation of the turbine throttle valves. The layout of the plant is somewhat devious and the manufacture and installation of the many individual items must be carefully controlled if reliability is to be good and maintenance minimal. Failure to achieve reliability and low maintenance stems from a failure to spend effort and money on development of the design and on close control of manufacture and installation. This expenditure is always considered essential for the development of a more unified type of prime mover. There is, obviously, a case for more experience with, and control of, a steam installation by the main contractor, and this is the underlying motive behind the work now being carried out on packaged units for propulsion of merchant ships. The steam plant has also been chosen for our first efforts in nuclear propulsion, and it therefore requires and deserves continuing research and development work to ensure that it is a worthy medium of this new form of power.

DIESEL ENGINES

The use of slow-speed engines of comparatively large power is widespread in the merchant fleets. Naval use is limited to medium and high-speed engines of lower power, except in some support ships, in order to reduce weight and size. This in turn limits the total power of the plant unless a number of engines are coupled to each shaft as in the Type 41 and 61 frigates. If this number is too large then maintenance loads will tend to be high, and operation more complex; the optimum number is probably two engines per shaft. The very great advances which have been made in Diesel engine design over the last ten years, particularly in the turbo-blown medium-speed range of engines, open up possibilities for much higher power plants with only two engines per shaft. With proper development, such a plant would be very competitive in its maintenance demands with other types of plant of up to 20,000 s.h.p. per shaft. With the increase in life between overhauls which is also being achieved, we could well see more extensive use of Diesel engines in some of the smaller ships of the Royal Navy.

GAS TURBINES

This country led the world in the use of gas turbines at sea and the Royal Navy has sponsored prototype plants of many different types in order to find out how to exploit the potential benefits of the gas turbine. This potential can be defined in a general manner by saying that one hopes for a very light-weight, high-power unit, which nevertheless is very reliable and of predictable and reasonably long life. Coupled to this is the hope that it will also be of reasonable cost. We have had considerable success in determining what our future policies should be, and indeed we have also been successful in many of our applications. Probably the most important lesson we have learned is the old one that if you want something good you must pay for it one way or another. The basic idea of the gas turbine is very simple, as it combines combustion and power production into one continuous process performed by an integral plant. However,

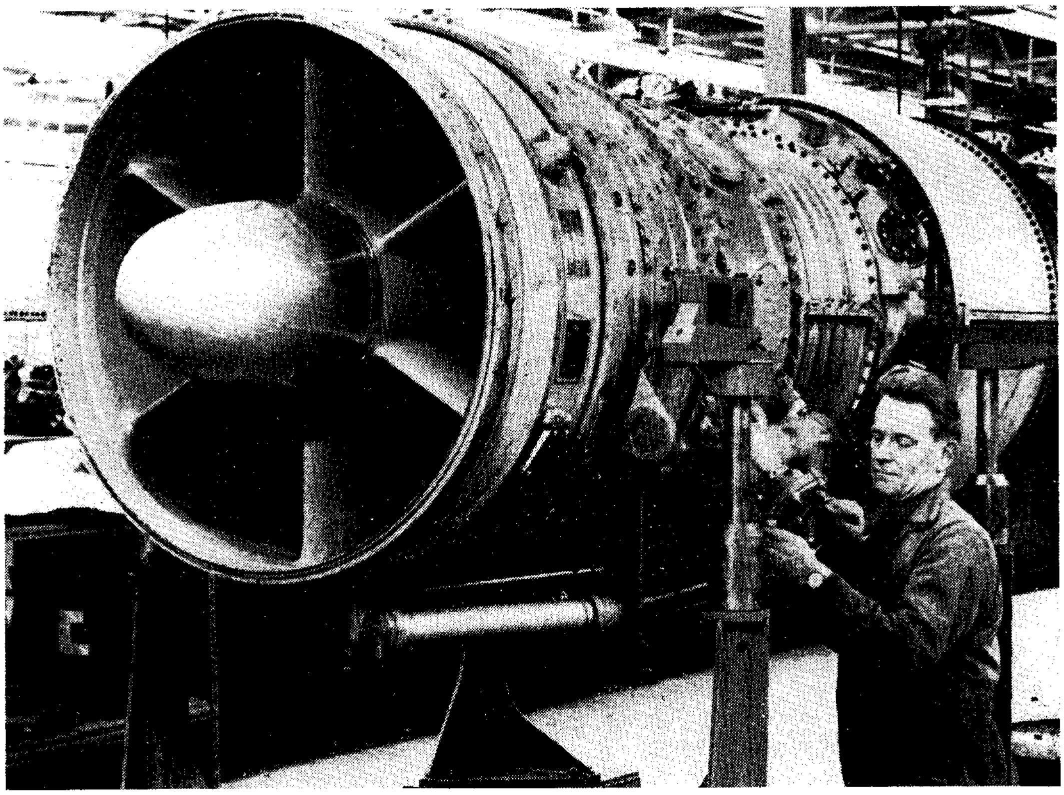

FIG. 6—THE OLYMPUS GAS TURBINE

the very simplicity of the arrangement demands that development be proportionately greater in order to produce a matched unit of similar durability to one of a more devious type. In addition, it is advisable to have as many engines as possible in service so that extensive operating experience can be fed back into continued development. This allows full exploitation of the potential of the engine and also has the advantage that development costs are spread to produce a more reasonably priced engine. We are also firmly of the opinion that we should stick to the simple type of gas turbine rather than involve ourselves in development of the complex type with many heat exchangers. These thoughts inevitably lead one to the use of aircraft gas turbines, suitably 'marinized', so long as this process does not involve redesign which would invalidate the original development work. The use of such engines, with their carefully controlled manufacture, has the added advantage that continuing development gives steadily rising output and predictable life between overhauls, which are features of aircraft engine development. The most important consideration, when contemplating the use of an aircraft gas turbine in a ship, is to ensure that it will be suitable for operation in the marine environment. Many times in the past the nature of this environment has been grossly misjudged. This is strange, for most people appreciate the harmful effect of the sea atmosphere of shore-side equipment in their gardens. The change from aircraft conditions, where the engine cruises at a comparatively moderate rating in a clean atmosphere, except for very brief take-off periods, is immense. It is, therefore, probable that the optimum conditions for the operation of a 'marinized' aircraft engine will be at a power considerably lower than the aircraft take-off rating, and in addition a further power restriction under high temperature input conditions may be imposed. Despite these restrictions the specific weight of the aircraft engine is so low that it shows to advantage in certain ship applications in which the somewhat poor part-load performance is acceptable. The need to consider the ship design as a whole, and the provision of ancillary services, must be emphasized once again. A typical aircraft gas turbine, which is also available in a 'marinized' version, is shown in FIG. 6; this is the Olympus gas turbine.

NUCLEAR POWER

The Royal Navy is now fully committed to an extensive nuclear submarine programme. This work started in 1956 with the Naval Wing installed at Harwell and working in collaboration with the U.K.A.E.A. It developed into the exchange arrangement with the United States of America whereby we bought a complete set of U.S. submarine propulsion machinery for installation in H.M.S. *Dreadnought*. Parallel with this project we continued the production and development of the Dounreay submarine prototype propulsion plant which is essentially of British design and manufacture, albeit benefiting very substantially from the U.S. Exchange Agreement. Submarine propulsion is, of course, the most obvious naval application of nuclear power as the benefits are so great.

The military attractions of nuclear power in surface ships, although great, are not so overwhelming as in submarines, and have to be balanced carefully against the cost. The Royal Navy conducts continuous studies of potential surface-ship plants, and recent developments in design may, before long, culminate in real possibilities of a viable installation of reasonable cost which may be exploited.

COMBINED PLANTS

There is scope for any combination of prime movers to produce combined plants. There is nothing new about these as they have been used throughout history. Sails and oars, steam and sails, Diesel and electric propulsion in submarines, are all combined plants. Such combinations were made either to exploit the different capabilities of each plant in the one ship, or to exploit the potential capabilities of a new type of prime-mover which was still in an early stage of development, and, therefore, either unreliable or inefficient, it being hoped that experience at sea would ultimately lead to a change over to the new type of propulsion alone. In the Navy we have the steam and gas turbine plants, referred to as 'Cosag', in the guided missile destroyers and the general purpose frigates. The original idea was to invest the steam plant, which was then our main propulsive power unit, with a boost capacity which would be required infrequently for high speeds. The boost plant could then be designed as a short life, high power-to-weight ratio unit, which would give an overall saving in machinery weight and space, without sacrificing, and perhaps gaining a little efficiency in the base load plant. It would also give the ship the ability to get under way immediately on a portion of its total power; although the ship would only be able to move ahead, this was considered valuable under the type of nuclear warfare thought possible at that time. However, the urge to exploit this capability to the full introduced a reversing train into the gearbox and the design of the gas turbine was directed towards a longer life unit, with consequent increase in weight and space demands.

The original boost concept therefore developed into a dual machinery plant. Another type of combined plant is the 'Codag', the combined Diesel and gas turbine plant. Here the offer is a plant which endows a ship with great endurance at low speed but with a high speed capability for comparatively short periods. The 'Codag' plant is, in fact, a method of saving machinery plus fuel weight where the Staff Requirements call for a ship with these capabilities. The price to be paid is the complication of using two types of machinery in the one ship. The future use of these combined plants is dependent upon whether the Staff Requirements for future warships are met by the particular attributes of such combinations.

BASIS FOR THE SELECTION AND DESIGN OF MACHINERY INSTALLATIONS

This brief summary indicates that the choice of machinery now open to us is very wide, and as each type develops the particular advantages that they offer are becoming very difficult to separate. This situation also means that the qualities of reliability, durability, maintainability and cost, both capital and running, occupy our attention to an increasing extent. Before judging these aspects of a machinery plant it is necessary to consider the natural, and man-made, but inevitable restrictions placed upon our methods of running and supporting ships.

I have already said that we have world-wide commitments with a reducing number of bases. Some of our vessels can undertake special tasks with the support of a nearby base, but the majority must either be capable of operating for long periods away from base, or they must be supported by a mobile base which can itself operate in the same area for long periods. The latter is expensive in both money and man-power and not always fully effective, and is therefore not a satisfactory solution to the problem. Our basic design philosophy must, therefore, be to aim for a ship which is independent of base support for as long as possible. Such independent operation can only be obtained firstly by using machinery which is reliable and durable, requiring only reasonable routine and breakdown maintenance, and secondly by training a crew to operate and maintain the machinery for the long, but planned, periods between base overhaul. Our efforts to obtain reliable, durable and easily run plants are based on the following observations:

(*a*) The first aim must be simplicity, not only of individual items, but of the installation as a whole. This can only be obtained by careful detail design and development work.

(*b*) Adequate testing, development and endurance running ashore must be carried out for those equipments which are not already proved by service.

(*c*) Layout must be such that there is adequate access for maintenance and repair.

(*d*) Trunks must be provided for the removal from the ship of complete engines or sub-assemblies, as appropriate, for refit by replacement or overhaul, whichever is the most suitable for the type of ship and its planned operational pattern. If trunks are impracticable, paths for equipment removal must be planned to give the minimum disturbance to other equipments.

(*e*) Pipework leads must ensure the optimum compromise between the conflicting requirements of flow paths, drainage, expansion and avoiding obstruction.

The achievements of these objectives is assessed by the use of models, full-scale mock-ups, computers, work-study techniques, quality engineering and critical path analysis. These are not just devices in the changing pattern of design procedure which take the place of the older intuitive designer; they are necessities without which a complex instrument of war could not be designed as a workable proposition, and without which we could not obtain the high usage rate and availability that our ships must now achieve.

We calculate the man-power required to maintain the machinery by summing the man-hours of routine and breakdown maintenance assessed for each piece of equipment, basing this on past experience and on maintenance requirements predicted by the designer. This process is valuable in that it gives incentive for the simplification and consequent reduction of the maintenance load. The anticipated usage rate of the ship is, of course, a factor in these calculations and this also allows the estimation of the size and frequency of the outside support that is needed. These assessments also indicate the suitability of the plant for the service envisaged. Financial assessments, both of capital and running costs, are also made to assist the process of selection, and to allow the weighing of any performance change against a design variation.

Finally, in the process of design and development, extensive testing is carried out at Admiralty establishments and within industry, not only to prove and develop untried components, but also to assist in the design and development of an optimum and satisfactory part or whole of an installation. A particularly interesting example is the installation of a guided missile destroyer boiler, with its associated auxiliaries and automatic and remote controls, at the Admiralty Fuel Experimental Station.[7] This installation was in advance of the first ship and did much to overcome the inevitable teething troubles that arise with new equipment and systems. Even though many of these ships are now in service, endurance testing and development is continuing so that long-term troubles can be anticipated, or at least quickly overcome. The value of such facilities lies in the increased ship availability and usage that become possible.

CONCLUSIONS

This Paper has given a brief account of the directions in which naval machinery has progressed over the last thirty years, and some indication of our hopes for the future. I have stressed the complex design and development problems and the need to employ all modern resources in these processes. However, they are of no avail if we do not have first class manufacture, top quality inspection and high standards of cleanliness, not only for our new ships, but for any refit or replacement of spare gear and parts.

I know that it is the desire of every engineer to produce a product which excels in every way. But I also know the economic pressures which exist to keep down prices, particularly where one is competing with other manufacturers. I do, however, suggest that excellence in performance, and by that I mean excellence in all aspects that I have discussed in this paper, brings its reward, for the striving for the optimum compromise results in the development of the cheapest unit even when its share of research and development overheads is included. The direction and control of that striving, which is the purpose of management, is what decides whether it will be successful, but if the desire for the longer term quality is there, the quality of management is unlikely to be wanting. As far as the machinery and equipment for ships of the Navy are concerned, we have learned, often through bitter experience, that this must be produced to the highest standards of design and manufacture, otherwise it will not meet the exacting demands made upon it. Looking into the future, it is safe to say that these demands will become more and more exacting, and we can never afford to relax our efforts in striving for perfection in the engineering of our machinery designs.

---

[7] 'Shore Testing of a Prototype Boiler Installation', Vol. 15, No. 1.