British Naval Gas Turbines

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During the past ten years, six different designs of naval gas turbine have been developed and tested under Admiralty contract and a further two designs have been brought direct from manufacturers for evaluation and testing.

Taking each of these eight gas turbine projects in turn, the paper gives a brief history of development and manufacture, describes the special features of the design, and gives details of the operating experience to date, both ashore and afloat. The lessons learned from this operating experience are discussed.

The author concludes that the greatest single advantage that the gas turbine can offer for warship applications is its ability to pack more power in less weight and space than any other prime mover. To achieve this, naval gas turbines must be of the open cycle type and constructed on lightweight lines.

The various factors likely to influence the use of gas turbines for naval applications are mentioned and the future rôle of the gas turbine in the Royal Navy is discussed.

INTRODUCTION

It was not until the pioneer work of Sir Frank Whittle had produced the first British aircraft jet engine in 1941 that serious consideration was given to the development of naval gas turbines. At this time the Royal Aircraft Establishment, Farnborough, were also actively engaged in gas turbine development and their first design, manufactured by Metropolitan Vickers and Co., Ltd., ran in December 1941. The idea of using a naval propulsion unit based on the aircraft type of gas turbine was first discussed between Metropolitan Vickers and members of the Engineer-in-Chief's Department of the Admiralty in 1942 and a contract for the construction of three complete Gatric engines was placed in August 1943.

In the ten years since this contract was placed, six separate designs have been developed and tested under Admiralty contract and a further two designs have been bought direct from manufacturers for evaluation and testing. Several of these gas turbines represent considerable advances in naval engineering and merit individual papers to themselves. The present paper aims only at presenting a general picture of the current state of British naval gas turbine development, with a review of the operating experience to date and the lessons learned. In the conclusions, the factors affecting the future rôle of this new prime mover in the Royal Navy are discussed.

The paper is divided into three main sections: —

I—Propulsion machinery for warships.
II—Propulsion machinery for landing craft and ships' boats.
III—Auxiliary machinery.

Appendix A gives design and constructional details of the naval gas turbines described, while the cycle diagrams with operating pressures and temperatures are shown in Appendix B.

I.—PROPULSION MACHINERY FOR WARSHIPS

REQUIREMENTS AND OPERATING CONDITIONS FOR NAVAL PROPULSION MACHINERY

In order to obtain a clear appreciation of the background from which naval gas turbines developed, it is necessary to understand the requirements and operating conditions for naval warship propulsion machinery. The requirements vary with the duties of each particular type of vessel and, as new weapons and tactics evolve, the relative importance of the factors alter. But, with very few exceptions, the propulsion machinery for all warships must be designed to meet the following specification[1, 2, 20]: —

(1) Minimum weight (including fuel) to meet the specified endurance.
(2) Minimum space.
(3) Good thermal efficiency over a wide range of power, with particular emphasis on the cruising power.
(4) Maximum reliability.
(5) Ease of maintenance: in particular, ease of component replacement.
(6) Maximum manœuvrability, including rapid starting and reversing.
(7) Ease of control and simplicity of operation.
(8) Low noise level and ability to withstand shock and other battle damage.
(9) Economy of strategic materials and production effort.

Many of these requirements conflict and any design must necessarily be a compromise.

Operating Conditions for Naval Propulsion Machinery

Records of the operation of naval warship propulsion machinery at varying powers show that, except for certain special types of vessels, such as high speed coastal craft, the major proportion of operating time is spent at a low percentage of total installed power. This cruising power at which the majority of time is spent lies between 5 per cent and 30 per cent of total installed power in most warships and it is essential that the endurance (and hence the efficiency of machinery) should be as high as possible in this range. Perhaps the extreme case is that of a destroyer where (according to U.S. naval sources) 70 per cent of the total installed power is used for only 1 per cent of the total steaming life[1]. Since warships very seldom use full speed, the life of naval machinery at high powers can be extremely short judged by commercial or merchant marine standards and this fact is of great significance when considering the application of the gas turbine to warship propulsion.

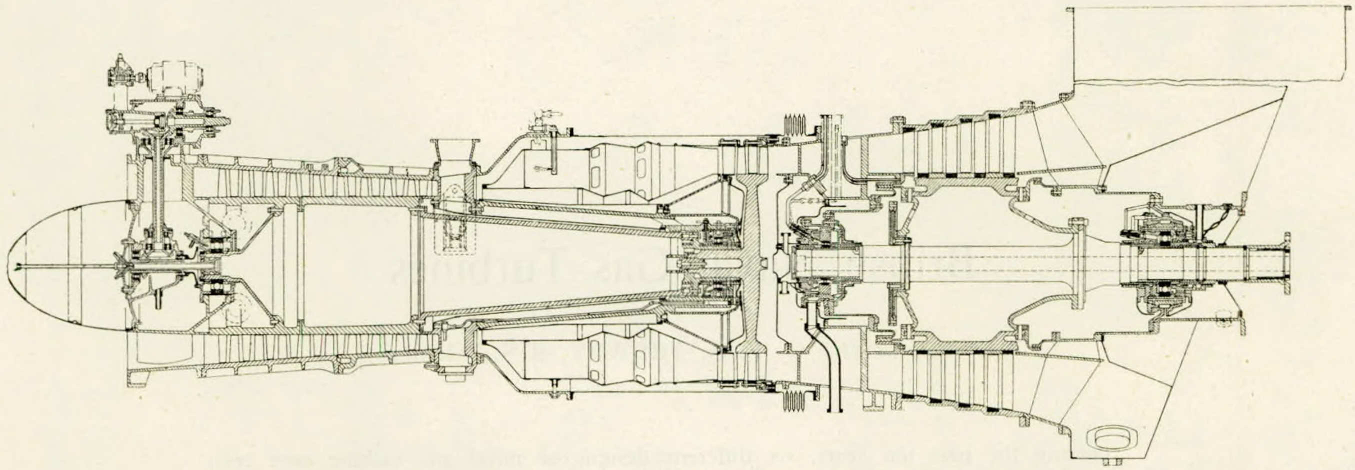

FIG. 1—*Sectional arrangement of Gatric gas turbine*

Naval vessels must also be able to get underway in the shortest possible time, without previous warning, and proceed to sea at high speed, often after violent and unassisted manœuvring; then, alternatively, cruise at fractional powers for long periods and at full power for short periods. Sudden manœuvring may occur at any time and it is desirable that full power should be instantly available.

One of the most obvious naval gas turbine applications is for the propulsion of high speed coastal craft, where the characteristics of this new prime mover can be used directly to obtain higher speeds. In many ways this is an ideal application and, being the most straightforward (as far as propulsion machinery is concerned), the progress in this field has been more rapid than elsewhere. Two different designs of simple gas turbine, the Gatric and G2, have already been operated at sea in naval coastal craft.

GATRIC GAS TURBINE[1, 2, 3, 4, 5, 6]

(See Appendix A, column 1; Appendix B, diagram 1)

Introduction

A contract for three simple cycle gas turbines, based on the F2 aircraft jet engine but with an output turbine fitted in the tail pipe, was placed with Metropolitan Vickers and Co., Ltd., in August 1943. The main object of the contract was to gain experience with the only type of gas turbine then available in Britain, a short life aircraft unit. The project was given the code word "Gatric" and a sectional arrangement of the engine is shown in Fig. 1.

The F2 ran on kerosene, and as this fuel was not considered suitable for naval applications, the first part of the work consisted in developing the combustion system of the engine to burn Diesel oil. It was found that very few modifications were necessary. Carbon formation was experienced at first, but with minor alterations to the fuel jets and the size and position of the holes for the admission of primary and secondary air, together with a slight increase in diameter of the annular combustion chamber, satisfactory combustion was achieved.

Bench tests on the first complete engine began in April 1946, and some alteration to the capacity of the compressor turbine was found necessary before the designed performance could be achieved. This alteration brought the turbine working line too close to the compressor surge line* at low powers and blow off valves at the fifth compressor stage were necessary to facilitate starting. The specific fuel consumption of the Gatric at various powers obtained during shore testing is shown in Fig. 2, together with the performance curves of other naval propulsion gas turbines.

Installation of the first engine in M.G.B.2009 (later renumbered 5559) was completed in July 1947, and in August of that year M.G.B.2009 made history by being the first vessel in the world to be propelled at sea by a gas turbine (Fig. 3) just fifty years after the trials of the *Turbinia*. The main objectives of this development were to gain experience of installing, operating and maintaining a gas turbine at sea. Details of the arrangement in M.G.B.2009, in which Gatric replaced the centre of three Packard petrol engines, are shown in Fig. 4, and Fig. 5 (Plate 1), and the arrangement of air inlet ducting to the compressor and the air circulation past the gas turbine are clearly visible.

During the early sea trials, trouble was experienced with bad temperature distribution at outlet from the combustion chamber. This resulted in distortion of the combustion chamber and overheating of the first stage power turbine blades. By this time Metropolitan Vickers had successfully developed a film cooled chamber and when this new design was incorporated in the engine of M.G.B.2009, no further trouble was

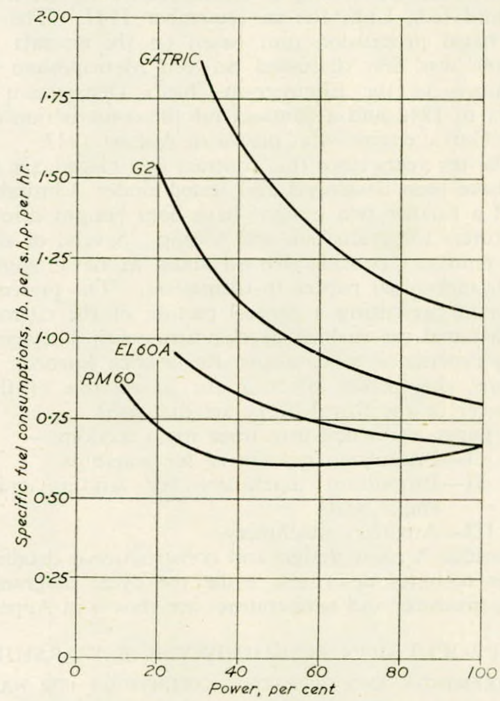

FIG. 2—*Specific fuel consumption of propulsion gas turbines. Actual test results using Admiralty Diesel fuel (gas oil), calorific value 18,500 B.Th.U. per lb. (10,300 C.H.U. per lb.)*

* Compressor surge: An aerodynamic instability which occurs in compressors and takes the form of a periodic reversal of flow.

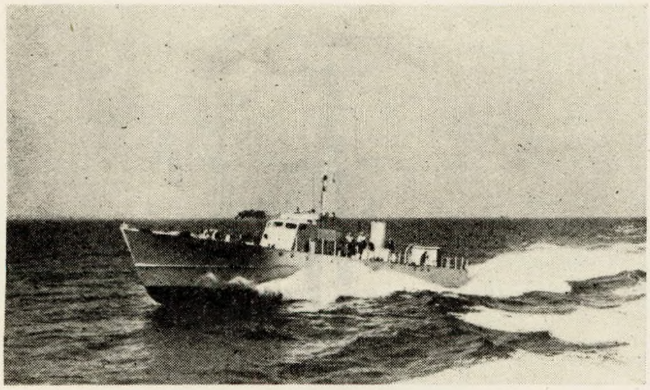

FIG. 3—*M.G.B.2009 in the Solent, August 1947*
By courtesy of the "Sunday Graphic"

experienced. It did not, however, completely eliminate stratification and some 50 deg. C. variation in the readings on the four thermocouples fitted at the power turbine inlet remained.

Lessons Learned from Gatric Trials

Sea trials of the Gatric gas turbines in M.G.B.2009 continued over a period of four years and were remarkably trouble-free. At the end of this time the following points were established:—

(*a*) *General*. The operation of a simple gas turbine at sea was a practical proposition which presented no insuperable difficulties and the general characteristics of this new prime mover were particularly well suited to the propulsion of high speed coastal craft.

(*b*) *Compressor fouling*. The deterioration in gas turbine performance caused by compressor fouling is well known and it was anticipated that the salt laden atmosphere might affect the performance of naval gas turbines, particularly in a comparatively small high speed vessel such as M.G.B.2009. The air intake arrangements shown in Fig. 4 were therefore designed to prevent salt spray entering the compressor, air being drawn from a sheltered position abaft the bridge and passed through a settling tank before reaching the compressor inlet. This arrangement was not entirely effective, however, and after 120 hours' running, the compressor efficiency had fallen to 94 per cent and the engine output to 86 per cent of their design values. Examination showed that the deterioration was caused by salt deposit on the compressor blades. To overcome this fouling problem a waterspray ring containing five equally spaced nozzles was fitted in the compressor inlet. A ten gallon injection of distilled water with the gas turbine running increased compressor efficiency and output to 98 per cent and 97 per cent of design and a second injection restored them to their design values. A routine was then established in which ten gallons of water were injected at the rate of about two gallons per minute every three to twelve hours, depending upon the drop in engine performance. This simple procedure was completely successful in combating the effects of compressor fouling both from salt spray and fog. Similar injection equipment has been fitted to the later G2 and RM60 gas turbines.

(*c*) *Bearings*. Two bearing failures were experienced near the completion of the sea trials of the Gatric and it began to appear doubtful if ball and roller bearings were capable of withstanding the high speeds and temperatures associated with gas turbines for long periods, particularly under seagoing conditions. In neither case was the cause of failure established.

(*d*) *Noise levels*. Before any silencing action was taken, a noise survey was carried out and it was found that the greatest noise level in the engine room, 117 decibels (db), originated from the gas turbine gearbox. On deck, just aft of the bridge, the level was also 117 db,

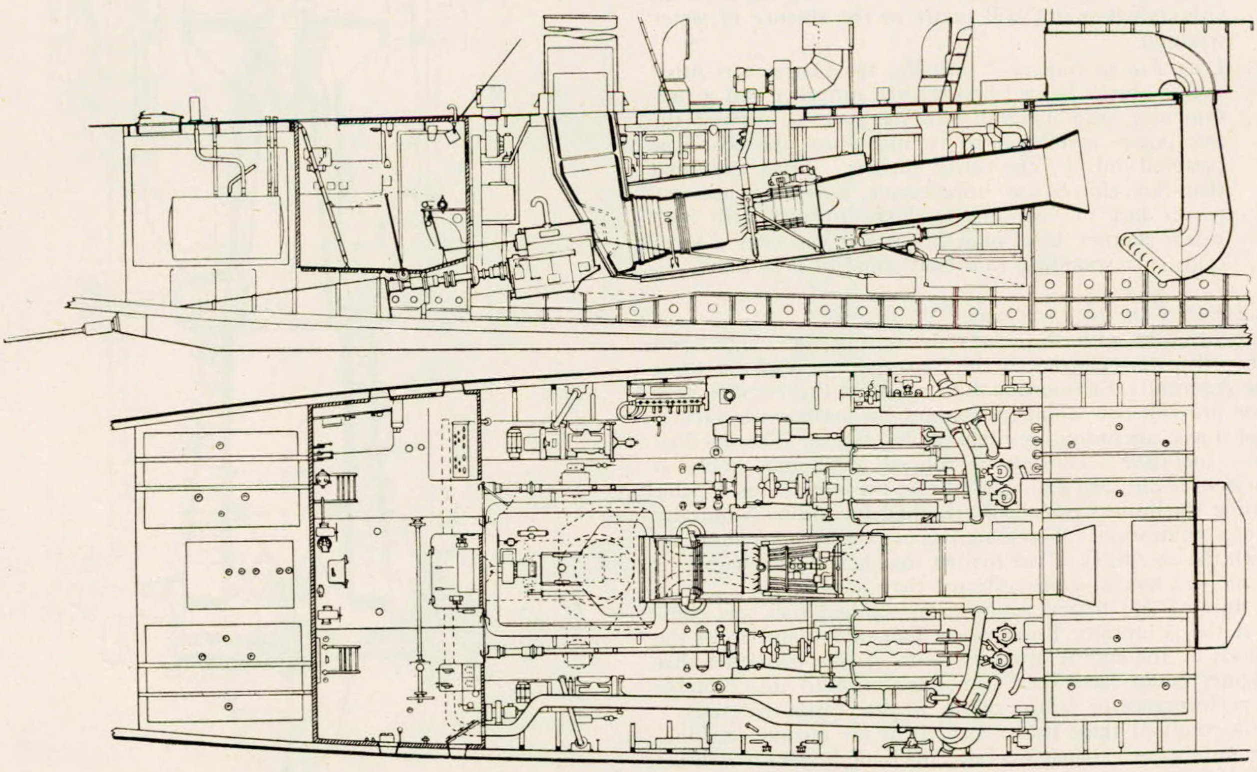

FIG. 4—*Elevation and plan showing details of Gatric installation in M.G.B.2009*

the major source being traced to the compressor air intake; on the bridge itself noise from the funnel predominated, the total level being 102 db.

The most serious component of noise was considered to be the high frequency note emanating from the axial compressor and transmitted through the air intake trunking and settling chamber. By lining the settling chamber with "Fibreglass" and fitting "splitters" of the same materials in the air intake, a reduction in the compressor blade note of 39 db was achieved. This reduction made possible a more accurate evaluation of the exhaust noise and it was found that the compressor blade note was present there also. Silencing equipment, including a "torpedo type" splitter, was fitted in the funnel and was most effective in reducing funnel noise.

(*e*) *Compartment cooling and heat insulation.* Owing to the proximity of two Packard petrol engines, great care was necessary in the design of the Gatric's heat insulation and it was decided to enclose the entire engine in a ventilated casing (Fig. 4). The gas turbine itself was lagged with 2-in. asbestos mattresses and a light metal casing was fitted over this lagging, but not in contact with it. Air was drawn between the casing and lagging by an engine exhaust operated ejector in the funnel. This method of cooling the gas turbine and the compartment by means of airflow insulation was extremely effective and the principle has been used in later installations. (A 12½-in. fan was originally fitted to supply air to the engine casing but the exhaust ejector in the funnel proved so efficient that the fan was removed.)

(*f*) *Compressor blade material.* The original Gatric compressor blades were of RR56 anodized by the chromic acid process. Examination after the first fifty hours' running revealed that the blades had suffered local intercrystalline corrosion, the average depth being 0·005 to 0·01 inch. The blade material was changed to RR57 and no further corrosion was experienced, although it might still occur in the absence of water washing.

(*g*) *Loss due to trailing.* Initially, the Gatric was fitted with a clutch located between the propeller and reduction gear (and integral with the gear) to prevent the free power turbine from trailing when the boat was powered only by the petrol engines. Trials indicated that this clutch was unnecessary, however, since the power lost in "windmilling" the turbine with both petrol engines developing full power was only 1·3 per cent, corresponding to a boat speed of 0·18 knots.

Residual Fuel Tests on the Gatric[7, 8]

Concurrently with the sea trials, testing was carried out with the other two Gatrics at the Metropolitan Vickers works and the Admiralty Engineering Laboratory. The engines were used for proving new components and for trials with various types of fuels, including residual boiler fuels. The residual fuel tests included a continuous run of forty-eight hours at maximum cruising load and showed that the engine was capable of running for limited periods on residual fuel oil to Admiralty standard specification. The materials of construction stood up well with the exception of the fuel jet shields and, on the whole, the engine was less adversely affected than anticipated.

A total of 200 hours' running on residual fuel was completed at the Admiralty Engineering Laboratory and from the appearance of the engine after the tests, it was predicted that 1,000 hours could have been completed without unacceptable loss of performance or failure of the turbine blade materials.

As a result of these trials, equipment for burning residual fuel, including an exhaust operated fuel oil heater, was fitted in M.G.B.2009, but only one short run could be completed before the hull was condemned and the vessel scrapped.

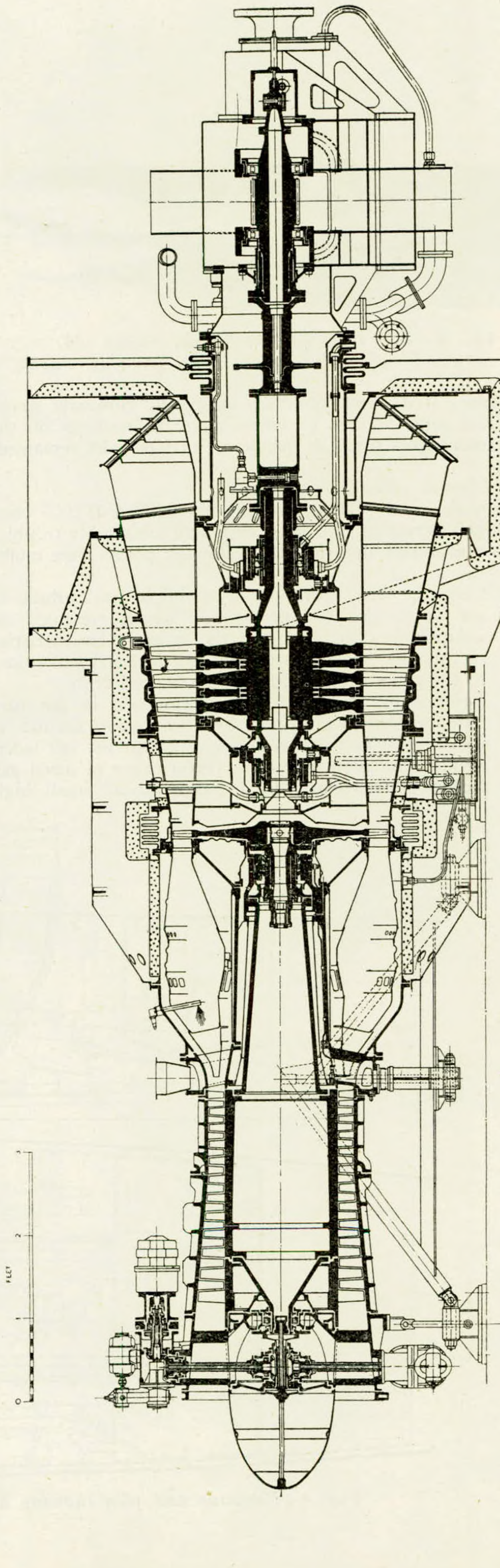

FIG. 6—*Sectional arrangement of G2 gas turbine*

The principal lessons learned from the residual fuel trials with Gatric engines were:—

(*a*) that a high degree of filtration of the fuel was necessary.
(*b*) that it is preferable to pump the oil cold if wear of the pumps is to be kept to a minimum.
(*c*) that exhaust heating of the fuel is a practical proposition.
(*d*) that a simple naval gas turbine operating with a maximum gas temperature of 750 deg. C. (1,382 deg. F.) can burn a residual fuel oil for limited periods.

Gatric Life

It should be noted that although the Gatric was designed for a life of only 300 hours, two of the engines have now operated for nearly 600 hours and this brings home the important point that when the "life" of a gas turbine has expired, it means only that certain components require renewal. It does not involve scrapping the whole engine, as was originally supposed in some quarters.

G2 GAS TURBINE[9, 10]

(See Appendix A, column 2; Appendix B, diagram 2)

Introduction

The Gatric project was originally planned as a convenient floating test bed for the only kind of gas turbine then readily available—a short-life converted aircraft unit. But it soon became apparent that this type of engine had many advantages for the propulsion of high speed craft and consideration was given to further installations on these lines.

In December 1948, a contract was placed with Metropolitan Vickers and Co., Ltd., for the design and manufacture of four larger gas turbines based on the Beryl aircraft jet engine, but with the addition of a separate power turbine driving the output shaft through single helical reduction gearing. This design, known as the G2, was ordered for installation in two fast patrol boats, *Bold Pioneer* and *Bold Pathfinder*. The gas turbines were intended for use at high speed only, Diesel engines being fitted for manœuvring and cruising. Each engine drives a separate shaft, the two gas turbines being on the wing shafts and the Diesel engines on the centre shafts. Fig. 6 shows a sectional arrangement of the G2 gas turbine, and a photograph of the engine in the maker's works is shown in Fig. 7 (Plate 1).

Shore Testing

Manufacture of the first G2 was completed in 1951, but initial testing revealed that the power turbine was not correctly matched with the gas generator, the maximum power available at the designed gas temperature being 3,800 h.p. Since manufacture of modified power turbine nozzles would have involved considerable delay, it was decided to install the first two G2's at the reduced rating in order to obtain early sea experience.

The third engine, with modifications to improve matching, went on test at the firm's works in December 1951, and the specific fuel consumption obtained over the whole power range is given in Fig. 2. It will be seen from this figure and Appendix A that the G2 gas turbine has a much improved fuel consumption compared with the Gatric, a lower specific weight and a longer life. This great improvement in performance achieved over a period of five years is most encouraging and there is every indication that the trend will be continued in future designs. During shop trials, noise measurements were taken and it was found that the noise level beside the engine was 102 decibels under idling conditions, rising to 114 decibels at full power.

Installation Arrangements in Bold *Boats*

A diagram illustrating the installation arrangements of the G2 gas turbines in the *Bold* boats is shown in Fig. 8, while Fig. 9 is a photograph showing *Bold Pioneer* at speed. The air intake and airflow cooling arrangements are similar to those employed with Gatric in M.G.B.2009, the ejector effect of the exhaust gases being used to draw air into the engine compartment and over the hot parts of the gas turbine, thereby providing an airflow insulation system considerably lighter than conventional lagging. No clutch is provided, the gas turbines being connected directly to the propeller shafts through a reduction gear of 4·73 to 1. Starting is by means of a small swashplate air motor which can be seen on the top left of the compressor in Fig. 7 (Plate 1). The Gatric had been started very successfully by an electric motor, but as an air supply

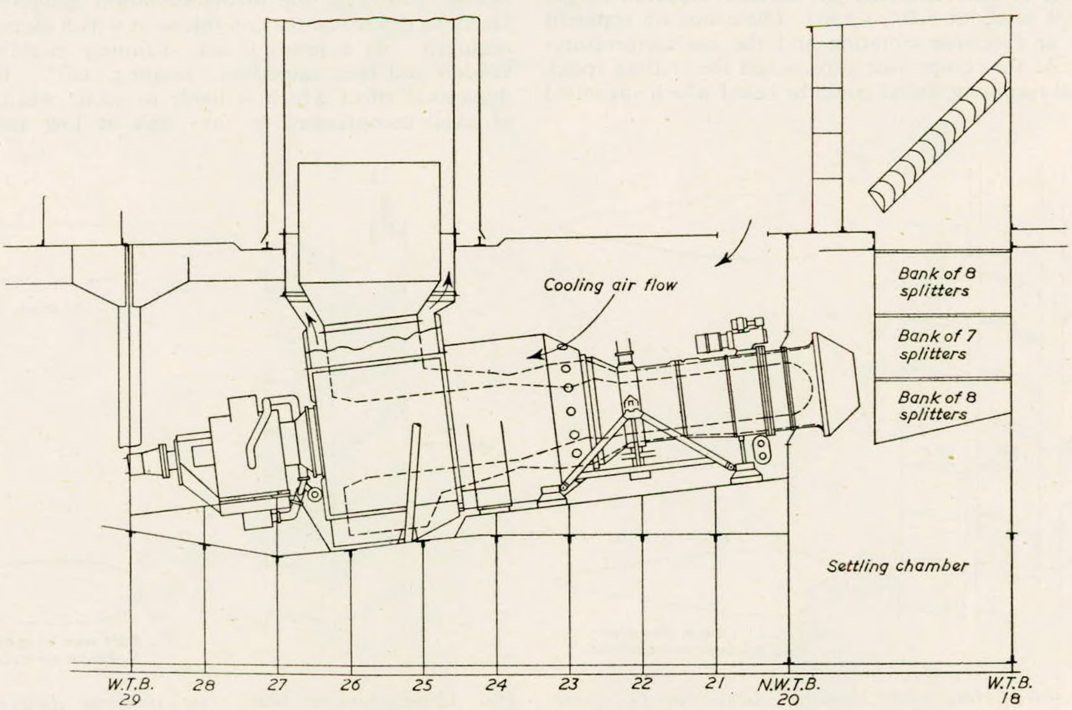

FIG. 8—*Diagram showing installation of G2 gas turbine in* Bold *boats*

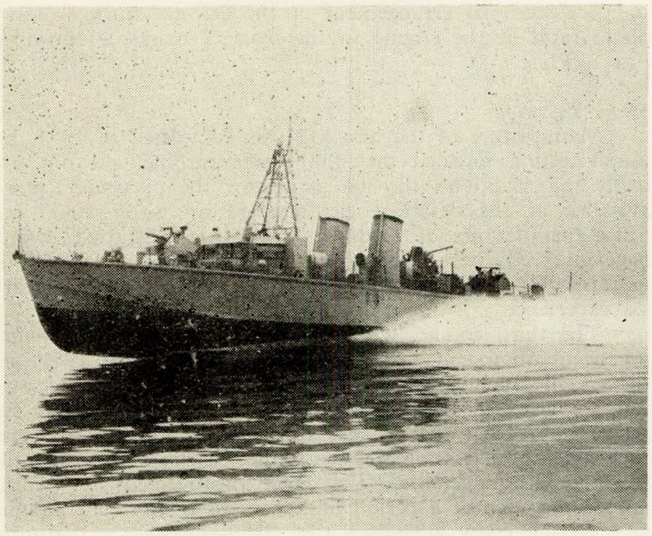

FIG. 9—*H.M.S.* Bold Pioneer *at speed*
By courtesy of "The Times"

was necessary in the *Bold* boats for starting the Diesel engines, it was decided to adopt this method for the gas turbines also.

Trials at Sea

Sea trials of the G2 gas turbines in the *Bold* boats began towards the end of 1951 and many more problems have been encountered than in the original Gatric installation.

The first was inadequate gearbox scavenge pump capacity. Originally two 35 gal. per min. scavenge pumps and a single 35 gal. per min. pressure pump were fitted, but it was found that the capacity of the two scavenge pumps operating in parallel from a single suction pump was not adequate and flooding of the gearbox resulted. The trouble was overcome by fitting a single 45 gal. per min. scavenge pump and restricting the capacity of the pressure pump to 25 gal. per min.

After some fifty hours' operation in *Bold Pathfinder,* repeated stalling of the starboard gas turbine occurred at gas generator speeds of about 5,500 r.p.m. There was no apparent loss of power or excessive vibration and the gas temperatures were normal. As the compressor approached the stalling speed, a slight internal rumbling sound could be heard which suggested the onset of compressor surge. On opening up the compressor it was found that six blades from the last moving row were broken near the root and all bore the characteristics of fatigue failure. Some of the blades had passed through the combustion chamber and had satisfactorily aluminized the compressor turbine without any apparent damage!

It was known that the natural frequency of the last compressor blade row coincided with a possible excitation from the ten outlet struts at 5,500 r.p.m., but it was thought that the two rows of fixed guide vanes would prevent excitation from this source. Closer examination of the design, however, indicated that the proximity of the struts to the last row of guide vanes and the aerodynamic shape of the passages between the unstaggered struts would aggravate rather than dissipate an excitation from the outlet struts. Fig. 10, showing an expanded plan view of the last rows of compressor blading and the outlet struts as originally fitted, illustrates this point. The defect was cured by removing the second row of outlet guide vanes and modifying the first row to suit, as shown in Fig. 11. The space left between the guide vanes and the outlet struts was then sufficient to dissipate any upstream disturbances and no further trouble has been experienced from this source.

As an additional precaution, automatic air blow-off valves have been fitted which are open on starting and close at a gas generator speed of 6,500 r.p.m. These minimize the risk of surging which would greatly increase any excitations set up from the outlet struts.

No sooner had this defect been successfully overcome than another vibration problem arose, first manifesting itself in the starboard gas turbine of *Bold Pioneer.* A first row compressor moving blade failed, causing considerable consequential damage. This particular blade had been noted as slightly damaged when the compressor was opened up after the acceptance trial, presumably by the passage of some foreign body through the compressor. This fact tended to obscure the real cause of failure but was a timely reminder of the very severe damage which can arise if any loose gear, etc., gains access to the intake ducting of gas turbine installations.

About five months later some second stage fixed and moving blades of *Bold Pathfinder*'s starboard gas turbine failed. A thorough investigation was then made into the cause of failure, including the fitting of strain gauges on compressor blades to determine the conditions at which excessive amplitudes occurred. As a result it was definitely established that both failures had been caused by "rotating stall". This is an aerodynamical effect which is liable to occur when the l.p. stages of axial compressors go into stall at low speeds. (A brief

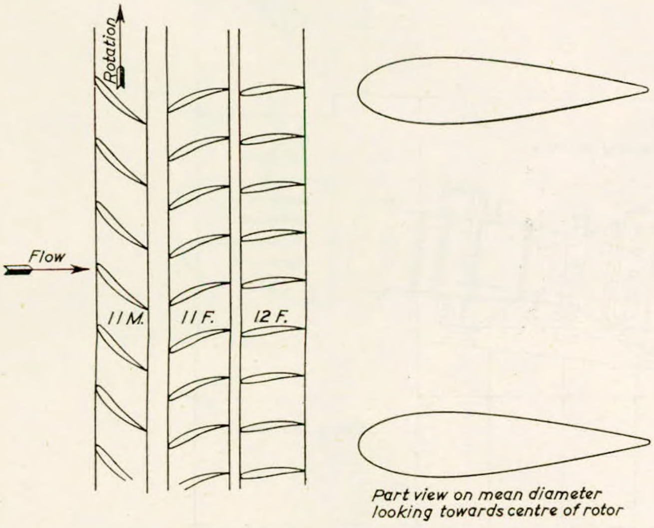

FIG. 10—*Expanded plan view showing details of G2 compressor blading at outlet end—before modification*

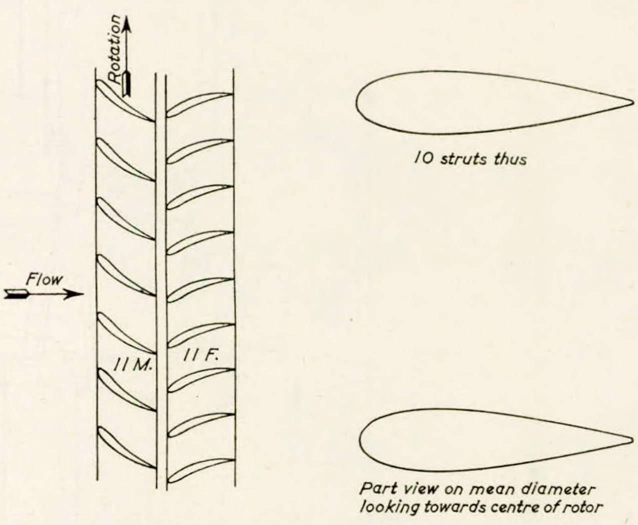

FIG. 11—*Expanded plan view showing details of G2 compressor blading at outlet end—after modification*

explanation of this phenomenon is given in the footnote below.)*

The blade vibration tests showed the existence of a group of gas generator speeds between 3,000 and 4,800 r.p.m. at which resonant vibration was likely to occur. This is below the normal propulsion range, but includes the speed at which the engines have been run after periods at high power to cool the bearings prior to shut down. The gas generator speed for idling and cooling down has been temporarily raised to 5,000 r.p.m. and design modifications to ensure the safety of the blading over the whole operating range are being investigated.

An interesting point arising from the three blade failures described above is that the G2 compressor is closely similar to that of the Beryl Mark I jet engine which had successfully completed an Air Ministry type test. The fact that an aircraft engine compressor has been cleared for flight duty, therefore, is no guarantee that blade vibration troubles will not be experienced when operating at low speeds, as may be necessary in naval applications.

One of the important points which it was hoped to establish from the trials of the G2 gas turbines was the behaviour of the ball and roller bearings fitted to these engines. Unfortunately, the experience in *Bold Pathfinder* has been masked by an extremely severe hull vibration which occurs under certain conditions when turning and caused two failures of the power turbine bearings during the early operation of the boat.

Investigations were made into the hull vibration and its effect on the engine. The analysis showed that a vibratory load, much greater than the normal thrust load, was occurring on the ball bearings. This caused the balls and cage to vibrate axially between the races and led to failure of the cage. Such vibration is most undesirable in ball bearings, especially with the air-oil mist type of lubrication which was employed initially. A change to flood lubrication of this bearing was made to improve the oil supply, both under normal operation and when trailing. At the same time, limitations on the operation of the boat have been imposed to prevent the hull vibration and no further bearing failures have occurred.

In *Bold Pioneer,* which has not suffered from this trouble, presumably due to the different hull form, no bearing failures have occurred.

G2—General Conclusions

There is no doubt that there have been serious teething troubles during the initial trials of the G2 gas turbine at sea, many of which would have been avoided if the engines had been given a more thorough testing ashore. The successful and trouble-free running of the Gatric had, perhaps, made the Admiralty over-confident and the first G2 was run for an aggregate of only thirty-seven hours before carrying out the official acceptance test of nine hours prior to installation.

Nevertheless, the difficulties experienced during the initial trials were not inherent in the principle of the gas turbine and the G2 has again shown that, basically, the characteristics of the simple gas turbine are ideal for the propulsion of high speed coastal craft. Other lessons learned to date from the sea trials of the G2 are: —

(*a*) *Starting and flexibility of operation.* Air starting has proved quick and reliable, the time taken to reach idling speed being about thirty seconds under normal conditions. The rate of acceleration thereafter is servo controlled and, although the throttle lever can be moved "instantaneously" from idling to full power, the fuel flow is gradually increased over a period of about twelve seconds, corresponding to the maximum surge-free rate of acceleration.

The automatic blow-off valves fitted to the compressor to avoid surge at low powers or when rapid changes of speed occur, have been successful and trouble free in operation.

(*b*) *Compressor fouling.* Water spray arrangements similar to those installed in M.G.B.2009 were fitted to the G2's, air being tapped from the compressor and used to blow distilled water into the spray ring fitted at the compressor inlet. This simple method has again proved extremely successful in restoring performance after salt spray fouling. The usual practice is to wash the compressors through daily at 5,000 r.p.m., using ten gallons of distilled water over a period of about three minutes. This frequency is not normally necessary from the performance point of view but is considered desirable in order to prevent corrosion.

(*c*) *Cooling down.* If the gas turbines have been operating at high power, the gas generators are run for five to fifteen minutes at 4,750 r.p.m. to cool the bearings down to a temperature of about 90 deg. C. (194 deg. F.) before shutting down. On occasions, however, the engines have been shut down immediately after high power running without consequent damage.

(*d*) *Instrumentation.* Accurate recording of gas temperatures is essential for the proper control of naval gas turbines. Several failures of gas temperature recording instruments have taken place in the *Bold* boats and false readings have occurred due to hull vibration at high speed. It may be advisable in future designs to record gas temperatures at the turbine outlet rather than at entry to the power turbine as in the G2's. This will enable a more robust instrument (designed for lower temperature) to be fitted. It will also safeguard the turbines as any internal failure will immediately result in a higher temperature at the end of the turbine blade path.

The Use of Simple Gas Turbines as Boost Units in Major Warships[11, 12]

Since major warships operate for only very short periods at high power, it is wasteful of weight and space to carry around heavy long life machinery whose full capacity is seldom used. A promising application for the gas turbine in naval vessels is, therefore, as a lightweight, short life "boost" engine for use at high powers, in conjunction with a base load or cruising engine. This conception of using simple gas turbines as "booster" units with more efficient longer life machinery for cruising is an important principle which avoids the need to install unduly heavy machinery solely to cover a range of powers which is seldom used in warships. The gas turbine is the only prime mover which can take full advantage of the short life required in booster units to reduce weight and space without increasing maintenance difficulties.

In M.G.B.2009 and the two *Bold* boats, the gas turbines and cruising engines drive separate shafts and piston engines are employed for cruising, but the boost principle is not necessarily confined to arrangements of this kind. Steam turbines, additional gas turbines or free piston gas generators can be used for cruising and the boost and cruising engines can be coupled to the same shaft if desired.

In this connexion it is interesting to note that a study has been made by Captain Simpson, U.S.N., and Commander Sawyer, U.S.N., for a 30,000 h.p. naval propulsion plant comprising 9,000 h.p. of steam turbine machinery and 21,000 h.p. of lightweight "boost" gas turbines connected to the same gear train through clutches[11]. The steam plant is intended to supply power up to a ship's speed of 20 knots, after which the gas

* *Note on "rotating stall".* The explanation of this phenomenon is briefly as follows: When a compressor blade row stalls it does so initially in patches, which tend to block the flow, and the air, therefore, diverges to each side of the patch. This has the effect of unstalling the blades in the same row ahead of the patch and stalling those behind. The result is a rotation of the stalled patch in the direction of blade rotation but at a reduced speed. This rotation of the stalled patches excites the blades in the fixed and moving rows and they are liable to vibrate in resonance at excitation frequencies depending upon the number and rotational speed of the stalled patches, both of which can vary.

turbines would be cut in. It is estimated that this arrangement would reduce the weight of propulsion machinery in a destroyer by 28 per cent and reduce the engine room length by ten feet. It would also be possible to design the steam plant for good economy at the low speeds for which it alone would be employed. If the gas turbines could be fitted with reversing arrangements, a further advantage would be the possibility of proceeding to sea in a matter of minutes should some unforeseen emergency arise.

The characteristics required of boost gas turbines are extreme lightness and compactness, reliability and reasonable efficiency at high powers with minimum air requirements. The life can be very short judged by normal standards. These qualities are similar to those of aircraft gas turbines and in this field the Navy is, therefore, in the happy position of benefitting directly from the vast aircraft engine development programme financed by the Ministry of Supply.

The development of naval gas turbines for main propulsion machinery presents a more difficult problem than the boost application. Nevertheless the gas turbine may offer sufficient advantages, particularly in the power range between 5,000 h.p. and 10,000 h.p., to warrant developments of this type. Two naval gas turbines in this category have been built and tested under the code names of E.L.60A and R.M.60.

E.L.60A MAIN PROPULSION GAS TURBINE[13, 14]

(See Appendix A, column 3; Appendix B, diagram 3)

Introduction

A contract was placed with the English Electric Co., Ltd., Rugby, in September 1946, for a gas turbine plant (known as E.L.60A) suitable for marine propulsion. The plant was intended to replace one set of steam machinery in the frigate H.M.S. *Hotham*, a Lend/Lease vessel which the United States kindly allowed the Admiralty to retain after the war for this special purpose. The *Hotham* was originally fitted with steam turbo-electric machinery developing 6,000 s.h.p. on each of two shafts, and appeared particularly suitable for a gas turbine installation since reversing was already available, the power and alternator speed were reasonable, and a direct comparison with steam machinery could be made.

The main object of the contract was to obtain sea experience with a long life gas turbine plant at an early date. It was decided, therefore, to base the design as far as possible on existing knowledge and techniques. A lightweight set of advanced design was thus out of the question and, in many ways, it was desirable that the weight of gas turbine plant should be similar to that of the steam machinery it was to replace. The E.L.60A was designed to drive the *Hotham*'s starboard propulsion alternator at its original design speed and power, and the layout was adapted to fit in the existing forward engine and boiler room.

Cycle

The cycle adopted was a simple cycle with heat exchange, the compressor (or charging) turbine being in parallel with a geometrically similar but smaller power turbine driving the alternator. The maximum gas temperature at inlet to the turbine was 704 deg. C. (1,300 deg. F.) and the heat exchanger was designed for 75 per cent heat recovery. Fig. 12 (Plate 1) shows a model of the complete E.L.60A gas turbine with details of ducting, starting motor, and main alternator, etc., while photographs of the actual set in the manufacturer's test house are shown in Fig. 13 (Plate 1) and Fig. 14 (Plate 2).

Adoption of a parallel-flow cycle solved the problem of providing an efficient 6,500 h.p. power turbine running at the alternator synchronous speed of 5,600 r.p.m., since only one-third of the total mass flow passed through the power turbine. This cycle was also felt to meet the requirements for rapid manufacture, and the pressure ratio necessary for efficient operation was within the range of operating experience for axial flow compressors. Manœuvring was also attractive, since any power from full to zero could be obtained by manipulating the throttle and blow-off valves without alterating the speed, mass flow, or pressure ratio of the compressor.

Control

Automatic control of the parallel-flow cycle of E.L.60A necessitated a complex system, the basic principles of which were as follows:—

Normal control was by means of a single lever regulating the speed setting of the power turbine governor. A movement of this lever in the "increase speed" direction started a small motor which increased the fuel supply to all combustion chambers at a predetermined rate until the power turbine reached the new governor speed setting.

A movement of the lever in the "decrease speed" direction had an immediate and a long term effect. The immediate effect was to reduce fuel supply to the power turbine combustion chambers and, if the required speed change was appreciable, to close the power turbine throttle valve and open a blow-off valve to atmosphere until the desired power turbine speed was reached. Rapid change of output shaft speed could thus be effected without immediately disturbing the fuel setting of the charging set.

The longer term effect was a slow reduction in the fuel rate of the charging set and a consequent reduction in its speed. During this progressive reduction, the power turbine speed was held at its governed value by a progressive opening of the throttle valve and a proportionate closing of the blow-off valve. Ultimately the set was restored to the normal condition of unthrottled operation at the desired speed, with the blow-off closed. If necessary, the long term effect could be cut out and the charging set allowed to run continuously at a chosen speed; this condition met manœuvring requirements, as it enabled the time from "stop" to "full power" on the power turbine to be reduced to a few seconds.

Starting

The 250 h.p. starting motor was capable of rotating the charging set at 1,000 r.p.m. without fuel, but the normal procedure was to light the combustion chambers at 300 r.p.m. and declutch the starting motor at 2,000 r.p.m. On a cold start the set would become self driving in five minutes and could sustain full load about fifteen minutes later.

Manufacture of Set

It was originally planned to complete the manufacture of the set by the end of 1948. However, as work proceeded it became apparent that a gas turbine of this nature could not be built using existing practice. Many of the manufacturing difficulties required the use of special techniques, some of which had to be developed or adapted especially for the job. All this caused considerable delay and it was not until 1949 that the first main component, the compressor, was ready for testing. At the designed operating point an overall adiabatic efficiency of 86·2 per cent was obtained, which was considerably higher than expected. The mass flow was also in excess of the design value and modifications were necessary to ensure matching of the turbines. To achieve this, the first stage of rotor and stator blades was removed from both turbines, thus increasing their capacities. It was hoped that any decrease in turbine efficiency caused by this modification would be offset by the increase in compressor efficiency compared with the design figure.

Further difficulties were encountered with the welding of the turbine rotors and it was not until September 1951 that the complete set was finally ready for shore trials. Thus the original object of obtaining early sea experience had not been achieved, while the initial trials of the R.M.60 had already indicated the potentialities of a lightweight gas turbine for warship propulsion. The heavier E.L.60A, based on steam turbine practice had, in fact, become obsolete and it was realized that the set would never become a prototype for future naval gas turbine machinery. It was decided, therefore, to abandon the sea trials of the E.L.60A in the *Hotham* and to

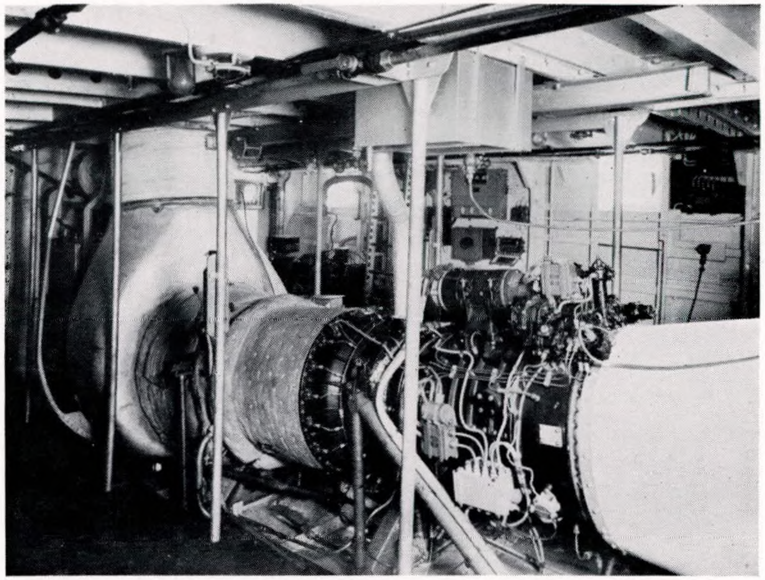

FIG. 5—*Gatric gas turbine as installed in M.G.B.2009*

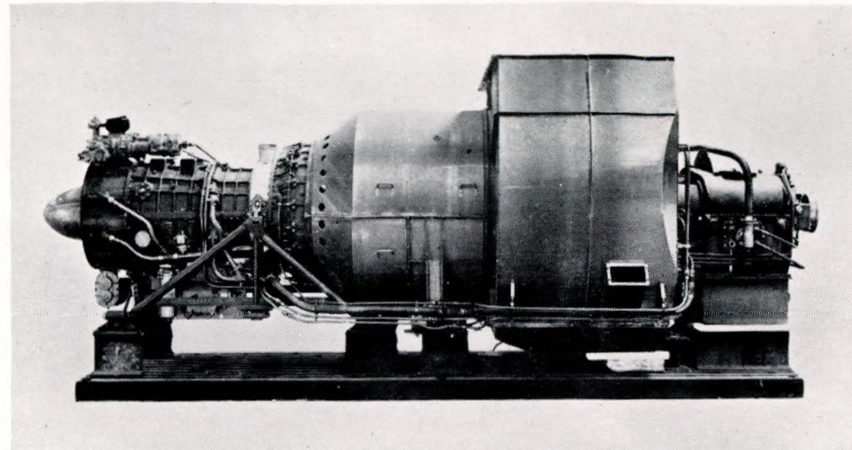

FIG. 7—*G2 Gas turbine on test stand*

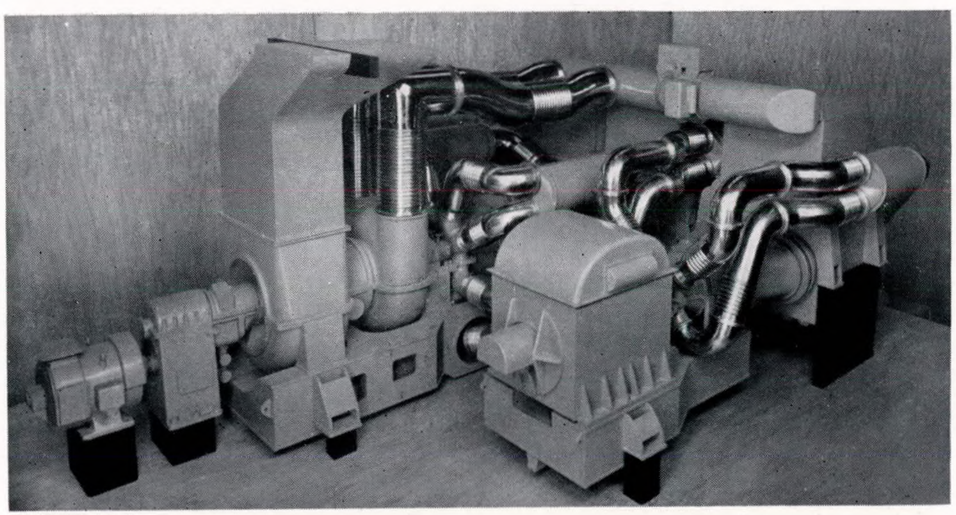

FIG. 12—*Model of E.L.60A main propulsion gas turbine*

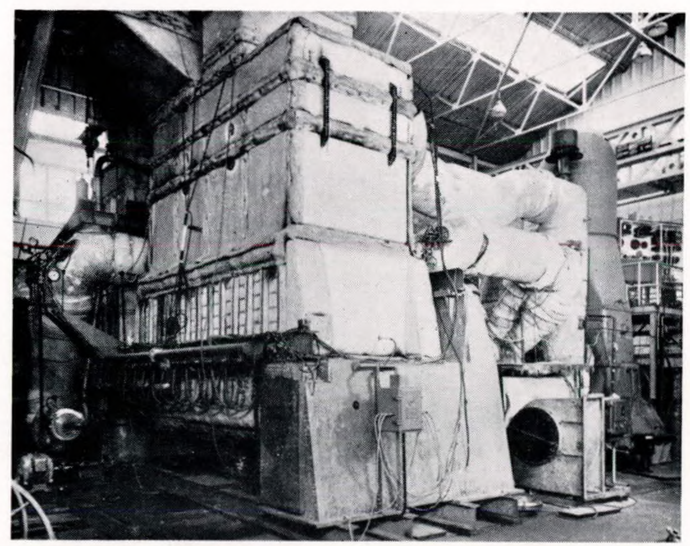

FIG. 13—*E.L.60A gas turbine in test house—view from heat exchanger end*

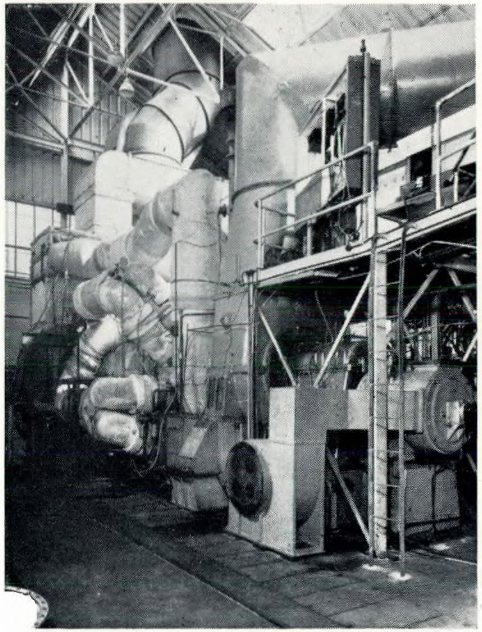

FIG. 14—*E.L.60A gas turbine in test house—view from starter motor end*

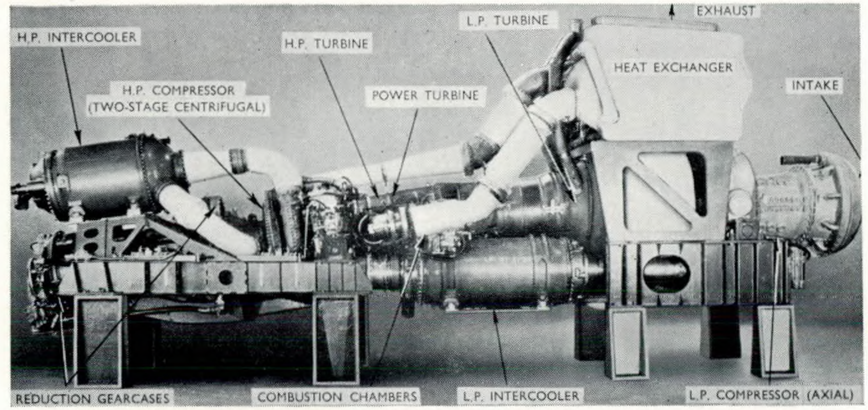

FIG. 17—*R.M.60 main propulsion gas turbine*

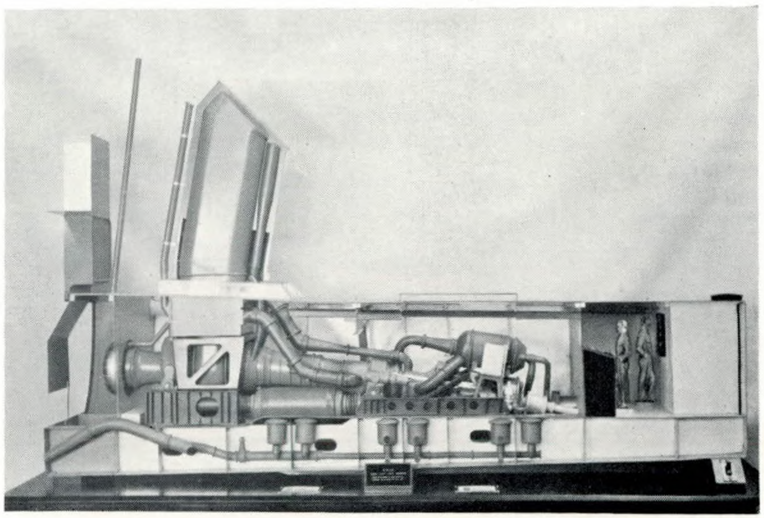

FIG. 21—*Model of R.M.60 in* Grey Goose

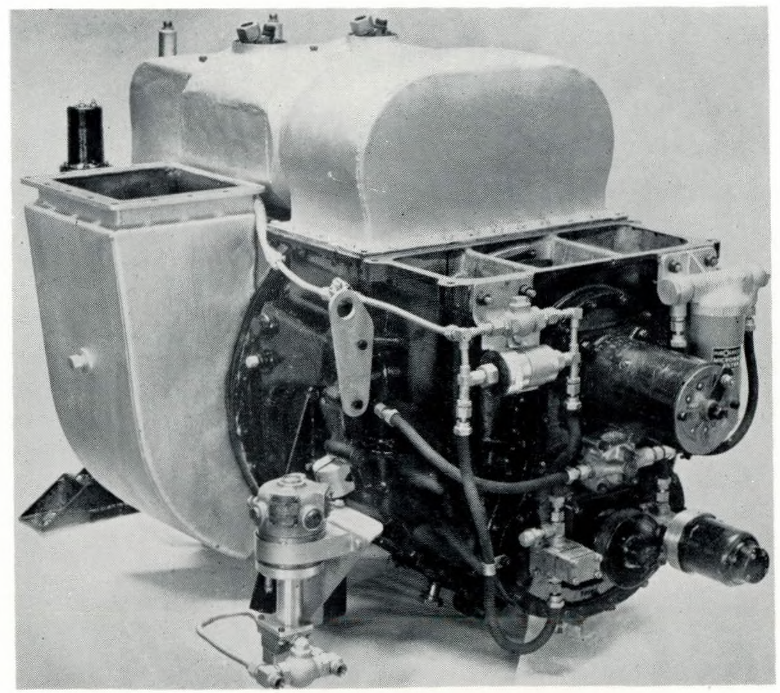

FIG. 24—*T8 gas turbine for small boat propulsion*

FIG. 26—*Gas turbine propelled harbour launch No. 3964 on the Thames*
By courtesy of the Keystone Press Agency, Ltd.

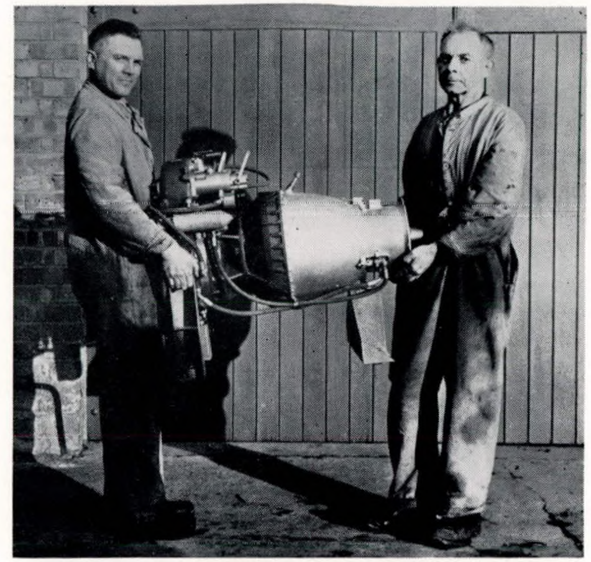

FIG. 28—*276-h.p.* Artouste *gas turbine as supplied to the Admiralty Engineering Laboratory*

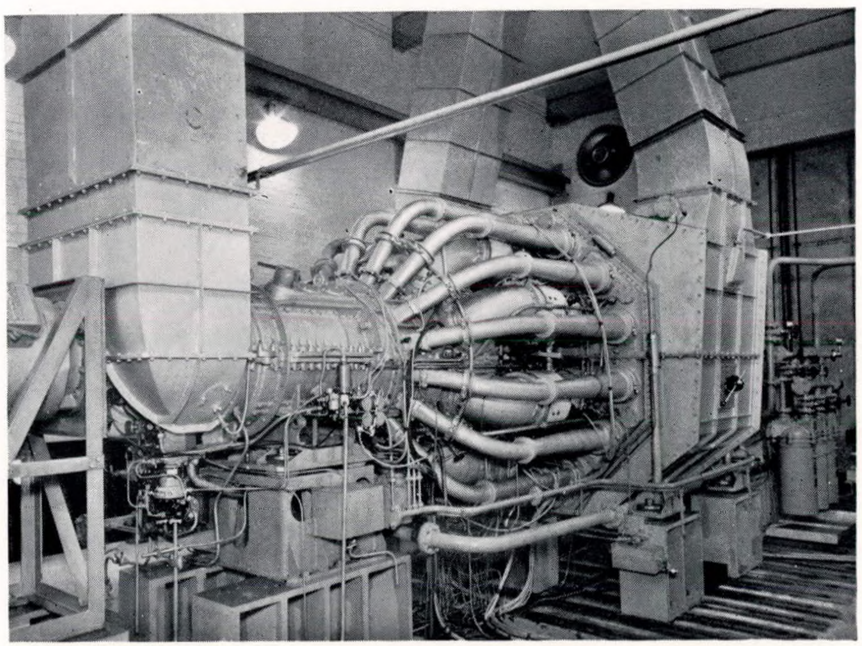

FIG. 31—*1,000-kW. gas turbo alternator in test house; view from compressor end with casings removed*

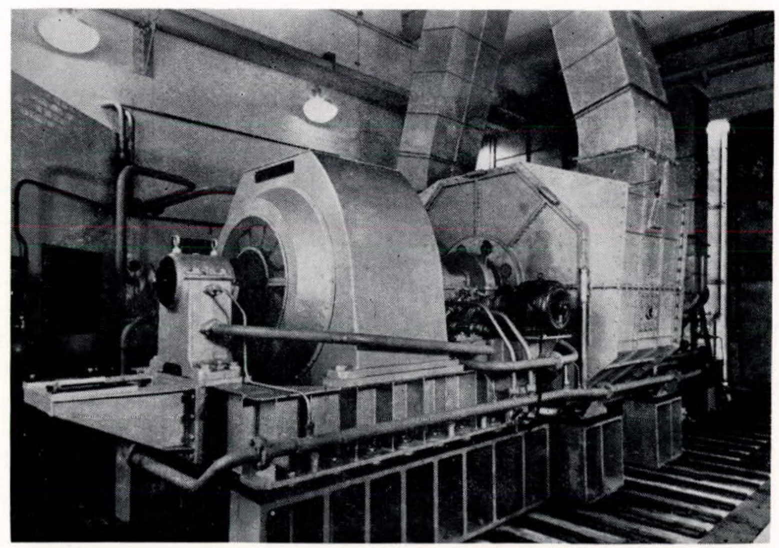

FIG. 32—*1,000-kW. gas turbo alternator in test house; view from alternator end*

Plate 4

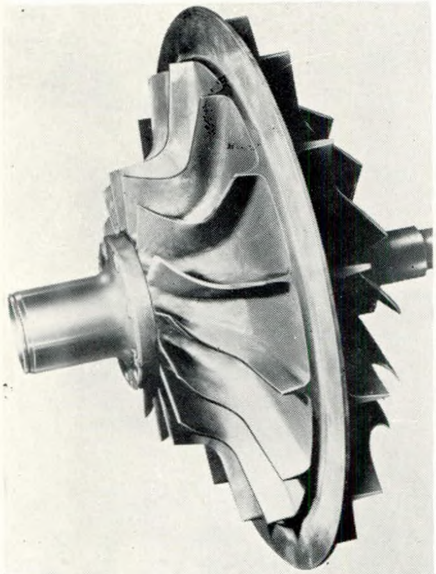

FIG. 35—*Small emergency gas turbine; combined compressor and turbine assembly*

FIG. 38—*Neptune gas turbine-driven portable pump*

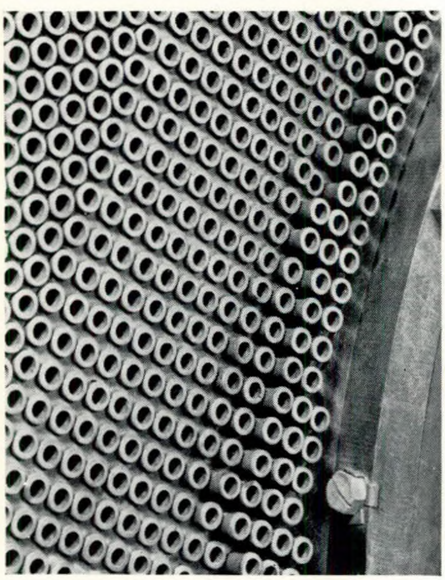

FIG. 34—*Details of heat exchanger tube defects in 1,000-kW. gas turbo alternator*

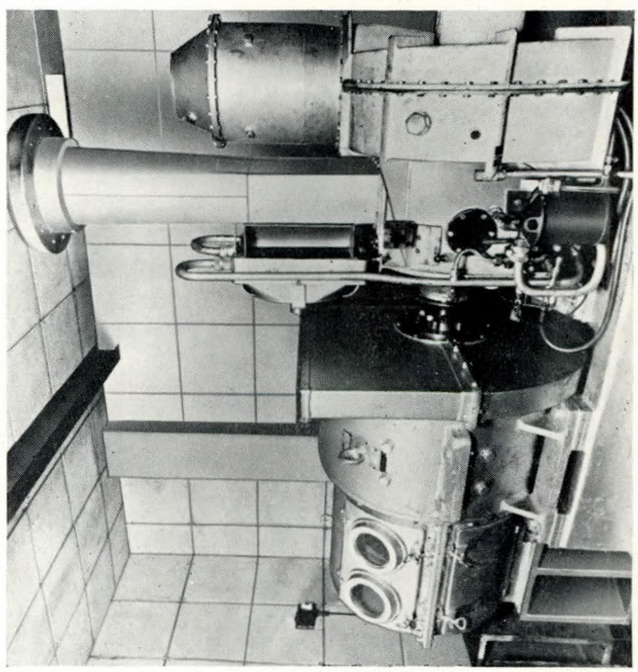

FIG. 36—*Small emergency gas turbine and generator in test house*

terminate the project at the conclusion of the first test runs ashore. The performance obtained on these initial runs is shown in Fig. 2, but it is only fair to point out that several significant and unnecessary losses were located on test and with further development these could have been eliminated and the consumption figures thereby substantially improved. On completion of the test programme in 1952, the set was stripped for a thorough examination of every component.

Lessons Learned

Although the original object of this gas turbine project was not achieved and the development was subsequently overtaken by more advanced designs, much valuable information was obtained, the more important points being as follows:—

(*a*) *General* (*i*) The cycle used, designed physically and mechanically on steam turbine lines, is intrinsically heavy. Even with complete redesign, it is doubtful if the weight could ever be reduced below about 50 tons or 17lb. per h.p.

(*ii*) Bearing in mind the weight of the moving parts and that the turbine casings are horizontally split and uncooled, the set appeared to be sufficiently flexible in operation for naval use except that in the event of a surge, it was necessary to slow the charging set down below the self-driving point before the plant could be put on substantial load again, and this operation took 5-10 minutes.

(*b*) *Compressor* (*i*) A very sound compressor, both aerodynamically and mechanically, has been developed, and the design could be confidently used as a basis for future projects.

(*ii*) It has been realized that a high efficiency over a wide range (over 85 per cent from pressure ratios of 1·5 to 4·2 obtained with this compressor) is often associated with a poor low speed surge line. Thus, more efficient overall performance may result from improving the surge line by deliberate interstage blow-off at low speed operation rather than by attempting to improve the complete compressor surge line by blading modifications.

(*c*) *Heat Exchanger* (*i*) The method of securing the tubes in the tube plates by induction brazing has proved satisfactory.

(*ii*) The aluminium bronze tubes have been corroded during the short duration of the tests and, so far as can be judged from this limited experience, the material appears unsuitable.

(*iii*) Correct spacing of the tubes between tube plates has been satisfactorily achieved by means of spiral wire spacers.

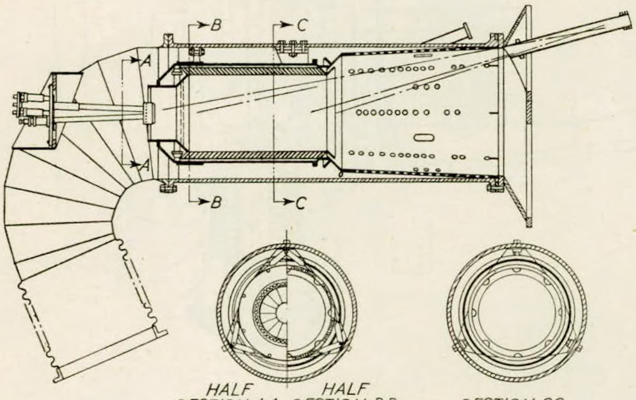

FIG. 15—*Details of louvred combustion chamber fitted in E.L.60A*

(*d*) *Combustion Chambers* (*i*) The louvred can-type combustion chambers developed by the Shell Petroleum Co., Ltd., for the E.L.60A were the first of their type. They were most successful, producing perfect combustion without any trace of smoke above a preheat temperature of 300 deg. C. (572 deg. F.), and remaining completely free from any distortion or corrosion throughout the whole of the tests. Details of the chamber are shown in Fig. 15, and it will be observed that the louvred wall construction is achieved by packing together large numbers of truncated conical rings.

(*ii*) Difficulties were experienced in matching the outputs of the multiple combustion chambers. (Unless this can be achieved, the turbines are liable to be locally overheated.) The matching was particularly difficult at low powers where the individual burner output was very sensitive to minor manufacturing errors, burrs, etc.

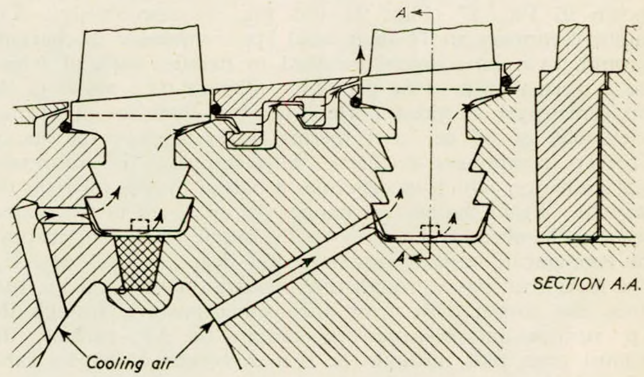

FIG. 16—*Details of turbine blade root cooling fitted in E.L.60A*

(*e*) *Turbines.* The turbine rotor and blade root cooling system (details of which are shown in Fig. 16) proved extremely effective, although complicated to construct. Air tapped from the compressor delivery was, after filtration, fed into the centre of the rotors. The air then passed outwards to the blade roots and the spaces beneath the segmented disc covers around the rotor periphery. By this means the rotor discs and the more heavily stressed parts of the blades were protected from direct impingement of hot gases. Fusible plugs indicated that the cooling system maintained the rotor everywhere at least 250 deg. C. (482 deg. F.) below the hot gas temperature. This highly effective cooling system, which required somewhat less than 2 per cent of the total air flow, would enable ferritic rotors to be used in future designs of this type.

Conclusion

The E.L.60A gas turbine did not achieve the original object of obtaining early sea experience with this new form of prime mover in a naval vessel. Nevertheless, many valuable lessons were learned, perhaps the most important being that heavyweight gas turbines constructed on steam turbine lines are not suitable for naval machinery. In addition, a number of components were developed which could be used in future gas turbine designs.

R.M.60 MAIN PROPULSION GAS TURBINE[15, 16]

(See Appendix A, column 4; Appendix B, diagram 4)

Introduction

The second development in this category originated when Rolls-Royce, Ltd., approached the Admiralty with the suggestion that a gas turbine would be a suitable propulsion engine for coastal craft. Investigations were carried out by Rolls-Royce under the direction of the Engineer-in-Chief and a contract for the design and development of a 6,000 h.p. naval gas turbine known as the R.M.60, for use in coastal craft, was placed in September 1946. The life of the engine was stipulated as 1,000 hours, comprising 300 hours at full power and 700 hours at 60 per cent power. It was later decided to install two of these engines in the gunboat *Grey Goose*. Design work started in December 1947 and in June 1951 the prototype R.M.60 was on test. In the succeeding three months the engine completed 227 hours of trouble free running, during which period a power of 5,300 h.p. was achieved.

Description of R.M.60

In order to comply with naval requirements for economical low power cruising, it was found necessary to employ a high pressure ratio, with intercooling between each major stage of compression, and a heat exchanger. A photograph and a diagrammatic sectional arrangement of the complete engine are shown in Fig. 17 (Plate 2) and Fig. 18 respectively. The engine comprises an 11-stage axial l.p. compressor discharging through twin intercoolers arranged in parallel, each of which has a thermal ratio of 86 per cent. The air then passes to the h.p. centrifugal compressor which is a two-stage design with an intercooler of 64 per cent thermal ratio between the stages. The h.p. compressor discharges to a compact "U" tube type heat exchanger which incorporates a partial bypass valve on the gas side. From the heat exchanger the air is led to twin combustion chambers and thence to the single stage h.p. turbine, the temperature of the gases being 827 deg. C. (1,521 deg. F.). The gases then pass through intermediate (power) and l.p. turbines, the output drive from the former passing through the h.p. turbine and compressors. From the l.p. turbine, the exhaust gases pass through the heat exchanger or bypass valve to atmosphere.

The straight compound cycle with intercooling, heat exchange and concentric turbines was chosen after an exhaustive analysis of various cycles and engine layouts. It is worth stressing that the comparison of different gas turbine designs, though a most interesting occupation, is also a most dangerous one. Quite a small error in the assumptions, particularly of losses in various parts of the system, can be magnified in the ensuing argument and lead to totally wrong conclusions. Although reheat appeared theoretically very attractive in these analyses for decreasing the bulk and air rate, it was not employed in the R.M.60 for a number of practical reasons, the most important of which were:—

(*a*) The difficulties of control, especially of manœuvring, would be increased to a serious degree since two separate fuel supplies must be regulated independently.

(*b*) Design of the reheat combustion chamber is difficult since it must work over a very large range of air/fuel ratios and the only cooling air available is already very hot.

(*c*) Reheat increases the temperature of the comparatively large l.p. turbine where the stresses are already high.

Aero-engine practice has been adopted for the general principles of many components. This policy has resulted in a light and compact power unit with a specific weight (based on maximum power obtained on test) of 5·3lb. per h.p. (including double reduction gearing and all accessories).

Preliminary Development

In the development of a complex engine of this type, employing a higher pressure than any other open cycle gas turbine, and with a gas temperature which at the time had only been employed in simple cycles, it will be appreciated that there were a considerable number of unknowns. This gave rise to extensive work on test rigs before the design of the various components could be finalized. One important requirement was for a high pressure, high temperature seal, and the type

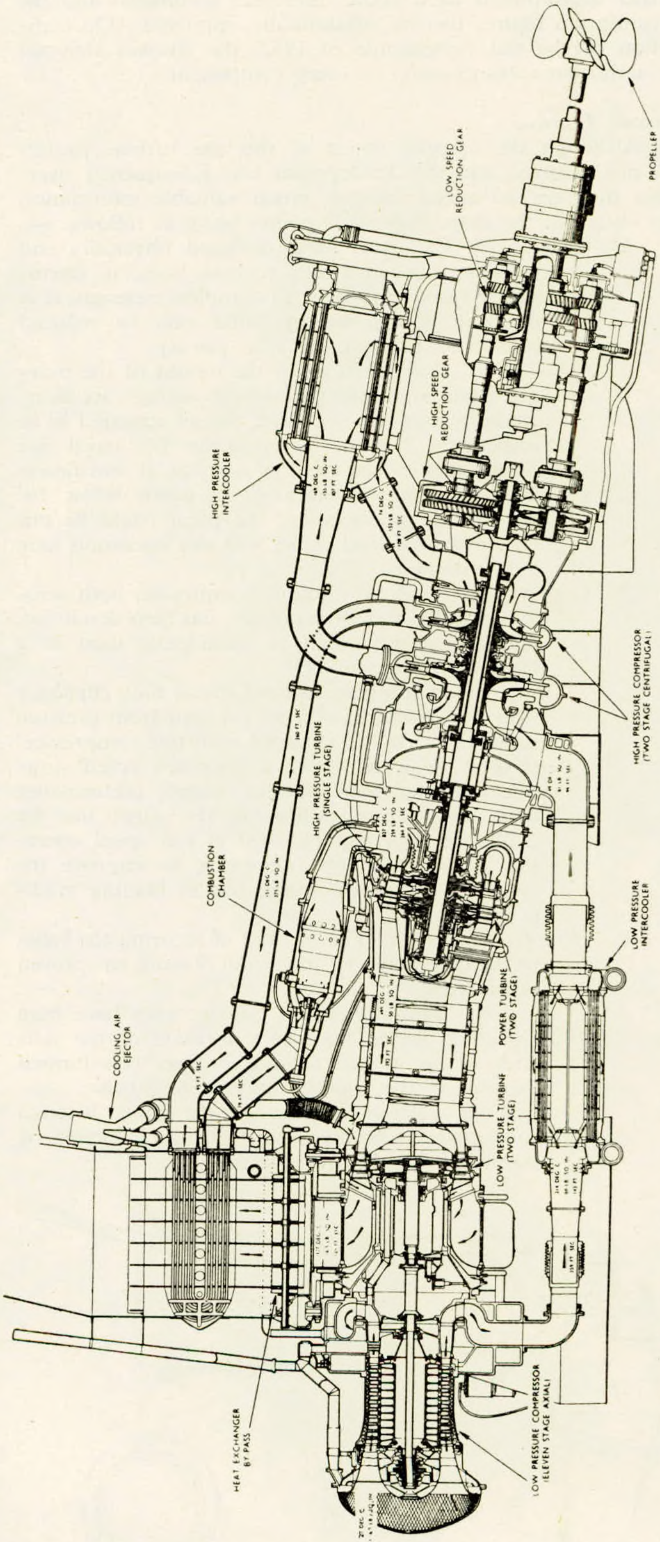

FIG. 18—*Diagrammatic section through R.M.60 with details of pressures, temperature and velocities throughout the cycle*

finally adopted, which has been used extensively throughout the engine, is shown in Fig. 19. The "concentric" design eliminated nearly all the problems with hot ducts (at the expense

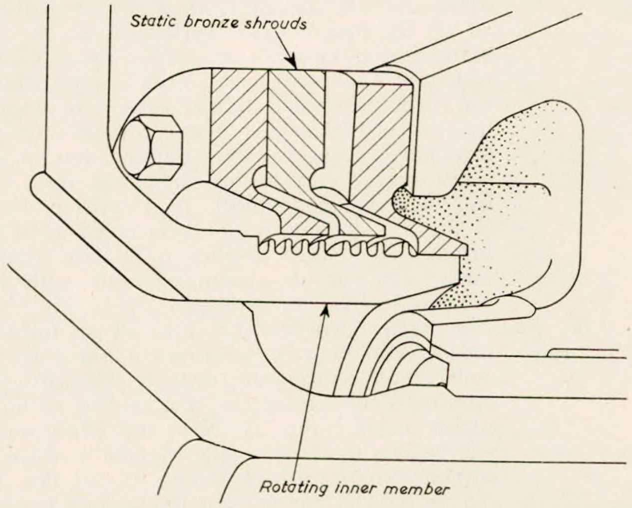

FIG. 19—*Details of high temperature, high pressure seals used in R.M.60*

of a concentric shaft and buried bearings) but one that remained was to provide sufficient flexibility in the duct between the heat exchanger and the combustion chambers. This was satisfactorily solved by the design of the flexible joint shown in Fig. 20, this type of joint also being used for the cold ducts connecting the h.p. compressor, intercooler, and heat exchanger.

Another difficult problem was to design a burner which would cover the whole load range of the engine, necessitating a turn down ratio of 30 to 1. This range is far too great for a simple pressure jet burner and an ingenious triple burner was developed in which three concentric pressure jet atomizers are brought into use in sequence as the pressure in the fuel line rises. The R.M.60 was only required to burn distillate fuel and the fuel system was therefore largely based on the use of aero engine components.

The division of the engine into separate units lent itself to testing the h.p. unit on its own, particularly as the power

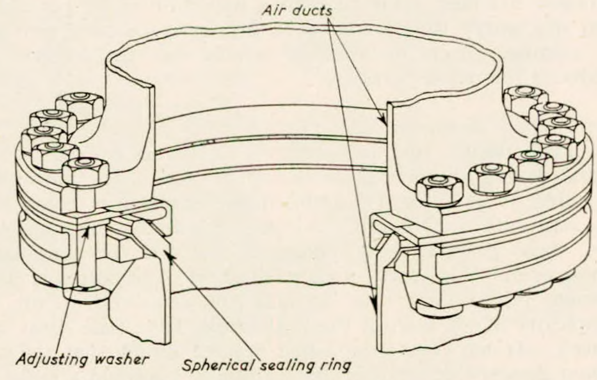

FIG. 20—*Details of flexible joint fitted in air ducting of R.M.60*

turbine was fitted immediately adjacent to the h.p. turbine and was, in fact, part of the same unit. The h.p. or "cruising unit", was first run in 1950 and 640 hours' testing was carried out before assembling the complete engine. No major mechanical trouble was experienced, but minor modifications were necessary to the blading of the power and compressor turbines to obtain correct matching and reduce proneness to surging.

Testing of the Complete Engine

Development running of the complete R.M.60 engine began in June 1951 and on the first occasion of opening up the throttle a power of 5,300 h.p. was achieved. Testing of the engine continued over a period of two years and a total of 1,100 operating hours (in addition to the 640 hours on the cruising unit) were amassed, during which time the characteristics of the engine were studied, the performance improved and the reliability tested.

At the time of writing, two R.M.60 gas turbines are being installed in the gunboat *Grey Goose* by Vosper, Ltd., of Portsmouth, and sea trials are expected to commence shortly. Fig. 21 (Plate 2) shows a half sectioned model of the installation and a line drawing giving the positioning of the engine in the hull is shown in Fig. 22. (In the actual boat installation the control room has now been re-sited on the upper deck.) By installing these engines in *Grey Goose*, a considerable increase

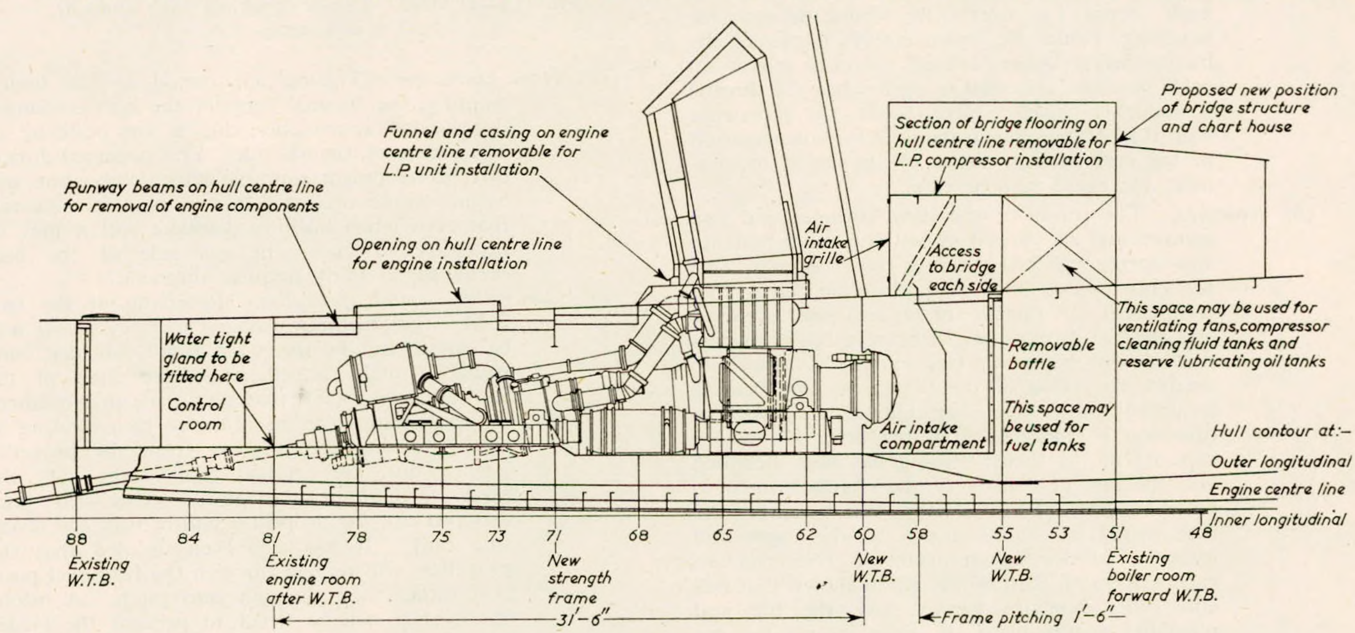

FIG. 22—*Diagram showing installation of R.M.60 in* Grey Goose

in power has been achieved with a reduction of 50 per cent in total machinery weight and a saving in space compared with the original steam installation, which was the lightest ever produced for naval purposes[17].

Performance Achieved

The specific fuel consumption achieved by the R.M.60 engine during shore trials is shown in Fig. 2, the power with a 15 deg. C. (59 deg. F.) ambient air temperature being 5,400 h.p. and with a 27 deg. C. (81 deg. F.) air temperature 4,900 h.p., these powers being obtained with the heat exchanger bypass open. This performance fell short of the original design estimate but, taking into account the advanced nature and complexity of the engine, the trial results have been most satisfactory. It has been established beyond doubt that the cycle chosen does enable a single gas turbine to maintain a good performance over a wide range of power. The rise of specific fuel consumption at the higher powers (see Fig. 2) emphasizes the price which must be paid if a small and compact heat exchanger incorporating a bypass is used. For naval applications this price is acceptable since only a small percentage of a warship's operating life is spent at high powers.

Experience Gained with R.M.60

(*a*) *Manœuvrability.* The engine is started by an electric motor rated at 40 h.p. for thirty seconds. The whole starting sequence is automatically set in motion by a push button in the control room and the engine reaches idling speed in less than thirty seconds. During shore testing of the R.M.60, the rate of acceleration and deceleration has had to be limited to avoid overfuelling or compressor surge. The time required to increase from idling to full power is about forty-five seconds, and about forty seconds is necessary to reduce from full power to idling. These times were obtained on the test bed with a "clean" engine, and the dash pot fitted in the throttle control for the ship installation has a sixty second rate for both acceleration and deceleration, to allow some margin for fall off in compressor performance. This limitation on the flexibility of the R.M.60 is mainly due to the low inertia h.p. turbine and compressor being more responsive to throttle movements than the high inertia l.p. unit. In future designs the handling could be considerably improved by incorporating larger blow-off valves at maximum cycle pressure, arranged to open when the throttle is suddenly closed. Nevertheless, the experience with R.M.60 has shown the need for consideration in the early design stages of the naval requirement for rapid manœuvring.

(*b*) *Bearings.* The rotors of the three turbines and two compressors are carried in ball and roller bearings and during test bed running these bearings have probably caused more concern than any other component. A number of failures have occurred and the h.p. turbine thrust bearing has been particularly troublesome. It is extremely difficult to predict the value of the thrust on this bearing accurately and when surging occurs even its direction is uncertain. In the final design, the capacity of the thrust bearing has been increased and the rate of control of the engine limited to avoid surging. Failures with other bearings have been cured by modifications to the cages and improved lubricating arrangements. Nevertheless, experience with R.M.60 has again shown that ball and roller bearings cannot give the life and reliability required for the main propulsion gas turbines of naval vessels.

(*c*) *Erosion of h.p. compressor impellers.* After the first 220 hours' running, severe erosion of the aluminium impellers of the h.p. centrifugal compressor was experienced. This was caused by the water droplets condensed from the atmospheric air in the intercoolers. Various anodizing and lacquering processes were tried without success and, as it was impracticable to fit a water separator, the impellers and diffuser vanes were replaced in stainless steel. This prevented erosion for the remainder of the test bed running, but in salt laden atmospheres further difficulties may arise and there will undoubtedly be material problems in the h.p. compressors of intercooled naval gas turbines. It may be desirable to fit some form of water separator if a compact unit with low pressure loss can be developed.

(*d*) *Effect of ambient temperature.* Like all gas turbines, the R.M.60 is very sensitive to variations in ambient air temperature and, in this particular case, sea water temperature also, as it is an intercooled design. Fig. 23 shows this effect and it will be seen that power falls off rapidly above an ambient temperature of 27 deg. C. (81 deg. F.) (In the R.M.60 the power is limited to 5,400 h.p. below 15 deg. C. (60 deg. F.).) This large variation in power with ambient temperature raises problems in naval installations, since warships must normally be capable of operating satisfactorily in arctic or tropical climates.

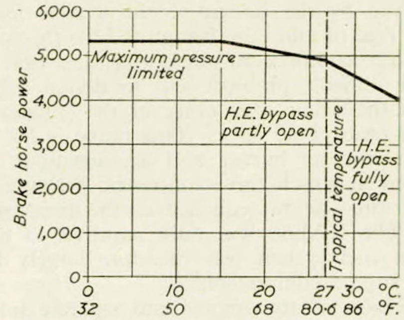

FIG. 23—*R.M.60. Power variation with ambient temperature*

(*e*) *Heat exchanger.* During one period of 320 hours' running, the thermal ratio of the heat exchanger deteriorated appreciably, due to the build-up of soft carbon on the gas side. This occurred during early development running when combustion was by no means perfect. It is a pointer, however, that even when burning distillate fuel it may be necessary to clean the gas side of the heat exchanger at fairly frequent intervals.

(*f*) *Controllable pitch propeller.* Reversing of the two R.M.60 gas turbines installed in *Grey Goose* will be carried out by means of Rotol 3-bladed controllable pitch propellers. Shore trials of the R.M.60 have shown that very little improvement in performance can be obtained by operating at power turbine speeds away from the propeller law. Thus, the original proposal to vary the pitch throughout the power range has been dropped and the propellers will be used for reversing only. It has also been decided that the propellers will reverse through the feathered position rather than through zero pitch. A mechanical stop will be fitted to prevent the blades taking any finer pitch than that required for ahead operation and, on reversing, the coarsening of the pitch to feather will act as a brake on the shaft system. Thus, there will be no tendency for the output turbines or shaft system to overspeed when manœuvring.

(g) *Noise.* The R.M.60, as built and tested, is undoubtedly noisy. The highest noise level of 120 decibels occurs at the h.p. compressor and appears to be excited by the centrifugal impeller vanes and resonances from the small bore ducts taking air at high velocity from the compressor. These ducts are very thin, and considerable noise reduction could probably be achieved by increasing the wall thickness and fitting insulation. When fitted with a closed intake duct, the forward part of the engine is distinctly quieter at 110 decibels. It is considered that, with the experience from R.M.60, a new design of engine should be possible, giving a much lower all-round noise level without sacrificing performance.

Conclusions

At the time of writing, the R.M.60 has not been tried at sea, so it would be premature to draw any sweeping conclusions on the future of this type of gas turbine for warship propulsion. Nevertheless, the first development project of this kind has produced an engine of 5,400 h.p. with a specific weight of 5·3lb. per s.h.p. (including reduction gearing) and a fuel consumption below 0·65lb. per s.h.p. per hr. over the whole range from 25 per cent to full power. These characteristics are suitable for a number of naval vessels but at present the life of the R.M.60 limits its application to coastal craft. It is worth noting, however, that on the basis of normal warship operation, the life of the hot parts would be nearer 10,000 hours than 1,000 hours for the same maximum gas temperature.

To improve the life and reliability, plain journal and thrust bearings will be necessary, causing increased weight and mechanical losses. The specific fuel consumption could be restored by the use of a larger heat exchanger, however, but the additional power absorbed by the bearings would be lost.

Criticism may be levelled at the complexity of the concentric shaft arrangement but, apart from early teething troubles, this feature in itself has caused no concern during test bed running, and the simple aerodynamic form of the engine which it makes possible largely accounts for the satisfactory performance which has been achieved.

When considering the future of this type of gas turbine it must be realized that the increase in size and complexity of modern fighting equipment has made the need to reduce the weight and bulk of machinery increasingly important, particularly in smaller warships where machinery weight represents a large proportion of the total displacement. The range of powers normally associated with these small warships, say, 5,000 h.p. to 15,000 h.p., is precisely that in which neither steam turbine nor Diesel machinery shows to best advantage. The lightweight Diesel has not yet been successfully developed to meet these powers, while the specific weight of steam turbine installations increases rapidly below 15,000 h.p. It is in this field that the gas turbine is first likely to supplant existing prime movers as the sole propulsion machinery for warships.

The naval requirement for high efficiency over a wide range of power can be met either by a single complex gas turbine of the R.M.60 type or by an installation comprising a number of simple gas turbines, each of which is designed to operate over its peak efficiency range. More operating experience will be necessary before deciding which of these arrangements will ultimately be adopted.

II.—PROPULSION MACHINERY FOR LANDING CRAFT AND SHIPS' BOATS

INTRODUCTION

The choice of prime mover for small naval craft normally takes into account the following factors:—

(a) Weight of engine and associated equipment plus fuel for the required endurance.

(b) Overall dimensions.

(c) Operating conditions for the particular craft.

(d) Reliability.

(e) Period between overhauls and the degree of skilled maintenance required.

(f) First cost of installation.

(g) Operating costs.

Small naval craft normally operate at a high percentage power with occasional bursts of full speed and, from the weight and space aspect, there are several applications where a simple gas turbine should show to advantage compared with existing Diesel installations. (Owing to the fire hazard, petrol engines are not normally fitted in naval craft.) The most promising of these applications are for short range landing craft and ships' boats.

Until small gas turbines are in production and several have been tested afloat, factors (d) (f) and (g) above must remain largely a matter for conjecture. Referring to (e), the lightweight high speed Diesels at present in service require a considerable planned maintenance effort to ensure their reliability, and the inherent simplicity of the small gas turbine should prove an advantage in this respect.

THE ROVER T8 GAS TURBINE

(See Appendix A, column 5; Appendix B, diagram 5)

With a view to gaining operating experience with small gas turbines, the Admiralty placed an order with the Rover Motor Company for four T8 engines in July 1950. This company was associated with Air Commodore Sir Frank Whittle's jet engine development and the T8 gas turbine was an early post-war venture designed for vehicle or boat propulsion. Although one engine was demonstrated by the company is a gas turbine car during September 1950 and two more in a launch the following month, it was emphasized that the units were still entirely experimental and the four engines were sold to the Admiralty on this clear understanding.

The T8 gas turbine is a simple cycle unit with an independent power turbine and, in its original form, developed 130 h.p. with a gas temperature of 800 deg. C. (1,472 deg. F.). The heat exchanger provided for in the original design was not fitted, since troubles were still being experienced with this component and the resulting gap was bridged by tubes. An integral gearbox reduced the power turbine speed in the ratio 7:1. A photograph and sectional arrangement of the T8 gas turbine are shown in Fig. 24 (Plate 2) and Fig. 25 respectively.

The four gas turbines were delivered early in 1951 after acceptance tests at the maker's works; one engine was installed in a 52½-foot harbour launch (No. 3964), shown in Fig. 26 (Plate 3), and the remainder went to the Admiralty Engineering Laboratory, West Drayton, for shore testing.

Harbour Launch 3964[7]

Details of the T8 gas turbine installation in the harbour launch are shown in Fig. 27. The engine was mounted on "Silentbloc" anti-vibration mountings and drove through a cardan shaft into a reversing gearbox which further reduced the shaft speed to 820 r.p.m. at 100 h.p. This gearbox was of a standard type, suitably modified to eliminate the unlocked neutral position, thereby reducing the risk of overspeeding the power turbine. The air supply to the gas turbine was drawn through twin deck cowls (one of which is clearly visible in Fig. 26 (Plate 3)), containing perforated zinc splitters packed with "Fibreglass" and passed down a trunk similarly lined. Exhaust gases from the twin ports passed into a common trunk of aluminized mild steel and thence to the funnel via an exhaust extractor designed to ventilate the engine room. The Rover gas turbine installation weighed 600lb. and occupied one-third of the engine room space required by the 2½ ton Diesel machinery originally fitted.

Trials of the harbour launch began in June 1951 and no difficulty was experienced with the operation or control of the

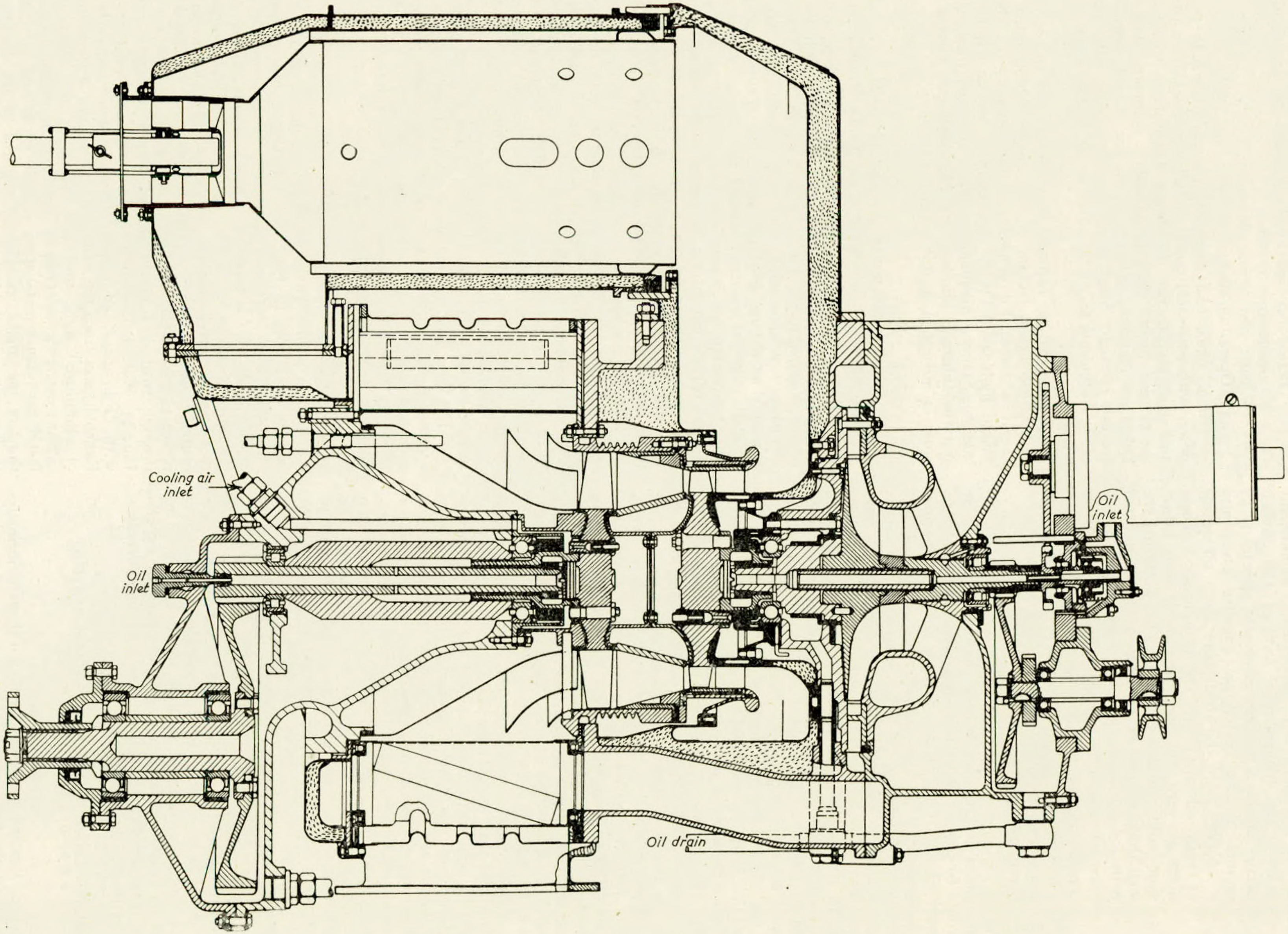

FIG. 25—*Sectional arrangement of T8 gas turbine*

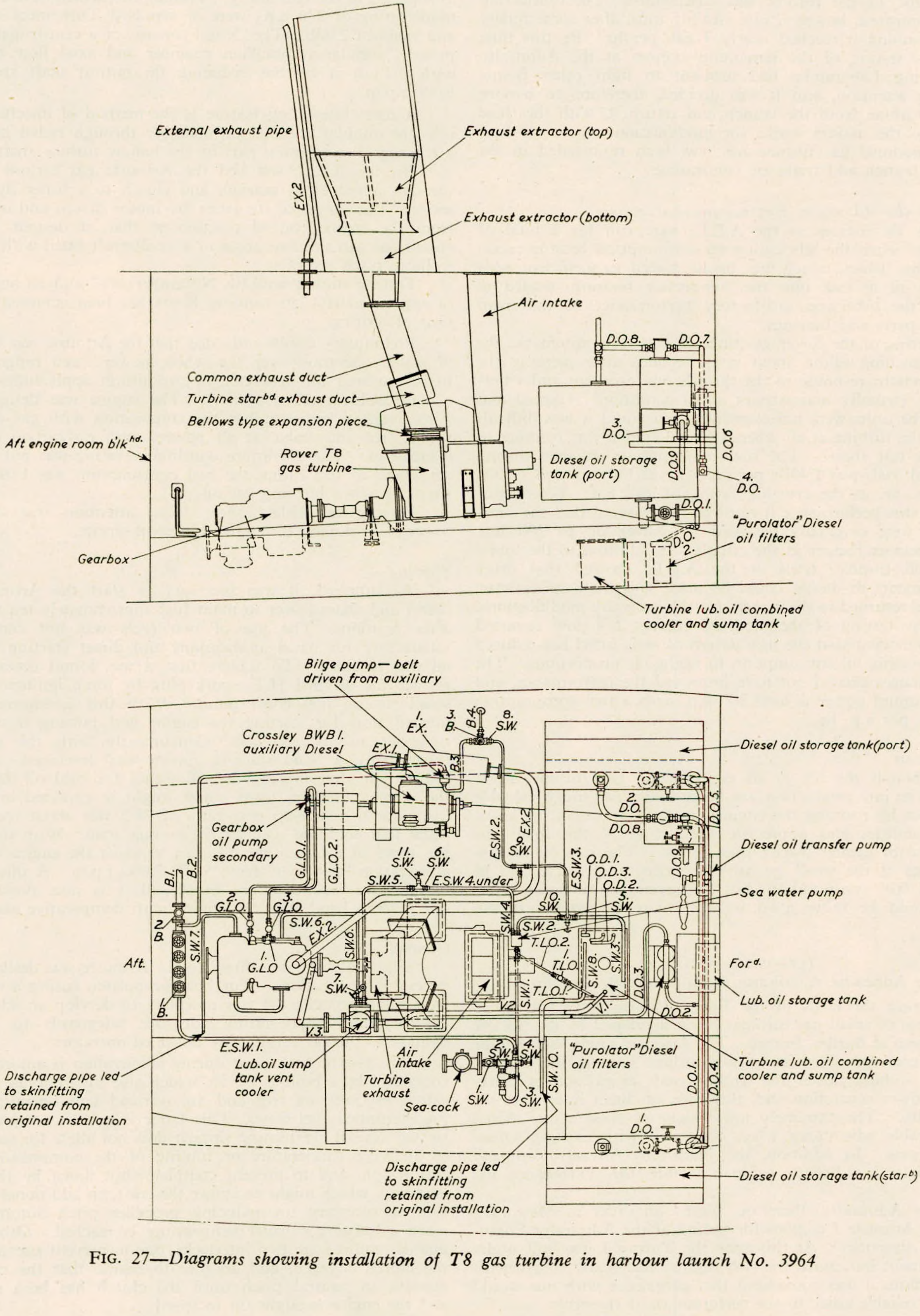

FIG. 27—*Diagrams showing installation of T8 gas turbine in harbour launch No. 3964*

craft. Apart from an impeller vane rub caused by wear in the main compressor bearing housing, the mechanical performance of the T8 gas turbine was satisfactory. The lubricating oil consumption, however, rose steadily until after some ninety hours' running it reached nearly 3 gal. per hr. By this time the shore testing of the remaining engines at the Admiralty Engineering Laboratory had brought to light other points requiring attention, and it was decided, therefore, to remove the gas turbine from the launch and return it, with the three others, to the makers works for modification.

A modified gas turbine has now been re-installed in the harbour launch and trials are continuing.

Trials at the Admiralty Engineering Laboratory

The T8 engines at the A.E.L. were run for a total of 212 hours when the lubricating oil consumption became excessive. This defect, which was finally traced to inefficient seals allowing oil to leak into the compressor housing, tended to obscure the otherwise satisfactory performance of the main rotating parts and bearings.

Starting of the Rover gas turbines was fully automatic, the engine reaching idling speed seven seconds after pressing the starter switch; response to the throttle was excellent and vibration was virtually non-existent at all conditions of speed and load. The units were not excessively noisy and it was difficult to hear the turbine at all when a Diesel engine was running in the same test shop! The fuel consumption obtained during the initial trials was 1·43lb. per s.h.p. hr. at 130 h.p. and 1·59lb. per s.h.p. hr. at the cruising rating of 100 h.p. When considering this performance it must be remembered that the components were originally designed to deliver up to 200 h.p. with a heat exchanger in the circuit. In addition to the lubricating oil trouble, trials at the A.E.L. showed that other improvements in design could be made and the engines were, therefore, returned to the makers for the necessary modifications.

Shore testing of the modified engines has now restarted and it is evident that the new design of seals fitted has reduced the lubricating oil consumption to negligible proportions. The other changes carried out have improved the performance, and the maximum power is now 200 h.p. with a fuel consumption of 1·1lb. per h.p. hr.

Conclusion

Although the T8 is an experimental gas turbine, never likely to go into production, the Navy has gained much valuable experience by running the engines, making it possible to assess the capabilities and appreciate the design of the small gas turbine with greater clarity than before. The sole major disadvantage of the small gas turbine seems, as predicted, to be its high fuel consumption, but for several naval applications this should be outweighed by the many advantages it can offer.

TURBOMECA ARTOUSTE

(See Appendix A, column 6; Appendix B, diagram 6)

During the trials of the Rover T8, publicity was given to a range of small gas turbines being developed by the Société Turbomeca at Bordes, France. The Artouste single shaft engine and its corresponding free power turbine version, the Turmo, were of suitable power for landing craft propulsion or emergency power generation and, therefore, of direct interest to the Admiralty. The extremely low weight of these units offered considerable advantages when compared with existing Diesel installations. In addition, the Blackburn Aircraft Company had obtained a licence to manufacture the Turbomeca gas turbines.

The Admiralty, therefore, placed an order in May 1952 for two Artouste I engines for testing at the Admiralty Engineering Laboratory. At this time the Turmo I was still under development but, since the two engines had many components in common, it was considered that experience with one would prove a reliable guide to the performance of the other.

Fig. 28 (Plate 3) and Fig. 29 show a photograph and sectional arrangement respectively of the Artouste gas turbines as supplied to the Admiralty. The engines, which have a maximum rating of 276 h.p., were of standard Turbomeca design, and weighed 216lb. The design consists of a centrifugal compressor, annular combustion chamber and axial flow turbine with a built-in gearbox reducing the output shaft speed to 6,000 r.p.m.

A most interesting feature is the method of injecting fuel into the annular combustion chamber through radial holes in a rotating disc forming part of the hollow turbine shaft.

On the A.E.L. test bed the Artouste gas turbine drives through a reduction gearbox and clutch to a water dynamometer. The sluices of the latter are motor driven and operated from the engine control position so that, if desired, testing conditions can simulate those of a small craft fitted with a controllable pitch propeller.

Testing started on 13th November 1952 and an aggregate of approximately 750 running hours has been achieved at the time of writing.

Preliminary results indicated that the Artouste was capable of stable operation over the whole power/speed range likely to be required for generator or propulsion applications (with a controllable pitch propeller). The engine was designed to burn aviation kerosene, but the combustion with gas oil was smoke free and stable at all powers with no carbon deposit whatsoever. The maximum continuous rating was put at 250 s.h.p. and at this rating the fuel consumption was 1·04lb. per s.h.p. hr. when burning gas oil.

Having established these facts, attention was directed towards developing the engine for naval service.

Starting

As supplied, it was necessary to start the Artouste on petrol and change over to main fuel approximately ten seconds after ignition. The use of two fuels was not considered satisfactory for naval applications and direct starting on gas oil was specified. To achieve this, it was found necessary to replace the original H.T. spark plug by torch igniters with a small electric fuel boost pump. With this arrangement the normal time for starting the engine and putting it on load is about twenty seconds. Concurrently with the ignition experiments, a hand starting system was developed. It was found that after making due allowance for cold oil drag and the various auxiliary loads which might be expected in a boat installation, a step-up gear ratio of 78·5 was about the maximum that could be used by the average man. With this ratio the speed of rotation was too fast to assist the engine over its acceleration "flat spot" from 5,000-7,000 r.p.m. A three-speed bicycle gear was therefore fitted and it is now possible for one man to hand start the engine with comparative ease.

Control

The control system fitted to the Artouste was designed for generator applications. For boat propulsion (using a controllable pitch propeller) it was necessary to develop an additional control unit incorporating adequate safeguards to prevent damage to the gas turbines by unskilled operators.

The rate of fuel input during acceleration is automatically controlled by a built-in device which also incorporates a lubricating oil pressure trip and an overload trip operating at a predetermined fuel flow. This latter is not an adequate protection against overheating since it does not allow for variations in air inlet temperature or fouling of the compressor. For this reason, and to prevent complete shut down by the overload trip, which might endanger the craft, an additional control unit is necessary for reducing propeller pitch automatically when a limiting exhaust temperature is reached. Other safeguards required are two interlocks, one to prevent starting with the clutch engaged, and another to ensure that the propeller remains in neutral pitch until the clutch has been engaged and the engine brought up to speed.

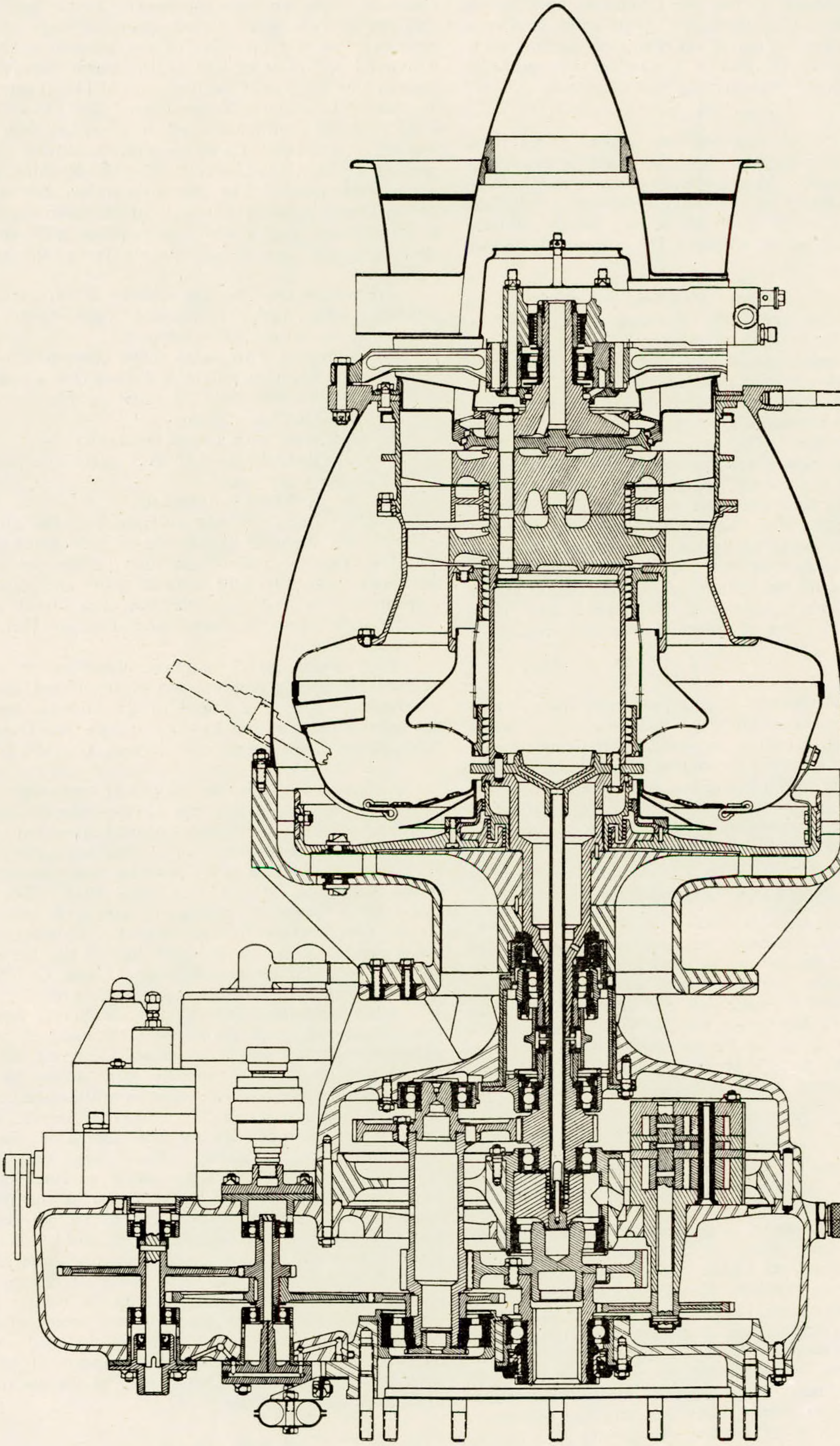

FIG. 29—*Sectional arrangement of* Artouste *gas turbine*

A simple and compact control box incorporating the above features has been designed at the A.E.L. and is now in use on the engine test bed. It consists of a single lever, used only on starting, which gives sequential operation of the fuel cock, clutch and speed governor, and a handwheel for propeller pitch, used in subsequent manœuvring and operation.

Silencing

A disadvantage of the Artouste gas turbine is the noise level, which is unacceptably high for most naval applications, and silencers are essential. Measurements taken at A.E.L. with an absorption type silencer on the exhaust showed a reduction in noise level from 111 db to 99 db at full power. Future work will be concentrated on silencing the compressor intake.

Running Experience

At the time of writing, some 750 hours' running has been carried out on the two Admiralty Artouste I gas turbines. Apart from periodic injection of kerosene to wash the compressor, the routine maintenance has been surprisingly small and the lubricating oil consumption negligible.

Stripping of the engines has revealed minor design deficiencies which can easily be rectified, such as fretting of the turbine bearing support pins. The only serious defect has been scaling of the turbine blades and casings. This confirms the makers' fear that the scaling resistance of their turbine materials might not be adequate when burning gas oil (average sulphur content 0·8 per cent). No similar defect has occurred in Rover turbines operating at higher temperatures with the same fuel, and it is considered that the use of normal British materials would eliminate the trouble. The combustion chambers remained in perfect condition throughout and these components are certainly one of the most attractive features of the design.

Conclusions

The Turbomeca Artouste is an extremely light and compact gas turbine with a fuel consumption which is most creditable for its size. If British materials are used for the turbines, no difficulty is foreseen in adapting the engine to suit naval requirements for short life propulsion engines and generators of the emergency type; but, before the evaluation can be regarded as in any way complete, many more running hours are required to establish life and reliability.

III.—AUXILIARY MACHINERY

INTRODUCTION

There are a number of naval auxiliary applications where gas turbines have potential advantages over other prime movers. These can be broadly divided into continuous running machines where low fuel consumption and comparatively long life are important, and emergency engines which run at very infrequent intervals and then only for short periods. In this latter category engines with a short life and high fuel consumption can be accepted in the interests of compactness and simplicity.

MAIN ELECTRIC GENERATORS

In the first category come the main electric generators supplying power for fighting equipment and general ships' services.

The requirements for naval generators are similar to those for propulsion machinery given on page 1, except that good efficiency is only necessary at higher powers (say, 50 per cent and above) and governing replaces the manœuvrability requirement. Unlike propulsion machinery, naval electric generators normally operate at a comparatively high percentage output and must therefore be designed for long life under this condition.

Warship generators are at present powered either by steam turbines or Diesel engines. It is generally agreed that steam turbo generators perform satisfactorily but they are comparatively heavy in themselves and require the services of a boiler, associated steam systems and auxiliaries. The most serious disadvantage, however, is that loss of steam involves loss of electrical power, and war experience showed that in many cases this proved vital in a seriously damaged ship. It is, therefore, desirable that a proportion of the generators should be self-contained and independent of the steam supply. Up to the present this has meant the inclusion of Diesel generators, which are heavy, particularly in sizes above, say, 350 kW., and require a considerable maintenance effort to ensure their reliability in service. Moreover, Diesel generators cannot idle for long periods at light load, which may be desirable under certain action conditions. The gas turbine has the essential virtue of the Diesel in being independent of steam supply but, being a simple rotary engine with few working parts, its maintenance should be less, and it has the ability to idle indefinitely on light load.

To summarize, the gas turbine is expected to have the following advantages over existing prime movers for the main generating machinery of warships.

1. Compared with steam turbo generators:—
   - (*a*) Reduced weight and space (for whole installation).
   - (*b*) Independence of steam supply.
   - (*c*) Quicker starting.
2. Compared with Diesel generators:—
   - (*a*) Reduced weight and space (particularly in the larger size).
   - (*b*) Reduced maintenance.
   - (*c*) Ability to run on light load for long periods.
   - (*d*) Reduced lubricating oil consumption.

The disadvantages of gas turbo generators are that comparatively large inlet and exhaust ducts are required, the fuel consumption is nearly double that of a Diesel (though comparable with steam machines) and distillate fuel is at present necessary.

In a steam driven warship, therefore, it would appear desirable to have a combination of steam and gas turbo main generators, while in a Diesel or gas turbine driven warship, gas turbo generators may have advantages over Diesel generators, particularly in the larger sizes (above, say, 350 kW.).

ALLEN 1,000-KW. GAS TURBO ALTERNATOR[1, 2, 18, 19]

(See Appendix A, column 7; Appendix B, diagram 7)

The potential advantages outlined above led the Admiralty to consider the development of a naval gas turbo alternator and a contract for a 1,000-kW. machine was placed with W. H. Allen, Sons and Co., Ltd., in April 1948. The specification called for a maximum continuous rating of 1,000 kW. with a 20 per cent overload for ten minutes, allowing for a loss of 0·6lb. per sq. in. in the air inlet duct, 0·4lb. per sq. in. in the exhaust duct and under temperate 15 deg. C. (59 deg. F.) or tropical 38 deg. C. (100 deg. F.) conditions.

After carefully balancing the conflicting requirements of low weight and space with reasonably good efficiency, a comparatively simple open cycle set was designed, having an axial compressor of 4¼ to 1 pressure ratio driven by a two-stage turbine, an annular heat exchanger, a multi-chamber combustion system disposed symmetrically round the engine, and a single-stage power turbine driving the alternator through Allen-Stoeckicht epicyclic gearing. Plain sleeve type bearings were used throughout. A separate power turbine was introduced to improve the part load performance in the normal service operating range from 50 per cent to 80 per cent of power, and to prevent the set stalling due to sudden overloads under action conditions. This complicates the governing problem, however, and to assist the speed governor during sudden load changes a small flywheel is fitted on the output turbine shaft (immediately adjacent to the reduction gear) whilst the compressor rotating assembly is specially designed to have a low moment of inertia. A sectional arrangement of the unit is shown in Fig. 30, while photographs of the gas turbine appear in Figs. 31 and 32 (Plate 3).

Trials at Firm's Works

Trials (without heat exchanger) started in March 1951 and full speed, full load and overload were achieved in the first series of tests with the minimum of mechanical teething troubles. The work was greatly facilitated by a consultancy agreement with the Bristol Aeroplane Co., Ltd., which entitled Allen, Sons and Company to design data, advice on production methods and the use of certain testing facilities. Testing was continued at the firm's works with the heat exchanger for a total period of 860 hours. Apart from mechanical defects in the heat exchanger which are discussed below, there were no major troubles. The result of the preliminary governing trials are of interest since they demonstrate that a gas turbo alternator with free power turbine and heat exchanger is capable of governing within close limits.

Detailed results are as follows:—

Condition	Measured fluctuation in speed, per cent
Gradual load changes, per cent, between	
0 and 100	1·2 maximum
Instantaneous increase of load, per cent, from	
0 to 25	−4·6
25 to 50	−2·5
50 to 75	−2·4
75 to 100	−2·2
Instantaneous decrease of load, per cent, from	
100 to 75	+1·55
75 to 50	+2·1
50 to 25	+2·3
25 to 0	+2·9

In addition, the set will accept instantaneous load changes of 75 per cent without the emergency gear operating and modifications are in hand to increase this to 100 per cent.

During the latter part of the trials at Allen's works, there was a steady fall off in performance which could not be accounted for other than by leakage. On opening up the heat exchanger, a ring securing the heat exchanger spacer to the power turbine casing was found to be sheared and as a consequence the tube plate was retained only at its outer diameter. The air pressure caused the unsupported tube plate to buckle and the innermost two rows of tubes released their grip and the ferrules projected through the plate as illustrated in Fig. 34 (Plate 4). This, of course, accounted for the leakage and loss of performance. Another defect revealed on completion of the 860 hours' testing was heavy scaling of the heat exchanger tubes in the vicinity of the incoming exhaust gases. The material of the tubes is aluminium bronze and the nominal steady temperature of the gases at entry to the heat exchanger about 480 deg. C. (896 deg. F.) though this may have risen momentarily as high as 650 deg. C. (1,202 deg. F.). The mean wall thickness of the tubes is 0·018 inch and the loss of material due to scaling was in the region of 0·002 inch.

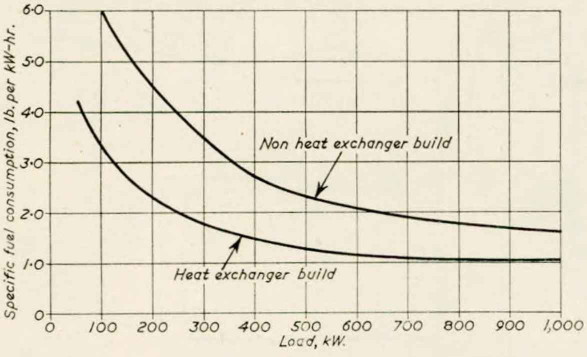

FIG. 33—*Specific fuel consumption curves for 1,000-kW. gas turbo alternator. Actual test results using Admiralty Diesel fuel (gas oil), calorific value 18,500 B.Th.U. per lb. (10,300 C.H.U. per lb.)*

Trials at Admiralty Test House

The 1,000-kW. set has now been re-erected at the Admiralty test house in the National Gas Turbine Establishment, Pyestock, with a stronger design of heat exchanger retaining ring and defective tubes replaced in alternative copper base alloys. A full programme of testing is being carried out, including endurance running, further governing trials and minor development work to make the machine suitable for shipboard use.

At the time of writing, 817 hours have been run at Pyestock and the specific fuel consumption curves obtained are shown in Fig. 33. (The curve for the heat exchanger build has been corrected to allow for leakage which has again been experienced.)

Testing at the Admiralty test house has revealed the following points:—

(*a*) The heat exchanger requires modification to give greater freedom for differential expansion. A better method of securing the tubes in the end plates, and fewer casing joints also appear desirable.

(*b*) Without expensive instrumentation, it is difficult to establish whether a heat exchanger is leaking. This difficulty will be very real in actual service.

(*c*) Initially there were occasional failures of the combustion chambers to "cross light" when starting. Larger interconnectors have been fitted and lighting up with the present system, with ignition provided by low tension glow plugs, has been very good.

(*d*) Some auxiliaries are of the aircraft type and the life of these components does not appear adequate for main generator applications.

(*e*) The general mechanical design (heat exchanger excepted) and the combustion system have proved extremely successful. When action has been taken to rectify (*a*) and (*d*) above, the set should be capable of operating for very long periods without maintenance.

Conclusion

Initial experience with this first naval gas turbo alternator design has been most encouraging. There is every indication that a thoroughly reliable and comparatively efficient machine can be developed for an all-up weight (gas turbine only) of 10·5lb. per h.p. Further trials at the Admiralty test house will be necessary, but it is also desirable to obtain early operating experience at sea. An order has been placed, therefore, with W. H. Allen, Sons and Company for two additional gas turbo generators, each of 500 kW. capacity, which it is intended to install afloat in the near future.

EMERGENCY ENGINES

There are a number of naval requirements for emergency or intermittent equipment where light weight, compactness, quick starting and low maintenance are of primary importance, while high efficiency or long life are seldom required. Perhaps the most important machines in this category are emergency electrical generators and portable pumping equipment. The simple gas turbine is the ideal prime mover for these applications and great savings in weight and bulk compared with existing Diesel engines can be made. Maintenance should also be reduced, but there may be difficulty in disposing of the large volume of exhaust gases in some cases.

ALLEN EMERGENCY GAS TURBINE FOR GENERATOR DRIVE

(See Appendix A, column 8; Appendix B, diagram 8)

In 1950, W. H. Allen, Sons and Co., Ltd., in collaboration with the Engineer-in-Chief's Department and the Naval Marine Wing of the National Gas Turbine Establishment, began a design study for a gas turbine suitable for driving a small emergency generator. In August 1951, the Admiralty placed a development contract for one unit, the firm agreeing to meet a proportion of the total cost.

Emergency generators normally run for very short periods and then only at infrequent intervals, so that fuel consumption is unimportant. It was possible, therefore, to reduce the design to the ultimate in simplicity and employ a simple cycle gas turbine with one single rotating element (see Fig. 35 (Plate 4)). A photograph of the Allen emergency gas turbine driving a generator on test as shown in Fig. 36 (Plate 4), and a sectional arrangement drawing of the unit (with combustion chamber omitted) appears in Fig. 37. In the interests of robustness, plain bearings are fitted and the centrifugal compressor and inward radial flow turbine are machined from the same forging of Rex 448 steel. Originally the complete rotor was overhung and was designed to run above the first critical speed under normal conditions. During the initial trials at the end of 1952, however, it was found that the amplitude of whirl was so great as the critical speed was approached that the rotor rubbed on the casing. It was, therefore, decided to change to the present design with a bearing either side of the rotor, which now runs well below the critical speed under all conditions.

Development testing of the engine continued during 1953, and at the time of writing a total of 763 hours have been run. From the mechanical point of view the engine has performed very satisfactorily and no major defects have been experienced, but the power output and thermal efficiency are below the design estimates (see Appendix A, column 8). The maximum power obtained at the designed gas temperature of 730 deg. C. (1,346 deg. F.) during the initial tests was 123 h.p. with a specific fuel consumption of about 2·0lb. per h.p. hr. The main reason for the disappointing performance was considered to be a poor design of compressor inlet casing, resulting in an overall compressor efficiency some 10 per cent below the estimated value.

After the initial trials a modified casing and compressor rotor were fitted which have raised the power output to 180 h.p., but the compressor efficiency is still too low and further modifications are being considered.

For naval emergency gas turbines it is most desirable that the starting arrangements should be entirely self contained and independent of any external sources of supply. Preliminary tests have, therefore, been carried out recently, during the development running, with a Rotax cartridge starter. This unit consists of two 720-gram cordite cartridges firing on to a small turbine wheel. The tests have been very successful, the cartridge starter taking only three seconds to accelerate the gas turbine to 9,000 r.p.m. when it pulls away under its own power up to synchronous speed.

Conclusion

Further development will be necessary before the designed performance is achieved, but an extremely simple, robust and durable emergency gas turbine has been produced which should prove valuable for many naval emergency applications. It appears that the inward radial flow turbine fitted in this set is on the upper limit for size and for larger units an axial turbine would be preferred.

GAS TURBINE PORTABLE PUMPS

Another emergency application where a lightweight gas

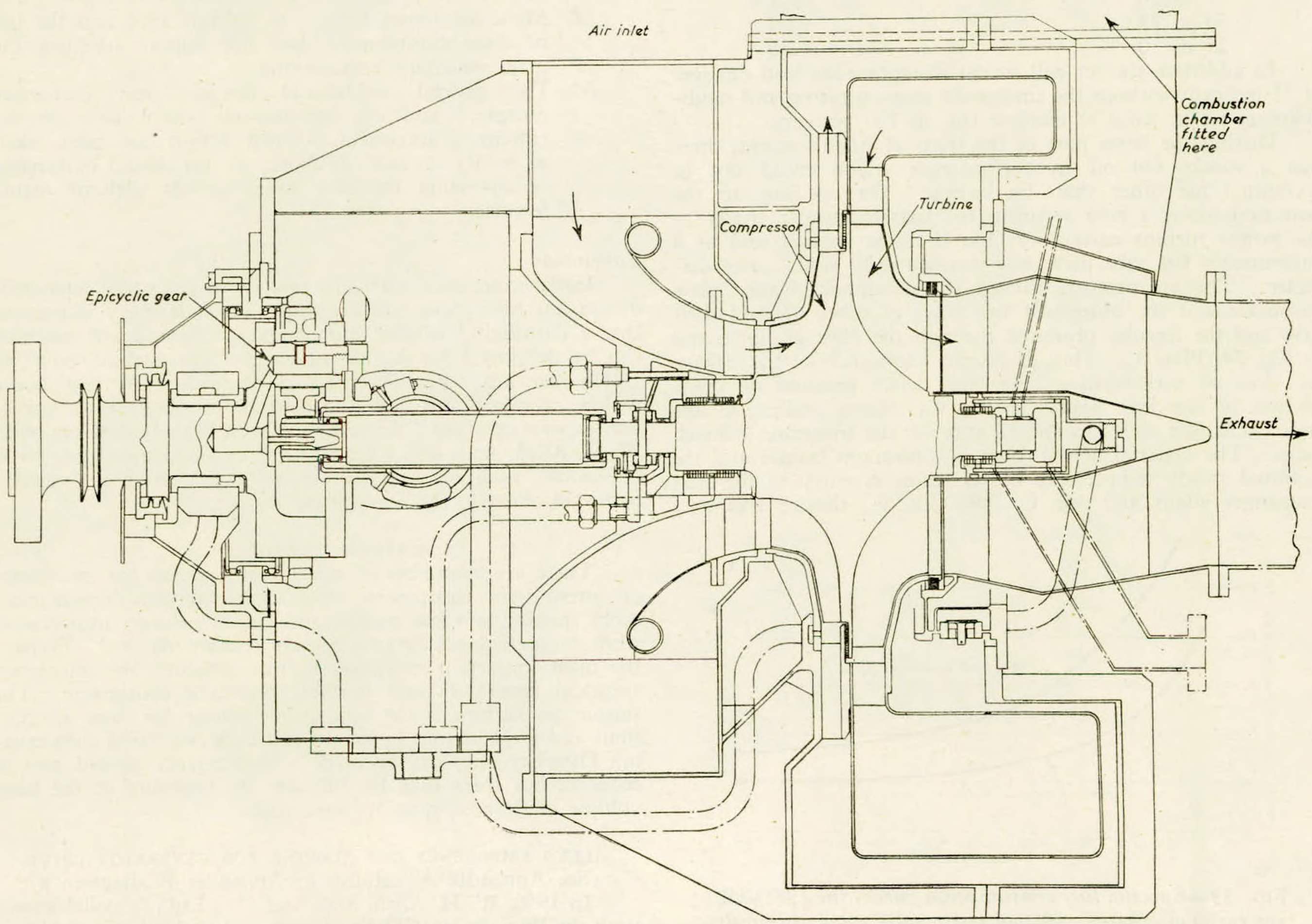

FIG. 37—*Sectional arrangement of small emergency gas turbine (without combustion chamber*

turbine has considerable advantages is for portable salvage or fire pumps. To investigate this application the Admiralty have very recently placed an order with the Rover Motor Company for three Neptune gas turbine driven portable pumps. A photograph of one of these pumps (without hand starting equipment) is shown in Fig. 38 (Plate 4). The output of the unit is 500 gal. per min. at a delivery pressure of 100lb. per sq. in. when pumping from a static lift of 10 feet. The dry weight complete with frame, fuel tank, hand starting mechanism and fully instrumented panel, is approximately 200lb. The pump will normally be hand started and the suction line is primed by an air ejector fed from the gas turbine compressor.

GENERAL CONCLUSIONS

Characteristics and Type of Construction Required for Naval Gas Turbines

The problem confronting the Navy in the gas turbine field has been to determine how the characteristics of this new prime mover can best be used to improve the fighting efficiency of the Fleet. This is no easy matter, since gas turbines can be built in a bewildering variety of forms, each type possessing widely different characteristics. Moreover, naval requirements are, in general, very different from those of industrial, merchant marine, or aircraft applications.

As a result of the experience obtained to date, the author considers that the greatest single advantage which the gas turbine can offer for naval applications is its ability (particularly in the simpler forms) to pack more power in less weight and space than any other prime mover. To achieve this characteristic, an open cycle plant is essential and this type also lends itself to the maximum amount of development in the future. But it is also necessary to construct the gas turbines on lightweight lines. Looking at the specific weights in Appendix A, the great difference between the aircraft type propulsion gas turbines and the E.L.60A, which adheres closely to steam turbine practice, is at once apparent. The heavy type of construction is also more prone to thermal distortion and reduces manœuvring flexibility. This does not imply that the aircraft designs described above are considered ideal for future naval machinery and, in most cases, they were only accepted in order to obtain early operating experience. Reliability would be improved by fitting plain sleeve bearings in place of ball bearings and the temperatures, stresses and corrosion allowances need modification for longer life. In short, the whole engine (including auxiliaries and control gear) must be made more robust. But it is nevertheless considered essential to base the design of naval gas turbines on the aircraft approach, with increased scantlings and modifications where necessary, than to follow in the tradition of established steam practice. Unless this is done, the important military advantages of reduced weight and space, rapid starting and great flexibility in operation may never be realized[20].

Assuming that the design of future naval gas turbines is based on the lines indicated above, the major factors likely to influence their use in warship applications are discussed below.

Performance

The high fuel consumption of the simple gas turbine, particularly at low powers, is clearly shown in the performance curves of the Gatric and G2 in Fig. 2. These engines are based on aircraft designs which are now over ten years old, however, and with modern components, fuel consumptions below 0·7lb. per s.h.p. per hr. at full power could be obtained with reasonable life. To effect this improvement a higher compression ratio is necessary, which tends to reduce flexibility and may create compressor blade vibration problems. By splitting the compressor (twin spool design), higher compression ratios can be achieved with improved flexibility and fuel consumptions below 0·6lb. per s.h.p. per hr. could now be obtained with this type of design. These developments will not alter the steeply rising performance characteristics of the simple gas turbine, however, and consumption figures at half load will remain some 25 per cent higher than at full power. Simple engines on their own are, therefore, intrinsically unsuitable for applications where economy at low power is required.

To obtain higher efficiencies and, more particularly, to improve part load performance, a more complex cycle with heat exchange and intercooling is necessary. Referring again to Fig. 2, the great superiority in part load efficiency of the R.M.60 compared with the G2 should be noted. This improvement has been obtained at the expense of considerable complication and an increase in specific weight from 2·28 to 5·3lb. per h.p. It is also interesting to compare the performance of the R.M.60 with the original steam machinery fitted to H.M.S. *Grey Goose*[17].

		R.M.60	Steam machinery
Total s.h.p.		10,800	8,000
Weight		5·3 lb. per h.p.	14 lb. per h.p.
Specific fuel consumption lb. per s.h.p. per hr.	Full power	0·66	0·88
	½ power	0·61	1·03
	1/6 power	0·76	1·56

Aerodynamically, the R.M.60 is certainly capable of further improvement in performance, but the introduction of plain sleeve bearings to increase reliability and give longer life would involve serious losses in a cycle of this type, particularly at part load.

Before leaving the subject of performance, it is worth noting that the specific weight of simple gas turbines increases with power. Theoretically, this increase should follow the "square-cube law"; e.g. if an engine were scaled up from 5,000 h.p. to 10,000 h.p., its specific weight should increase by $\sqrt{\frac{10}{5}}$ = 1·4 times. In practice, the increase appears to be about half the amount predicted by the square-cube law.

Life

The "life" of a gas turbine normally refers to the number of hours which the high temperature turbine discs and blades will run before there is danger of failure from creep. In a simple cycle gas turbine, this life increases rapidly at lower powers. For example, at 4,500 h.p., the life of the G2 (on a creep basis) is 300 hours, but at 3,500 h.p. it would be over 2,500 hours. This characteristic is not so marked in complex cycles of the R.M.60 type, however, since the improved part load performance is mainly achieved by a slower fall in gas temperature. Nevertheless, the increase of life at reduced output is important when considering the application of gas turbines to naval machinery. As explained in the introduction, a warship uses high power for only a very small fraction of the total operating time. It is doubtful, for example, if many warships exceed 2,000 hours at full power during their whole life and in some cases this figure may be as low as 500 hours. For naval propulsion machinery, therefore, the full power life can be extremely short, judged by industrial standards, and there is only a requirement for longer life at reduced output. Even main generators seldom operate at full power and, although detailed records are not available, the majority of running probably occurs in the range between 50 per cent and 80 per cent power.

In the present state of gas turbine development, combustion chamber liners, bearings, seals, auxiliaries, etc., usually fail before the engines are "life expired" on a creep basis. From the mechanical point of view, however, there is no fundamental reason why the lightweight type of construction advocated above should not be capable of giving reliability and long life in all components except the "hot parts". The overhaul periods would then be controlled by the combustion chamber liners and the "creep life" referred to above.

Effect of Ambient Temperature

It is well known that gas turbine performance is extremely sensitive to ambient conditions and stated figures of power or efficiency mean little unless associated with a definite temperature and pressure. Fig. 23 shows the power variation in the R.M.60 with changes in air and sea temperature. In the case of the G2, the maximum power reduces from 4,500 h.p. to 4,000 h.p. with an increase in inlet air temperature from 15 deg. C. (59 deg. F.) to 27 deg. C. (81 deg. F.). This large variation in performance may give rise to difficulties in naval vessels which must operate satisfactorily in arctic or tropical climates. The size of gas turbine will usually be fixed by the output specified for tropical conditions, and in cold climates considerably more power will theoretically be available at the same gas temperature. To take advantage of this power, it is necessary to stress the turbine, gearing, shafting and propellers accordingly, which results in a heavier installation.

There are obvious advantages in quoting all gas turbine performance figures at a standard temperature and a figure of 15 deg. C. (59 deg. F.) is used throughout this paper. When specifying the ambient conditions for naval gas turbines, it should be borne in mind that propulsion machinery can only be run near full power in the open sea, where the air temperature seldom exceeds 33 deg. C. (91 deg. F.), whereas main generators may be required to develop full power in land-locked tropical harbours where the air temperature is considerably higher.

Duct Sizes(1)

Gas turbines require much larger quantities of air than other prime movers. Compare, for example, the air rate of the R.M.60 (70lb. per h.p. per hr.) or the G2 (87lb. per h.p. per hr.) with average figures for Diesel machinery or steam turbine plant (11 and 14lb. per h.p. per hr. respectively). This situation is aggravated by the greater sensitivity of gas turbines to inlet and exhaust pressure losses. (The power falls approximately 10 per cent for each 1lb. per sq. in. inlet pressure loss and by 5 per cent for each 1lb. per sq. in. exhaust pressure loss. A pressure loss of 1lb. per sq. in. in either the inlet or exhaust causes approximately 5 per cent loss in efficiency in addition to the loss of power.) The large duct sizes necessary in gas turbine installations are a disadvantage, since they take up valuable space, and the increased sizes of deck opening are a source of structural weakness and increase the vulnerability to battle damage.

Reliability and Maintenance

The naval gas turbine is still in its infancy and many defects and teething troubles have occurred in the early designs. Basically, it is the simplest of all engines, however, and when the accumulated experience to date is incorporated in new designs the author is convinced that the gas turbine (in its simple forms) can be made superior to all other prime movers as far as reliability and maintenance are concerned, without sacrificing its very high power-weight ratio. Moreover, the small size of components will greatly facilitate their removal and replacement for maintenance purposes.

The more complex cycles will inherently have somewhat less reliability but should compare favourably with other engines. It also appears that a heat exchanger designed for minimum weight and space may add appreciably to the maintenance commitments.

Flexibility and Control

The majority of gas turbines described in this paper have independent (free) output turbines, giving flexibility of torque and speed over the whole power range. This characteristic is essential for propulsion with fixed pitch propellers, but at idling speed some residual torque will always be available, equivalent to about three per cent of full output. For generator applications a free power turbine improves part load efficiency, and enables the machine to accept sudden overloads in emergency without stalling; but the governing problem is greatly increased.

A single shaft gas turbine delivers no power below about 30 or 40 per cent of maximum speed and this type will normally be confined to constant speed machines such as generators. It does appear feasible, however, to operate a single shaft design as a propulsion engine with a controllable pitch propeller, but this arrangement would be most uneconomical for low speed cruising.

It has been effectively demonstrated in the Gatric, G2, and Rover T.8 installations that gas turbine controls can be reduced to a throttle lever and starting switch. This simplicity has obvious operational advantages.

Production Costs(1)

An assessment of production costs at this early stage in the evolution of naval gas turbines may be misleading, since manufacturing experience is very limited and any new design may involve considerable development. Nevertheless, the present cost of manufacturing a proven design of simple engine in small numbers should not exceed £15 per h.p., which compares favourably with other prime movers ordered to special requirements.

The production of lightweight gas turbines involves precision machining to high standards of accuracy but is well suited to mass production in time of war. If the numbers justify full scale tooling-up, the cost of simple cycle naval gas turbines should approach that of aircraft propeller turbines, which are currently being manufactured for about £7 per h.p.

Fuel

The gas turbines described in this paper will operate satisfactorily on a wide range of distillate fuels, including Admiralty Diesel (gas oil) and aviation kerosene, but they can only burn residual fuel for short periods in emergency and then only if suitable heating equipment is provided.

There are many naval applications where distillate fuel is acceptable, but it is generally assumed that before gas turbines can replace steam installations for the main propulsion of large warships, they must be capable of burning residual fuel. The burning of residual fuel in open cycle gas turbines presents formidable problems, the most important being deposition and corrosion of the turbine blades by inorganic constituents in the ash. A large programme of research and development is being directed to the solution of these problems and a Ruston and Hornsby 750-kW. TA gas turbine alternator will shortly be installed at the Admiralty Test House, N.G.T.E. with the object of carrying out extensive trials on the burning of residual fuels. It appears that by controlling combustion and using small quantities of additives in the fuel both deposition and corrosion may ultimately be reduced to acceptable limits. At the time of writing, however, little practical experience in burning residual fuels at the high temperatures necessary for naval gas turbines exists.

Reversing(2)

In steam installations reversing is provided by a separate astern turbine which idles in the condenser vacuum during ahead running. There is no such vacuum in a gas turbine so that windage losses would be excessive. In addition, there would certainly be difficulty in keeping the control valves gas-tight at high temperatures and the complicated ducting necessary might compromise ahead performance. If gas turbines are to be used as the sole means of propulsion, some external means of reversing is, therefore, essential. Possible methods of providing this reversing are:—

(*a*) Electric drive.
(*b*) Controllable pitch propellers.
(*c*) Mechanical reversing gears.
(*d*) Hydraulic reversing couplings.
(*e*) Separate lightweight gas turbine for astern use only.

A detailed discussion of these methods is outside the scope of this paper, but it is worth mentioning that (*e*) is only practical when the astern power required is a small fraction of the ahead power. Experience with (*b*) will be obtained in *Grey Goose,* and (*c*) has been used successfully in Harbour Launch No. 3964.

Noise

High intensity noise appears to be inherent in the design of gas turbines approaching the required standards of lightness for naval applications. The majority of this noise emanates from the compressor inlet and the exhaust, where silencing can be readily applied. At the compressor inlet the noise is usually of high frequency, consisting of fundamental and harmonics of the number of blades per row times the speed of rotation. Noise from this source can be reduced simply and effectively by fitting splitters and by lining the inside of the duct with sound insulating material. In M.G.B.2009, for example, this procedure resulted in a noise reduction of 39 decibels from the original level of 117 decibels. At the exhaust, noise covers a wide band of frequencies, and can best be silenced by reducing gas velocities, by fitting torpedo type splitters, and by lining the funnel with silencing material.

THE FUTURE OF THE GAS TURBINE IN THE ROYAL NAVY

The gas turbine will only supplant existing machinery in warship applications where it is shown to be generally superior, based on the special naval requirements listed earlier in this paper. The only true criterion for comparison is service experience at sea, and this is unfortunately still extremely limited, but sufficient knowledge has been gained from the projects described above to indicate the future of the gas turbine in the Royal Navy with some confidence[21].

In the author's opinion, gas turbines will be introduced in increasing numbers for the propulsion of high speed coastal craft. In major warships the first applications will be as "boost" units for use at high powers with steam turbines or possibly Diesel machinery for cruising. At a later stage, gas turbines may become the sole means of propulsion in some warships. Gas turbines will also be found in certain landing craft and ships' boats in the near future.

Turning next to the auxiliary machinery field, gas turbine generators for normal or emergency use will be fitted in increasing numbers and gas turbine portable pumps introduced for fire fighting and salvage. For generator applications the possibility of combining a waste heat boiler with the gas turbine is an attractive means of providing two essential auxiliary services in one machine.

There are other naval applications, not yet fully explored, where the characteristics of the gas turbine may show to advantage. Among these are boiler blowers, de-icing equipment for use in arctic regions[21] and the provision of low pressure air for salvage and other purposes.

Looking further into the future, it must be remembered that the first tentative steps in British naval gas turbine development were taken just over ten years ago, and this new prime mover is, therefore, still only on the threshold of development. Component efficiencies will certainly increase in the future and, when cooling techniques allow higher gas temperatures to be used, it is the author's opinion that gas turbines will find very wide applications in naval vessels. The consequent saving in weight and space, the reduced maintenance and the rapid starting and manœuvring will greatly increase the fighting efficiency of the Fleet. In fact, the partial supersession of existing machinery by gas turbines may well prove as revolutionary as the change from reciprocating engines to steam turbines at the turn of the century.

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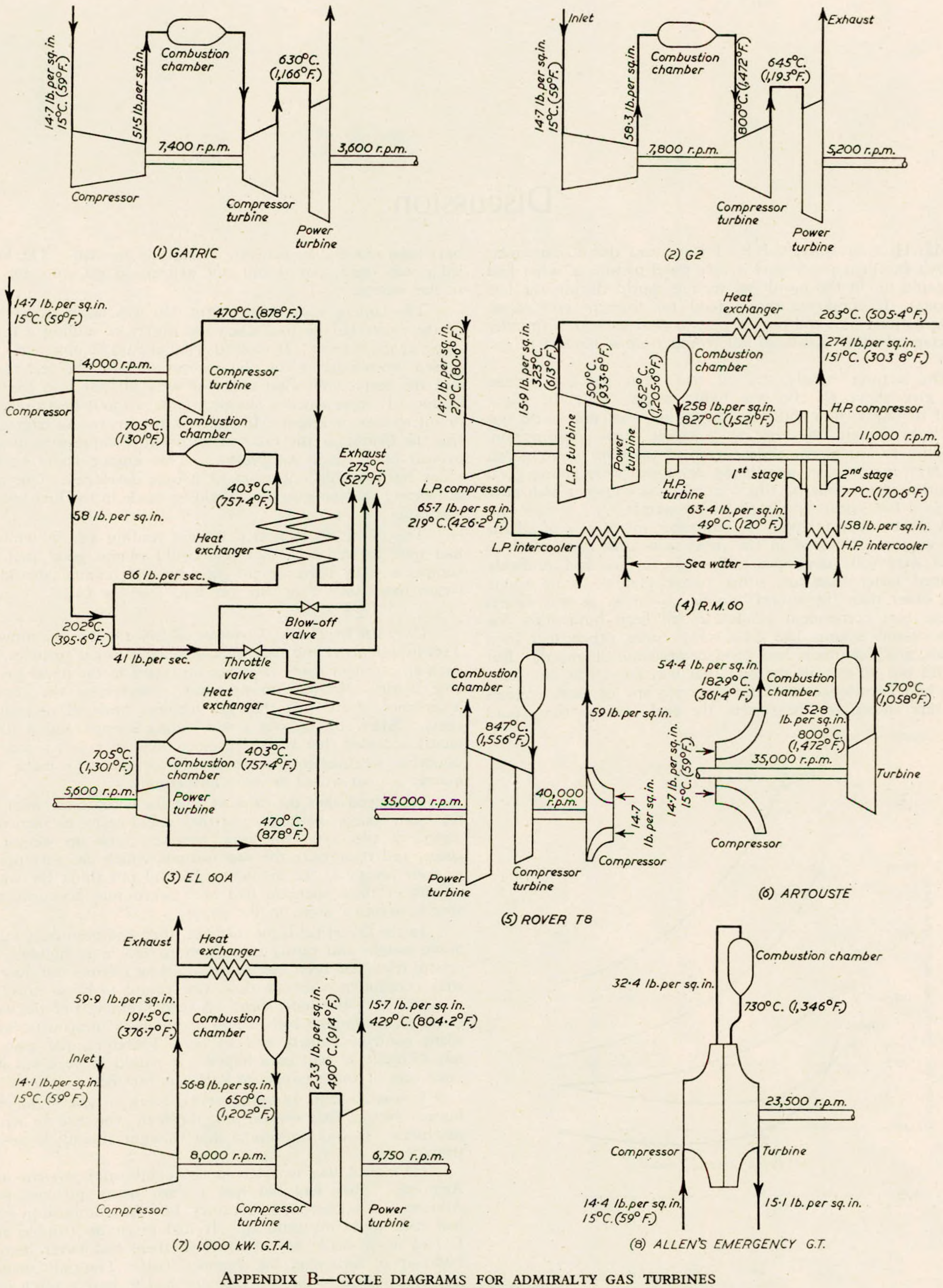
APPENDIX A—DESIGN DETAILS OF BRITISH NAVAL GAS TURBINES

Column Number		1	2	3	4	5	6	7	8
Engine		Gatric	G2	E.L.60A	R.M.60	T8	Artouste I	1,000kW.G.T.A.	EmergencyG.T.A.
Maker		Metropolitan Vickers and Co., Ltd.	Metropolitan Vickers and Co., Ltd.	English Electric Co., Ltd.	Rolls Royce, Ltd.	Rover Motor Co., Ltd.	Turbomeca (Blackburns)	W. H. Allen, Sons and Co., Ltd.	W. H. Allen, Sons and Co., Ltd.
Maximum power at 15 deg. C. (60 deg. F.) air inlet temperature, h.p.		2,500	4,500	6,500 (See note 4)	5,400	200	276	1,512	200
Duty		Boost propulsion	Boost propulsion	Main propulsion	Main propulsion	Craft propulsion	Utility	Main generator	Emergency generator
Cycle (see Note 1)		1/LP	1/LP	1/P/E	2SC/IP/IE	1/LP	1/C	1/LP/E	1/C
Turbine inlet temperature at maximum power, deg. C.		750	800	704	827	847	800	650	750
deg. F.		1,382	1,472	1,299	1,521	1,557	1,472	1,202	1,382
Overall pressure ratio		3·5	4·0	4·02	18·5	4·0	3·7	4·25	2·65
Air flow at maximum power, lb. per sec.		47·5	65·6	128	64·6	3·5	4·75	37·1	5·7
Thermal efficiency at maximum power		12·8	17·2	20·4	20·4	12·5	13·75	19·75	12·9
Thermal efficiency at 50 per cent power (see Note 2)		9·5	13·4	17·75	22·6	9·2	9·8	15·6	7·5 (Design values)
Specific weight, lb. per h.p. at maximum power (see Note 3)		2·77	2·28	27·2 excluding bedplates	5·3	2·25	0·78	10·5	3·0
Designed life of hot parts, hr. (Based on creep data)		300	1,000	10,000	1,000	800	500 (estimated)	50,000	1,000
Compressors	Number and type	1 axial	1 axial	1 axial	1-l.p. axial 1 h.p. 2-stage centrifugal	1 centrifugal	1 centrifugal	1 axial	1 centrifugal
	Number of stages	9	11	15	11/2	1	1	13	1
Turbines	Number and type	2 axial	2 axial	2 axial	3 axial	2 axial	1 axial	2 axial	1 radial
	Number of stages	2/4	1/3	6/6	1/2/2	1/1	2	2/1	1
	R.P.M. ÷ 1,000	7·4/3·6	7·83/5·2	4/5·6	15/11/7·18	40/35	35	8/6·75	23·5
Number of intercoolers and thermal ratio		None	None	None	3 (l.p. 2 in parallel): l.p. 86 per cent, h.p. 64 per cent	None	None	None	None
Heat exchanger thermal ratio, per cent		None	None	75	48 at full power with bypass open	None	None	70	None
Number and types of combustion chambers		1 annular	1 annular	6 cans	2 cans	1 Single can	1 annular	8 cans	1 Single can

NOTE.—1. Cycle notation adopted from Mallinson and Lewis's paper (22).
2. With the exception of column 8, thermal efficiencies are actual values obtained on test using Admiralty Diesel fuel (gas oil), calorific value 18,500 B.Th.U. per lb. (10,300 C.H.U. per lb.)
3. Specific weights quoted include reduction gearing (when fitted) and all engine driven auxiliaries.
4. 6,500 h.p. is obtained at 27 deg. C. (80 deg. F.) air inlet temperature under the design conditions stated. The power is limited to this figure at lower air temperatures.



APPENDIX B—CYCLE DIAGRAMS FOR ADMIRALTY GAS TURBINES

Note: Pressures and temperatures shown are design figures; pressures are absolute

Discussion

MR. H. CONSTANT, C.B.E., F.R.S., said that Commander Trewby's excellent paper gave a very good picture of what had been going on in the naval gas turbine world during the last ten years. It contained much food for thought and raised many questions. He did not propose to steal anybody's thunder by asking all those questions but would confine himself to one point.

The lecturer rightly stressed that what the gas turbine could give above all else was light weight. But the paper seemed to imply, if it did not exactly say, that one could not have light weight together with good fuel consumption. According to one of the slides, some of the more complicated and heavy engines that were being developed were giving good fuel consumption, but no single engine was shown which gave both good fuel consumption and light weight.

A most important point to remember in the case of all the major engines discussed in the paper was that none of these engines were fully developed. The gas turbine had probably developed faster than any other power plant. In no single engine other than the aircraft engine, as far as he was aware, had the best component efficiencies all been built into one engine. Some engines had good compressors, others had good turbines, and yet others had good combustion chambers. But they did not all exhibit the best that was known at any date. If the best knowledge had been put into any of those engines that were shown on the screen, the fuel consumption could have been reduced by between 20 and 40 per cent. The knowledge was there, but it did not happen to get into one particular engine.

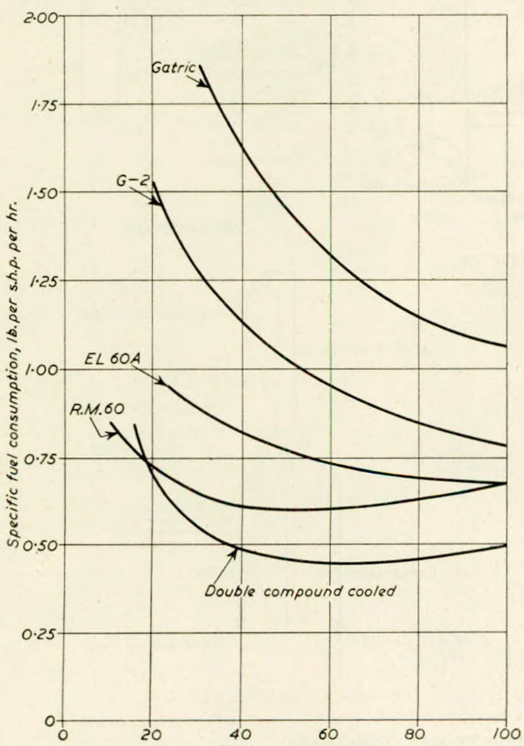


FIG. 39

The lantern slide shown (Fig. 39) was taken from Fig. 2 of the paper but he had taken the liberty of adding a further curve at the bottom. It showed what should be obtainable with present knowledge if the best compressor and the best turbine and the best combustion chamber were all put into the same engine. It represented a simple engine without heat exchanger or intercooler or reheat. In other words, it was an engine just like the Gatric or the G2 but with two compressors in series instead of a single compressor. That engine could be built today but it would only come if it were developed. One could not expect that no mistakes would be made in the first one that was built.

The point up to which he was leading and at which he had now arrived was that one could obtain good fuel consumption with light weight, because that engine should not weigh more than 2 or 3lb. per h.p., like the G2.

CAPTAIN(E) D. A. COTMAN, R.N., thanked Commander Trewby for providing him, as a newcomer to gas turbines, with such an excellent ready reference on events in the naval gas turbine world. He was disappointed, however, at the apparent acceptance of the fact that gas turbines must of necessity be noisy. After all, this was a very young science, and if it were tacitly accepted that all gas turbines must be noisy, it was very doubtful whether any work would be done to make them quieter. That would be most unfortunate.

He agreed that the exhaust and the compressor inlet were the main sources of noise, and they could easily be silenced by means of silencers. Silencers, however, took up weight and space, and these were the two features which gas turbines had in their favour at the moment. He did not think the weights of any of these silencers had been taken into account in the specific weights given in the paper.

In the Diesel field, for instance, they had been busy cutting down weight and rating engines more and more highly. Successful trials had been carried out on these engines but now they were coming into service they were found to be so noisy that one could not live with them. A certain amount of the weight saved on the engine had had to be put back in acoustic hoods, silent control cabinets and so on. Therefore, the gain was not so much as had been hoped. It would be very sad if the same sort of thing happened with gas turbines.

It was so easy on experimental work to lose sight of the human factor; that was to say, the men who had to run the machines. It was important that thought should be given to them.

He would like to refer to the combustion system in the Artouste. They had not had a great many turbines at the Admiralty Engineering Laboratory, but this combustion system had been quite outstanding. It had given no trouble at all. It had never made any smoke and there had never been any build-up of carbon in the chamber itself. The only snag that had been found so far was that one had to have a torch igniter if one was going to light it on Diesel fuel. However, he did feel that the system had a very great future.

MR. A. HOLMES FLETCHER, B.Sc. (Eng.), said that the paper was extremely valuable in giving a comprehensive survey of all the gas turbine work which the Admiralty had carried out and in drawing conclusions from the running of the various types which had been made. He himself might make a reasonable contribution to the discussion, therefore, by commenting further on some of the points that had been mentioned.

Firstly, there was the question of ball bearings. In the R.M.60 engine, the concentric shaft layout which was employed to achieve compactness, to eliminate hot ducting difficulties, and to improve aerodynamic efficiency, brought with it the necessity to increase the diameter of the high-pressure unit shafts and bearings over that required from considerations of stress alone, in order to permit the power turbine shafting to pass through them. Ball bearings were used because of his firm's experience with them on aero turbines, Michell bearings having been shown on early Derwents to be prone to sudden and inexplicable failures. The type of Michell bearing used on these earlier aero engines was of a variety calculated to reduce oil-churning power loss, and had been reported on by Fogg in a paper to the Institution of Mechanical Engineers*. If standard type Michell bearings had been fitted in R.M.60, the high-pressure turbine location bearing alone would have been responsible for about 150 h.p. of frictional loss, and since the high-pressure shafting continued to rotate at high speed at fractional loads, bearings of this type would have had serious effects on low-power cruising consumption.

He had to agree, however, that the R.M.60 bearings had been a source of considerable trouble and a retarding feature in the rate of accumulation of running hours. Expediency had influenced the original choice, it having been considered more important to get the engine built at an early date to investigate its other problems rather than to embark on the course of plain bearing research which otherwise appeared essential.

Secondly, the use of heat exchangers to improve, in particular, the part-load efficiency. With a high-compression ratio engine, a heat exchanger was not essential at the full power end of the scale for naval requirements, and a useful reduction in its size might, therefore, be made by bypassing it partly out of circuit above cruising powers, as had been done on the R.M.60. Nevertheless, it still remained a bulky object which was difficult to install in the smaller warships, and if small-bore tubing was used to give minimum bulk the problem of cleaning became acute. They had, in their consideration of R.M.60 developments, abandoned brush-cleaning as impracticable, had doubts about the efficacy of soot blowers, and almost accepted that chemical cleaning alone presented a possibility of success, although a trial on an experimental exchanger was not unqualified in this direction. Furthermore, the weight and cost of the unit were high, particularly if, as Commander Trewby's remarks about the E.L.60A exchanger suggested, stainless steel tubing had to be employed. For a 10,000-h.p. turbine, a high efficiency exchanger could easily absorb £10,000 to £20,000 material cost in tubing alone, its total length being measured in miles. As a matter of fact, the conclusion reached about the heat exchanger was that it was a pity!

Thirdly, there was the problem of erosion of subsequent compressor stages by water carried over from the condensation in the intercooler. Their experience of this was, of course, limited to centrifugal compressors, but if the problem remained serious in axial types, one must achieve separation of the condensate. This could only be done by an increase in bulk, either by lowering air velocities to a point where the water fell out, or introducing some form of separator—possibly a cyclone—and accepting the ensuing pressure loss.

The last two points he had discussed added weight to Commander Trewby's suggestion that the future main propulsion machinery might consist of simple gas turbines of small size, without intercoolers or heat exchangers, but brought into operation in increasing number as the power demand rose. If the simple engines were designed to the optimum compression ratio for their combustion temperature, the efficiency at the higher end of their power curves was adequate to be competitive with other forms of engine, and a reasonable combined consumption curve could be shown.

On the other hand, with this multiple type of engine, one ran into difficulties. For instance, complication arose in the reduction gearing, where a number of small high-speed turbines must be clutched together, with a high reduction ratio, and where, to give operational flexibility, this clutching device was preferably automatic to safeguard against "free" overspeeding dangers. Again, the optimum compression ratio might be as high as 10 or 12 to 1, when the engine might have to be made of the "two-spool" type. This was, in fact, a compound engine. The concentric design became attractive in this case, and once more one was up against the problem of frictional losses in plain bearings. Mr. Constant had suggested the same type of engine in the curves he had illustrated, but he was somewhat optimistic at the low power end of the scale. He himself hesitated to say so, but he wondered whether there was enough frictional loss allowance.

The high specific output of engines of this type made it difficult to obtain efficient working if they were designed for powers less than about 2,000 h.p., owing to their very small dimensions. Nevertheless, an installation consisting of half-a-dozen of them showed appreciable reductions in weight and space as compared with a pair of engines of the R.M.60 type, in spite of the extra gearing, and compared well on a performance basis.

Alternatively, a simpler installation consisting of one or two small engines plus a large "booster" could be employed if the duty of the ship was so well defined that one could be sure of never being required to cruise for long periods at a power just in excess of that given by the small engines, where the "booster" would be in operation at an inefficient loading. It must be noted here that the small engines spent most of their time at a high fraction of their output, and hence their service life would be short, but they would be very easy to replace, of course, by new or reconditioned units, owing to the small dimensions and light weight to which they could be made.

The second part of the paper, dealing with auxiliary machinery, brought to mind the connexion between this problem and the main engines. No provision was made on any of the main gas turbines described to furnish any part of the ship's auxiliary load. Dealing with the vessel as a whole, therefore, to the main machinery must be added the space, weight and fuel requirements of the engines or boilers supplying these services, and the all-in figures must be compared with those for the machinery with which the gas turbine was in competition. Exhaust-heated boilers were not attractive for several reasons, firstly, because in turbines with heat exchangers the gas temperature was low; secondly, because exhaust back-pressure had serious effects on output and efficiency; and, thirdly, because in a multiple turbine installation cross-connexion of the exhausts to serve a single boiler was undesirable.

Commander Trewby had given a factual account of past work and had drawn individual conclusions. His combined conclusions, however, were somewhat indefinite and did not give a firm guide for future work. It was evident that many problems remained to be solved, and a most interesting course of investigation could be visualized for the immediate future.

In conclusion, he would like to congratulate Commander Trewby and to ask him what he thought the future type of gas turbine for main propulsion would be.

DR. D. M. SMITH congratulated Commander Trewby on his excellent presentation of excellent material. With its full account of failures as well as successes, the paper would be of the utmost value to both designers and users of naval gas turbines.

He pointed out that the lecturer had referred in two or three different places to the bearing of aero-engine practice on

* Fogg, A. 1946. "Fluid Film Lubrication of Parallel Thrust Surfaces". Proc.I.Mech.E., Vol. 155, p. 49.

naval gas turbine development. Aero-engine practice, particularly in post-war turbines, both jet and propeller driven, had moved in a direction in which margins everywhere were extremely small. Consequently, an aero-engine on a new frame required a very large amount of development in bench testing and flight testing to bring it to the stage where it was serviceable. The figures for development costs on the Proteus and the Avon, published in the last few months, were £11 million and £22 million respectively. He did not think development charges of that character could be economic for naval gas turbines.

Looking at the field of naval gas turbines generally, and in particular at the conventional mercantile marine engine, and also at past naval practice, propulsion plant of very high reliability had been produced but, of course, in weights which were much greater than the weights now being obtained with naval gas turbines. Personally, he felt it was still possible to work to standards of robustness which had at least a great deal of experience behind them in marine and in land practice. He was thinking specially of steam turbines and of the limited experience there had been of industrial types of gas turbine. It was possible to produce naval gas turbines of high reliability and comparatively long life, at least life which was perfectly suitable for the naval application, taking the naval load factors into account, and at the same time to show very considerable reductions in space and weight, as compared with the alternative propulsion machinery that was available.

This was meant to be a general comment and he did not propose to enter into a detailed discussion of the very interesting specific turbines described in the paper. With regard, however, to the *Grey Goose* installation, he would draw attention to the table showing various comparative figures of the previous steam plant and the gas turbine plant now being installed. He thought it was the fact that the steam plant would be of higher durability than the gas turbine plant. One of the items entering into this, on which Mr. Holmes Fletcher had commented, was the plain bearings in the steam turbine plant as compared with the ball and roller bearings in the turbine plant.

Mr. H. Norman G. Allen, M.A. (Member), said that in making a contribution to the discussion, he would like to stress that his interests covered steam turbines, Diesel engines and gas turbines. He had, therefore, no particular axe to grind.

The paper was a factual statement of the steps which had been taken by the Admiralty to exploit the tremendous achievements of Whittle and the other pioneers in aeronautical gas turbine engineering. A first reading of the conclusions might lead one to the wrong superficial impression that a great deal had not been achieved. This was, however, a completely false picture. The Admiralty had had the courage and faith to go ahead with gas turbine developments with relatively little data and certainty in some of these projects and, furthermore, they had had the courage to go ahead and build hardware in the early stages so that some practical experience could be obtained. The whole approach had been most commendable and, for once, history was not repeating itself because half a century ago industry was pressing the Admiralty to take up steam turbine work whereas today it was the Admiralty who had seized the initiative. The nation should be grateful to the Admiralty for the initiative and enterprising spirit they had shown.

Commander Trewby had rightly stressed the many alternative approaches to the problem and the need for compromise in design. He had shown that there was no set answer to the controversy between those advocating the light weight kinematic approach and the heavier industrial approach. Each set of circumstances might need a different solution.

It was perhaps a pity that the term "life" had been used in such a loose sense in gas turbine engineering generally, as it had caused quite an erroneous impression amongst older established engineering circles. Some such term as "period between major overhauls" would be far more applicable. No one would suggest that the life of a Diesel engine consisted of the time it ran before a piston or a cylinder head were replaced.

He was interested to see that Commander Trewby stressed that the difficulties encountered with the G2 were not inherent in the principle of the gas turbine. This was very important, and it had been the general experience of those engaged in this type of work. Many of the problems met with were those associated with mechanically driven auxiliaries rather than with the gas turbine proper. This was true, he thought, except perhaps for the heat exchanger, which did involve special problems of its own, especially for naval requirements where weight and space were so important.

Commander Trewby stated that the field for propulsion gas turbines could be usefully extended if a reversing mechanism could be fitted which would enable a ship to put to sea in a matter of minutes without waiting to raise steam. The principles of such a mechanism were already available, using the planetary gear system, and it only awaited development; if a fraction of the money which had been spent on gas turbine development were applied to the development of epicyclic reverse gears, the problem should be capable of solution in a matter of three or four years.

It was stated that one of the limiting points of mechanical construction in the R.M.60 was in the use of ball and roller bearings. Everyone who was using high speeds was very conscious of the limitation of ball and roller bearings which, in naval applications, was made more difficllt, in some cases, by shock requirements. Unlike Mr. Holmes Fletcher, his own company had encountered no major difficulties with journal type bearings even with speeds up to 20,000 or 30,000 r.p.m. on small diameter bearings, but a scientific and artistic study of the phenomenon of oil film whirl had been necessary. However, here again, where the arrangement would lend itself to the use of epicyclic reduction gears the losses which would be incurred by the use of journal bearings in the turbine might to some extent be avoided by the use of epicyclic gears. It had been conclusively demonstrated that the high-speed pinions would run most satisfactorily without bearings at all, with the pinion floating between the planet tooth contacts.

The paper also stated that for boost gas turbines the design could benefit directly from the vast aircraft experience. He would go further than this and say that most gas turbine applications could benefit from this experience. One of the main reasons why the Allen 1,000-kW. set was able to achieve full speed, full load and overload in the first series of tests was that, in addition to the accumulated steam turbine mechanical experience which went into the set, there was such a close association between his own company and the Bristol Aeroplane Company. This applied to both the aerodynamic side and the testing side. Reliability and weight were not necessarily synonymous, and it was very much in the national interest that all the money being poured into the aircraft gas turbine should be carefully studied and sifted for use in other applications.

The low lubricating oil consumption associated with gas turbine work was not always fully appreciated in assessing the relative running costs as between different prime movers and with base load sets, particularly in the mercantile marine. This might prove a most important factor.

In closing, he would like to say how important it was that the mercantile marine should take full advantage of the naval data for application and modification where necessary, in just the same way as the Admiralty had taken advantage of all the aircraft data. This country had led the way in aircraft gas turbine development. The Royal Navy had followed up the advantage very swiftly, and it would be a tragedy if it were not exploited in other fields as well. This nation had always led with quality in its engineering products, and it must continue to follow that policy if it were to maintain its position in the world. It was sometimes difficult to see where some of these new developments could be fitted into existing patterns of engineering. But, as an example, he would mention that Messrs. Alfred Holt and Company had placed orders for 350-kW. stand-by and emergency generators for six of their new ships. With their permission he was showing a slide (Fig. 40) which

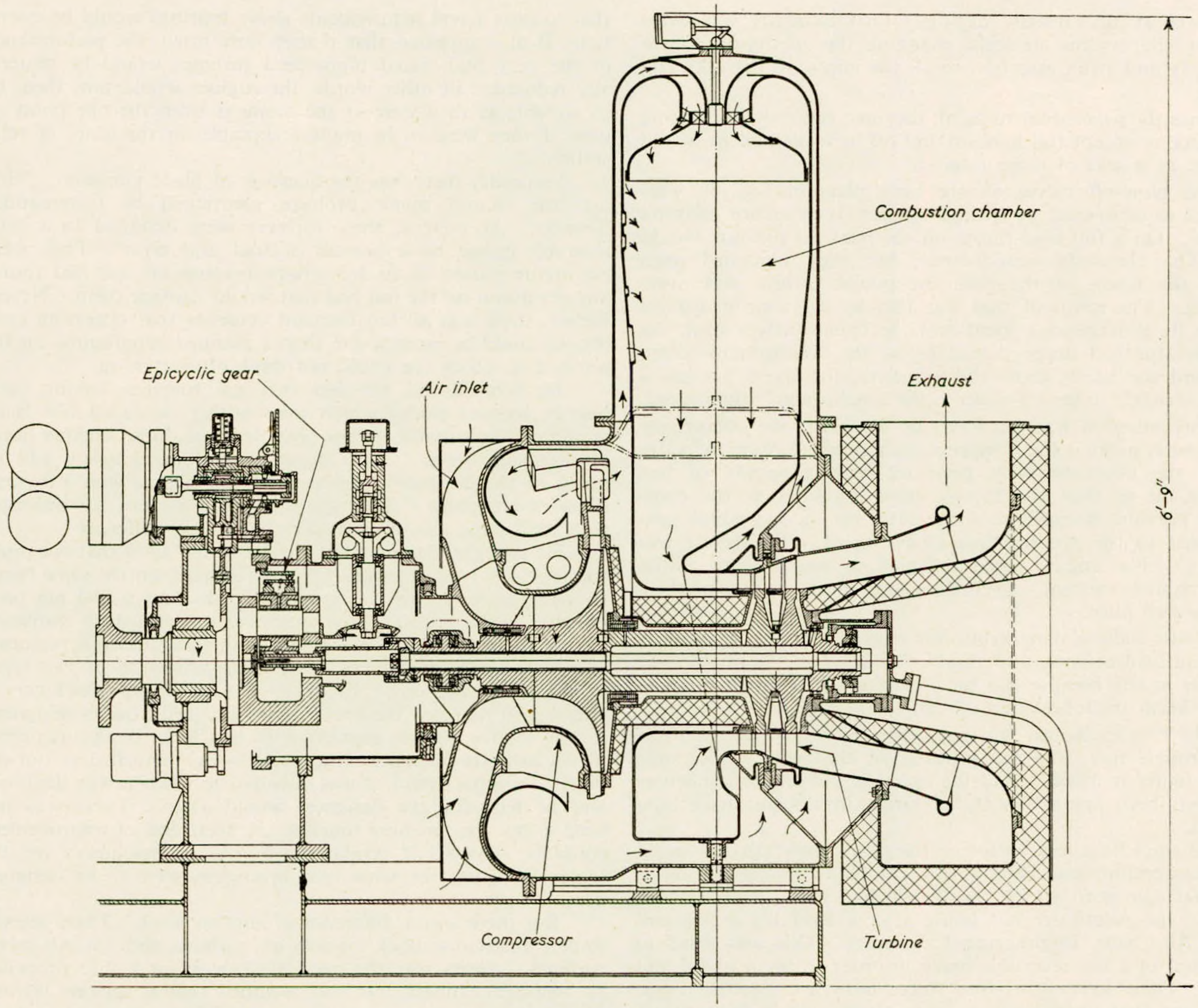


FIG. 40—*350-kW gas turbine*

gave a general impression of the unit. It should be appreciated that in this case by fitting an emergency generator well above the power requirements for statutory emergency generators, it had been possible to eliminate one Diesel generator in the main engine room. This was an example of the enterprise which he hoped would be followed up by still further developments. It was a natural development arising out of the work on the 200-h.p. emergency unit built and under test for the Royal Navy.

CAPTAIN(E) H. FARQUHAR ATKINS, D.S.O., D.S.C., R.N. (Member) said he was happy to be able to agree with almost everything that had been said. He thought he agreed with every word said by Commander Trewby.

He shared Mr. Holmes Fletcher's dislike of heat exchangers; but he thought it might be possible to make use of waste heat boilers to some extent with the simple type of gas turbine. As Mr. Constant had shown, it could achieve a very fine efficiency.

As some people were aware, he himself was sent to the Admiralty test house at the National Gas Turbine Establishment to get it built and working as soon as possible. In order to hasten that happy day, he decided to ask the Director if they could have an opening ceremony and get some important personage to come down and declare the test house open. He knew from past experience that it was the only possible way to get a date kept! The rumour went round that the Duke of Edinburgh was coming, and everybody was galvanized into activity. As silken ribbon and golden keys were rather out of place for opening a test house, he decided that it would be declared open by starting the Allen 1,000-kW. gas turbo alternator. This meant getting it away from the makers rather sooner than they wanted. As always, on these occasions, there was a frightful rush at the end, and they just managed to get a couple of runs before the day. Half-an-hour before the timing of the start and just as the Controller of the Navy and Third Sea Lord's car hove into sight, he got a message that both glow plugs were out of commission and the engine would not start. However, when the button was pressed it did start and accepted load at once; and that was his impression of the engine. As a result, he was very sold indeed to gas turbines. He thought they had a very great future in the Navy.

The engine had been improved in one or two ways. The size of the interconnectors was increased, and glow plugs were fitted in place of the torch igniter. The engine could now be started with absolute certainty. It was found to be vitally important to stop oil leaks into the compressor. It was hoped from the Gatric experience that everything could be washed away, but it did not work with oil vapour. It baked hard on the last stages and small diffusers and rapidly decreased the compressor efficiency. The compressor was pushed much nearer the surge line, so that there was great difficulty in altering power at all without surging. That difficulty was overcome by altering the air seals, changing the oil drain and the air supply and strict attention to all the joints on the inlet end bearing.

Since the paper went to print, they had succeeded in getting the engine to accept full load on and off by a method he would describe, as it was of some interest.

The blow-off valves on the back plate in Fig. 30 were arranged to be opened by springs against the governor relay oil pressure. On a full load throw-off the relay oil pressure would fall. The blow-offs would open, but they remained open during the whole of the time the power turbine was overspeeding. The result of that was that by the time it did get back to its synchronous speed and the bypass valves shut, the gas generator had dropped well below the synchronous idling speed and was barely above the self-sustaining speed. It had a terrible struggle to get up again to the synchronous idling speed.

This situation was improved by balancing the compressor air pressure, making the compressor air pressure open the valve against the governor relay pressure, with a supply of low pressure oil to shut the bypass valves as soon as the compressor pressure dropped to about 11lb. per sq. in., which corresponded to the synchronous idling speed. The result was startling. The engine speed dropped to synchronous idling and remained constant. Everything was steady instead of there being a wild hunt.

It was really a remarkably fine engine, very quick starting, accepting load at once, and thoroughly reliable. It might even be better at sea, because if a bit of salt got in it might be possible to wash the lubricating oil off.

The heat exchanger was not quite right yet, but the principal trouble now was the splitting of the tubes, which was due to faulty material. Had the ordinary Admiralty condenser tube tests been applied to the material, that might have been avoided.

He agreed entirely with Commander Trewby that it was a great disappointment having this trouble with the G2 after the great ease with which the Gatric had run. Both Gatrics came to the Admiralty test house after a hard life at sea and in the Admiralty Engineering Laboratory. One was fitted to either end of a big reversible brake in order to try it ahead and astern. There were eighty-four starts on Gatric 2 before it was found out that unfortunately some of the nozzle guide vanes had been put in the wrong way round. That was put right, and the engines were connected up and were run in opposite directions at either end of the brake, which meant one engine had to start when its power turbine was already being driven astern by the other. One could imagine that there were a lot of surges until the right way to do it was discovered. Sometimes the engine would start and push the other into surge. Sometimes one being started would surge. Eventually the right method was found. The Gatrics stood up to that beautifully without turning a hair.

One small point struck him on the question of portable pumps. He was very keen on damage control. The loss of the *Empire Windrush,* where one did not know the details, and the loss of the *Empress of Canada,* filled him with gloom and despondency. There should be as many portable pumps available—really portable pumps—as possible. These gas turbine pumps *were* portable, and there seemed to be no reason why they should not do two jobs, supplying air for salvage as well. He was convinced that one of the best ways of keeping air out of a leaking compartment, though at present contrary to naval instructions, was to put pressure on the compartment that was slightly damaged. A gas turbine-driven portable pump could be bled to provide air for salvage or used as a pump.

MR. H. G. YATES, M.A., said he had two points to make in connexion with the suitability of the engines described in the paper for the purposes for which they were built. Both had received some attention already.

Firstly, there was the question of bearings. It appeared that to meet naval requirements sleeve bearings would be essential. It also appeared that if they were fitted, the performance of the very high rated high-speed turbines would be materially reduced. In other words, the engines would not, then, be so suitable as they were at the moment from the one point of view if they were to be made acceptable on the score of reliability.

Secondly, there was the question of blade vibration. This was the second major problem mentioned by Commander Trewby. At present, these turbines were designed to a considerable extent by a process of trial and error. They were eventually passed as fit for service because no one had found any condition on the test bed that would damage them. Nevertheless, there was all too frequent evidence that operating conditions could be more severe than a planned programme on the test bed in which one could not think of everything.

He himself did not feel that gas turbines having such heavily stressed blades which were neither shrouded nor laced would ever be suitable for the propulsion of ships, whether naval or merchant ships. This change would immediately add so much to the designer's problem that the engine would become different altogether. This was one of his reasons for believing that the engine would eventually be entirely different.

He thought Commander Trewby would agree that one must compare one type of machinery with another on the same basis. In some respects, this was not easy to do, and it had not been possible in the paper. For instance, in comparing gunboats having the new R.M.60 machinery with their previous performance with steam machinery, there were differences of two types to take into account. First of all, the steam machinery—although it reflected the greatest possible credit on its designers, if only for the extreme rapidity with which the design was completed and the actual engines built—was nevertheless out-of-date. To some extent, it was out-of-date when it was designed, and he felt sure the designers would agree. There was not time to put the finishing touches. A great deal of improvement could be achieved if similar machinery, or machinery for the same job, using the same type of engine, were to be designed now.

But there was a difference of another kind. There seemed to be a different outlook towards gas turbines and towards steam turbines. Steam was the maid-of-all-work in a ship propelled by steam machinery. It was assumed that if anyone wanted steam for any purpose from evaporating water to making auxiliary electrical power, the main engine designer had to submit. He must maintain his boiler pressure constant at all powers so that these bits of ship auxiliaries not connected with the propelling plant could be served. It would be interesting to see the result if the designer of the propulsion plant were given complete freedom to design it as he wished, and if he did not have to expect criticism on comparison with existing steam plant, merely because it happened to use steam.

The Admiralty had adopted a much more generous outlook towards the new gas turbine, and they and others might benefit if a little of that attitude were extended towards the good old-fashioned steam cycle, not with old-fashioned methods but with the modern and more scientific approach to engineering design.

Finally, he would like to mention one point that had not been referred to and that seldom received attention: that gas turbines were inherently unsuitable for large powers. They had been referred to as the best way to pack power into a small space with light weight. That was true in the range of power which suited the gas turbine. He suggested that that range was between 200 h.p. as the lower limit, limited by conditions of economy, and perhaps 10,000 as the upper limit, limited by conditions of robustness and handleability. The corresponding range for steam was five or six times higher up the scale. It began at, say, 1,500 h.p. and extended to 60,000 or 70,000 h.p. Somewhere in the middle steam was at its best, and in the middle of the lower range gas was at its best. It would never be possible to compare them on an equal h.p. basis. As powers increased, specific weights increased also, as Commander

Trewby had been careful to point out. In view of the short time available, he would not go into all the reasons for the limited power range of gas turbines, but be believed the argument to be sound.

Personally, he thought that ultimately naval ships, even large ones, would come to be propelled by gas turbine machinery at the right time and in the right form. But he submitted that that time was not yet, and that form was not the form exemplified by the engines described in the paper. In his heart Commander Trewby would not disagree with that very strongly, he thought; and he would like to quote one sentence from the paragraph referring to the future of the gas turbine in naval use, and underline two words:—

"At a later stage, gas turbines *may* become the sole means of propulsion in *some* warships".

That modest sentence gave a very different impression from the general tone of the paper, but he believed himself that it was a more realistic impression.

Mr. P. Draper (Associate) noted that very little comment had been made in the discussion on combustion and combustion chambers. His firm had had the honour of being connected with several of these units, and he would confine himself to underlining one of Commander Trewby's statements. On page 133 it was stated that:—

"Difficulties were experienced in matching the outputs of the multiple combustion chambers. (Unless this can be achieved, the turbines are liable to be locally overheated.) The matching was particularly difficult at low powers where the individual burner output was very sensitive to minor manufacturing errors, burrs, etc.".

The ideal number of combustion chambers was certainly one, and there were two types of single combustion chamber, the can type and, where there is no heat exchanger, the very interesting annular type. In referring to the latter as one combustion chamber, one must appreciate that the fuel was injected by multiple burners and that they must be very evenly matched. In that connexion, he would emphasize the very great advantages of the Turbomeca type of fuel injector. It achieved very even distribution and very fine particle size in the spray.

Mr. B. J. Terrell said that Dr. T. W. F. Brown (Member) deeply regretted his inability to attend the meeting owing to a prior engagement. The following were the comments Dr. Brown wished to make: —

The author was to be congratulated on his survey of gas turbines for naval propulsion purposes, which contained a great deal of valuable operational experience. It was noteworthy that practically all the gas turbines which the author described were for small lightweight high-speed craft with a very limited radius of action. He truly remarked that the gas turbine could be built in a bewildering variety of forms and went on to say that the final form to be taken by the marine gas turbine was as yet by no means clear. It was, however, certain that the form of gas turbine machinery for merchant ship propulsion would not be similar to the types of machinery shown in the paper, as in all cases the type of fuel used was too costly, and the fuel consumption was far too high for merchant ship use. The lowest specific fuel consumption was well above 0·60lb. per s.h.p. per hr.

Gas turbine machinery developed from the aircraft engine was applicable in a special field; i.e., that of light coastal forces, in which the following factors operated in its favour:—

(1) Compactness and light weight were of supreme importance.

(2) It was competing with machinery operating on petrol or Diesel fuel which required a fair amount of maintenance after short periods of service.

(3) The vessels were normally away from their base for short periods, so that there were ample opportunities for skilled maintenance.

(4) Only limited endurance was required so that the higher fuel consumption and consequent space in the vessel devoted to fuel with the simple gas turbine was not a serious drawback.

For merchant ship machinery, the emphasis would be on high efficiency with the corresponding figure of low fuel consumption and long life at full power.

The Admiralty experience so far with gas turbines at sea was limited to the type of craft used by coastal forces. The author's opinion that very light gas turbines of the aircraft type were also suitable for the main propulsion machinery of larger vessels remained to be proved. It was clear that in such larger vessels the ordinary machinery required for use under cruising conditions would have to have high efficiency and long life. In comparing gas turbine machinery of the conventional steam turbine type with the ultra lightweight gas turbine, the chief differences were seen to be:—

(1) Much lower stresses, velocities and loadings.

(2) Less use made of alloy steels and light alloys.

(3) Much heavier scantlings mainly due to the use of cast cylinders normally employed in high pressure steam machinery.

These were not, in general, factors which reduced reliability. Even the heavy lowly-stressed 3,500 h.p. Pametrada gas turbine which was designed in 1946, gave a thermal efficiency of 29 per cent, and this could be improved in space, weight and thermal efficiency at this date. It was clear that the true answer to gas turbines for both naval and merchant ships (as opposed to boats) was a truly balanced design intermediate between the lightweight gas turbine machinery described in the paper and the steam turbine which was still the main propulsion machinery for all naval vessels larger than the boats shown in the paper. Machinery weight should be balanced against a reasonable degree of robustness to cover the effects of thermal transients and simplicity against available skilled operating labour and maintenance facilities.

These remarks applied particularly to the machinery for cruising conditions in a large ship. It would be agreed that the machinery normally required for the propulsion of large ships would have to combine the robustness and reliability of the steam turbine with good starting and manœuvring qualities. There was, however, no point in flying to extremes. The ship could not and did not need to start as rapidly as a fighter aircraft. It would be an absurd requirement that the main machinery started up in a tenth of the time required to get the generators and auxiliary pumps into operation. It was suggested that the low specific weights of the engines described in the paper could not be achieved in the main propulsion machinery of large vessels without the sacrifice of desirable qualities.

It might be of interest to state that a 6,000-h.p. gas turbine design was submitted by Pametrada to the Admiralty in 1946 in which a long-life cruising unit in association with boost units for higher powers was shown. This was now being put forward as the right answer in the United States. A second cycle submitted at the same time to the Admiralty showed the whole of the cycle adopted in the R.M.60, including bypass of the heat exchanger at full power and bypassing of the low pressure compressor and low pressure turbine at part power. On these features, Pametrada claimed prior knowledge. The only difference in the cycle put forward by them was the provision of reheating between the h.p. turbine exhaust and the i.p. turbine inlet which the author agreed would be very attractive in decreasing bulk and air rate and which was not adopted in R.M.60 for the reasons stated by the author. The overall weight, including reverse gear, gear controls and starting gear, based on a propeller r.p.m. of 300 would have been 47 tons, and the fuel consumption at cruising power (20 per cent) 0·52lb. per s.h.p. per hr. The improvement in radius of action was obvious.

The author gave little information on the residual fuel problem which had always been stressed by the Admiralty as a major problem. Had there been a change of heart? The work carried out at Pametrada would appear to show that in a suitable design the problem of burning residual fuel and the consequent vanadium problem had been solved.

The following comparative figures had been abstracted from this year's Herbert Akroyd Stuart Lecture* given by the writer. It would be noted that the R.M.60 figures at 30 per cent load were considerably better than those shown in the Pametrada cycle, but if a Pametrada turbine were used for cruising purposes 30 per cent of cruising power was a very low power indeed.

	Pametrada 3,500 gas turbine	R.M.60 engine
Overall compression ratio	5·2	18
Maximum cycle temperature	1,250	1,520
Life, full power	100,000 hours	Less than 1,000 hours
Pressure losses, lb. per sq. in. Total loss, $\Sigma\, \delta P$	4·2	23·8
Air bleeds, per cent ...	2·5	9·5
Specific fuel consumption; full load ...	0·53	0·66
30 per cent load ...	0·83	0·68

There did not seem to be much point in working at high pressure ratio and high temperature if the resulting gains were dissipated merely to obtain light weight.

With very considerable assistance from the Admiralty, it was hoped to achieve still higher economy and much lighter gas turbine machinery by the use of cooling as outlined in the Thomas Lowe Gray lecture given in January before the Institution of Mechanical Engineers†.

The programme of gas turbine development outlined in the paper demonstrated the progressive policy now adopted by the Admiralty for the development of new machinery. With regard to steam turbine machinery, the principle was now accepted that prototypes of new designs should be thoroughly tested on shore before installation in a ship. With regard to gas turbines this policy was seen to be extended to the construction of units which were largely experimental, in order to explore the possibilities and limitations of the gas turbine.

One gathered from the paper that the next step might be a boost/cruising turbine unit in the medium power range, but presumably the design and construction of such a unit was awaiting a final solution to the problem of using heavy fuel.

In conclusion, he would most seriously ask the author to state whether he was entirely satisfied that the aircraft type of gas turbine machinery had not become even too light, as some of the weight would surely be better employed in the engine than in providing armour for the fuel tank.

Speaking on his own account, MR. TERRELL said he would suggest that the aircraft type of turbo construction was not necessarily the ideal at all. The aircraft was out for lightness at all costs, but weight did not matter so much in a ship. For a really reliable design one must have a balanced design. The disc in a gas turbine must be of a certain thickness. If it were thinner, it would fly apart. The casings must be of a thickness suitable to the disc scantlings. That was to say, they must both expand and contract equally under conditions of thermal transients. One did not want the casing to close on the rotor, as had happened in certain engines, and one did not want to go to excessive clearances.

He would like also to mention the popular assumption that the gas turbine had inherently worse thermal transients than the steam turbine. This was not true. The steam turbine was far worse. But the gas turbine used austenitics and they were the real trouble. The difference in design was not so much that between gas and steam turbines as that between austenitic and ferritic turbines.

A battleship was built round its guns and an aircraft carrier round its aircraft. The chief feature of these little ships about which Commander Trewby had been talking was speed. Surely they were built around their power plants, and they were a very specialized type of ship. He would believe in the replacement of more robust machinery by aircraft machinery when the Navy substituted aircraft 30-mm. cannon for its Bofors guns and when it substituted light and resonant aluminium utensils for the utensils at present in use.

Commander Trewby was to be congratulated. Some years ago Sir Frank Whittle said that far more hot air had been spoken about gas turbines than had been blown through them. The Admiralty had certainly done a good deal to put that right in the naval field.

MR. I. LUBBOCK said Commander Trewby's opening remarks were too modest. He had shown a keen appreciation of engineering problems and had produced a paper of great interest. He himself had little to add to the discussion as one of his major points had been anticipated to some extent, chiefly by Mr. Constant.

He could not help thinking that some of the criticisms on thermal efficiency had been justified. It was dangerous, as the author said in his paper, to work out cycles on assumptions. Appendix B contained data about R.M.60 and other turbines and anyone with a comparatively small amount of thermodynamic knowledge could pick out what should happen.

The figures for R.M.60 were a little depressing. The thermal efficiency of the unit at 27 deg. C. should be about 27 per cent and at 15 deg. C. it should be about 29 per cent, which was what one should expect from a two-stage intercooler and even a very modest heat exchanger.

Could the author say where the losses occurred? Mr. Constant had given a hint of what was obviously happening. In other words, a unit like the R.M.60 stressed a point of which everyone was fully aware. From the thermal efficiency point of view the gas turbine suffered enormously from any reduction in component efficiencies. Only a short while ago, he had taken part in a discussion on a very different class of plant with the same cycle, the Beznau plant. It was extremely unfair to the designer of the R.M.60 to compare a large power station unit with enormous weight and all the space in the world with this aircraft type turbine. But against that there was the fact that this bulky and very large power station plant operated at 600 deg. C., where this unit had the advantage of 827 deg. C. and still produced an efficiency of 20·4 against over 30 per cent for the Beznau plant. Thus, the table was depressing from the thermal efficiency point of view.

Even the G2, in spite of the fact that it swallowed more air than the R.M.60, with a very modest pressure ratio, gave a thermal efficiency of 17·2, although it must be admitted that the part-load characteristics were not very good. If, as the author maintained, these plants were going to be used to boost, one would want full power most of the time and a reduction in the flatness of the curve became of lesser importance. It emphasized the point made by a previous speaker as to a more suitable turbine system. This light kind could serve very well for certain conditions.

Personally, he was prepared to favour the halfway mark between the very low-weight turbine without heat exchanger or intercooler as put forward by Mr. Constant and the intercooled heat exchanger system of the R.M.60. The latter could be produced—without, perhaps, condensing it quite so much—to give efficiencies more in the region of 30 per cent as compared with those which had been obtained.

MR. N. E. ROWE said that his only excuse for being present was that he was connected with a company, one of whose engines was mentioned in the paper. Perhaps he had a far away connexion with this classical branch of engineering, however, in that he had had the good fortune to serve an apprenticeship in marine engineering. He had always regarded this as a piece of good luck, although the whole of his professional life had been spent in aeronautics.

* Brown, T. W. F. 1954. "The Long-life Internal-combustion Turbine". "Engineering", 4th June 1954, Vol. 177, No. 4610, pp. 717-724.

† Brown, T. W. F. 1954. "High-temperature Turbine Machinery for Marine Propulsion". Proc.I.Mech.E., Vol. 168.

He could confirm that after 1,100 hours of type test running at their factory (i.e. cyclic running at various outputs, including full power), the combustion chamber of the small Turbomeca gas turbine proved to be extremely good. There had been no serious trouble. A few small cracks were generated, but the whole combustion chamber stood up extremely well, and there had been no deposit of any sort.

Another point made in the paper which he would like to emphasize was the serviceability of the unit and the time taken for repairs. After seeing the picture of one of these small engines being carried by two men and hearing of its low weight, he could easily see that repairs could be made by replacement. Hence, the ship or a major piece of machinery would be out of action for the minimum amount of time.

The author had referred to air starters. Were these likely to be standardized in the Navy for gas turbines? Would that apply also to small turbines, or would they always be started by hand up to certain powers?

A number of speakers had referred to comparative economy. The paper contained a table showing the relative economy of R.M.60 and steam plant. He himself had been interested enough to plot the economy of the steam plant on Fig. 2 of the paper. It coincided almost identically with the curve for G2. This was most interesting as well as most unexpected. He had expected it would be very much superior.

Following up the comparative idea, he would like the author to say what the comparative cost figure of the steam plant would be per h.p. In the paper a figure for the cost of the gas turbine had been given of £15 per h.p., possibly falling to £7 per h.p. if a large number were built.

He would support the idea of ample test running before these engines were put into service, since only in that way could one be sure that the maximum reliability and serviceability were obtained.

The author had pointed out in his paper that aero-engine practice had been followed in order to reduce weight and secure compactness.

He would like to ask whether, in the operational trials, limited as they were, there had been any loss in the serviceability, maintenance or general overhaul life or servicing which could, in the author's view, be attributed to the use of aero-engine practice. This would be very interesting.

Finally, he would like to make a plea—it might sound a very odd one—for the development of high-speed electrical machinery. The generator which could be driven by the Artouste or Turmo 2 would generate 250 K.V.A. running at 1,500 r.p.m. The generator would weigh about 2½ tons, whereas the engine would weigh a little over 300lb. When allowance was made for various things which were very necessary, such as noise reduction and so on, it would be a little more.

The only way to get the machinery down in size and weight and so match the engine was to put up the speed of the electrical machinery and hence reduce its size and weight.

MR. R. J. WELSH, Wh.Ex. (Member) said that the paper not only contained a very comprehensive survey of British naval gas turbine practice: it was also extremely well balanced. It was fair to everyone concerned, and he would like to congratulate Commander Trewby on the way in which he had balanced all the factors.

It was pointed out in the paper that the requirements of naval vessels did not coincide with those of merchant ships. This ought to be emphasized, in spite of the fact that some of the speakers had suggested that the lessons of one could be transferred to the other.

There was no need to point out to marine engineers the difference between naval and merchant practice, but there were guests present who might not realize that each must be tackled in a different way.

In the Merchant Navy, it was essential to use residual fuel. It was quite uneconomic to run a merchant ship on distillate fuel with turbine efficiencies. In the Royal Navy this was to some extent a secondary requirement but the clue might be the point to which Mr. Lubbock had called attention—namely that a heavy plant running at 600 deg. C. could burn residual fuel with high efficiency.

He would like to suggest that for cruising power, consideration might be given to a comparatively heavy gas turbine running at 600 deg. C. and burning residual fuel with an efficiency of, say, 32 per cent. For full power conditions this same machine might be run at high temperature on a short-life basis and would thus be inherently light in weight per s.h.p. of full-power rating; judging from the Gatric experience mentioned in the paper, such a machine might run perfectly well up to a thousand hours on high temperatures with heavy fuel.

In this way, by looking on full power as a temporary condition, one might get the best of both worlds and have an engine that not only burned residual oil exclusively but was at one and the same time a heavy long-life high efficiency cruising unit, and a lightweight high-temperature unit for full power.

In conclusion, might he say to Commander Trewby that he had just come back from the United States and had visited Washington and New York in the last week or two. People there were looking forward very much to hearing the paper and he would have a great welcome.

MR. A. W. POPE said he might add a few facts about the running of the little Allen 200-h.p. engine. They might throw light on the magic term "development" and what it really meant to engine makers.

Firstly, a word about the form of the engine. For reasons of robustness a centrifugal compressor was chosen, with a single combustion chamber. The compression ratio was restricted to under 2½ so there was a single-stage turbine. A choice had then to be made between axial and radial turbines. Again, partly for reasons of robustness and partly because there were exaggerated claims at the time as to the efficiency of radial turbines, a radial type was chosen.

Having decided on a centrifugal compressor and a radial turbine, the design did not start off with a single rotor forging, as shown in the paper. They had to cool the radial turbine and they found it needed a lot of air. They put some small fan blades on the back of the turbine disc, but that was not enough. They then put in a small contrifugal compressor on the back of the turbine disc and day by day it grew until it was as big as the original centrifugal compressor. Thus, the combined rotor was born.

Originally, there was no bearing fore and aft, as shown in Fig. 37. There was an overhung rotor running on a stationary stub shaft, coming out from the casing. The drive was taken up the centre to a reduction gear. This was done for two reasons; (*a*) to get as short a set as possible and (*b*) to avoid having a bearing in an exhaust gas stream at 600 deg. C. (The drawing (Fig. 41) showed both the original bearings A and B and the bearing in the exhaust stream C).

It was known that the natural frequency or critical speed of this stationary shaft was about 7,000 r.p.m. and it was hoped to do as other people seemed to have done and run up through that speed to a supercritical speed of 23,000, but it had not been possible. The problem had not been examined theoretically. If anybody had done this, he would be most glad to hear from them. They got to the 7,000 r.p.m. calculated critical speed quite happily, but at that speed the vibration was shocking. More and more power was put into the motor rotating the shaft but the speed did not rise at all. There was no doubt where the energy was going; the noise was terrific.

This went on until the rotor blade tip rubbed on the casing which meant that the whole thing was vibrating at ± 0·040 inch. Rather than investigate this, they cut their losses and put a bearing at either end, as shown in the paper. This had been absolutely satisfactory, and there had been no trouble with the hot bearing.

As the paper said, at 730 deg. temperature maximum, the temperature originally chosen, they obtained at first only 123 h.p. It was soon obvious that the compressor was the cause of the trouble. They first opened up the diffuser throats but it did not make the slightest difference. Attention was then turned to the casing, where it led up into the combustion chamber. Some of the air was going up one side of the casing, round the back of the combustion chamber and coming back into the casing with a high velocity. This was remedied by out with one or two simple baffles, but it did not make a marked improvement to the output. The cause of the trouble, therefore, was elsewhere and attention was turned to the inlet. The inlet was not originally as shown in Fig. 37, but as in Fig. 41. It did not have a long axial entry. It had a much sharper right-angled bend going down into the compressor, and it had two side supports for the bearing at either side. When this was blown with a fan in the test shop, there was considerable break-away from the two side vanes and the air had a whirl of up to 20 degrees. As this was now thought to be the cause of the trouble, a wooden model was made and when a nice shape was obtained for the inlet, a new inlet was made,

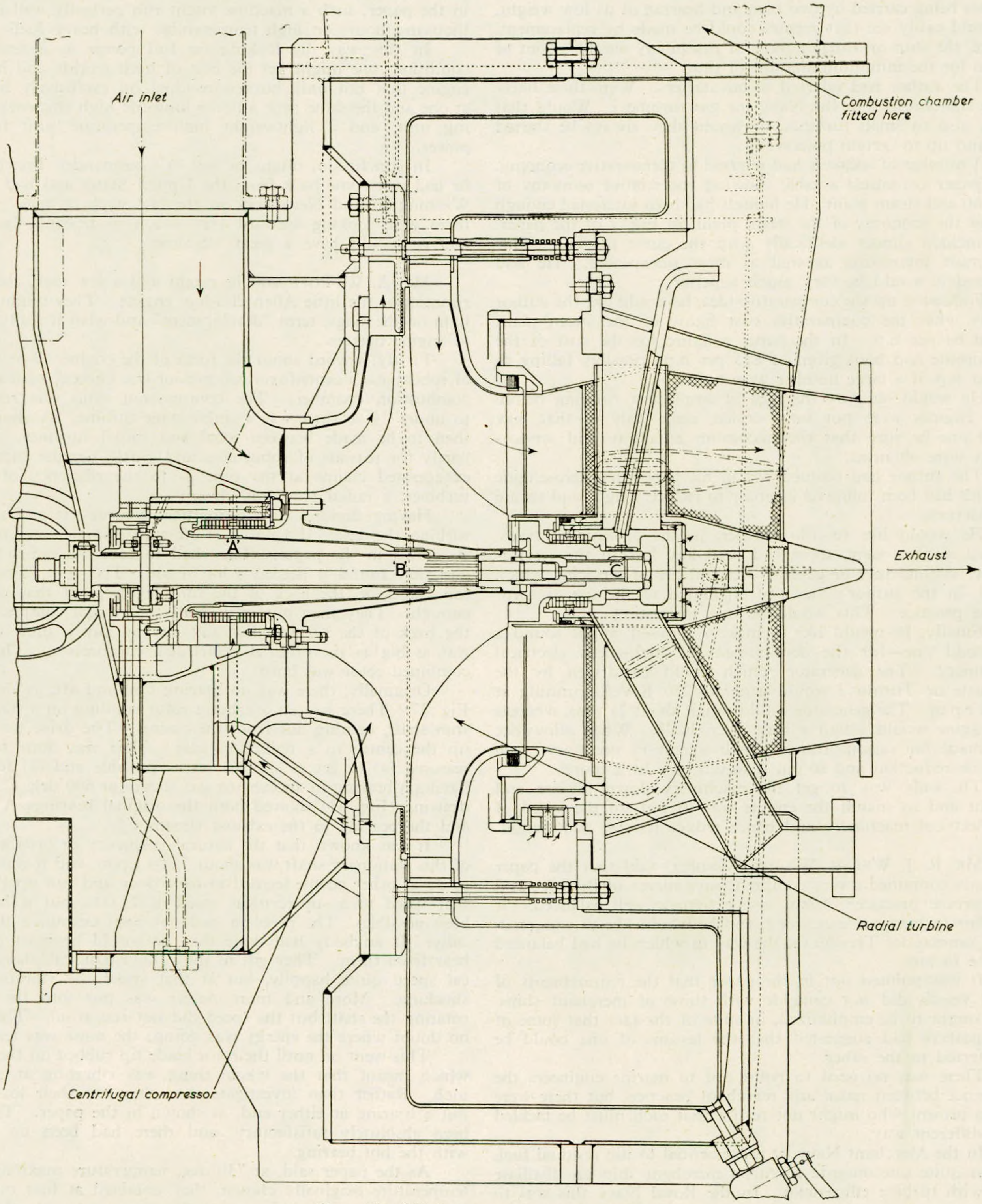


FIG. 41—*200-h.p. emergency gas turbine*

which meant moving the auxiliary drive back two inches. This was most annoying. When it was run on the engine, it gave a gain of 7 h.p. for all that effort. Probably the benefit was not reaped until a little later, but that was the immediate story.

Obviously, the main cause of the trouble was in the impeller itself; there was a restriction of flow. The channel area was increased by carving into the disc, and at the same time, the vane thicknesses were reduced and these modifications were worth a lot, giving another 27 h.p. and raising the output from 130 to 157 h.p. That was the figure when the paper went to press.

The speed was now increased from 22,000 to 23,000 and the last thing was to unbend the inlet vanes a little and so increase the throat area, and put a slight positive angle of incidence on the vanes. These changes raised the output to 170 h.p.

A new rotor was now to be made to give a better passage area on the compressor side. Up to this time the engine had completed 750 hours at 730 deg. maximum temperature. The temperature had now been put to 780 deg. C. and endurance tests had been restarted. At 780 deg. C. 200 h.p. was obtained and 212 h.p. at 800 deg. C. maximum temperature.

The efficiency of the radial turbine was round 86 per cent, which was not bad. It was nowhere near the original claim but it meant that turbines of this size and larger (not less than 100 h.p.) were good but not superior to the normal axial type.

A last word about design philosophy: if a customer or the Admiralty set a low standard in specific output and fuel consumption, one would get it the first time, no doubt, but the engine would not be very advanced. If the standard was set a little higher, with good design and a certain amount of luck one would get the design efficiencies and specific outputs, and they would be better than the original. If, however, the standard were set too high, one would not get the efficiency or the specific output. Moreover, it would be very difficult to improve the engine, because having designed it for higher efficiencies one would find it too small. If one put up the mass flow to increase output, the fuel consumption would suffer due to larger duct losses, etc. The final result would be to produce an engine inferior to what would have been obtained with less optimistic assumptions.

CDR.(E) PETER DU CANE, O.B.E., R.N.(ret.) said, though he was not claiming any detailed knowledge or experience of the design problems confronting a turbine designer, there were certain questions which occurred to him mainly as a result of such opportunities as he had had to observe the running of the *Bold* class of fast patrol boat with G2 turbines installed.

To start with it seemed very clear that to produce the horse power required to drive these fast patrol boats at operational speeds envisaged today, the gas turbine in some form would become a necessity owing in the main to the large horse powers obtainable from relatively light and compact units.

Commander Trewby gave an idea of the difficulties which had been met and overcome. He thought it most important to realize that these teething troubles were almost inevitable to obtain the required development. Most of the engineers associated with this type of development realized this and, in fact, expected it. It was not so clear, however, that those responsible for formulating future policy were always quite so understanding of these difficulties.

To the air people, where this type of development had been undertaken in the case of a number of prototypes, it would be unthinkable to attempt to clear a new type of its "bugs" with only two units to work on (even this was misleading because the two hulls had different characteristics to be evaluated). Only recently this matter was touched on, he believed, in the course of the debate on the air estimates, when it was disclosed that for a new type of supersonic fighter on order, no less than twenty prototypes were approved for construction so that no undue delay should be incurred in the trial stage. This policy could be followed to advantage in the case of naval prototypes, though it might be considered that a quarter of the numbers involved would suffice. Coming from a boatbuilder this might be considered to be in the nature of sales talk, but most of those who were intimately connected with the fast patrol boat business would know what he was driving at!

To touch as briefly as possible on technical matters, it seemed compressor surge was still a "headache" very much with them. For the naval units he wondered whether it would pay not to be quite so ambitious as regards the work done per stage in an axial compressor. If they could aim to do, say, 20 per cent less work on the air per stage, it would seem possible to keep further down the lift/incidence curve or its equivalent in turbine parlance and away from the stalling region.

It was true this would cost, say, 20 per cent more in weight of compressor but the naval applications could perhaps put up with this.

The free power type of turbine seemed to have a lot to recommend it for naval use, certainly with a fixed pitch propeller, but overspeeding of the power turbine appeared to worry designers. Would it be possible to do, say, 25 per cent of the work necessary for compression on a separate compressor driven direct from the power turbine to match up with another separately driven compressor? In this way it might seem the power turbine could never be unloaded to a dangerous extent while the characteristic flexibility as far as power output at varying revolutions might not be unduly compromised.

He asked forgiveness if these suggestions were known by the experts to be quite impractical.

MR. F. R. BELL said he would like to follow up what Mr. Holmes Fletcher had said. He absolutely agreed that the heat exchanger was a pity. He had wasted a lot of energy on heat exchangers but there was another thing that seemed a pity from the marine point of view. A boat was surrounded by water. It was very useful for cooling but very difficult to use. There were several ways of using water in gas turbines and all of them were difficult. He did not know how it was going to be done with salt water but there were two things he would suggest. First of all, had anybody ever tried to develop an evaporator for making fresh water that would work continuously and simply and efficiently? If that could be done a very small amount of water could be sprayed on to the blades and it would make a big difference to the turbine's specific output. That would be a very big gain.

Further, if water could be fed in large quantities into the combustion system of the turbine, it would make a very big difference in power in any given engine. It would raise the mass flow through the turbines but not through the compressor, thus the output of the engine would be increased by two or three times. The consumption of water was very large, however. He did not know whether one could use an evaporator, but there was plenty of waste heat in the turbine and this was really a form of heat exchanger, though much easier because it was running relatively cool. If the water was brought to a saturated steam condition and fed into the combustion system, it produced a very big gain.

Further, he thought salt water could be used. He had been connected with steam cars at one time where a continuous tube boiler was used. The velocities were high and the pressure drop in the boiler was fairly high. There were no deposits of scale, because the velocity was high enough to scour it off. If that could be done and an inhibitor could be added, one might make a very satisfactory unit. There was room for development and research there, but whether anything could be done in that way, he did not know.

MR. B. G. MARKHAM said that, like Mr. Rowe, he had started life in marine engineering but was wrested from it. If his remarks had an aeronautical flavour he must apologize.

The modern aircraft propeller turbine engine weighed between ½ and ¾lb. per h.p. and it was expected to do a thousand hours between overhauls. One could measure the reliability during that period in different ways.

He had in mind light coastal craft, and he did not know what was expected of a coastal craft engine in reliability. He did know, however, what air line operators expected from turbine engines: they expected at least the same sort of reliability as from piston engines. In fact, there would be a row if reliability were not better.

This could be measured by the number of hours one went between the times an engine had to be shut down in flight. The figures had been published by air line associations, and normal figures, which had not caused any complaint, were between 5,000 and 10,000 hours per engine stoppage. Some shut-downs were due to nothing more serious than instrument faults. Some engines were doing 14,000 hours. He did not know whether that would be acceptable for coastal craft. But that was the sort of serviceability that was obtained.

He did not want to dwell on the expense. It had been mentioned already. But the aero-engine manufacturer expected to build two or three dozen engines purely for bench and flight testing before he delivered one for production use. Surely the Royal Navy ought to cash in on that. If the marine engineers followed too far the aircraft principle of lightweight construction without corresponding facilities for testing and a very long purse, they would come unstuck. Marine adaptations of existing engines might double the weight, but they would still be lighter than any of the engines described.

On the question of the simple engine, a body of opinion held that it was the most promising line of development for some time. Commander Trewby stated that modern aircraft practice could give consumptions of below 0·7lb. of fuel per s.h.p. per hr. with 0·6 round the corner with twin spool designs. When the Proteus III was put on the test bed for the first time it ran rather well. This had pleased them, and they had pushed open the throttle. It was running with a bigger jet nozzle, so there was less power into the jet and more into the turbine. The figure was below 0·6, and the only thing that was required for the engine to run at 0·6 consistently was to put on a big nozzle so that power went into the turbine with less going into the jet.

Consumption at half power went up in the order quoted. As an alternative to heat exchangers, had consideration been given to multiple engines and perhaps two engines per shaft, and stopping one or more engines? Was that not an easy way to get part-load economy? If one engine per shaft was used, the loss during trailing was not very high and this had been confirmed by motoring tests on a turbine at Bristol. It was appreciable, but not as high as might be expected. On the other hand, clutches were a possibility. He believed the Gatric had a clutch but it was removed because it was not necessary. What sort of clutch was it? Was it discarded because it was not necessary or because it was a little troublesome and was not worth developing?

Did all the engines share a common intake? He could not make out from the drawings whether they did. With one engine shut down the other would be operating under more favourable intake conditions, and there would be a gain in fuel consumption if common intakes were used.

Aircraft engines did not have to have an engineer standing by. It was obviously an advantage to be able to get at them in operation but the engineer would not be standing by. He wondered, therefore, whether the large settling chamber could not be part and parcel of the engine room. After all, if an engine would stand salt water inside there was no difficulty about making it stand salt water outside, which was a much easier problem. Why was that not done?

Fig. 2 showed the power curve consumption on a number of engines. Were they on a propeller load or the optimum r.p.m. power?

MR. B. E. G. FORSLING, Civ.Ing. (Member) considered that it was fortunate that the Admiralty had taken an active interest in the gas turbine and had ordered a number of sets already at an early stage of development.

Although his company had not yet taken a direct interest in the naval gas turbine, largely because of other commitments, he took a personal interest in propulsion sets for naval application. The following points gave a line which seemed to be logical: —

(1) The gas turbine was at present unsuitable for large naval sets because the square-cube law was operative already at a moderate power.

(2) An open-cycle gas turbine, suitably designed, particularly of the simple type, could be started very quickly.

(3) The open-cycle simple gas turbine—for a marine set with independent power turbine—could be made light and built in a compact unit taking up little space.

(4) The open-cycle simple gas turbine had a comparatively high fuel consumption. Although improvements might be obtained, the open simple cycle could not be expected to produce a really high thermal efficiency.

(5) Improved thermal efficiency could be obtained by using more complex cycles which required increased weight.

(6) The fuel consumption of the gas turbine increased fairly rapidly at reduced power. For sets operating at varying speed, according to the propeller law, the specific consumption was increased by about 20 per cent at half load for a number of gas turbine cycles.

(7) A flat consumption curve over a wide range could be obtained mainly at the expense of higher fuel consumption at high loads.

(8) A gas turbine set could not readily be made reversible. Reversing and manœuvring must, therefore, be done by other means.

The conclusions from the above points were as follows: —

(*a*) Small or moderate sized units should be adopted. For large power a fair number of sets would be required. Development would, of course, lead to larger output per set at maintained or reduced weight per s.h.p.

(*b*) Naval gas turbine sets should be designed for a compromise in fuel economy based on the anticipated time in service for the required duty, i.e. the amount of fuel normally carried.

(*c*) Two types of propulsion sets would generally be required for most ships, usually simple short-time rated "spurt" sets for high power and more economical long-time rated sets for cruising. The cruising sets need not be gas turbines.

Applying this conclusion to light coastal craft which would operate at full power for only a few hours at a time, the minimum weight was obviously of first importance. The additional weight which could be accepted for obtaining improved economy was negligible. Hence, simple cycle sets of the lightest possible type should be adopted.

On this basis, the development on the lines followed for the Gatric and *Bold* type boats was correct.

For larger ocean-going ships, in the first place destroyers and cruisers, a simple cycle should be maintained for the "spurt" sets, but as full power might be required for an appreciable time, a design giving some improvement in fuel consumption could be considered.

For instance, if the "spurt" sets were fuelled for fifty hours on full power, a saving in fuel of 0·1lb. per s.h.p. per hr. corresponded to a saving in fuel of 5lb. per s.h.p.

For the cruising sets a good fuel consumption could be aimed at. If the sets were fuelled for 500 hours at 60 per cent rating, a saving of 0·1lb. per s.h.p. per hr. corresponded to a saving in fuel carried of 30lb. per s.h.p. The cruising sets would thus approach merchant navy requirements, particularly when their rating was low compared with the maximum power of the ship. As "spurt" sets could be used for a small increase in speed, lower rated cruising sets were a possible choice worth considering.

The "spurt" machinery could suitably comprise groups of four or five gas turbine sets of, say, 4,000 to 6,000 h.p., driving a common gear wheel through separate pinions, two sets being located aft and two or three fore of the gears.

If gas turbines were used for the cruising machinery, the size of the set should be limited to about 6,000 h.p. at present.

The proposed arrangement would probably necessitate the use of variable pitch propellers because the sets would be called upon to operate over a wide range of ship speeds at the same power.

In order to obtain the best propulsion machinery, one should neither adopt "the outlook which adheres closely to steam turbine practice" nor "base a design on the aircraft approach", but, using available experience, adopt the marine approach. The marine approach had led to the development of lightweight steam machinery, which was particularly suitable for naval requirements.

MR. R. G. VOYSEY said his thanks were due to Commander Trewby as well as to the Institute and the Admiralty for the opportunity to listen to the paper.

Commander Trewby had shown how one of the snags of naval turbines running at sea, namely the building-up of salt deposits on the compressor, could be obviated by spraying with distilled water. Had there been any evidence so far that the salt might also be an embarrassment to the turbine through hot corrosion of austenitic alloys?

The paper referred to the choice of fuels—distillate versus residual. This was a thorny topic and there was not much time in which to develop it, but he had known the problem for a long time. He thought he was the first person to run a gas turbine in this country on residual oil. That was seven years ago. He had been in touch with developments since then. It seemed to him, if he might summarize, that people seemed to have fairly adequate solutions against deposition and corrosion at temperatures below 650 deg. C., but at higher temperatures the prospects were extremely gloomy. The time had now come to look at the problem again and re-assess it. It must be borne in mind that aircraft designs were now touching some 500 deg. C. above the temperatures discussed in the paper, and this could not be ignored. It certainly could not be ignored on efficiency and even more on the gain in specific power. A vessel, particularly a naval vessel, was extremely sensitive in design to the size of air ducts and one must look ahead to higher temperatures. It was very difficult to think of any solution for the residual oil problem in the framework of the present periodic table.

It was presumably their very high efficiency which made mechanical transmissions predominant, but the gas turbine was a high-speed affair and it did have difficulty in providing astern drive. It asked for variable pitch propellers and both cruising and boosting turbines coupled to a number of propeller shafts. One wondered whether the time had been reached when one might look again at the electrical link, bearing in mind the use of modern ferritic materials which would permit the running of the system on several hundred cycles per second.

A previous speaker had asked about the future form of naval turbines. If the author could be tempted to such an indiscretion would he extend it to the mercantile side?

Correspondence

CDR.(E) A. D. BONNY, R.N.(ret.) wrote that in this paper the author showed how for certain specific naval requirements the aircraft gas turbine or its smaller versions could be adapted conveniently to form a very useful adjunct to the normal methods of power supply.

These special cases included machinery for fast coastal craft, emergency generators and fire pumps, ships' boats and possibly also as boost engines providing, say, 50-70 per cent of the power in high powered vessels, in which only a very small fraction of the ship's life was spent at higher powers. In fact, this covered the cases where the amount of fuel consumed and its cost was of little interest, working life was short, and a high power/weight ratio all-important.

Coming to the more normal requirements of ship propulsion, one found that despite a very large expenditure of design effort and money the attempt to design a long life and economical gas turbine based on aircraft engine design had not in fact yet succeeded and more steam practice needed to be added at the expense of weight before it could achieve the necessary reliability, while further weight would need to be added to reduce the fuel consumption.

What a contrast this was to the development of the steam turbine. Ever since twenty years ago a high-pressure set was fitted in a destroyer and had teething troubles, all experimental designs had been frowned on. No shore testing facilities existed and design definitely lagged until late in the war when efforts were made to catch up some of the leeway. Even now the old tradition died hard and the steam design was expected to be 99 per cent sure of working first time.

He would like to envisage what could have happened if, say, half of the money and effort had been spent on a steam set in which similar temperature conditions and stresses were allowed. Taking a steam temperature of 1,450 deg. F. to give approximately the same maximum metal temperature, a steam set of 10,000 s.h.p. could be designed for an overall fuel rate of 0·42-0·43lb. per s.h.p. hr. decreasing to about 0·4 as the power increased. Advanced design allied with fabricated construction would go far to reduce weights though boiler construction would need fairly drastic reconsideration—it was not suggested that the low figures of the semi-aircraft design could be equalled, but the saving of fuel would offset this for a reasonable endurance.

Further, if the naval requirements were such that boost by an inefficient machine above some 30-50 per cent power was considered to be desirable, then surely "steam boost" could equally be applied, i.e. heavy overloading of boiler and turbines without the duplication consequent on two different sets of machinery being fitted. This was, of course, already done to a considerable extent in naval design but there was still room for further development on these lines.

By these comments the writer did not wish to belittle the very considerable efforts of the Admiralty to get the gas turbine on to its feet in the shortest time but wondered nevertheless whether a forced hothouse flower had not resulted rather than the hardy growth needed for sea service.

MR. A. W. DAVIS, B.Sc. (Member) had understood that lightweight construction of gas turbines was to be associated with design for short life and that heavier construction with the disadvantages of high thermal inertia of the parts was only justified by the requirement for a relatively long working life, and perhaps by higher efficiency. Referring to the table in Appendix A, this impression was borne out by the English Electric design E.L.60A in comparison with six of the other designs compared by the author, but was largely contradicted by the 1,000 kW. G.T.A. engine manufactured by W. H. Allen, Sons and Co., Ltd., wherein a long designed life was associated with a relatively low specific weight and a relatively high thermal efficiency. It was possible that this comparison was to some extent upset by the absence of reduction gearing to the output shaft for this latter set and, if this were the case, it would be illuminating to have estimated specific weight and efficiency figures were this unit to be driving through reduction gears.

In this connexion, some loss was also to be associated with the need of reversibility and it would be valuable to know the allowance, if any, made for the losses associated with such mechanism in the statement of thermal efficiency for each of the designs enumerated in the aforementioned table.

MR. S. J. MOYES thought there was no doubt that Commander Trewby's paper presented an admirable survey of the developments in gas turbine engines as applied to naval craft over the past years. Many interesting points arose for further consideration and of these the writer would select the following as important questions that would need study in the conception and planning of future designs.

(*a*) Frequent references were made in the paper to the unreliability of ball and roller bearings when used under conditions of service obtaining in naval engines. In the cases quoted of failure of ball and roller bearings, the cause of failure was not stated or not known. The evidence thus offered was surely insufficient by which to judge the ball and roller bearing as a component fundamentally unsuitable for naval use. Bearing in mind the advantages of smaller mechanical losses, lightness and simplicity of design that the ball and roller bearing could offer in comparison with the plain bearing, it was to be hoped that the issue of reliability would not be prejudged and provision made for suitable experimental work for the furnishing of more adequate data.

(*b*) The rather controversial question of heat exchangers had been touched on and here again the shore trials' experience described in the paper was insufficient to decide whether on future engines heat exchangers would be worth while. It could be shown that in a properly integrated design where the heat exchanger was designed to function under cruising (low load) conditions only, significant gains in fuel economy, compared with the non-heat exchanger engine, were made available without the heat exchanger becoming the space-consuming component that it was sometimes made out to be. There was no doubt that to ensure reasonable capital cost and reliability, problems of construction and maintenance of heat exchangers loomed very large, but it should not be outside the resources of a reasonable experimental programme to decide whether these problems were so great that their solution involved disadvantages of such magnitude as to render the heat exchanger of no value to the naval gas turbine engine.

(*c*) It was stated in the paper that for propulsion machinery in major warships, the naval requirement for high efficiency over a wide range of power could be met either by a single complex engine operating over the whole load range or by a number of simple gas turbines each operating over its peak efficiency range. In the majority of cases, however, the greater part of the fuel carried was consumed under cruising conditions, and a logical development of the scheme employing a number of simple gas turbine engines was to use units of simple design covering the higher load ranges in conjunction with more complex high efficiency units for cruising. It was true that by so doing certain advantages in respect of interchangeability, provision of spares and maintenance were diminished, but the potential saving in engine plus fuel weight rendered the use of specialized gas turbine engines a line of development well worth consideration.

MR. C. P. RIGBY congratulated Commander Trewby on his excellent presentation of this most useful survey of naval activities in the gas turbine field and offered some comments which he would have liked to make, had there been time, at the end of the very interesting discussion which followed.

First, he noted the author's desire to substitute plain journals and Michell thrusts for the roller and ball bearings used in aircraft engines; while agreeing that this was desirable and presented no insuperable difficulties in simple engines where shaft diameters could be kept small relative to their speeds, he feared that insistence upon this policy might prejudice performance when compound engines with unavoidably large concentric shafts were navalized.

The alternative was to improve the reliability of ball and roller bearings and here he believed that it was not the bearing but rather its application to the engine which had been at fault where failures had occurred.

Factors apparently contributing to failure in various cases included inadequate lubrication, insufficient knowledge of axial thrust loads, underloading of roller bearings permitting roller slip, overloading due to unsatisfactory dynamic balance and heavy vibration from external sources. The engine designer could do much to alleviate these conditions; for instance, in both Turbomeca engines and Napier turbo-blowers the outer races were supported in resilient mountings to reduce dynamic loads.

It might be of interest to record that in a total of 2,190 hours running at the Admiralty Engineering Laboratory, comprising 440, 1,000 and 750 hours on Gatric, Rover T8 and Turbomeca Artouste I engines respectively, they had had no signs of a bearing failure.

Admittedly they had as yet no really long runs but in a T8 now on test the compressor turbine ball thrust bearing had so far run for 585 hours, principally at 35,000 r.p.m. and with an outer race temperature of 170 deg. C. This was a large bearing for its speed, having a ball track in the outer race some 2·8 inches diameter, and assuming that the cage rotated at half shaft speed the balls had already rolled about 85,000 miles.

The really interesting point about this was that at one stage in the development of the T8 the Rover Company suffered from repeated failures of identical bearings which ceased without any radical change in design. The bearing now had rather more oil and less ingress of air than originally, and there was no doubt that better dynamic balance was being achieved.

The second point he would make, more perhaps concerning the verbal discussion than the paper itself, was that certain items of steam propelling machinery had by no means the infinite life with which they tended to be credited. It would be of interest, for example, to know how the anticipated life of superheater tubes under the steam conditions being used in new construction compared with that envisaged for the combustion chambers and h.p. turbine rotors of projected gas turbines.

MR. B. WOOD, M.A., noticed that Commander Trewby referred on page 145 to the fact that the specific weight of simple gas turbines increased with power and correctly implied that the specific weight varied as $\frac{1}{\sqrt{P}}$. However, the power P was not the only variable and the following analysis might be of interest.

For the case of similar shapes and the same fluid the power per annulus

$$P \propto M H_u \propto \rho V_a D^2 H_u$$

where M was the mass flow, H_u the heat drop utilized per pound, V_a the axial velocity, ρ the density, and D the diameter. Hence, for a given H_u there were three ways of getting bigger output, viz., larger D, higher V_a or higher density. For the comparison of unpressurized machines ρ was dependent only on temperature and did not vary appreciably between compressors or greatly between turbines.

The leaving loss per pound $= \frac{V_a^2}{2g}$ and the proportional leaving loss $Z = \frac{V_a^2}{2g H_u}$.

In jet propulsion types a very large leaving loss in the turbine was acceptable because this was what the machine was designed to produce. In gas turbines which had to produce shaft power, on the other hand, leaving loss represented a loss of which, in general, only a small amount could be recuperated by diffusers. Moreover, on the assumption of similarity, the leaving loss was indicative of the general parasitic loss throughout the cycle.

The first equation could now be written as

$$P \propto \rho D^2 Z^{\frac{1}{2}} H_u^{3/2}.$$

Now the weight of the rotor $\propto D^2 L$ (where L was the axial length) and that of the casing $\propto t\,D\,L$ where t the thickness would vary with Dp, p being the internal pressure. Therefore, for a given p level, W, the total weight $\propto D^2 L$, i.e. to D^3 for similar shapes. Therefore, the output per unit weight

$$\frac{P}{W} \propto \frac{Z^{\frac{3}{4}} H_u{}^{9/4}}{P^{\frac{1}{2}}}.$$

This sort of relation must be true for both compressors and turbines and, therefore, could be taken as giving a general trend applicable to the whole plant, excluding alternator and regenerator. It was not, of course, a rigid law for all designs because there was scope for individual design, selection of material, factors of safety, and general form, i.e., designs were not similar.

The simple relation was not true for other than simple cycles since, if a higher pressure ratio was used the upper part of the cycle benefited from the higher density at the expense of increased weight of the casing but not of the rotor.

It was the fashion amongst the aircraft school to decry land gas turbines on the ground that they were big and clumsy and that they used far too much material. If they were viewed with the above relation in mind, it would be found that they were not so bad as the aircraft-minded might think. Thus, they might take the Ruston and Hornsby 900-kW. machine as a good representative of "aircraftized" design. This weighed approximately five tons (without alternator or regenerator) with an output of 180 kW. per ton. Brown Boveri might be regarded as exponents of the land school. Their single exhaust 2-shaft 22·5 MW. set recently ordered for Leghorn weighed about 250 tons, excluding alternator. This gave an output of 90 kW. per ton, exactly half of the Ruston. The heat drop was approximately 230 B.Th.U. per lb. as against Ruston's 132 and, assuming the same value of Z, the above criterion would account for an output per ton of

$$180 \times \frac{\dfrac{230^{9/4}}{132}}{\dfrac{22{,}500^{\frac{1}{2}}}{900}} = 126 \text{ kW.}$$

The actual output per ton of 90 kW. was accordingly only about 30 per cent below par, partly, no doubt, because of the benefit of a wider pressure ratio, though it should be noted that the intercooler and second combustion chamber were included in the weight. Moreover, the price per kilowatt or per ton of the large machine was much lower, viz., £16 per kW. or £1,130 per ton, including alternator as against £40 per kW. or £3,100 per ton including alternator for the small machine. The efficiency was also better and the life longer and these factors, though possibly of lesser account to the Admiralty, were of first-rate importance in land service for which the machines were intended.

MR. H. WOOD wrote that Commander Trewby's paper put on record the Admiralty's work in finding the proper niche in their propulsion and auxiliary machinery of that very modern prime mover the gas turbine. They should all feel very grateful and comforted by the systematic way in which the Admiralty were exploring this field in their efforts to improve the fighting efficiency of the Fleet and doubly thankful that Commander Trewby had given such an excellent picture of that exploration. There must necessarily be some omissions but what he had described left no doubt that the development programme was a vigorous and a continuing one.

If the requirements for propulsion machinery quoted at the beginning of the paper were considered they must agree with the author that they conflicted and that the best design must be a compromise.

As a member of the team which was responsible for the design and development of the R.M.60, he felt that some comments on how this particular engine fitted or failed to fit the requirements might be useful. They could claim that it met requirements 1, 2, 3 and 6 very well indeed. As it was never intended to be a prototype production engine, 4, 5, 8 and 9 were not designed into it and they confessed that R.M.60 would not satisfy operational requirements in these respects. The problem was how best to meet *all* the requirements in one unit or simple combination of units.

Their preliminary investigations of R.M.60 started nearly eight years ago and at that time there was no other way of achieving good thermal efficiency over a wide range of power than the way finally chosen and now known as R.M.60. As manufacture and development progressed they had misgivings about the ultimate suitability of such a complex plant for a fighting service, particularly if it were to be redesigned to make it withstand shock loadings, resist battle damage, have an acceptable long life and still better thermal efficiency at low power.

They concluded that the resulting design would be no more amenable to cheap and rapid production than steam turbines and boilers, that provisioning for spares would be expensive and difficult and parts of the engine would be prone to action damage.

This led to a reconsideration of the whole problem and an investigation into the state of the art now as compared with 1946 when R.M.60 started. For several years the view had been current that the special requirements of the Navy could best be met by a combination of a cruising engine at about one-quarter or one-third of the total power with the infrequent use of the balance of power being covered by a lightweight relatively short life booster gas turbine. But at that time no simple gas turbine had a sufficiently good thermal efficiency to meet the consumption requirements unless a heat exchanger were added. The installation of such a cruising plant with its booster gas turbine then becomes sprawly and complicated. The advances since 1946 had been in the improvement of component efficiencies, the effective utilization of higher pressure ratios, improvement in materials and ability to use higher operating temperatures. All these added up to the fact that simple gas turbine power units could now be made to give a fuel consumption of the order of 0·51b. per b.h.p. per hr. at the design power. It was true that such a unit would need a compressor with a pressure ratio of 10-12:1 but this could be achieved by adopting the twin spool principle, which was rapidly getting established. On the other hand intercooling and heat exchange could be dispensed with. How then could such a unit be employed to meet the requirements for naval propulsion?

If, say, 9,000 h.p. per shaft were required, it could be met by a twin spool engine of, say, 3,000 b.h.p., and a booster gas turbine of 6,000 b.h.p., geared together with declutching means. By using the small engine for cruising and manœuvring, consumptions of the order of 0·551b. per b.h.p. per hr. at $33\frac{1}{3}$ per cent total installed power, 0·65 at 15 per cent and 0·75 at 10 per cent became possible.

As Commander Trewby had pointed out, the top 70 per cent of power was used for less than 5 per cent of the total steaming time, so that the booster gas turbine could quite well be an aero-type gas turbine modified only to suit seagoing conditions.

Considering now how such combinations of simple gas turbines met the stipulated requirements, it would be seen that by designing the cruising engine sufficiently robustly to give long life and resist shock, all the requirements were adequately met. Moreover, such an engine for 3,000 h.p. would have its gas generator portion up to the power turbine casing flange as a unit about 9ft. long, $2\frac{1}{2}$ft. diameter, weighing less than 3 tons. Complete spare units could be carried on board and if the demand were sufficient a production line could be set up with enormous consequent reductions in cost per h.p. and the cost of replacements.

Author's Reply

Replying to the discussion, the author remarked that several contributors had expressed views on the type of construction best suited for naval gas turbines.

He wished to reiterate what had been stated on page 145 of the paper, namely, that in most cases the aircraft designs described were only accepted in order to obtain early operating experience. Aircraft gas turbines without modification might be suitable for the propulsion of high speed coastal craft, but a more robust design was necessary for major warships. The author agreed with Dr. Smith that it was possible to produce naval gas turbines of high reliability and comparatively long life, and at the same time to show very considerable reductions in weight and space compared with other forms of propulsion machinery.

Gas turbines would only supplant existing machinery in operational warships where they were shown to be generally superior, based on the special naval requirements listed on page 125 of the paper. Modern naval steam machinery was light and compact and, in addition, steam was a convenient means of providing auxiliary and hotel services. For gas turbine installations additional weight and space would be necessary, not only to provide satisfactory hotel and auxiliary services, but also to incorporate some external means of reversing. The gas turbines themselves must, therefore, be considerably lighter than equivalent steam plant if an overall reduction in the total machinery installation weight was to be made.

There could be two fundamentally different starting points for naval gas turbine design. Aircraft gas turbines with specific weights of less than 1lb. per h.p. or units constructed on steam turbine principles with specific weights (at present) of over 25lb. per h.p. The design of naval gas turbines could be approached by starting with an aircraft engine, lowering the stresses, thickening the scantlings and reducing the rating, or by starting from a steam turbine design, putting up the rating and reducing the scantlings. In the author's opinion these two fundamentally different approaches would not produce the same type of final design. He considered that the correct starting point for naval gas turbines was the aircraft approach, but the engine must be redesigned on more robust lines with lower stresses throughout, reduced gas velocities (where possible), and plain bearings if long life was required. Vast sums of money had already been spent by the Ministry of Supply on the development of aircraft gas turbines and their components; it was up to the Navy to make the fullest use of this development work.

The author fully realized that the machinery requirements and operating conditions for warships and merchant vessels were fundamentally different and a very different type of gas turbine might be required for merchant marine applications.

Dealing now with individual comments, the author thanked Mr. Constant for showing the good performance which could be obtained with a lightweight, simple gas turbine if the best components at present available were all put into the same engine. The practical difficulty in achieving this was that any one gas turbine manufacturer might not be in a position to provide the best of each type of component. Moreover, the cost of developing all the components of a naval gas turbine up to the highest standard was enormous. The high cost could not generally be justified for the comparatively small number of gas turbines which the Navy would require, and this was one of the reasons why the Admiralty must make the fullest use of Ministry of Supply development work.

The author fully agreed with Captain Cotman that more work on the silencing of naval gas turbines was necessary. In general the Admiralty had concentrated first on obtaining operating experience, but in every installation so far attempted some degree of silencing had been achieved. He did not consider that the successful silencing of naval gas turbines would prove such a formidable problem as with highly rated Diesel engines.

Mr. Holmes Fletcher had pointed out some of the difficulties inherent in complex naval gas turbines designed for long life and good efficiency over a wide range of power. As a result he had come to the conclusion that a number of simple gas turbines, mechanically coupled together, would provide a better installation for warship propulsion. The author agreed in general with this conclusion, but installations of this sort must be limited to three, or at most four, engines per shaft, to prevent the gearing, clutching, and control from becoming too complicated.

The provision of auxiliary services in a gas turbine-propelled warship certainly required further investigation. There were many possibilities. In addition to waste heat boilers, it might be possible to tap off compressed air from the main engines and use it for auxiliary services. Mr. Holmes Fletcher had drawn attention to some of the disadvantages both of heat exchangers and waste heat boilers. A heat exchanger would usually be the most efficient means of reclaiming heat from the exhaust but it might not be the most convenient; firstly because a heat exchanger would be larger than an exhaust boiler for the same heat recovery, and secondly because steam was an extremely useful commodity in any warship.

Mr. Holmes Fletcher had asked what the author's views were on the future type of gas turbine for warship propulsion. It was difficult to make any long term forecasts since naval gas turbines were still only in the early stages of evolution. Nevertheless, it appeared that the characteristics of the gas turbine which should be exploited to the utmost for naval applications were small size and weight, basic simplicity (leading to reduced maintenance), rapid starting, and great flexibility in operation. It might be necessary to sacrifice thermal efficiency to some extent in order to obtain these qualities. Higher gas temperatures would be introduced as soon as blade cooling was successfully developed, and this, together with higher pressure ratios, would enable simple gas turbines to meet the majority of naval requirements.

The author agreed with Dr. Smith that the steam plant originally fitted in H.M.S. *Grey Goose* was probably more durable than the R.M.60 gas turbine, but the forthcoming trials should provide more information on this point.

Mr. Allen had referred to the use of epicyclic gears for reversing. The Admiralty appreciated the importance of developing reversing mechanisms for gas turbine installations and various forms of planetary and epicyclic gears were being considered, together with other arrangements, including controllable pitch propellers. Epicyclic gears had advantages for single turbine drives in restricted space and might also prove useful as primary trains in multiple turbine installations. As the study of the reversing problem advanced it became apparent that each case required individual treatment and undue emphasis on any one technique might be misleading.

The author thanked Captain Farquhar Atkins for adding further details of the running experience obtained with the Allen 1,000 kW gas turbine at the Admiralty Test House, National Gas Turbine Establishment. He shared Captain Farquhar Atkins's enthusiasm for using compressed air bled from gas turbine compressors for salvage purposes.

Replying to Mr. Yates, the author pointed out that sleeve bearings only brought significant losses in complex gas turbines. For example, the fitting of sleeve bearings and Michell type thrusts in the G2 gas turbine (in place of ball and roller bearings) would involve an additional loss of some 40 h.p. at full power (less than 0·9 per cent of the total power). Mr. Yates had rightly drawn attention to the difficulties of designing gas turbines free from surge and vibration troubles. The provision of shrouding would always be an advantage in avoiding blade failures, but lacing would not be acceptable due to the excessive loss of efficiency. As more knowledge became available on aerodynamical vibration problems, it should be possible to operate compressors over a wide range of speeds without surge or vibration failures.

The optimum range of powers for gas turbines was certainly lower than for steam turbines, but he thought that Mr. Yates had set the upper limit of gas turbine power too low. Aircraft gas turbines were at present developing the equivalent of over 15,000 h.p. in single engines and they were comparatively small units. The author agreed that it was difficult to compare steam and gas turbines directly. The only valid comparison was on the basis of a complete machinery installation of similar power. The sentence quoted from the paper by Mr. Yates on the future of gas turbine propulsion represented the author's opinion and he had not intended to convey any different impression in the rest of the paper.

Replying to Dr. Brown, the author hoped that his opening remarks had clarified the position regarding lightweight gas turbines for warship propulsion. Dealing with the question of starting, a properly designed naval gas turbine could be made to start and develop full power in a matter of minutes. The Navy intended to make full use of this important military advantage. Steam plant generally took two hours or more to develop full power from cold. There were many instances in war when this period was unacceptably long and it was therefore necessary to keep steam up continuously. This meant that the majority of the engine room staff were on watch both at sea and in harbour, and their efficiency in action suffered thereby. It also added appreciably to the maintenance difficulties.

Dr. Brown had asked whether the residual fuel problem was still considered a major one so far as the Admiralty was concerned. It was not the intention to hold up the development of naval gas turbines until a solution to the residual fuel problem was found. The gas turbine had so much to offer for certain naval applications that operation on Diesel fuel could be accepted, for the time being at any rate. But concurrently research on the burning of residual fuel would continue to be given high priority in the hope that a satisfactory solution would ultimately be found. He agreed that in a suitable design of gas turbine the residual fuel problem could be solved providing the gas temperature did not exceed some 650 deg. C. (1,202 deg. F.). There was little operating experience at the higher temperatures which were necessary to keep down the weight and size of naval gas turbines. What experience there was suggested that the corrosion problem was extremely formidable. Referring to Dr. Brown's criticism of fuel economy in the lightweight aircraft type of gas turbine, it should be stressed that full power economy was not of great importance in naval designs. The efficiency at cruising power was the point that really mattered. This might be anywhere between 5 per cent and 30 per cent of total power and under these conditions the thermal efficiency of the R.M.60 was superior to any gas turbine known to the author.

Mr. Lubbock had pointed out the somewhat disappointing performance of the R.M.60 gas turbine at full power. The author wished to emphasize again that the main object of the design was to produce a reasonable efficiency over as wide a range of power as possible and the heat exchanger was deliberately bypassed at high powers. The following data obtained during test bed running of the R.M.60, when the engine was developing 5,650 h.p., gave an indication of the various losses in the system.

Intake pressure	14·8lb per sq. in.
Intake temperature...	8 deg. C. (46 deg. F.)
Intake pressure drop	0·21lb. per sq. in.
L.P. compressor adiabatic efficiency	81·1 per cent
Intercooler pressure drop	3 per cent of total head
H.P. compressor inlet temperature	42 deg. C. (107 deg. F.)
H.P. compressor adiabatic efficiency	80 per cent, including intercooling
Heat exchanger air-side pressure drop	2·44 per cent of total head
Combustion chamber pressure drop	3·3 per cent of total head
Combustion efficiency	99-100 per cent
H.P. turbine adiabatic efficiency ... Pressure drop between h.p. and power turbine ... ... Power turbine adiabatic efficiency	90·4 per cent
Pressure drop between power and l.p. turbines	Zero
L.P. turbine adiabatic efficiency ...	86 per cent, including diffuser and elbow
Heat exchanger gas-side and exhaust pressure drop...	7·4 per cent total head

Mr. Rowe had asked about the starting requirements for naval gas turbines. It was unlikely that all engines would employ the same method of starting and the choice would depend mainly on the application and the services already available in the vessel. For propulsion gas turbines of large power, electric or compressed air starters would probably be used. In the latter case fuel might be burned in the starter to cut down air quantities. For smaller sizes it would always be an advantage if the gas turbines could be hand started in an emergency. Cartridge starters might also be employed if very fast automatic starting were required as, for example, in emergency electric generators.

It was true that the performance of the original steam machinery fitted in the *Grey Goose* was no better than the G2, but that machinery had been produced under great pressure at a critical period during the last war. It was now out-of-date and did not give a true picture of the performance of modern steam machinery.

Comparable cost figures for different types of machinery were often misleading. Average costs of present-day steam propulsion machinery in the larger sizes were around £16 per h.p. when manufactured in single units. The author agreed that high speed electrical machinery would be very desirable from the weight and space aspect. However, he understood that the use of very high frequencies in warship electrical installations presented many problems.

It was difficult to say categorically whether aircraft practice had resulted in loss of serviceability or maintenance life. The use of ball and roller bearings had, however, caused some failures which would not have been anticipated with normal marine practice.

Replying to Mr. Welsh, the author thought that the use of a heavy low temperature cruising gas turbine would only be attractive in applications where the cruising power was a very small fraction of the total power. A fair margin over the nominal cruising power would be essential for a cruising engine to cover operational contingencies.

Mr. Pope's comments on design philosophy were interesting, but surely it was also the duty of the manufacturing firm to ensure that they did not overstretch themselves in meeting too stringent requirements put forward by the customer?

Replying to Commander Du Cane, the author considered that the ordering of large numbers of prototype gas turbines could only be justified if substantial production orders were to follow. The numbers required by the Admiralty in peace were never very large, but development would certainly be hastened if more engines were available.

Commander Du Cane had raised two interesting points in connexion with compressor design. It was possible that a decrease in the work done per stage might result in a compressor that was less prone to surge, but there were many other factors affecting this problem in multi-stage axial compressors. The suggestion of driving a few compressor stages from the power turbine would certainly prevent overspeeding; but to obtain any stability at all it would be necessary for the power turbine to drive the l.p. stages, and even so the flexibility would be seriously compromised unless a controllable pitch propeller were fitted.

Mr. Bell had raised the question of using sea water to improve the performance of naval gas turbines. At present intercooling appeared to be the only practicable means of doing this. If substantial benefits were to be obtained from spray cooling of the turbine blades or from wet compression, the quantities of water involved would be of the same order as the fuel flow, and it appeared essential to use distilled water. Salt spray cooling had been tried experimentally but the corrosive and fouling effect on the blades had been so severe that the tests were abandoned after a few hours' running. Evaporators at present available were bulky and required a considerable maintenance effort to maintain their serviceability. A simple and comparatively inefficient unit, evaporating the same quantity of distilled water as the gas turbine fuel flow, would weigh as much as a complete gas turbine of the G2 type. A more efficient evaporator would be twice as heavy as the gas turbine. No development work has yet been carried out on a waste heat evaporator.

Replying to Mr. Markham, the author thought that the figures quoted for aircraft engines would be acceptable for naval coastal craft but not for major warships. It was interesting to hear that the fuel consumption of the Proteus III was below 0·6lb. per s.h.p. per hr., and this emphasized Mr. Constant's point that good efficiencies could be obtained with simple lightweight engines.

Consideration had been given to multiple gas turbine arrangements and this point was covered on page 137 of the paper. With regard to Mr. Markham's query on the type of clutch fitted with the Gatric, this was of the SSS type. It was discarded, since the loss due to trailing the power turbine of the Gatric, when running on the Packard engines alone, was only some 20 h.p. The complication of the clutch, with which there had been a little bearing trouble, was considered unnecessary. It would be a mistake, however, to underestimate the trailing loss, particularly if the cruising engines could propel the vessel at comparatively high speeds. In the *Bold Pathfinder* and *Bold Pioneer*, the G2 gas turbines shared a common intake, but the velocity at entry was only some 20ft. per sec. with both engines in operation. A settling chamber was desirable in order to dispose of green water in a heavy sea and also to act as a separator and thus reduce the amount of salt in the form of small particles entering the engine. There was no reason why the settling chamber could not be part and parcel of the engine room provided that other machinery which required tending was not situated in the same compartment. The power consumption curves shown in Fig. 2 were on a propeller law basis.

Mr. Forsling had put forward a very convincing and logical analysis of the factors influencing naval gas turbine design. It was gratifying to find that he concluded that the Gatric and *Bold* boat gas turbine developments were correct. The author agreed in general with the analysis and its conclusions but pointed out that fuel and engine weights were not always strictly interchangeable in warship application. The important question was the price to be paid in complication and bulk for improving the fuel consumption of a cruising gas turbine in a naval vessel. The author thought that boost engines of larger power than those proposed by Mr. Forsling might have an advantage since fewer would be required in a given installation. If too many sets were fitted the weight of additional ducting, control, clutches, gearing, etc., would swamp any differences arising from the square cube law.

Replying to Mr. Voysey, there had been no evidence so far of hot salt corrosion on the austenitic alloys in naval gas turbines caused by the salt-laden air. The author agreed that, while a solution to the problem of burning residual fuel could be obtained for gas temperatures below 650 deg. C. (1,202 deg. F.), the corrosion problem appeared formidable at the very high gas temperatures which would come in the future. The successful development of the cooled gas turbine might provide efficiencies so high that distillate fuel could then be economically used.

The weight, bulk, and cost of electric transmission made it unattractive for warship applications and, in addition, it was more prone to action damage due to flooding. The author did not feel qualified to speak on the future of mercantile marine gas turbines since the whole of his experience had been obtained in naval vessels; he would like to emphasize once again that there was a fundamental difference in the requirements and operating conditions of propulsion machinery for the warship and the merchant vessel.

In answer to Commander Bonny, the author stated that it was the intention to use the characteristics of the gas turbine in the best way to improve the fighting efficiency of the Fleet. These characteristics lent themselves more readily to short life and emergency applications than to continuous base load operation, where high thermal efficiencies and long life were demanded.

He fully agreed that steam turbine machinery was still capable of considerable development, and if this were carried out gas turbines would not be competitive for some years as long life propulsion plants in sizes above, say, 10,000 h.p. The gas turbine was still only on the threshold of development, however, and when cooling techniques allowed really high gas temperatures to be used, the author was sure that gas turbines would supersede steam turbines in the majority of warship applications.

"Steam boost", i.e., heavy overloading of boiler and turbines, employed a fundamentally different principle to gas turbine boost. The great attraction of the latter was that the highly rated short life plant was entirely separate from the long life cruising machinery. Moreover, the warship could proceed to sea in a matter of minutes on the gas turbines alone if some unforeseen emergency arose.

As a counter to Commander Bonny's last sentence, if the Admiralty had not followed the best horticultural tradition in rearing some of their initial projects in a hothouse, they would not now be in a position to plant out the hardy growths which Commander Bonny so rightly advocated.

Mr. Davis remarked that in the Allen 1,000-kW gas turbine alternator a long designed life was associated with a relatively low specific weight and a relatively high thermal efficiency. This machine was an excellent example of the type of construction which the author advocated for long life naval gas turbines. It was based on aircraft practice (the Bristol Theseus) but the whole engine was more robust and there was every indication that very long periods between overhauls would be achieved. The Allen 1,000-kW gas turbine was fitted with epicyclic gearing which reduced the normal turbine output speed of 6,750 r.p.m. to the alternator speed of 1,500 r.p.m. For marine propulsion a lower propeller shaft speed would be necessary and, as a rough approximation only, this would increase the specific weight of the complete unit to a figure of about 12lb. per h.p. The reduction in thermal efficiency would be extremely small.

The author agreed that some loss would always be associated with the need for reversibility, but the thermal efficiency figures quoted in Appendix "A" did not include any allowance for this. They were obtained from measured results of b.h.p. and fuel flow taken during test running ashore.

Both Mr. Moyes and Mr. Rigby had raised the question of the reliability of ball and roller bearings for naval gas turbines. Ball bearings have obvious advantages in reducing the mechanical losses and simplifying design, but at present ball bearing life, under the conditions obtaining in naval gas turbines, does not appear adequate for major warships; it may be acceptable for high-speed coastal craft and in emergency applications, however. In addition, ball bearings are apt to suffer from brinnelling when not in use, and have a comparatively poor resistance to shock loads and hull or shaft vibrations. The author agreed with the implication that many ball bearing troubles could be overcome with further development, and Mr. Rigby's figures showed that reliability could be obtained in the smaller sizes when tested ashore. Plain sleeve bearings and Michell type thrusts, on the other hand, can give guaranteed long life and reliability at the expense of higher mechanical losses and a bulkier lubricating oil system. It was essential to keep an open mind on the problem and if ball and roller bearings with adequate life and robustness could be developed, they would have many advantages. At the present time the author considered that plain sleeve bearings were necessary for long life naval applications.

The author agreed with Mr. Moyes that heat exchangers enabled significant gains in fuel economy to be made, but they were costly, bulky, difficult to clean, and presented a considerable fire risk. There was substantial development work to be done before heat exchangers became really attractive for naval applications.

Mr. H. Wood had shown very clearly how the requirements of naval propulsion machinery could be met by a number of simple gas turbines (possibly with twin spool construction for the cruising units). The author was in general agreement with Mr. Wood's conclusions but there were two comments he would like to make. Firstly, if the supply position demanded the use of residual fuel for all major warships, then a very different type of gas turbine would be required for cruising; something more on the lines suggested earlier in the discussion by Mr. Welsh. Secondly, although "boost" engines were required for less than 5 per cent of the total life, they must be sufficiently robust to withstand the specified shock loading and this might involve considerable modification to an aircraft gas turbine.

The author thanked Mr. Rigby for pointing out that certain items of steam machinery had by no means the infinite life with which they tend to be credited. This was very true and there was often a tendency to compare a complete gas turbine engine with a steam turbine alone, omitting boilers, auxiliary machinery, steam piping, etc., which were all essential parts of a steam turbine installation. It was necessary to renew the tubes in Admiralty type superheaters about every six years in peace time, and this corresponded to somewhere between 12,000 and 24,000 operating hours.

Mr. B. Wood had developed an interesting relation for the power/weight ratio of geometrically similar gas turbines and had used this relation to compare two gas turbines with fundamentally different cycles. As a result the author did not consider that the conclusions drawn were valid, and it was possible to obtain a very different result if two gas turbines employing similar cycles were compared. For example, the Allen 1,000-kW gas turbine with simple cycle, free power turbine, and heat exchanger, could be taken as representative of the lightweight aircraft approach. The weight (gas turbine only) was 7·1 tons, heat drop 177 B.Th.U. per lb., and output 1,000 kW. The B.T.-H. gas turbine fitted in the *Auris* employed an identical cycle and was a good example of the heavy steam turbine type of construction. The output was 860 kW, the heat drop 163 B.Th.U. per lb., and the thermal efficiency was identical to the Allen gas turbine. According to Mr. Wood's similarity relation the weight of the *Auris* gas turbine compared with the Allen's should be:—

$$7{\cdot}1 \times \frac{860}{1{,}000} \times \frac{\left(\frac{860}{1{,}000}\right)^{1/2}}{\left(\frac{163}{177}\right)^{9/4}} = 6{\cdot}85 \text{ tons}$$

whereas, in fact, the weight was nearly 50 tons, and this clearly showed the advantages of the lightweight type of construction in reducing weight without sacrificing thermal efficiency or life.

In conclusion, the author wished to thank all those who had taken part in this most stimulating discussion. He could assure them that their contributions would be of great assistance to the Admiralty in determining the future application of gas turbines to naval vessels.

INSTITUTE ACTIVITIES

Minutes of Proceedings of the Ordinary Meeting Held at the Institute on Tuesday, 13th April 1954

An Ordinary Meeting was held at the Institute on Tuesday, 13th April 1954, at 5.30 p.m., when a paper by Commander(E) G. F. A. Trewby, R.N. (Member), entitled "British Naval Gas Turbines", was presented and discussed. Mr. J. P. Campbell (Chairman of Council) was in the Chair. Members and visitors present numbered 180 and nineteen speakers took part in the discussion. A vote of thanks to the author was proposed by the Chairman and enthusiastically accorded. The meeting ended at 8.5 p.m.

West Midlands Section

The Summer Golf Meeting took place on Thursday, 27th May 1954, at Hadley Wood Golf Club. On a day of brilliant sunshine twenty-one members played for the honours in the two competitions.

Mr. H. E. Upton, O.B.E., won the cup in the morning competition with a net score of 72; Mr. A. Bartholomew was second with a net score of 73. Mr. R. Ward, the architect of the War Memorial Building, playing by invitation returned a net score of 66, but as a non-member could not qualify.

In the afternoon Messrs. A. Bartholomew and W. Ridley and Messrs. H. Armstrong and W. Donaldson tied for first place in the bogey greensome competition with a score of one down. As they also tied on the best net score for the last nine, twelve and fifteen holes it was decided that first place should be awarded to Messrs. Bartholomew and Ridley for a fully filled-in card. However, as no competitor can take more than one prize Mr. Bartholomew had to forego the afternoon prize and it was decided that it should be given to Mr. Ward in recognition of his excellent round in the morning competition. This was a record round for the competition, breaking Mr. R. Rainie's record of 68 in 1933.

The prizes were presented after tea by Mr. A. Robertson, C.C. (Honorary Treasurer). Mr. Upton received a clock and Mr. Bartholomew a Thermos picnic case. Messrs. Ridley and Ward received travelling clocks and Messrs. Armstrong and Donaldson cigarette cases.

All the members attending the meeting stood for a few minutes out of respect for the late Miss O. T. Wood, who had arranged and managed every golf meeting since the inception of the competition in 1931 and whose cheerful assistance would be so much missed at future meetings.

Mr. Robertson proposed that a hearty vote of thanks be accorded to the committee, the secretary, and the catering staff of Hadley Wood Golf Club, for the excellent arrangements which had been made for the meeting. This was carried unanimously. He also proposed a vote of thanks to the donors of the prizes: Messrs. F. P. Bell, C. P. Harrison, R. Hunter, S. J. Jones, P. R. Masson, J. M. Mees, R. B. Pinkney, A. Robertson, W. Sampson, C. C. and P. C. Speechly, W. Tennant, H. E. Upton and A. Walker.

The meeting terminated with a vote of thanks to the Convenor and Committee of Social Events.

West Midlands Section

A visit of the West Midlands Section to the Rugby works of the British Thomson-Houston Co., Ltd., was made on 10th June 1954 and attended by twenty-two members.

They were conducted around the works by Mr. H. R. Canning and other members of the Marine Department and entertained to luncheon and tea. Films of the *Auris* gas turbine, turbo-electric propelling machinery and a cartoon on tanker construction were also shown.

All members found the visit extremely interesting and enjoyable and Mr. G. A. Plummer (Vice-Chairman) thanked officials of the Company for the courtesy and care taken which made the visit such a great success.

OBITUARY

HENRY TEARE (Member 2462) served an apprenticeship with Elder, Dempster and Co., Ltd., and George Forrester and Company, Liverpool, and at the time of his election to membership of the Institute in 1910 he had completed twenty-one years at sea, fourteen as chief engineer; he was then engaged as chief engineer with the Canadian Pacific Railway Company. Mr. Teare died in 1945.

ROBERT WILKINSON (Member 3231) died on 7th April 1954. He served an apprenticeship at the Union Iron Works, Millwall, London, and then joined the Peninsular and Oriental Steam Navigation Company as an assistant engineer in 1905, sailing in the *Palma* until 1911 when he obtained a First Class Board of Trade Steam Certificate and was transferred to the *Oceana*; he was serving in this ship when she was sunk off Eastbourne in 1912. His next appointment was to the *Marmora* but he was transferred to the *Pera* in 1913, remaining with her until she was sunk by enemy action in 1917, after which he joined the *Novara*. In 1919 Mr. Wilkinson was promoted second engineer and in 1931 he was appointed chief engineer of the *Alipore,* after which he continued to serve as chief engineer in various ships of the company, including the *Viceroy of India,* until his retirement in 1936.

Mr. Wilkinson was known by his brother officers and the younger engineers who served under his command as an engineer of outstanding ability. As a chief engineer he took a great interest in the younger members of his department and whilst he could drive his team hard if necessary, he had a kindly disposition which made him beloved by all who knew him.