NAVAL PROPULSION ENGINEERING

A REVIEW OF PROGRESS IN THE LAST TEN YEARS

BY

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This Paper, the twenty-first Parsons Memorial Lecture, was read by the Engineer-in-Chief of the Fleet before the North-East Coast Institution of Engineers and Shipbuilders, by whose permission it is reproduced here, and in whose Transactions *it has already been published.*

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 optics, and each Memorial Lecture deals with one of the subjects in which his interests lay and in which his genius played a part.

INTRODUCTION

It is with a sense of very great privilege that I have accepted your Institution's invitation to present this lecture. Sir Charles Parsons' genius is one to which the Royal Navy owes an enormous debt. For many years, it assured us of a supreme place in marine engineering among the navies of the world. This is a heritage of which we are very proud and it is part of the tradition of naval engineer officers. Today, we are doing our utmost to be worthy of this heritage. On each side of us giants in the field of technology, as in other fields, have arisen to overshadow our past pride of place. With far smaller resources we have nevertheless set ourselves, as a country, to match them. Our chief asset is still technical genius, but it is no longer vested in the tremendous stature of one man's inventions and pertinacity. We have to turn to the great industrial groups and associations, where the wisdom of what is still a comparatively small number of men acts as the focus of team-work for a large body of technical experts specializing in particular fields.

It is to this task of synthesis of the nation's ability and adaptation for our own purposes that the Engineering Branch has bent itself in the last ten years.

THE POST-WAR TASK

The end of the war, in 1945, is an appropriate time at which to start a review of recent progress in naval machinery because the beginning of a new era really did take place then, in this field as in so many others. In the sphere of naval engineering, probably the greatest new factor was the general recognition of the need for money for research and the development of propulsion machinery.

Between the wars, progress in the design of propulsion machinery was confined to improvements that could be incorporated without expenditure on development, full-scale testing ashore or risk of teething troubles afloat. It was a requirement that ships should be fully operational from the time they completed contractors' sea trials. Although in terms of reliability our war-time machinery was satisfactory, the Pacific War, in particular, brought home to us

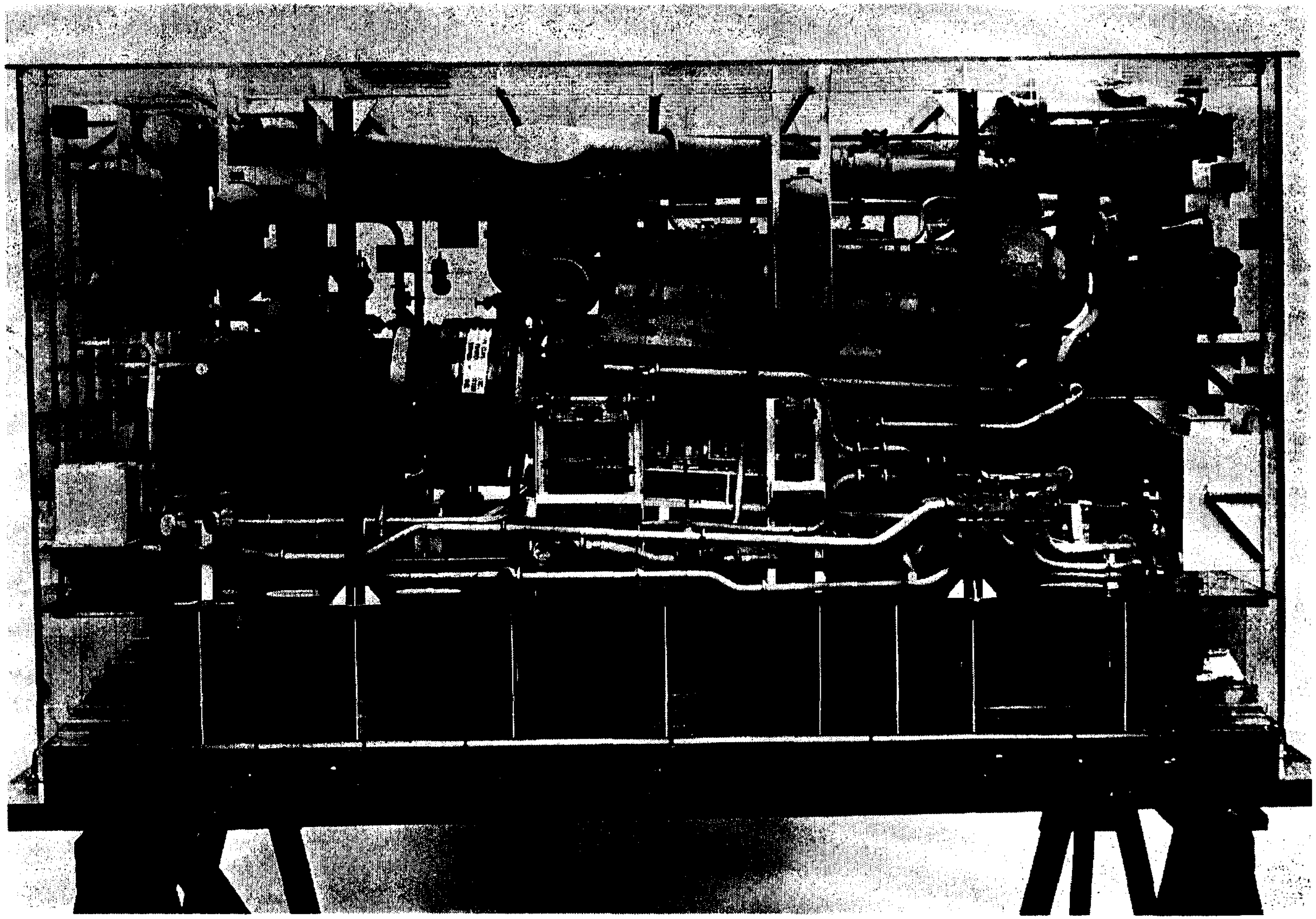

FIG. 1—A MODEL SHOWING THE INBOARD A.S.R.I.16 VTS MAIN PROPULSION ENGINE IN THE AFTER ENGINE ROOM OF A FRIGATE. THE OUTBOARD ENGINE IS HIDDEN. NOTE THE SHAFT FROM THE INBOARD ENGINE OF THE PAIR IN THE CENTRE ENGINE ROOM, THE GEARBOX AND THE FLUID COUPLING

the fact that we could not steam the very long distances demanded by ocean warfare with the simple steam-turbine machinery then in use. It was clear that, if we were to meet the challenges of the post-war world, we should need to pursue a more adventurous development policy. This again would require money, testing facilities, and the acceptance of teething troubles in the early days at sea. The recognition by the Government of the need to provide money for research and development in this, as in other fields, put upon the Branch a wider responsibility. We now had the opportunity, and indeed the obligation, to support financially the development of the best that the country was capable of producing to fulfil the increasingly difficult requirements of the Naval Staff. It was, therefore, with a feeling that we had money in the bank, albeit jealously guarded, that we were able to look out on a world of particular fascination after the great technical strides made during the war, particularly perhaps in the gas turbine field. Resulting from our close co-operation with the United States Navy and our post-war examination of German naval developments, we had a wide background against which to view our future and compare our existing standards.

Looking back, it is possible to recognize two phases of development over the past ten years. It is also clear that we are already embarked on a third phase. Of course, engineering development cannot be precisely defined and analysed, despite our immutable aim of attaining the best solution to the naval propulsion problem ; this is because the naval problem itself is altered by the advance of the science upon which it relies for solution. Furthermore, development is a continual growth in which new and better machinery is evolved from that already known. Nevertheless, with this understood, I will try to present a picture of naval engineering development, spanning some twelve years, divided into three phases :—

Phase I Development based on requirements learned from analysis of World War II and using engineering achievements up to 1950.

Phase II Development influenced by new armament fitted in ships, combined with the requirements to face attack by nuclear weapons and using engineering achievements up to 1955.

Phase III Development influenced by the use of atomic energy for propulsion, using engineering achievements that can be reasonably attained by 1960.

To avoid obscuring the trend of major developments, the details of development made in individual components, each of which has contributed to the overall progress, are given separately as an appendix.

Before taking these three phases, it is in place here to describe the means whereby we have sought to achieve this development.

THE MEANS OF DEVELOPMENT

The challenge of the post-war world led to an appraisal of the best method of developing the machinery of the future and for this it was clear that the Navy would need all the help available to it in the country. It also received a great deal of assistance from close collaboration with the United States Navy, which has continued throughout the years. The two mainstays of our policy, therefore, have been to depend upon industry to fulfil our needs, where necessary under development contract, and to go wherever we can obtain the best answers to our problems. There are, however, certain fields where an item has no application in the commercial field and its development is not technically rewarding to industry. In these cases, it becomes necessary to undertake the work at Admiralty Research Establishments or, at times, in H.M. Dockyards. The primary function of these establishments, however, is testing and undertaking research into test procedures. The Engineer-in-Chief has at his disposal the Admiralty Fuel Experimental Station, primarily concerned with fuel-burning methods and equipment, the Admiralty Engineering Laboratory, primarily concerned with internal combustion engines and gas turbines, the Admiralty Oil Laboratory, the Admiralty Distilling Experimental Station and the Admiralty Fire Test Ground. He also has naval wings at the National Gas Turbine Establishment and the Royal Aircraft Establishment, Bedford. A recent addition to these teams of naval officers and scientists has been the Naval Section at the Atomic Energy Research Establishment, Harwell.

In the somewhat special field of gearing, in which the fulfilment of naval requirements was dependent upon the improvement of production techniques not normally demanded commercially, special measures were taken and the Admiralty-Vickers Gearing Research Association was set up. The Admiralty Development Establishment at Barrow was also started to deal with special submarine propulsion problems. From 1950, we have also had the Admiralty Oil Quality Committee (in permanent form, now the Admiralty Fuels and Lubricants Advisory Committee) which has marshalled talent from many quarters, not least the oil industry, to help solve the increasingly severe problems of combustion and lubrication.

The need for facilities to test steam turbines for advanced conditions was met when the shipbuilding industry, in conjunction with the Admiralty, established Pametrada. Continuous use has been made of this organization, the testing of the main turbines of the *Daring* Class being the first Admiralty work undertaken. This was followed by the testing of complete machinery installations for A/S frigates and of new advanced prototype machinery.

What we still lacked was the capacity to survey the whole world of engineering development to enable us to pick and choose the best bits and then weave them into complete installations that really represented the best that the country could provide. It was for this purpose that the Yarrow-Admiralty Research Department was set up. This team does not compete commercially in the design of any components. It has the task of studying the requirements for naval machinery as they develop and investigating the feasibility of all the conceivable combinations of components that might fulfil them. The evaluations that result are designed to ensure that each class of ship has the most suitable installations that can be derived to meet its particular requirements and give the best possible performance within a minimum of weight and space.

THE FIRST PHASE OF DEVELOPMENT

Our first need, of course, was to find out what requirements we should have to fulfil. During the years following the war, much consideration was given to the new shape and size of the Fleet which the Navy would have to achieve by new construction and conversion. One fact, which seemed to be quite settled, was that we should need a predominantly small ship new construction programme consisting largely of frigates and minesweepers. These would require long ranges, low machinery and fuel weights, and had to be easy to build and maintain.

Hitherto, our propelling machinery policy had been fairly clear cut ; steam turbines for large ships, Diesel engines for boats, and a mixture of steam reciprocating or turbine main engines for minesweepers and frigates. This last choice had largely depended upon the type of shipbuilder constructing the class of ship concerned, since it was customary for the shipbuilder to manufacture the main engines. During the war, however, we had become accustomed to supplying the shipbuilders of some smaller classes with the machinery to install.

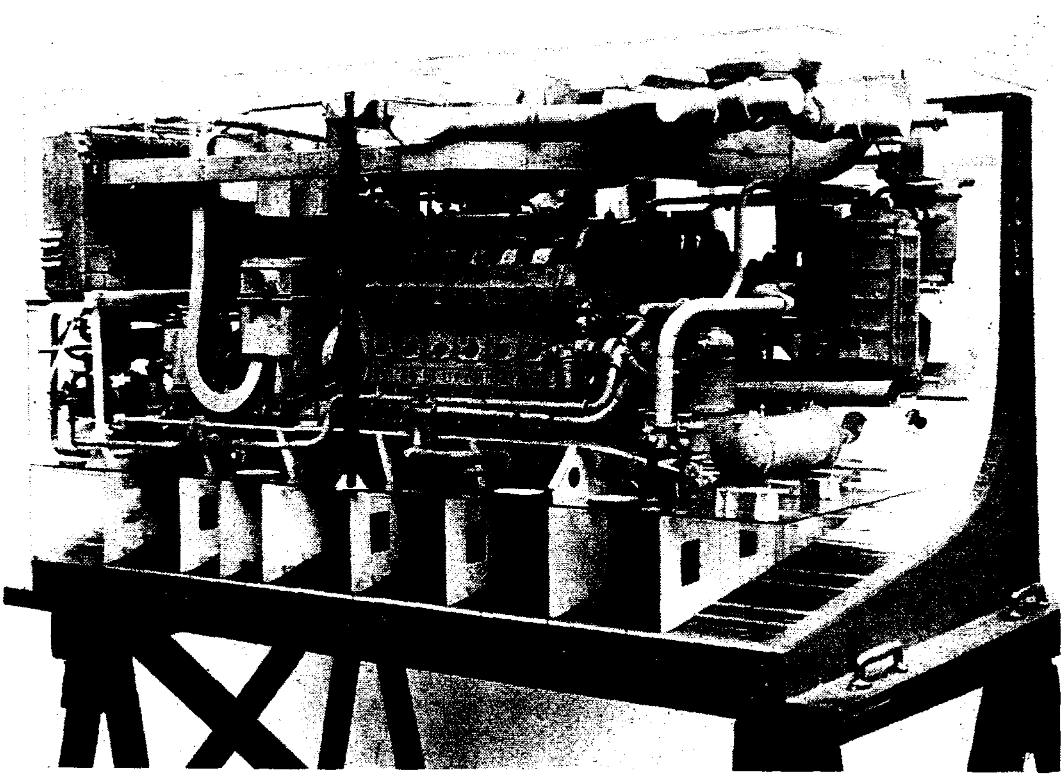

FIG. 2—A MODEL SHOWING THE PAIR OF A.S.R.I. 6 LTS GENERATORS IN THE AFTER ENGINE ROOM OF A DIESEL FRIGATE. NOTE THE SWITCHBOARD ON THE LEFT AND THE VAPOUR COMPRESSION EVAPORATOR WITH THE PORT MAIN SHAFT BELOW IT

The need for a large programme of small ships with long range made the choice of machinery controversial. The Diesel enthusiasts offered low fuel consumption ; the gas turbine enthusiasts offered exceptional gains from machinery weight and space ; while those who studied developments in steam plant promised results in which reduction in fuel consumption and in weight and space would go together. The range of horse powers required would undoubtedly cover applications for all three types. At the outset the team formed by Yarrow & Co. and the English Electric Company working in the closest co-operation with British industry, were given the task of making a world survey of engineering practice in the naval, merchant marine, and power station fields in order to present the Admiralty with an assessment of how far each had progressed and what use could be made of this progress in the naval machinery of the future. They were given the particular task of studying the optimum steam plant of 30,000 s.h.p. that could be devised to follow quickly upon the *Daring* Class machinery. After this initial investigation, however, English Electric Co. withdrew entirely from the team so that it could obtain turbine designs on a competitive basis from any firm.

The *Daring* Class machinery had been designed on the pattern of U.S. naval destroyer machinery because we knew theirs had proved very satisfactory. It was the quickest way to produce ships that would be able to steam for equal ranges with U.S. warships in the Pacific War and, in 1944, it seemed more than likely that they would be needed for this.

This machinery had involved the introduction of four simultaneous steps into fields that were new to us. The steam temperature was raised to 850 degrees F. and thus we entered the creep range ; the boilers had two furnaces for superheat control and, although this type was being planned for the *Weapon* Class, they were not then at sea ; the gearing was double reduction, which had been dropped in the 1920's by most people after a spate of trouble ; the turbine rotors were solid and of low-alloy steel. Technically, the last two steps were the most difficult to take and the most profound in their consequences. We were freed from the limit on steam temperature and rotor speed imposed by the shrunk joint of our previous H.P. turbine rotors, and we were freed from a virtual limit of 10 : 1 turbine to propeller speed ratio for cross-compound turbine sets. From this point the turbine speeds adopted for any set of steam conditions were limited solely by metallurgical considerations for turbine rotors. Moreover, instead of being forced to design turbines for the maximum efficiency at about full power, we could bring the point of maximum efficiency down the power range where we needed it more to give a large cruising range for a minimum of fuel. The two-furnace boiler was large and heavy but, now that we had entered the creep range, why stop at 850 degrees F ? Now that we had double-reduction gears and the turbines had become so small and light, why not have more than two per shaft ? These were some of the aspects that the Yarrow-Admiralty Research Department was set to explore in conjunction with members of E.-in-C.'s Department. The material gathered and possibilities examined in the first two years after the war represent a formidable accomplishment.

Machinery for the New Frigates

It was while this study was proceeding that the need for new frigates of various types emerged. The accent was still on long steaming ranges and small ships. The anti-aircraft and aircraft-direction frigates were to be two-shaft ships with 8,000 s.h.p. on each shaft. No suitable steam design was available. The Admiralty Standard Range I Diesel was under development and gave promise of being a good engine of low weight—about 17 lb per s.h.p. The installation, compared with those of our war-time frigates, was a great improvement and it was decided to engine these ships, therefore, with four A.S.R.I. engines geared to each shaft. Being a range of engines from 6 cylinders in line to 16 supercharged cylinders in 'V' form containing mainly standard components throughout the range, the Diesel generator engines, of which there are four, were also chosen from this range (FIGS. 1 and 2).

This was followed by a requirement for an anti-submarine frigate of about 30,000 s.h.p. on two shafts. The urgency was great and we diverted our effort from the study of possible progress in destroyer machinery to this problem. The conditions were very severe. The displacement of the ship was limited to achieve manœuvrability. My Department was told that this displacement could not be met unless the weight of machinery and fuel to achieve the long range specified was reduced by between 25 and 30 per cent compared with our war-time machinery, and a similar reduction made in the length of the machinery spaces. One of the interesting aspects of this was that it made weight of fuel and weight of machinery interchangeable. It was, therefore, worth adopting a less efficient unit if it was so much lighter that it compensated for the extra fuel which its inefficiency would make necessary. The converse was also true ; if a heavier machine or heat exchanger would give added efficiency, to justify its use, it must save more fuel than its own weight in one voyage, assuming all fuel to be expended. Such calculations delight the hearts of the academically inclined and it is necessary to bring common sense to the many problems and answers derived in these circumstances. We set out to meet the target by cutting all the margins we could. I believe this was the only way of achieving our object. If one starts off with the idea that everything must be made quite safe and adds margins to every component, starting with the boiler, in the end all the auxiliaries have become larger and the boiler gets bigger still. We hoped to prevent this spiral but risked failure to get full power. Various adjustments were made after the shore test of a prototype plant, but in general the result of

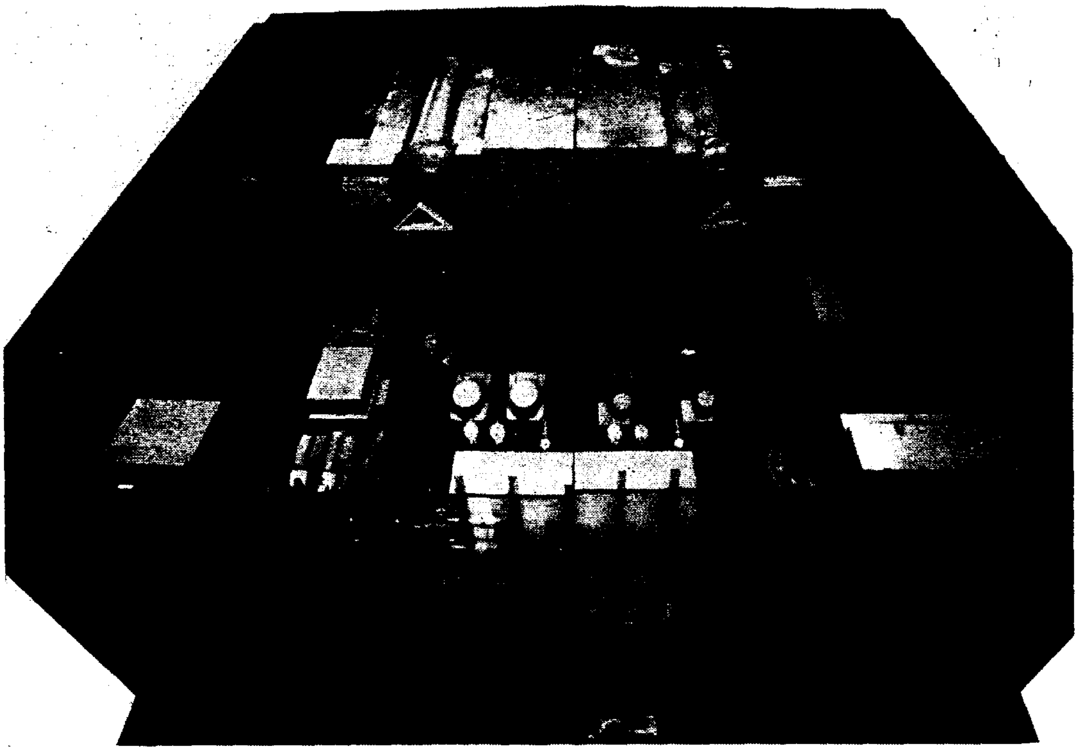

FIG. 3—THE Y-100 BOILER ROOM

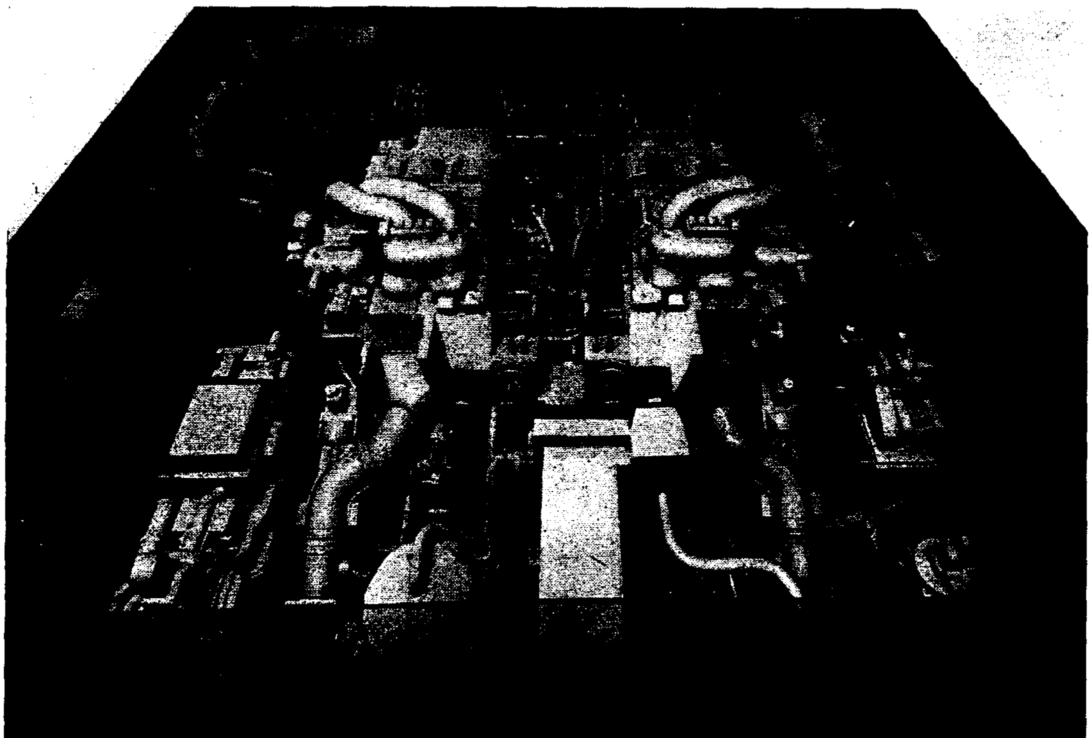

FIG. 4—THE Y-100 ENGINE ROOM

the experiment has justified the method adopted. As I have said, the targets set were severe and the method of attack was our first attempt at a fundamental study, using every source of information in the country, and it led finally to installing the machinery in a ship. The design, known as Y.100, should be judged against this background (FIGS. 3 and 4).

This requirement was quickly followed by another for smaller A/S frigates that would be cheaper to build. It was decided to produce a single-shaft version of the larger anti-submarine frigate machinery, using the same main engines. The larger ship had only two boilers and, as no one would accept a single boiler in a ship, almost everything except the main engines and turbo generators had to be re-designed. This resulted in a set of machinery of comparable horse-power in a somewhat similar ship to the two shaft Diesel driven frigates. It is known as Y.101. It will be of interest to see how the maintenance, operation and ship-handling aspects compare. The steam version is superior on the weight and space occupied by the machinery and fuel and, of course, burns a cheaper fuel. However, a single shaft ship cannot be compared with a twin shaft except after operational experience has been gained.

At about this time, the development of a gas turbine engine for naval use showed promise of giving very good results for coastal craft. This engine was being developed as the sole method of propulsion to give good economy over a range of 20 per cent to full power. It was thought that an enlarged version might well provide a rival for both steam and Diesel engined frigates. A paper investigation was therefore instituted for a two-shaft gas turbine installation of 7,500 s.h.p. on each shaft. The so-called R.M.60 engine of 5,400 h.p. has fulfilled its promise and is now successfully undergoing a long series of trials in H.M.S. *Grey Goose* under various climatic conditions. It was found, however, that the attempt to scale up this design for a major ship installation was not such an attractive proposition after all and it was finally abandoned.

Steam Machinery for Higher Powers

The effort to progress was now re-directed to the original target of a 30,000 s.h.p. steam set as a successor to the *Daring* Class machinery. This became known as the Yarrow-English Electric Advanced Design, since it was a continuation of the original development contract for their investigation of more advanced machinery. The first of these designs, known as Y.E.A.D.I., was so planned that it lay within the experience of the component designers and could be built without research. The steam temperature of 950 degrees F. was selected as being within the experience already gained with land boiler installations. Our requirement for economy at low powers did, however, make the maintenance of this temperature necessary at low flows through the superheater and this presented a particularly severe problem.

An extensive survey was carried out on the pressure level most suitable to various temperatures and for various types of ship. This resulted in the conclusion that the boiler pressure of 650 lb/sq in adopted in the *Daring* Class was still close to the optimum for this power in destroyers, although, for greater power and larger ships with different characteristics, somewhat higher pressures offered some advantages. The gains, however, within the range of 600 to 1,200 lb/sq in are not very significant on a basis of overall weight of machinery and fuel. Other factors, such as the effect on steam catapults in aircraft carriers, therefore, play an important part in the final choice of pressure for any given class of ship.

The Y.E.A.D.I. prototype set (FIG. 5) is now running on test at Pametrada and marks the end of this first phase of development.

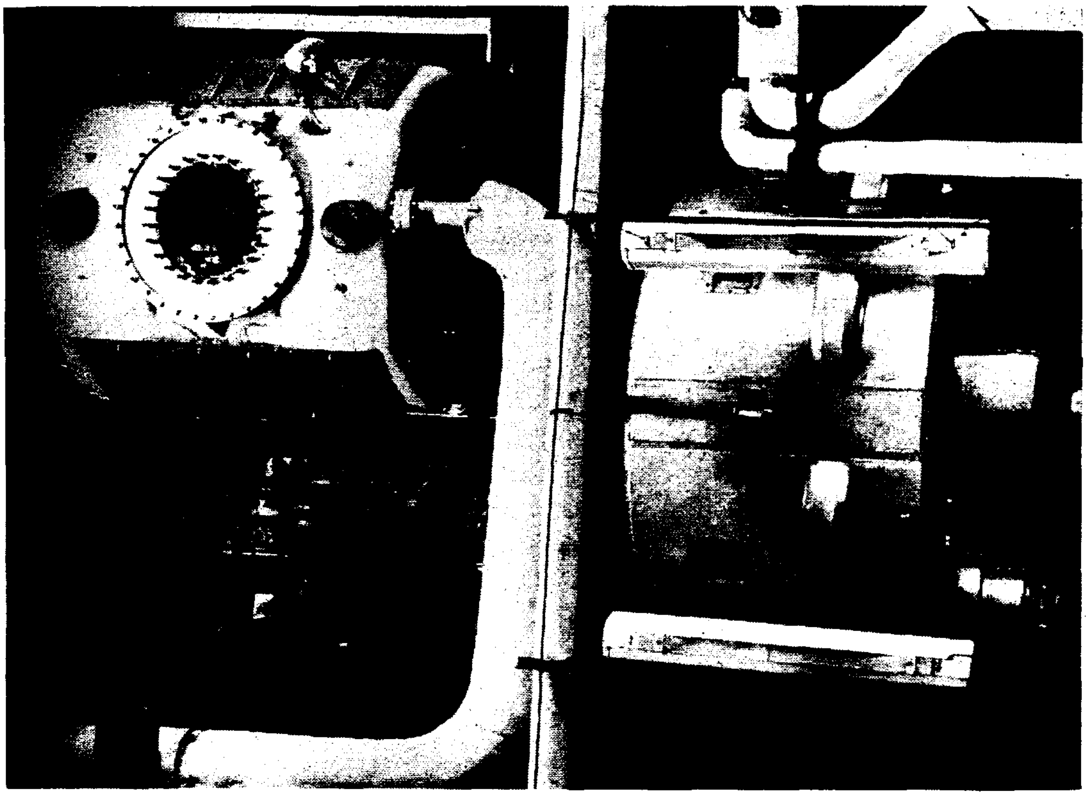

Fig. 5—The English Electric Turbines for Y.E.A.D.I.

We have reached a stage in the increase of steam conditions where, for any further thermodynamic gains, the effort in terms of development cost is increasing rapidly and the law of diminishing returns must be studied. There are problems of corrosion of metals at high temperatures caused by the products of combustion of oils containing sodium, vanadium, sulphur and even sea water, and these have to be solved before we can advance further. What we are looking for now is something more profound than the small percentage gain which the next 100 degrees F. rise will offer.

In this first phase we have developed each component along conventional lines to a logical economical limit. Boiler sizes, which, in natural-circulation boilers particularly, depend on the size of the furnace, have been reduced by increasing the heat-release rate to the point where the advantages are offset by the increases required in blower power. Draft losses have increased to 50 in. in Y.100 and to 85 in. water gauge in Y.E.A.D.I. Turbine speeds have been pushed to the limit of strength of rotor alloy steels which can be produced in a reasonable period. Gear loading has been taken to a point where full use is being made of the best surface-finishing techniques and the materials available. These researches are continuing and may well offer further gains, as will investigation of bearing losses. Condenser water speeds have been increased to the point where circulating pumps have to be used to supplement the maximum head that can be generated by carefully designed scoop inlets. Small high-speed auxiliary turbines, with epicyclic gears where appropriate, have been introduced. A study has been made to reduce steam pipe weight by increasing steam speeds where pressure drops can be afforded. There is, of course, much to be done still, particularly in the realm of welding steam pipes, improving materials and reducing propeller and other losses. On the whole, however, I feel that we must turn increasingly to the adaptation of new techniques, rather than further development of the old ones, to solve our future problems.

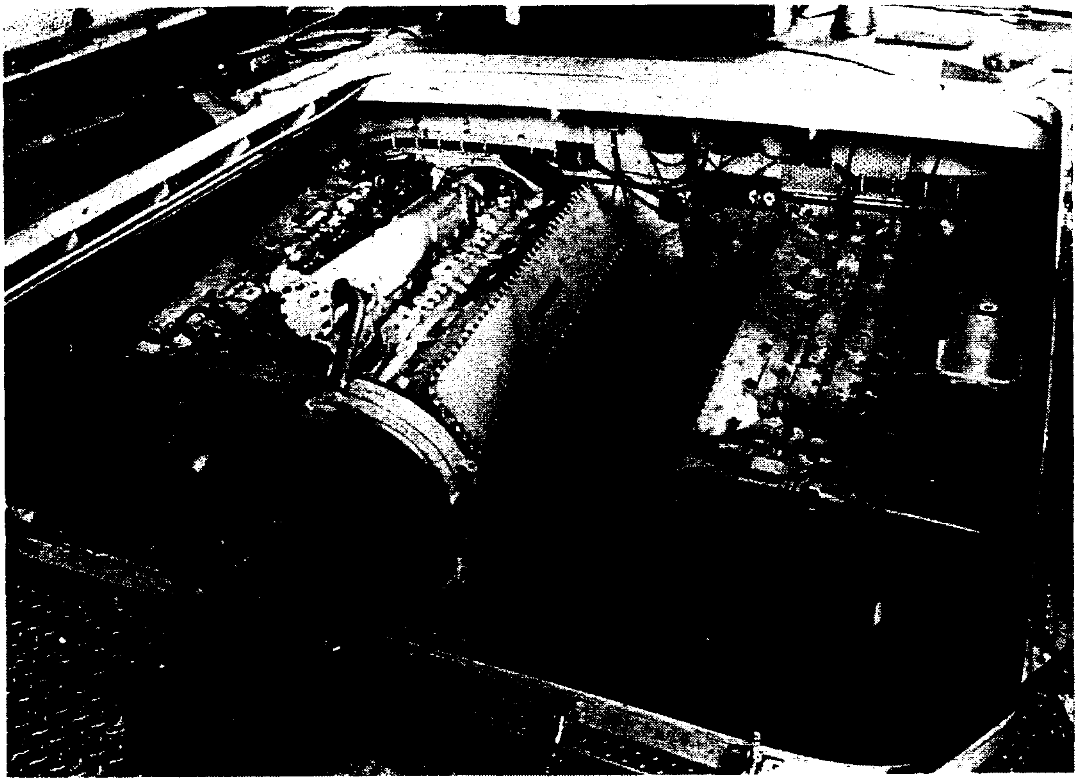

FIG. 6—A TWIN DELTIC INSTALLATION

Small Craft

The Deltic Engine

In parallel with the developments in ships of the Fleet and escort vessels, there has been great activity in small craft engine development. In the field of fast patrol boats particularly, there have been developments in both gas turbine and Diesel engines. There was no light-weight Diesel engine in being which could serve the purpose. A committee was set up therefore, in 1944, under the chairmanship of Sir Roy Fedden to investigate the possibilities, and from its deliberations the development of the Deltic engine emerged (FIG. 6). The development of this engine, to provide in the eighteen cylinder version a horse power of 2,500 at 2,000 r.p.m. with a specific weight of 5 lb per s.h.p., was undertaken under Admiralty contract and it is now in full-scale production both for the *Dark* Class fast patrol boats and for coastal minesweepers. It has already proved its excellence in service and has justified the large development effort that was required.

The Gas Turbine

A gas turbine was installed in a motor gunboat in 1947 and ran successfully to give the boat its high speed, while internal combustion engines were used for cruising. This was followed by the so-called G.2 gas turbines in the *Bold Pioneer* and *Bold Pathfinder* which have done one series of trials and have now had Deltic engines installed as cruising engines. The R.M.60, already referred to, is the first gas turbine to be used as the sole method of propulsion and has been very successful. This, however, is a complex cycle with heat exchangers and compound turbines and compressors.

From these experimental craft we have gained an appreciation of the best line of development to be pursued. In the face of the many claims, some extravagant, which were put forward for gas turbines of various types, there was probably no other way in which we could have collected evidence on which to base our conclusions. The fact that we may abandon one of these engines certainly does not reflect in any way on it as a technical achievement, but merely that it does not fit into naval requirements in their fullest sense.

Our conclusions about the gas turbines are :—

(a) *Cycles.* The most important advantages offered by the gas turbine for naval service generally are :—

(i) compactness and low weight
(ii) ease of maintenance
(iii) great flexibility in operation.

We now feel it probable that these can be fully realized only in open-cycle engines of simple form with a minimum of heat exchangers, ducting and general complexity.

(b) *The Design Approach.* Our experiments have shown that it is best to approach the design of naval gas turbines using the light weight aero-engine technique rather than modify steam turbine practice to cope with the rapid temperature changes and other problems involved. The design, of course, has to be suitably modified to provide more robustness at the expense of the extreme weight-saving necessary in aircraft.

The performance of simple gas turbines has increased with striking rapidity in recent years, a development aptly illustrated by the G. series of engines. This, coupled with growth of the boost concept, has offset the handicap of high fuel consumption from which simple engines were originally seen to suffer as propulsion engines when compared with compounded plants, particularly of course, at low power.

THE SECOND PHASE OF DEVELOPMENT

While we have been struggling to produce the right sort of machinery for these types of ships, however, other developments in the spheres of nuclear weapons, of submarine detection, of radio and radar communications, and guided weapons, have profoundly affected the conception of the type of ship that we need to build. Add to this launchers for guided weapons and the stowages and handling arrangements for the weapons themselves and the proportions of the problem start to emerge. Moreover, the conditions of our day have produced the now familiar differentiation between cold, warm, and hot wars. This new classification of types of war creates another problem for the Naval Staff in defining the conditions for which they wish ships to be designed. It once more alters the delicate balance in which the various needs for a ship design are weighed, when the most desirable compromise is being judged.

There is another factor which I have not mentioned but which is also of profound importance, and that is the realization that, if we are to have a Navy at all, we must make great improvements in the living conditions on board warships. To the Engineering Specialization this has meant two things : more room for living spaces on board, and machinery designed to need fewer men to operate and maintain it. In fact, all modern developments in detection and attack seem to take up weight and space, in spite of the use of new names such as ' miniaturization ' by which it is implied that they do not ! The cost of a ship depends largely on its size. The size of a ship is very much influenced by the size of its machinery spaces and the volume of oil it must carry, and so we are continually trying to reduce these to make room for more fighting equipment. A large part of this equipment goes high up in a ship, and so we also

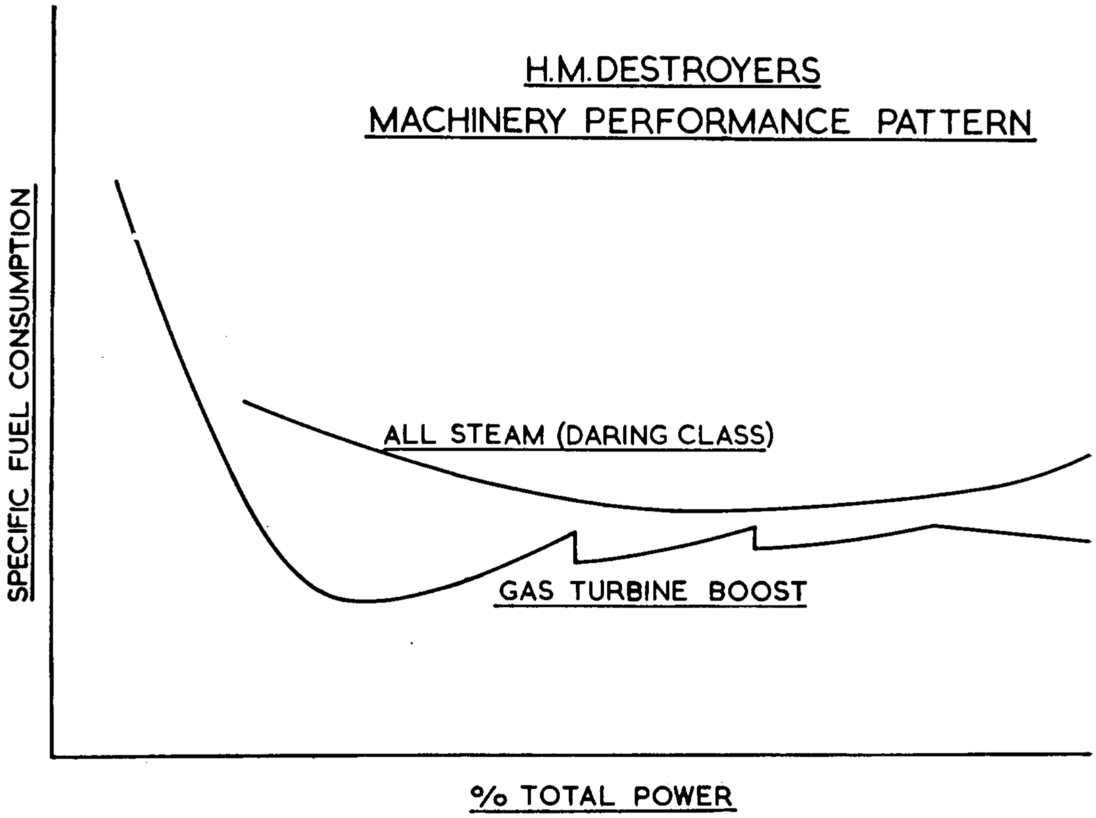

FIG. 7—THE BOOST CONCEPT CHARACTERISTIC CONSUMPTION CURVE

must do our best to reduce the height of the machinery spaces because this influences the level of the upper deck, the top-weight moment, and hence the beam of the ship. We had already gone as far as possible—some think too far—in cheese-paring our steam machinery and a new conception was, therefore, required. One of the most serious problems in warship design is maintaining stability with all the added top-weight. Reducing machinery and fuel weight does not help in this direction. We therefore turned our attention to the possibility of lowering the height of the deck above the machinery spaces. This height is determined by the boilers and the turbines and condensers, and the matter was examined to see if the size of these could be reduced appreciably by some new concept. This has proved to be possible.

The Boost Concept

The analysis of war-time and peace-time records showed that a warship needed to steam at maximum power for a relatively short period, so that the full power component of any system could be designed for a medium life and thus permit light-weight scantlings. Following this line of reasoning, we arrived at the idea of a base steam plant which provided power for, say, twenty-five knots, boosted by gas turbines to give maximum power. The result offers a wide radius of action under war cruising conditions, with an acceptable fall-off in efficiency for the higher powers at which extreme radius is unimportant (FIG. 7). A prototype plant is now in course of construction and the gas turbines and gearing, with its clutches,will be tested ashore, A similar plant is being designed for a guided weapon destroyer and the first of the Class will be available as a prototype for evaluation trials for a period of about one year. A simplified version is also being designed for a small frigate of the new building programme.

This boost concept also has attractive features from the aspect of nuclear warfare, to which I will refer shortly. The boost conception is by no means the only solution for a compact machinery installation with low headroom but, pending experience, it does provide an attractive one. There are inevitably complexities, such as automatic engaging clutches for the gas turbines and for manœuvring gear, and the whole plant requires a high degree of manufacturing skill. This, however, can be a national advantage rather than a handicap.

One of the advantages of this type of combination is that, since there is an alternative source of power to the steam plant, it is permissible to reduce the number of stand-by units that are normally incorporated to allow for failure of components of the steam installation. In order to take full advantage of this, it is necessary to incorporate a reversing gear so that the ship may be manœuvred on gas turbines alone. This has given rise to many ingenious proposals, but it seems that nothing more simple and effective than a reversing train of gears can be devised. This train is being incorporated in the gearing train from the gas turbines and can be clutched in for emergency manœuvring.

One of the well known disadvantages of gas turbines is the size of air inlet and exhaust ducts and a depression on the air inlet side has always been viewed with horror by gas turbine compressor designers. In this case, however, in order to allow of slightly higher air-head losses in the air and gas ducts, we are accepting a somewhat larger gas turbine than is strictly necessary, at the price of encroaching slightly on the savings made by using this form of prime mover.

PROTECTION AGAINST NUCLEAR ATTACK

Remote though we hope it may be, the possibility of a war introducing the use of nuclear weapons demands the following additional requirements of a warship :—

(i) that it may be able to leave harbours and anchorages at a few minutes' notice

(ii) that it may remain at sea with little logistic and maintenance support for very long periods

(iii) that it may be capable of steaming without adverse effect through radio-active atmosphere.

The first aspect, the ability to get under way quickly, favours the Diesel or gas turbine.

The second requires rugged machinery that can continue to operate, albeit at reduced efficiency, with a high degree of reliability even though maintenance is neglected.

The gas turbine boost concept meets these two requirements admirably, providing, as it does, a rugged steam plant which fulfils the needs of item (ii) and a gas turbine unit that can always be ready at short notice to meet item (i). There are, of course, other solutions. An all-steam four-shaft ship can be equally suitable, although the maintenance requirement may not be so easily met.

The requirement to be able to steam through a contaminated atmosphere presents some interesting problems. It appears to be essential to seal all spaces where personnel are operating. To this end, engine-room ventilation must be closed down and the air in the compartments re-circulated to avoid an excessive rise in temperature locally in the vicinity of machines, particularly electric motors. Boiler air must be trunked direct into the boiler, or the boiler room must be treated as a closed box capable of being operated from outside. The solution being adopted in warship design is to place the boilers within an air-tight box and to provide an a irconditioned control room within, or contiguous to, the engine room. The control of all essential machinery is effected from within the control room. This has required the development of remote control systems and automatic watchkeepers on some machines, such as turbo generators and distilling plant. One of the fundamental needs has been the development of burners with a very wide range of output to make remote or automatic control of boilers feasible. This has been achieved successfully and the results of Y.E.A.D.I. boiler trials have been very encouraging.

As an incidental to such a system, the number of operating personnel should be considerably reduced and experience on service, of ships so fitted, is awaited with interest to see if this is indeed borne out in practice.

THE THIRD PHASE OF DEVELOPMENT

The third phase of development is that influenced by the use of atomic energy for propulsion. This is not so much demanded at present by a change in the naval problem, but the opportunity of finding a better solution to the present problem in the practicability of nuclear propulsion. Once one navy has changed to nuclear power, however, the whole tempo of naval operations may well alter, since ships will be able to steam for weeks at high speeds instead of for only a few days. Any navy that is unable to do this will then be at a very severe disadvantage, so the naval problem will in fact alter. To summarize the naval problem, we now have ten main requirements:—

(*a*) Reliability
(*b*) High endurance at cruising speed combined with a high top speed
(*c*) Low weight
(*d*) Small space, including height
(*e*) Ease of operation
(*f*) Ease of manufacture
(*g*) Ease of maintenance
(*h*) Resistance to shock
(*j*) Silence of operation
(*k*) Adaptability to automatic control.

In the selection of a judicious compromise of these requirements lies the artistry of design and this compromise may vary for each class of ship as the emphasis is moved to meet a particular duty. It was with these guiding factors in mind that a feasibility study of atomic propulsion for warships was undertaken.

Because the engineering for atomic propulsion is one of the offspring of the atomic bomb, strict security has overshadowed and undoubtedly retarded its development. However, its application to warships and commercial vessels remains almost wholly an engineering problem and one that can only be solved by the engineering industry.

Nuclear propulsion is immediately attractive for submarine propulsion and we therefore decided that our first step should be in this direction. The prototype propulsion unit, which will consist of a pressurized water reactor, heat exchanger and steam turbine, is under development and the first unit will be operated at sea when shore trials have been successfully completed. The engineering problems include those of heat flow in the core, shielding, pumping radio-active water at high pressures and temperatures without leakage, and the design of pressure vessels and heat exchangers. As an increasing number of engineers throughout the country are becoming conversant with these problems, I look forward to rapid progress.

At some future date all warships, apart from minor ones, will probably be powered by reactors and, as the cost of nuclear fuel falls, it will become economically attractive for commercial vessels. At present, no one can predict when this will be, but, in my opinion, it is an inevitable step, like the transition from coal to oil. It is always the lot of a new component that it must, in its early days, be compared with its fully developed predecessor. So it was when the first turbine was scorned by supporters of the reciprocating engine. The battle of opinion was settled finally only by a practical demonstration. In the case of the reactor, however, we have already a convincing demonstration of what can be achieved in U.S.S. *Nautilus*. The experience with this ship has done much to allay fears and we believe that, on a basis of ease of operation and reliability, the pressurized water reactor has been outstandingly successful. While we can see no insuperable technical problems in the development of marine type atomic engines, there is a vast task ahead of industry calling for wise direction, tenacity of purpose and technical excellence. We shall be failing in our heritage if we do not recognize this and direct ourselves accordingly.

THE FRUITS OF EXPERIENCE

From time to time it is wise to take stock and review our experience objectively so that we may apply in the future the lessons of the past. From such a review of naval development over the last twelve years certain lessons can be emphasized and some generalizations are possible. In the main these come under three headings :—

(*a*) The need for careful planning
(*b*) The need for manufacturing excellence
(*c*) The importance of unconsidered trifles.

The Need for Careful Planning

The phasing of the development and production of machinery installations requires careful study and realistic planning. The pace of development is high ; the process of building naval ships in this country is slow. We cannot wait to get sea experience of a new type of machinery, modify it and then start to build the rest of the class. If we attempted to do this, the time, from starting to design the machinery until the first of the production line of ships went to sea, would be, on present showing, about eight years. By then the ship would be obsolescent.

Shore trials have proved very valuable in eliminating many causes of trouble in new installations where fundamental changes have been made to components or systems. They allow errors to be corrected before installation in a ship instead of after and thus save much time and annoyance. On the other hand, they are very expensive. Installation, running costs, and the costs of unpredictable delays mount up rapidly and discourage such trials unless they are essential to prevent later delays. It is not possible, however, to cover such things as propeller and shafting characteristics, and we have experienced troubles at sea after successful shore trials had given us a sense of security. These troubles were negligible, however, compared with what we should have experienced without the shore trials. It follows, that it is still essential to get machinery to sea in a ship as soon as possible.

We must, therefore, overlap so that while the prototype is undergoing shore trials, machinery for other ships is started and while the first ship is undergoing sea trials, the rest are building. This involves feeding back modifications, shown up by prototype experience, into the production installations. The process has to be accepted as normal and some allowance made for it in planning. I am well aware that alterations made while production is proceeding cause dislocation and uncertainty in the shops. They are only demanded when essential, and difficulties can be lessened if firm action is quickly taken to reorganize the production of the parts concerned.

The Need for Manufacturing Excellence

Before and during the war, materials used were comparatively simple and the production processes straightforward. We have now been taken into a field where alloy steels and other alloys are essential in such major parts as boiler steam drums, steam pipes, turbine rotors ; they are used, of course, much more extensively in gas turbines and Diesel engines. Welding techniques for alloy steels and non-ferrous materials are increasingly important. Surface finish, hardening techniques, and production processes generally have, in fact, become fundamental features of the process of developing new machinery. The evidence for this grows every day. Gas turbines, free-piston gas generators, the Deltic Diesel engine, superheaters for high temperatures, highly loaded gears, to take a few examples, have all depended for their existence upon the development of suitable techniques to overcome difficult production problems. Gearing is a particularly good example. The vital effect of gearing on weight, layout, efficiency, reliability and maintenance has led to increasing complication in this component. We have learnt a tremendous amount about heat treatment, surface finish and so on and, provided we can meet the problems of gearcase production, gears will be like the main turbines which are usually the seagoing engineer's least worry. It is fruitless to undertake development unless production techniques can keep pace and these have now become of paramount importance in all our projects for meeting high machinery ratings.

There is a second reason of almost equal importance. The delays during the war from lack of interchangeability of parts resulted in ships remaining in harbour when they could have been on the high seas. Some aspects of this were dealt with in Commander A. F. Smith's paper in 1953 (*N.E.C. Inst.*, Vol. 69 and *Journal*, Vol. 6, No. 3). The whole problem of availability of machinery is influenced by the standard of production. This includes the vital need for meticulous inspection. Errors in production are bound to occur but, if inspection is rigid, they can be corrected under the best conditions in the shops with all the appliances and experts to hand. It must pay in terms of time, which after all is measured in hard cash, to take all possible pains to ensure that an article is well and truly made, for only in this way can painful corrective effort be avoided afterwards when conditions are much less favourable. It is costly, wasteful, and nationally dangerous to take risks in this matter.

The Importance of Unconsidered Trifles

The reduction in size of the major components throws into high relief the minor fittings. Drain cocks, pressure gauge valves, drain pipes, vent pipes, gland evacuation pipes, gland water sealing pipes ; they are legion, and the tendency is that more and more of them, with remote servo and automatic controls now coming in, will add to the host. Often a diagrammatic sketch is all the guidance the fitter is given. The result can easily be, that machines which looked accessible enough on a drawing or even in a scale model are so hedged round with small cocks, valves and pipes, that it is impossible to approach them at all, let alone maintain them, without dismantling the surrounding forest. Recently it was found worthwhile to spend a considerable effort in studying the drain system of *Eagle* and *Ark Royal* and it was demonstrated that the overall improvement in the maintenance effort required in these ships was out of all proportion to the small effort deployed on the re-design.

It is essential, therefore, to carry detailed design into every part of the installation. Something more than the present full scale mock-up with its limited scope is needed for the designer to see that the final result is as tidy and accessible as he thought of it in his most ambitious moments.

Cleanliness is at present another unconsidered trifle. For ships with remote-controlled or nuclear powered machinery, almost clinical cleanliness will become a firm requirement. Much can be done and is being done in the design and manufacturing stages to ease this problem but eventually it rests with the people who install the machinery to ensure that it is achieved in practice. I feel that installation, which is possibly the most difficult stage of all, has not perhaps received the attention it deserves. That it can be done has already been proved in the submarines driven by ' high test peroxide '.

EPILOGUE

Looking back over the last ten years with which this survey has been primarily concerned, I feel that they have been years of high endeavour. I think, too, that they have been fruitful years. Many have shared in this endeavour and the things that have flowed from it. It is due to the combination of industry and the user that many of our hopes have become facts.

The results in terms of saving of space and weight have been impressive and there is no going back. For an expenditure of 1 per cent of the capital cost of A/S frigates, building and ordered, we have reduced the cost of each ship by about 10 per cent by the saving made on the size of the ship by reductions in the machinery.

Not all our hopes, of course, have been fulfilled ; that was not to be expected, although I believe we have learned from our mistakes as well as our successes.

The reputation of any machinery depends ultimately on its reliability in service. But the challenge of modern naval requirements is such that the reduction of weight and space and increase of efficiency have to receive at least equal consideration. This challenge we accept knowing full well that, in going beyond the bounds of our own experience, we shall initially meet troubles. Difficulties there have been and still are, but they have yielded and will continue to yield to professional skill, courage and tenacity of purpose. It is not in man to be omniscient ; particularly is this so with machines which have the salutary power of humbling him by showing the defects of his own creation.

I take this opportunity of thanking all those who, in industry, research and many other occupations outside the Service, have sustained us in our endeavour to raise the level of engineering in the Royal Navy. Without their co-operation and hard work, it could not have been done. The task is a continuing one ; I dare to hope that they will continue to accompany us along the road ahead and share with us, as I hope they are now sharing, the fruits of our joint efforts.

I think that the words of Sir Francis Drake (in a letter to Sir Francis Walsingham written in the good ship *Elizabeth Bonaventure* on 27th April, 1587) are apposite to our present situation for, although development is a continuing process and in that sense is never finished, yet each step along the road must be a complete one in itself. So his letter to Sir Francis Walsingham is applicable to us today in engineering as in so much else—'There must be a begynnying of any great matter, but the contenewing unto the end untyll it be thoroughly ffynyshed yeldes the trew glory.'

APPENDIX
THE DESIGN OF COMPONENTS

The general installation design has been dealt with, but this is made up of a number of components each one of which has been the subject of much study and development. The outstanding changes in turbines, gearing, and boilers have been mentioned but some more detailed explanation of where we have arrived in each field may be of interest.

BOILERS

When using high steam conditions, it is prudent to have a boiler in which the temperature can be lowered for manœuvring or to meet unforeseen difficulties. The engines can then be run at a lower temperature with a sacrifice of endurance only. For this reason we adopted superheat control instead of relying on a boiler with a flat temperature characteristic to give us the higher efficiency needed at low power. A further advantage of controlled superheat is that the turbines can be designed to withstand a steam temperature of 850 degrees F. at full power when the stresses are a maximum. Below, say, 60 per cent power, when creep is not a problem because stresses are lower, the steam temperature can be raised to 950 degrees F., thus gaining even more efficiency at the lower speed. This has been done in Y.E.A.D.I.

In both Y.100 and Y.E.A.D.I. the temperature is controlled by dampers beneath the economizer and these have proved reliable after much shore testing and experience at sea. The boilers have a single furnace with one main bank of tubes containing the superheater and an economizer. The general type devised has passed into commercial use as the ' Selectable Superheat Boiler '. It has particular advantages for naval use because brickwork has been largely eliminated by the use of water-wall tubes, the efficiency characteristic fits our requirements and the superheat control is easy to operate either manually or automatically.

The new designs of boiler have been tested at Pametrada with the associated machinery and, while this does not wholly prevent trouble when sea trials are carried out, it is of very great importance.

We have adopted a policy of using the designs of specialist boiler firms for new construction instead of using mainly Admiralty three-drum designs, as we did before the last war. Besides the boilers already referred to, we have used D-type boilers of standard design, built to Admiralty requirements, for ships that are being modernized but retain their existing main engines.

The fundamental limit on engine-room height imposed by natural circulation boilers is becoming an increasing obstacle to the trend of development we need to follow. With the development of automatic controls suitable for use in warships, it seems probable that we shall be able to go to some form of forced circulation in the near future.

Oil Burning Equipment

The size and weight of boilers is governed mainly by the heat-release rate in the furnace and the size of the flame. The heat-release rate must be increased and the diameter and length of the flame reduced as much as possible. Much development of burners and air registers at the Admiralty Fuel Experimental Station, in conjunction with firms, has resulted in heat-release rates of half a million B.T.U. per cu ft in Y.100, which doubled previous experience in this country. To achieve these results oil pressures up to 900 lb/sq in and air pressures of 50 in. and 85 in. water gauge respectively were used in Y.100 and Y.E.A.D.I.

The next step has been to develop a wide range burner and here the control of the flame size, depending as it does on the position and output of the burner, has posed a host of difficult problems. The success of the spill system devised for the Y.E.A.D.I. prototype has been most encouraging and probably the greatest stumbling block to the introduction of automatic combustion control

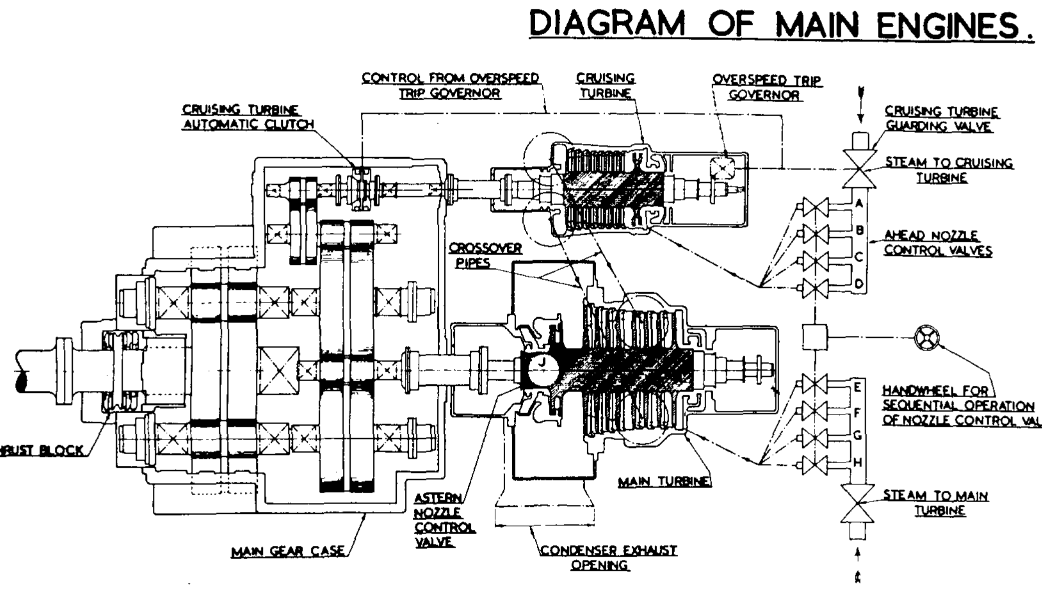

FIG. 8—DIAGRAM OF MAIN ENGINES WITH AUTOMATIC CRUISING TURBINE CLUTCH AND DOUBLE REDUCTION GEARING

has thus been overcome. It is believed that a ship could go from ' ready to get under way ' at anchor to full power without having to light up the extra burners.

Remote and Automatic Controls

As explained, we have a military requirement for remote and automatic controls, but I believe that, in the normal course of engineering development, we should have had to adopt them in any case. Increasing forcing rates, the eternal struggle to prevent smoke at the funnels, the search for efficiency and the need to reduce the number of skilled operators, all tend to persuade the engineer that automatic control is desirable. Add to these the pressing need to get men away from noisy and hot places which are difficult both to ventilate and protect from the various hazards of modern war, and it will be clear why we have had to adopt the modern power station practice of centralizing control somewhere remote from the actual machinery rooms.

Here again Y.E.A.D.I. has made extensive shore trials possible. We had, however, already embarked on some automatics to improve the lot of the operators and to assist in gaining good efficiency. These were chiefly concerned with maintaining a steady pressure in the auxiliary exhaust system to enable it to be used for distilling and supplying gland steam for the main turbines. The control of the gland steam itself has also been made automatic.

Other operations, such as control of lubricating oil and furnace fuel oil temperatures, have been tackled. The rapidity of change under naval conditions and the use of high pressure steam for fuel heating have posed some very difficult problems in this field, but gradually they are being overcome.

There is no doubt that this whole field must be given great attention if we are to move rapidly into a nuclear age. Even our next steps in the control of boost gas turbines will need careful development.

MAIN TURBINES

The need for economy of fuel at 20 per cent or less of full power means that the steam must be used efficiently in the turbines at these powers. Either extra stages must be incorporated for this purpose or every endeavour must be made to keep the blade speed high even at quite low powers. This involves very high blade speed at full power. We have tried to achieve this by the use of alloy steel rotors, but, where the ship's speed at which long range is required represents a very low proportion of full power, we have fitted cruising turbines. This was the case in the Y.100 machinery fitted in the A/S frigates. A great deal of calculation has been done on the relative merits of one, two, and three turbines with cruising turbines either permanently coupled or de-clutched at high powers. In the *Daring* Class we fitted a normal two-cylinder cross-compounded arrangement ; in Y.100 a single cylinder main turbine with a de-clutching cruising turbine ; in Y.E.A.D.I. we have returned to the destroyer arrangement. This is not vacillation in policy ; it is governed by the requirements for the ships concerned. Each case must be treated on its own merits.

At the same time, ease of operation is important and in Y.100 the turbine is controlled by the movement of one astern and one ahead valve wheel. This means that the operation of the cruising turbine clutch must be automatic. Such a clutch has been developed although it is still suffering from teething troubles, in spite of having passed its shore tests successfully. I think, however, that success is not far off and I am confident that the clutch will shortly fulfil its early promise. This experience does show however that, even by testing a plant ashore, it is not possible to reproduce all the conditions met afloat.

The single hand wheel operation was adopted originally from U.S.N. designs, and was first fitted in the *Daring* Class. It opened a series of nozzle control valves against springs by means of a rotating camshaft, thereby ensuring that the turbines were operated at their designed efficiencies. Our experience with hand operated nozzle control valves and with hand operated cruising turbine clutches was that, in war-time, an extra nozzle group, or possibly all groups, would be kept open to avoid delay in increasing speed. For the same reason the cruising turbine would usually be left out of engagement. Any suspicion that this was due to mere laziness could be dispelled by anyone who has experienced the joys of bomb-dodging in a convoy. Control by the single handwheel is therefore a source of much economy. It was repeated in Y.100 with the improvement that the cams were arranged to return the valves to the shut position as well as opening them, instead of relying on springs.

To those who experienced, during the war, the frustration of trying to find a rotor or a turbine blade from one firm that would fit a turbine made to the same drawings by another, the achievement of real interchangeability is worth a high price. This has demanded a great deal of effort from industry and from us, but already it has paid dividends. For example, we have been able to take a rotor from one firm and put it in a turbine casing made by another and run it without any adjustment.

Condensers

The reduction in the size of condensers has been the subject of much investigation. Circulating water speed has been increased from 7 to 10 ft per sec in the tubes and different shapes and sizes of inlets, outlets, and circulating water pumps have been investigated for each new design. In these, the water speed has been increased to 15 ft per second. The use of small tubes to produce a larger surface for a smaller volume has been looked into as has the possibility of making fabricated doors of non-ferrous sheet material. The only practical development, however, has been the reduction of condenser weight by designing for a lower vacuum at full power, which has more than offset the added boiler weight needed for the larger evaporation then required. This has to be re-assessed, however, for each new set of circumstances. The vacuum at low powers is comparatively unaffected so that endurance does not suffer.

Work is also proceeding on drop-wise condensation.

Auxiliary Machinery

The effort on auxiliary machinery has been threefold. The development of very small high-speed turbines, rotating at between 10,000 and 30,000 r.p.m., the development of pumps, both small and efficient and, since these generally have to be confined to low speeds, the development of gears to connect the two without loss of the hard-won efficiency in each. New designs of boiler blower have also been developed which, instead of using two or three stages, will give high heads in one stage with very much less noise than the multi-stage blowers.

In the field of small high-speed auxiliaries there is always a danger of increasing parasitic losses of some sort, due to windage or bearings for instance, to such an extent that efficiency gained in one place is lost in another. The relative merits of centrifugal, gear, scroll, and other positive displacement pumps have also been the source of much study for different applications. It is not possible to draw sweeping conclusions, but we have established a great number of limiting frontiers beyond which one type of pump ceases to be suitable and another comes into its own. The gearing is dealt with under another section of this Appendix, but the ability to apply either epicyclic gears, to maintain the same centres, or conventional helical gears, where the turbine and pump are better offset, offers some real advantages.

Attention has also been paid to making the fundamental design of auxiliaries such that the turbine or motor, pump, and gears can be detached separately and replaced or removed for refit. It has also been the object to make each auxiliary so that it can be broken down into the minimum number of components which can be removed individually through the hatch of the machinery space.

A policy of repair by replacement of components has been adopted and for this complete interchangeability of spare components has to be achieved. We hope that the days of leaving machining allowances on spare gear are over and that the time required for refitting machines will be radically reduced.

GEARING

To some extent the advantages of the turbine development derived from the adoption of double reduction gears have been offset by the complication and increased weight of the transmission system. Double reduction gears are essential and in the majority of cases in warships a dual tandem articulated design has to be used. It has been, therefore, of great importance to reduce the weight of the transmission system. This has been done by increasing the load carrying capacity which has required a high standard of gear cutting.

Admiralty-Vickers Gearing Research Association

In the period 1946–1948, several far-reaching decisions were made which have led to the achievement of an outstanding advance in the field of naval marine gearing over the past ten years. These were :—

(*a*) The foundation of the Admiralty-Vickers Gearing Research Association to deal with the development of improved accuracy and investigate alternative methods of manufacture.

(*b*) The purchase from Messrs. Maag of Switzerland of gear-grinding machines to grind pinions and wheels up to 11 ft in diameter.

(*c*) The purchase from Messrs. Maag of a set of hardened and ground main gearing for H.M.S. *Diana.*

The various bodies co-operating in Admiralty-Vickers Gearing Research Association ; machine manufacturers, gear cutting firms and Government

Departments ; have dealt with the research as part of their own research work. Pametrada, too, has made a valuable contribution in testing. The Admiralty has contributed to the cost, but the firms have also paid a large share. The development has been a classic example of how efficiently and economically research can be done when competitors pool their resources.

This pooling of information in A.V.G.R.A. and the combined efforts of the machine manufacturers, the gear manufacturers, and the Admiralty as customers, have resulted in gear hobbing machines manufactured in this country reaching a standard that is as high as anywhere in the world. An incidental part of this work was the preparation of a *British Standard Specification* 1948–1954, for gear hobbing machines, which is now accepted on the Continent as a standard. There is a growing demand for British hobbing machines on the Continent and they are also being sold to the United States.

Improvement in Gears

The improvement of standards and the use of harder materials has permitted an increase in loading of up to two and a half times that previously used. In spite of the increase of running speed and in the numbers of gears, the gearing is appreciably quieter than the earlier single-reduction type. In fact, when questioned about noise, the engineer officer of a destroyer stated recently that the noisiest thing in the engine room at full power was the engine-room ventilation fan !

I believe that the future lies in the field of hardened and ground gears. In this type of gear we are in a position to design with confidence for loads four and a half times those carried in earlier designs with conventional materials. The early decisions, therefore, have brought considerable return, and have led to major steps forward in the development of marine gears. The advantages have not been limited to the naval field for the merchant fleet has also benefited. The marine gear cutting industry and machine manufacturer deserve great credit for the way in which this rapid progress has been achieved. The grinding process is another step in gearing development. At present it is generally accepted as primarily of interest to the Navy, but I feel that it is essential that firms should not be left behind if they are to retain their position as leaders of the world's gear cutting industry.

Future Development

We are now on the threshold of a new stage in the development of gear hobbing machines. Two manufacturers have designed and made machines for the production of master wheels. These should be a major asset to the gear hobbing machine industry in this country because the master wheel is the key factor in machine performance.

The development of an entirely new type of grinding machine is proceeding and it is hoped that this will give an appreciably higher rate of production, with a degree of accuracy corresponding to that of the machines at present available.

Research is proceeding on the major problems associated with the production of case-hardened and ground gears. The distortion of large wheels is the greatest difficulty, but results with induction hardening as an alternative have been very encouraging. Research is also proceeding on the many other facets of the gear cutting technique.

In the new double-reduction gears, the number of bearings and the necessity of carrying spares on board present a difficult problem. Our object is to get standard bearings of the thin-wall type which can be replaced without adjustment. Jig boring is one possible solution and study of other methods of achieving this is proceeding.

Lubrication

Another feature that has been considered is lubrication. Primarily from the point of view of test gears, research was started to select extreme pressure oils which would give greater load carrying capacity than the normal oil. Experience shows that with more highly loaded gears it may be essential to use these oils. The design loadings envisaged are within the capacity of normal oils, but under the transient condition of manœuvring, high torques are experienced which can break down the oil film momentarily and cause scuffing. Gearing appears particularly prone to this during the initial sea trials when the gears have had no opportunity to run in. A panel of the Admiralty Fuel and Lubricants Advisory Committee, on which both the leading oil companies and Admiralty-Vickers Gearing Research Association are represented, has drawn up a specification for this new oil and it is hoped that we shall soon to able to obtain it from all our main suppliers. One complication which arises in Service requirements is that the various manufacturers' oils, and hence also additives, should be compatible.

The need to reduce bearing losses has led us to increase bearing loads to 500 lb/sq in on the projected area, and to reduce the length/diameter ratio of bearings as far as possible. Consideration is also being given to the use of less viscous oil.

Reversing Gears

The introduction of the gas turbine as a prime mover, either by itself or combined with steam or Diesel machinery has added another requirement to the transmission system, namely that of reversing. There are two possible approaches : controllable pitch propellers or the provision of a reversing gear in the transmission system. In the transmission system a design has been prepared that uses hydraulic coupling for the reversing of the drive and absorbing the inertia of the system. The gear will go to sea as an emergency reversing unit in gas turbine boost machinery. The steam turbine part of this machinery will carry normal astern elements, but this gear will not enable the ships to be manœuvred in the event of steam failure and get under way in an emergency without the delay entailed in raising steam. The disadvantages of this system are the added complication to the gearing and the large quantities of lubricating oil required to absorb the heat.

GAS TURBINES

In addition to the general development of propulsion gas turbines, a programme of gas turbo generators from 100–1,000 kW has been carried out. We have also evaluated and assisted in the development of various small gas turbines for emergency fire pumps and boat propulsion. These have been described in a paper by Commander Trewby to the Institute of Marine Engineers in 1954 (*Inst. Mar.E.*, Vol. 66, and *Journal*, Vol. 7, Nos. 2 and 3). Here, however, we have deliberately relied on commercial products and, although this policy has been fully justified by events, the rate of development is largely outside our control.

The great majority of our development work and testing has been carried out by firms whose resources and enthusiastic co-operation have been the backbone of the whole programme. Vitally important contributions have been made also by the Admiralty Engineering Laboratory, whose experience in the development of smaller units is now considerable, and by the National Gas Turbine Establishment, within which we have a Naval Wing including a test house with a capacity for proving machines up to 10,000 s.h.p. under ideal conditions. Here it is appropriate for me to acknowledge the debt we owe to the Ministry of

Supply. We have conceived it as not only being convenient, but our duty, to take advantage of their immense effort in the gas turbine field by using the resulting techniques and experience in the various firms wherever possible. The signs of this are visible to the discerning eye and, with the continued use of simple light-weight designs, 'cross breeding' from the aero-field may be expected to continue. In addition we receive continuous and direct help in the form of technical vetting and advice from the National Gas Turbine Establishment itself.

At this time, when the early introduction of gas turbines into the Fleet for boost and auxiliary purposes is being planned and with further possibilities foreseen, it is salutary to mention some disadvantages of gas turbines in naval applications, together with our thoughts on how these may be met :—

(*a*) *Fuel.* Despite extensive research, to which we have contributed directly by our own experiments and indirectly by the provision of residual reference fuels, no really satisfactory system for burning residual fuel in naval gas turbines has yet been developed. Methods are now available to enable industrial and merchant service plants to burn high-ash fuels at conservative inlet temperatures (say 650 degrees C. or below) ; but these involve bulky equipment unsuitable for warships, and flexibility of operation is limited. In addition, it is not possible to realize fully the advantages offered by the gas turbine unless higher temperatures are used. It has been our policy that naval gas turbine development should not be retarded because of inability to use residual fuels continously, although it has always been hoped that the problem would be solved before the time came to put gas turbines into main propulsion service. If the difficulty cannot be overcome, the advantages offered will have to be balanced against the expense and other problems of using some kind of distillate fuel only. The decision may well be influenced by considerations of the ship ballasting problem.

(*b*) *Air Rate.* The ducting and large deck openings required to pass the high specific mass flow of existing gas turbines are a considerable embarrassment. We see an eventual solution to this problem in increasing specific output by raising the maximum cycle temperature. Some form of blade cooling will be required, and rapid developments are taking place in the aero-field which we can adapt to our use. As a longer term development, we have sponsored the research work at Pametrada on liquid-cooling methods. It is unfortunate that the need to use higher temperatures conflicts with the desire to use cheap fuel.

(*c*) *Reversing.* The high-power reversing problems, inherent in warship propulsion by gas turbines alone, remain within the transmission field, since developments do not indicate that it is practicable to provide an astern turbine or other means of reversing within the prime mover itself.

It may be noted that I have made no mention of closed-cycle gas turbine plant. We have watched developments in this field closely, but nothing has occurred to change our original view that this system is not suitable for naval use, despite its ability to burn low-grade fuel. We do not forget, however, that a special form of closed-cycle gas turbine may eventually prove an attractive way to use nuclear power for warship propulsion.

OPPOSED PISTON GAS GENERATORS

The advent of this type of cycle has been carefully watched since before the war, when we first saw a gas generator under development in France. We also tested one at the Admiralty Engineering Laboratory. The success of this machine has depended, however, upon the development of production technique to give long life. This, we believe, has been achieved recently and studies are being carried out to see whether there is an application in which this type of plant can replace our existing or planned machinery with advantage.

INTERNAL COMBUSTION ENGINES

Experience in World War II with internal combustion engines showed beyond doubt that a new approach was necessary to their provision for inter-Service use. At the end of the war, some 300 different types of engines were in Admiralty service and the refitting and provision of spare parts presented such problems that the Admiralty resolved that it should not happen again. Experience in the other Services was similar, and the Admiralty proposed in 1945 that an inter-Service committee should be set up to consider the requirements for internal combustion engines for all general purposes between the limits of 1 h.p. and 2,000 h.p. The findings and recommendations of this committee were published in May, 1947. The long-term aim was to be the production of a standardized range of engines under Admiralty or Ministry of Supply supervision and the short-term aim the selection and modification of commercial engines expanded into ranges for inter-Service use.

The short-term aim has been implemented by the formation of a permanent inter-Service committee and the Admiralty or Ministry of Supply accept ' parenthood ' for the engines with which they are most concerned. As far as the long-term aim is concerned, the Admiralty has gone further than the Standardization Committee had believed possible, because in covering the top range of powers, 2,000–1,000 h.p., the Admiralty has designed and developed a range of engines which are being built in large numbers to suit a variety of ship requirements.

The Admiralty Standard Range 1 engine, as it is called, is designed to be built with varying numbers of cylinders in ' V ' or in-line formation. For the frigate propulsion sets, the engines are ' V ' 16-cylinder turbo-supercharged and the generator engines are 6- or 8-cylinder in-line engines. For other applications, 12-cylinder models are available with different methods of supercharging. In all these models complete interchangeability of spare parts has been ensured between the engine builders by using close tolerances in design and adequate jigs.

The 16-cylinder ' V ' turbo-supercharged engine is rated at 2,200 h.p. on a twenty-four hour tropical rating with a b.m.e.p. of 139 lb/sq in. Further development of this engine up to 150 per cent of its present power is quite practicable.

In the range of 1,000–500 h.p., the long-term aim is being met by the commercial development of a series of engines to suit Admiralty requirements. Furthermore, the Deltic engine, with its exceptionally low power/weight ratio, was developed for the Admiralty for the specific task of propelling fast patrol boats. We believe that it is capable of further development for higher horse powers. Its construction follows aircraft practice and it cannot be refitted in place. It must be replaced, therefore, by another engine when due for periodical overhaul, a feature that makes it particularly suitable for use where quick turn-round is required. The ability to refit the engine in a workshop instead of the usually cramped conditions on board may be set against the disadvantage of having to carry more spare engines than would be the case with an orthodox design.

For other applications covering horse powers from 500 downwards, the Admiralty has selected a restricted number of commercial engines which are on the inter-Service list. Before selection all engines undergo a 2,000-hour ' type ' test at the Admiralty Engineering Laboratory.

STEAM PIPES AND FITTINGS

Experience in the Second World War and in the Korean War showed that an enormous amount of work was caused by pipe joints and valves. These have been the subject of much study and we now use selected types of valves made by specialist firms. Steam pipes become of increasing importance. The reduction in the size of the main components, accompanied as it is by an increase of pressure and temperature, makes it increasingly difficult to accommodate the steam and exhaust systems in the correspondingly smaller machinery spaces and provide them with adequate flexibility. The positioning of flanges and hangers becomes increasingly complicated and the whole problem is aggravated by every rise in temperature. We may well reach a stage very soon where the steam and exhaust pipe ranges become the governing factor in the size of machinery space. It may be of interest that we have put up the steam speed in the main range of the A/S frigates from our usual 100–150 ft per sec. to 300 ft per sec. to keep pipe sizes down. The only trouble to which this has given rise so far has been the breakage of a thermometer pocket at the turbine inlet due to vibration. The concept of boost gas turbines helps us out of some of these problems, but welding instead of flanges helps too, particularly as this allows the use of tube turns.

DISTILLING MACHINERY

It is probably no exaggeration to say that distilling machinery caused engineer officers more anxiety during the war than any other single piece of equipment. Feed water expenditure rose because sufficient time could not be spared for maintenance. Furthermore, as the capacity of distilling machinery was based on trial output when new, service capacity was only about 60 per cent of the figure given in the specifications and the fear of breakdown was ever present. We have tried, therefore, to fit adequate capacity to keep up with the increasing demand for water for the ship's company, which has risen from something of the order of 15 gallon/man/day to about 25, using lowly rated evaporators working normally on closed exhaust and giving the specified output after hundreds of hours' operation. Experiments are proceeding with different sorts of treatment, but I believe the basic cure for evaporation trouble is to keep the difference of temperature between brine and heating steam low so that the tendency for scale formation is reduced fundamentally. There is much also to be said for flexing heating surfaces which really will break off scale when blowing down.