THE G.6 GAS TURBINE

FOR NAVAL BOOST PROPULSION

BY

F. R. HARRIS, A.C.G.I., B.SC., A.M.I.MECH.E

This paper was first presented at the Gas Turbine Power Conference of the American Society of Mechanical Engineers at Washington D.C., in March, 1961, by the Author who is Chief Engineer, Gas Turbine Department, of the Turbine-Generator Division of Associated Electrical Industries (Manchester) Limited.

Permission of the Author, his Company and the Society to reproduce the paper is acknowledged.

Introduction

The advantages to be gained, in certain classes of naval ships, from the use of compact gas turbine power plant for boost purposes, in combination with conventional steam turbine or Diesel machinery for cruising, have been described by several authors[1, 2] and require no further elaboration. The application of gas turbine boost to naval ships, which was first demonstrated in a gunboat of the Royal Navy in 1947, has now spread to ships of much larger size, and the purpose of the present paper is to deal with the G.6 gas turbine which forms part of the power plant now installed in some ships of the Royal Navy.

Historical Background

Design studies carried out by Yarrow-Admiralty Research Department, in close collaboration with the Admiralty and the Author's Company, into the best arrangement of propulsion machinery for two projected classes of ship, (the general purpose frigate and the guided missile destroyer), led to the conclusion that steam turbines (of reasonably advanced steam conditions) should be used for normal propulsion and manœuvring, and that the upper portion of the power range, only rarely used in these ships, should be provided by gas turbines. Various ratings were considered for the gas-turbine plant, and that eventually specified was 7,500 h.p., measured at the propeller shaft.

The frigate and destroyer installations each used the same gas turbine, the G.6, with only minor installational differences ; the frigate machinery (single-shaft) included one gas turbine and a steam turbine, driving into a common reduction gear ; while the destroyer machinery consisted of two shafts, each powered by a steam turbine and two gas turbines, driving into a common reduction gear.

The G.6 gas turbine was the fifth member of the family of naval gas turbines designed and built by the Author's Company, which commenced with the 1947 ' Gatric ' plant. Leading particulars of all five machines are given in TABLE 1. The G.1 and G.2 series I gas turbines have already been described[1], details of the G.2 series II and G.4 gas turbines form part of the subject matter of a further article, to be published shortly. These four machines were all intended for installation in small coastal craft.

---

[1] ' British Naval Gas Turbines '
Cdr. G. F. A. Trewby, *Transactions of the Institute of Marine Engineers.* Vol. 66, No. 6, 1954, p.125.

[2] ' The Marine Gas Turbine Plant in 1951 '
W. T. Sawyer, presented at the annual meeting of the Society of Naval Architects and Marine Engineers, New York, November 1951.

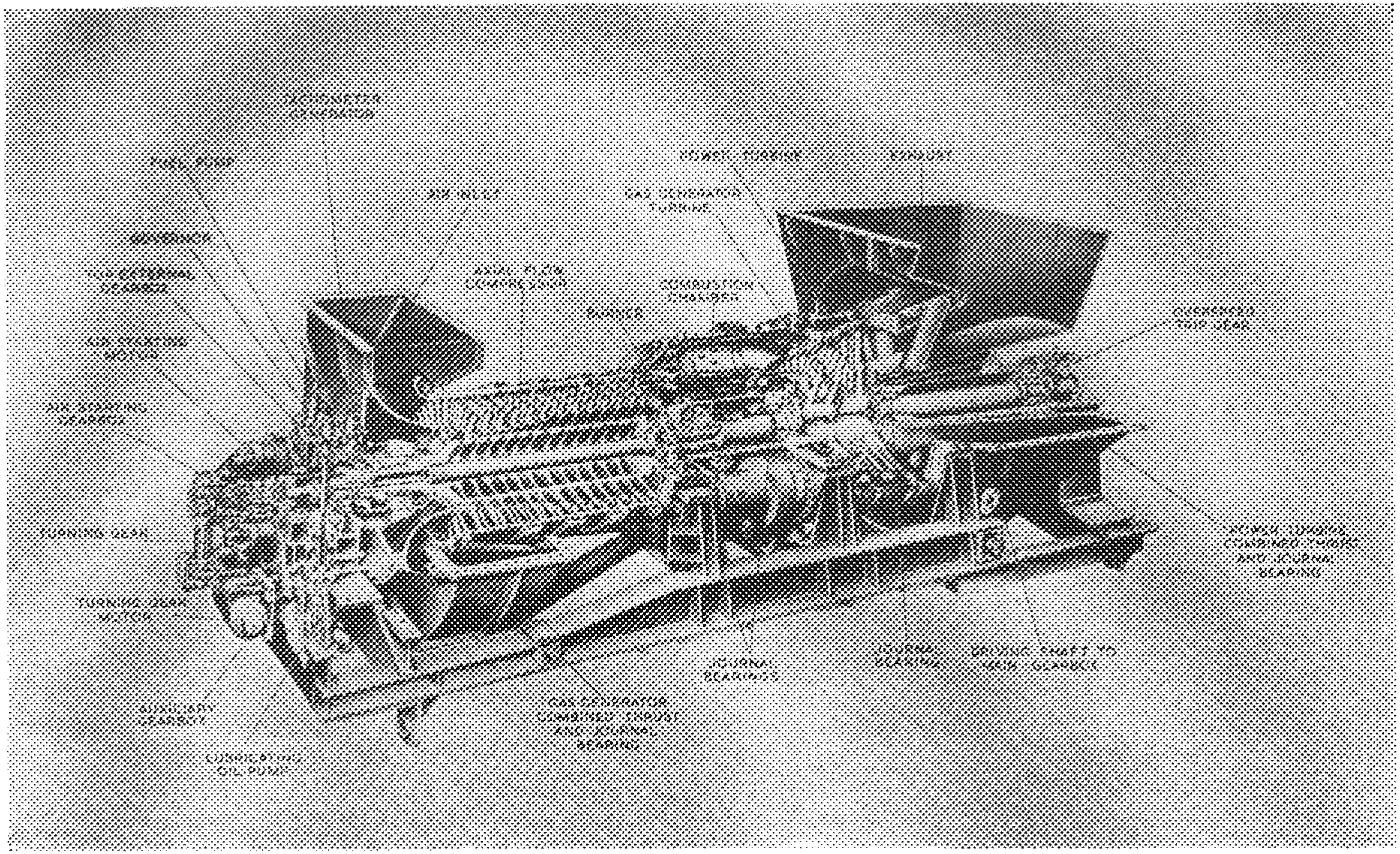

FIG. 1—CUT-AWAY SECTION OF THE G.6 TURBINE

TABLE I—*Leading particulars of naval boost gas turbines*

Designation	*G.*1	*G.*2	*G.*2/*II*	*G.*4	*G.*6
Year of order	1943	1948	1951	1951	1955
Year of test	1946	1951	1955	1956	1958
Specified blading life at full power, hours	300	300	300	1000	1000
Specified output at propeller shaft, h.p.	2500	4800	4800	5000	7500
Engine dry weight, lb	4030	6950	6950	8160	41,440
Weight, pounds per s.h.p.	1·61	1·51	1·51	1·63	5·52
Reduction gear weight, lb	2600	2770	2750	4500	—
Total weight, gas turbine plus gear,* lb	6630	9720	9700	12,660	—
Weight, gas turbine plus gear,* pounds per s.h.p.	2·65	2·02	2·02	2·53	—
Air mass flow, lb/sec	47·5	65·6	65·6	64	106
Compressor pressure ratio	3·5	4·0	4·0	6·3	6·3
Compressor speed, r.p.m.	7400	7830	7830	11,000	6850
Turbine inlet temperature, degrees F.	1380	1470	1470	1500	1460
Power turbine speed, r.p.m.	3600	5200	5200	6200	4900
Full load specific fuel consumption, lb/s.h.p.-hr.	1.06	0.82	0.82	0.68	0.77

* Excluding lubricating oil system and tank.

All performance figures refer to ambient air conditions of 59 degrees F., 14·7 lb/sq in. abs. Ducting pressure losses are only nominal for all machines except G.6, for which the losses are 0·30 lb/sq in. at exhaust, and 0·35 lb/sq in. plus silencer loss at inlet.

The designations G.3 and G.5, which do not appear in the table, refer to projects which were not built ; G.3 was to be a 12,000 s.h.p. machine which used the ‘ Sapphire ’ aero-engine for the gas generator portion, and G.5 was was to be a 15,000 s.h.p. machine which was investigated in connection with the requirement (for the guided weapon destroyer) for 15,000 gas turbine horse-power on each propeller shaft. After studying operational requirements and convenience of machinery space layouts, it was decided that two 7,500 s.h.p. gas turbines were preferable ; this also enabled one similar gas turbine to be used in the frigate power plant.

Design Requirements

The G.6 gas turbine, rated at 7,500 s.h.p. at 59 degrees F. ambient air temperature had a specified life of blading at full load of 1,000 hours ; the output had to be developed under conditions of duct pressure losses of 0·65 lb/sq in. plus an inlet silencer. Severe shock acceleration had to be withstood, and an additional requirement was that the gas turbine had to be airtight, so that the air passing through the machine did not leak into the engine room. The machine had to be capable of operation partially submerged in water ; and starting and control of output were effected remotely.

The cycle chosen required a compressor pressure ratio of 6·3 and a turbine inlet temperature of 1,460 degrees F. (1,470 degrees F. at 90 degrees F. ambient air temperature, when 6,750 s.h.p. was specified). The predicted specific fuel consumption at full load was just over 0·72 lb/s.h.p.-hr.

In order to obtain full benefit from the quick-starting capabilities of the gas-turbine machinery, provision was made in the reduction gear for driving the propeller shaft in either direction, so that manœuvring of the ship on gas turbines only was possible. The reduction gear already contained automatic over-running clutches of the S.S.S. type so that the L.P. turbine of each gas turbine was disconnected except when it was providing power ; by this means the problem of power loss due to windage was avoided.

Mechanical Design

The mechanical construction of the G.6 gas turbine was a good deal heavier than in previous boost gas turbines. This was for two reasons : shock acceleration requirements required a certain amount of increased rigidity, and, more important, was a determination on the part of the designers and the Admiralty, that the G.6 machine should, so far as was humanly possible, be free from all the troubles which had been experienced on previous lightweight boost machines.

By the time of the initial conception of the G.6 machine, Admiralty experience with several lightweight propulsion gas turbines, based on aero-engine concepts, had shown that, for one reason or another, ball and roller bearings did not seem to be suited to naval propulsion machinery, and both G.4 and G.6 gas turbines used sleeve journal bearings and Kingsbury thrust bearings for that reason. This experience indicated that no existing aero-engine should be used, without conversion to white-metal bearings, as part of a naval propulson gas turbine for vessels of the size and importance then contemplated.*

Current aero-engines have the highest reputation for performance and reliability, but the development cost of a new model is such that it needs to be sustained by sales of thousands of units; and the cost of modification of a 'standdard ' model to incorporate, for instance, white-metal bearings, would also be high. Naval gas turbines of the ratings concerned would be required in dozens or, at the most, a hundred or so, and the cost of development cannot be spread over large numbers of units. Such considerations, together with several other important modifications which would be required for naval purposes, justified the design of the G.6 as a completely new machine, specially tailored to its specification.

Because of the desire to keep the development cost within limits, it was considered prudent to adopt design criteria somewhat more conservative than those applicable to aircraft practice ; the naval gas turbine has to be right, or at least nearly right, first time, and a too-ambitious project may lead to a disappointingly large amount of development before success is achieved.

At the time of the G.6 design, the difficulties due to rotating stall in variable-speed compressors were being encountered in aero-engines, but there did not appear to be any easy way out of this trouble, except to reduce the blade loading below the point where the vibrational stresses induced could cause failure. The G.6 compressor blading, as a result, is of markedly more robust design than that used in previous naval machines. Consideration of a somewhat similar nature led to the use of more robust turbine blades.

One effect of the use of wider-chord blades is, naturally, to increase the size and weight of rotors, cylinders, and many other components ; and TABLE I shows how the weight per horse-power of the G.6 has increased compared with earlier machines ; only a small part of this increase is due to ' square-cube law ' effects, although some increase is undoubtedly due to the provision for loading by shock acceleration.

Test Installation

The extent of the Admiralty's commitments in respect of the G.6 machine was reflected in their determination that no part of the plant involving any untried principle should go to sea until shore testing had, so far as was possible, demonstrated its ability to meet its duty. To ensure the implementation of these requirements a special test plant was laid down at the builders' works, simulating one propeller shaft set of destroyer machinery, except for the steam turbines, and consisting of two gas turbines, a reduction gear and its associated clutches, a hydraulic dynamometer of 10,000 h.p. for power measurement, and

---

*More recent experience has shown that reliability can be expected from highly developed aero engines, e.g. the Bristol ' Proteus ' in the *Brave* Class boats, and certain near standard types of aero engines are therefore given consideration for major warship propulsion. (Editor)

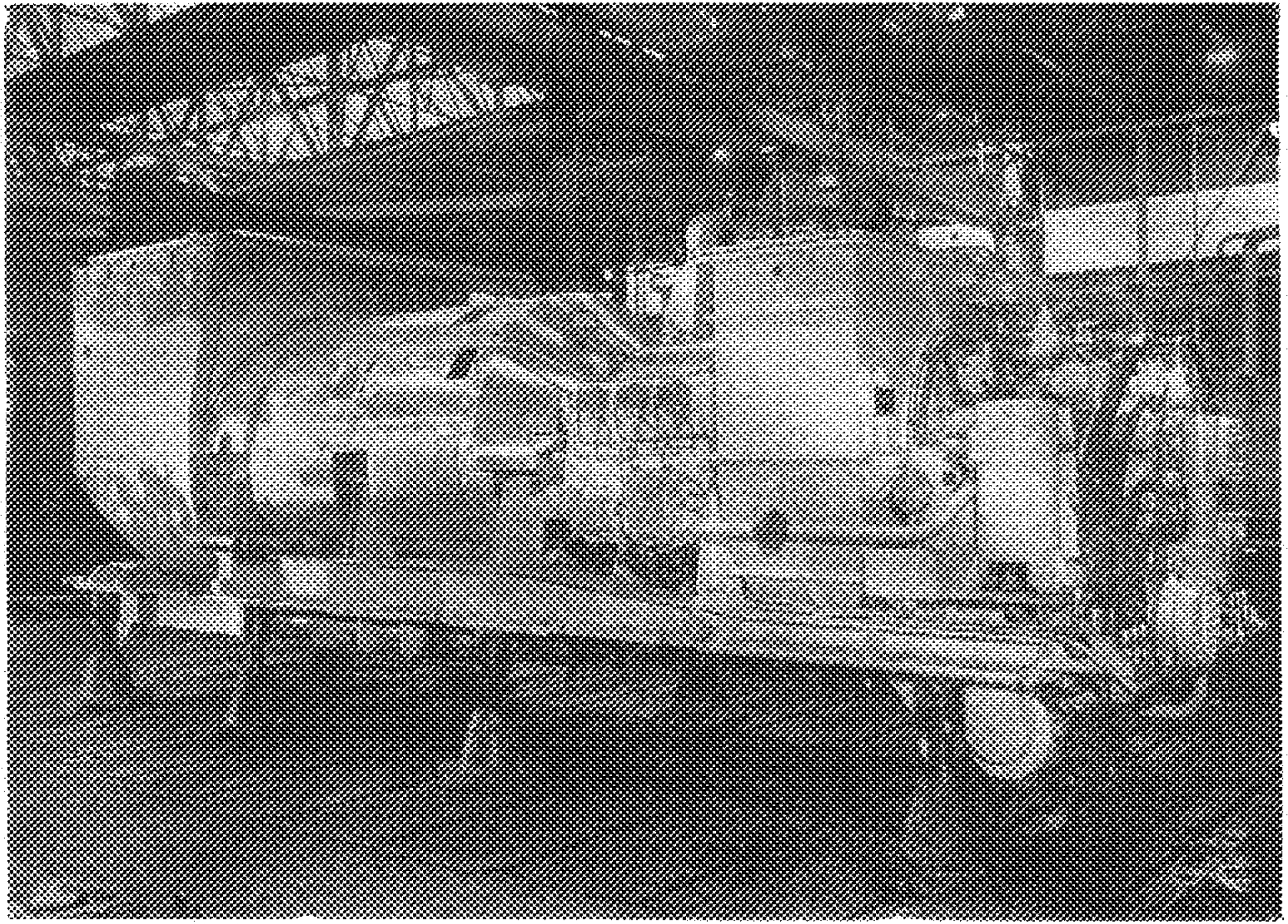

FIG. 2—THE G.6 GAS TURBINE READY FOR INSTALLATION WITH LAGGING IN PLACE

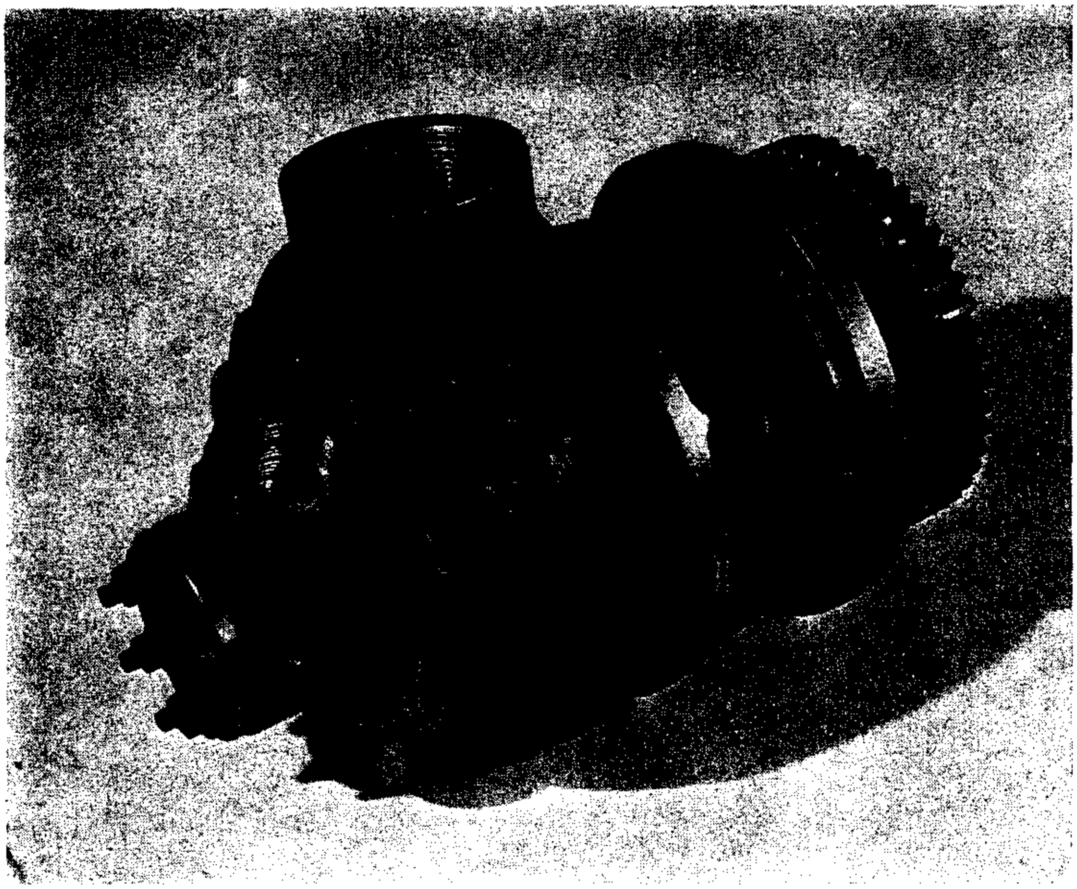

FIG. 3(*a*)—THE SWASHPLATE TYPE COMPRESSED AIR MOTOR STARTER

duplicates of the remotely-operated shipboard controls. The two ' shore trials ' gas turbines were completed and run well ahead of those turbines destined for ship installation, and a great deal of development, involving minor changes both to the gas turbines and to the reduction gear, was carried out ; if the development had had to be done in a ship at sea the difficulties would have been enormous, the time taken completely unacceptable, and the cost (including that associated with the ship and its crew) astronomical. The whole ' shore trials ' installation remains a tribute to the foresight of the Admiralty in this respect.

Details of Construction

The G.6 gas turbine (shown in FIGS. 1 and 2) bore a strong family resemblance to the previous naval boost gas turbines listed in TABLE I ; some of the principal features were :—

(i) The annular combustion chamber, used in all previous designs, was abandoned and six flame-tubes were used. This offered the facility of a machine completely split at the horizontal joint for access ; no other condition could be tolerated in the type of installation now contemplated. It also allowed the rig-testing of combustion chambers at full load, not possible with the annular chamber.

(ii) The compressor inlet casing now faced vertically upwards, not axially as in previous machines.

(iii) The compressor blading was completely in aluminium bronze, which had the highest fatigue strength, in a marine atmosphere, of any alloy available at the time of design.

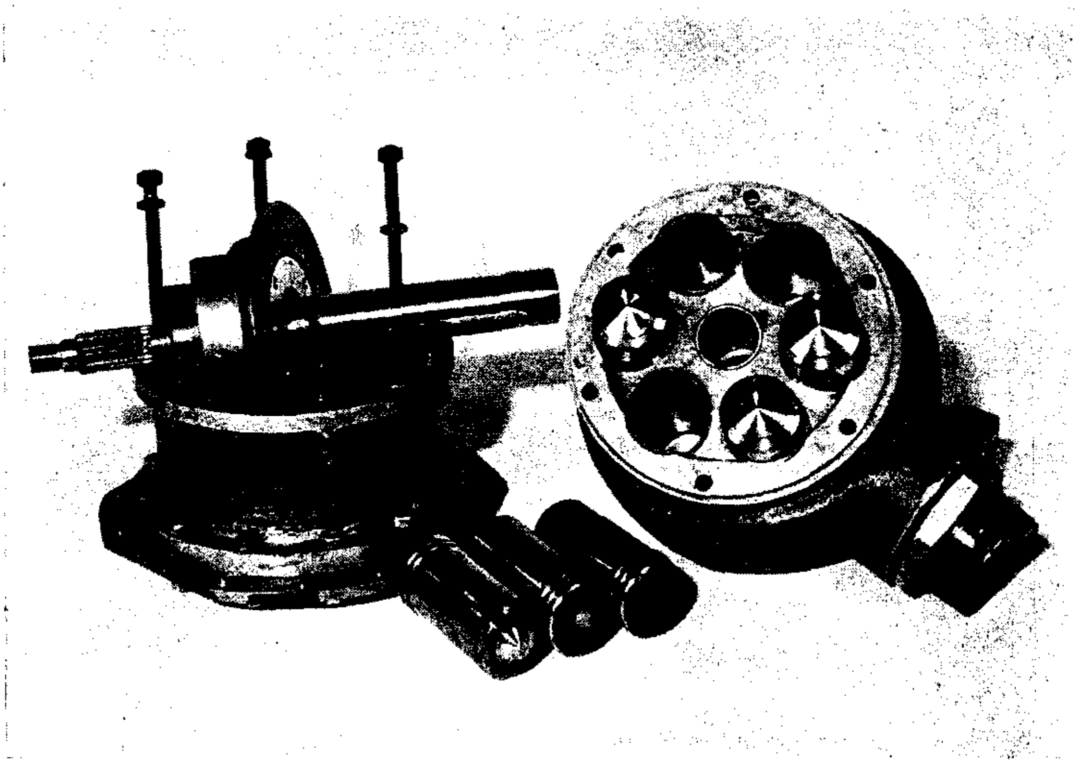

FIG. 3(*b*)—THE SWASHPLATE TYPE COMPRESSED AIR MOTOR STARTER

(iv) The compressor fixed blading was unshrouded at the outlet end, but at the inlet end five stages were built into diaphragms, as in conventional steam turbines. This was necessary to ensure freedom from blade vibration.

(v) Both turbines were two-stage, overhung back to back, and each turbine casing was fitted with liners to reduce distortion due to temperature gradients.

(vi) Light alloy castings, used extensively on previous machines, could not now be used for structural parts because of the severe shock requirements, and steel fabrications took their place.

(vii) A large lubricating oil pump was driven from the compressor, and formed part of the main lubricating system of the propulsion machinery.

(viii) Starting was again by compressed air, as on G.2, G.2/II and G.4, after exhaustive analyses of many other methods. Six motors (developed versions of an Admiralty torpedo motor, shown in FIG. 3) were used, driving through sun-and-planet gears on to the compressor shaft. An over-running clutch of the S.S.S. type was provided for disengagement. The motors operate on air stored at 3,000 to 4,000 lb/sq in. and supplied to the motors at 600 lb/sq in. At this pressure, each motor is capable of 43 h.p. peak output, at 4,000 r.p.m. ; during the starting cycle the motors disengage at 3,200 r.p.m., at which condition the output of each is 41 h.p. Each start requires about 1,100 cubic feet of free air. The motor capacity is large enough to ensure starting at air supply pressures down to about 450 lb/sq in.

(ix) Ignition was by magneto, driven from the starter gear train. This system, together with the ability of starting from air stored in bottles, and of providing sufficient lubricating oil for starting by means of a hand-operated pump, offered the facility of starting the gas turbine in emergency in a completely ' cold ' ship, without electricity supplies of any sort.

FIG. 4—COMPRESSOR TOP HALF CASING AND ROTOR LIFTED FOR INSPECTION

(x) Provision for increased ease of maintenance was made ; all top half casings, and rotors, can be lifted on screwed columns for inspection (see FIG. 4). Large components, such as the compressor inlet casing and the turbine exhaust, were subdivided into small pieces for ease of handling.

(xi) The gas turbine is mounted completely on a sub-frame, which is designed to be strong enough to transmit to the ship's seating the forces arising out of shock loads due to underwater explosions. It so happens that the deck openings required by the gas turbine ducting are large enough to admit each major component of the machine, with the exception of the sub-frame. (The subdivision of large components, mentioned above, also has this in view). This means that the whole gas turbine may be removed and replaced, piece by piece, if required, without having to cut special apertures in the deck ; a facility which is rare in respect of propulsion machinery for naval vessels of this size.

(xii) The fuel control system is shown in FIG. 5. Interlocks are provided to ensure safety of the gas turbine and its manœuvring gear under all conditions of operation. The normal fuel is gas oil (a distillate) but provision is made (as specified) for burning untreated furnace fuel oil in an emergency, although it is accepted that the turbine may be damaged as a result.

Testing

The first gas turbine was programmed for completion some time ahead of its reduction gear, so testing with power absorption by the conventional method was not immediately possible. By running with a variable area nozzle in place of the L.P. turbine, it was not difficult to run the compressor and H.P. turbine over a wide range of operating conditions, including full load, without the use of reduction gear or dynamometer. This facility has been of the utmost

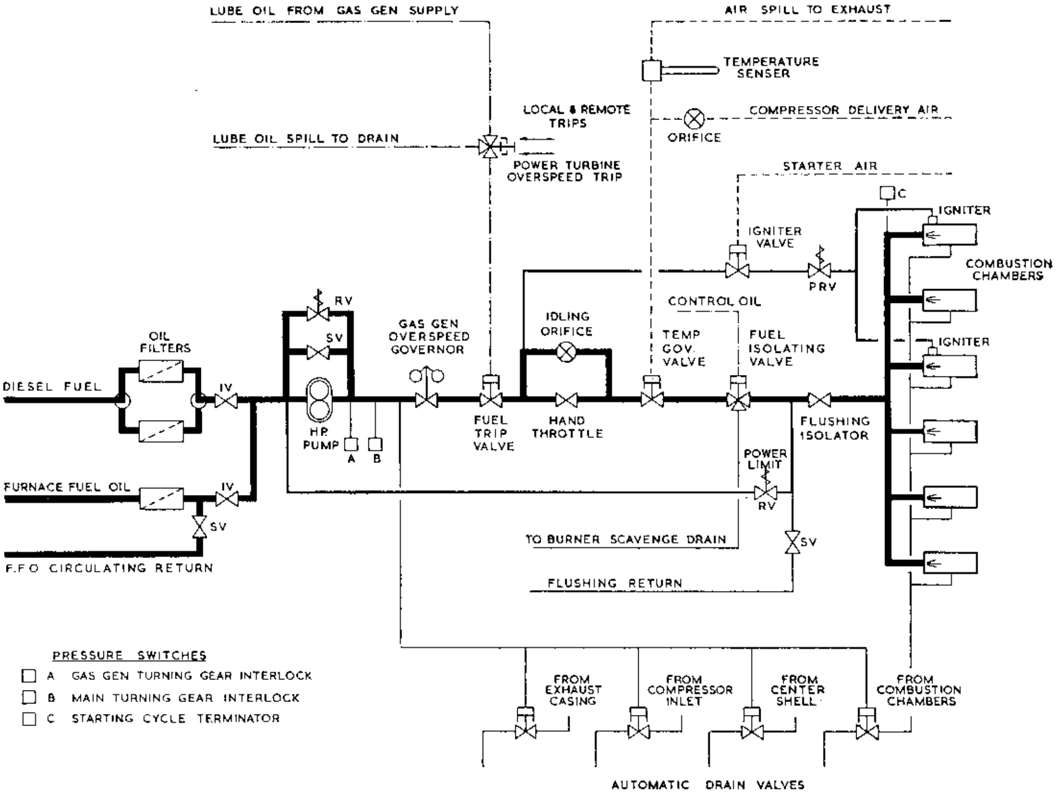

FIG. 5—DIAGRAM OF FUEL SYSTEM

value ; the G.6 turbine is being manufactured in Britain by several shipbuilders as well as by the Author's Company, and the expense of several sets of power-measuring equipment could not be considered. But, by running with a nozzle in place of the L.P. turbine, the gas generator portion of each machine can be given a mechanical run to full load, and sufficient test readings can be obtained to enable reasonable predictions of its performance to be made, by direct comparison with the prototype machine, tested both with a nozzle and with a dynamometer. The additional ' full load ' running achieved on these gas turbines has also contributed significantly to the development investigation of various features as they have arisen.

No major design modification has been found to be necessary as a result of the experimental testing, although a great many minor improvements have resulted from the running ; a good deal of gas turbine running has, however, been carried out in connection with development of the main reduction gear, with its many novel features.

The compressor was rig-tested in three slightly different builds, before running the gas turbine. The characteristics of the three builds were closely similar, and that of the build actually used is shown in FIG. 6. The surge pressure ratio of this compressor at medium and high speeds was surprisingly high ; the reason for this is imperfectly understood. The possibility of removing stages from the compressor H.P. end without sacrifice in performance was considered, and one machine was built with an 11-stage compressor instead of the standard 13-stage. The overall performance was not much different, but the 11-stage engine proved difficult to start, particularly when hot, without the use of compressor bleed, which was not required in the 13-stage build. The first three moving stages of the compressor were instrumented to record vibrational stresses during the compressor rig testing ; during early engine running, these rows, together with certain other fixed and moving rows, were again instrumented in the same way. No major vibrational stresses were recorded apart from those associated with rotating stall ; these occurred at compressor speeds below

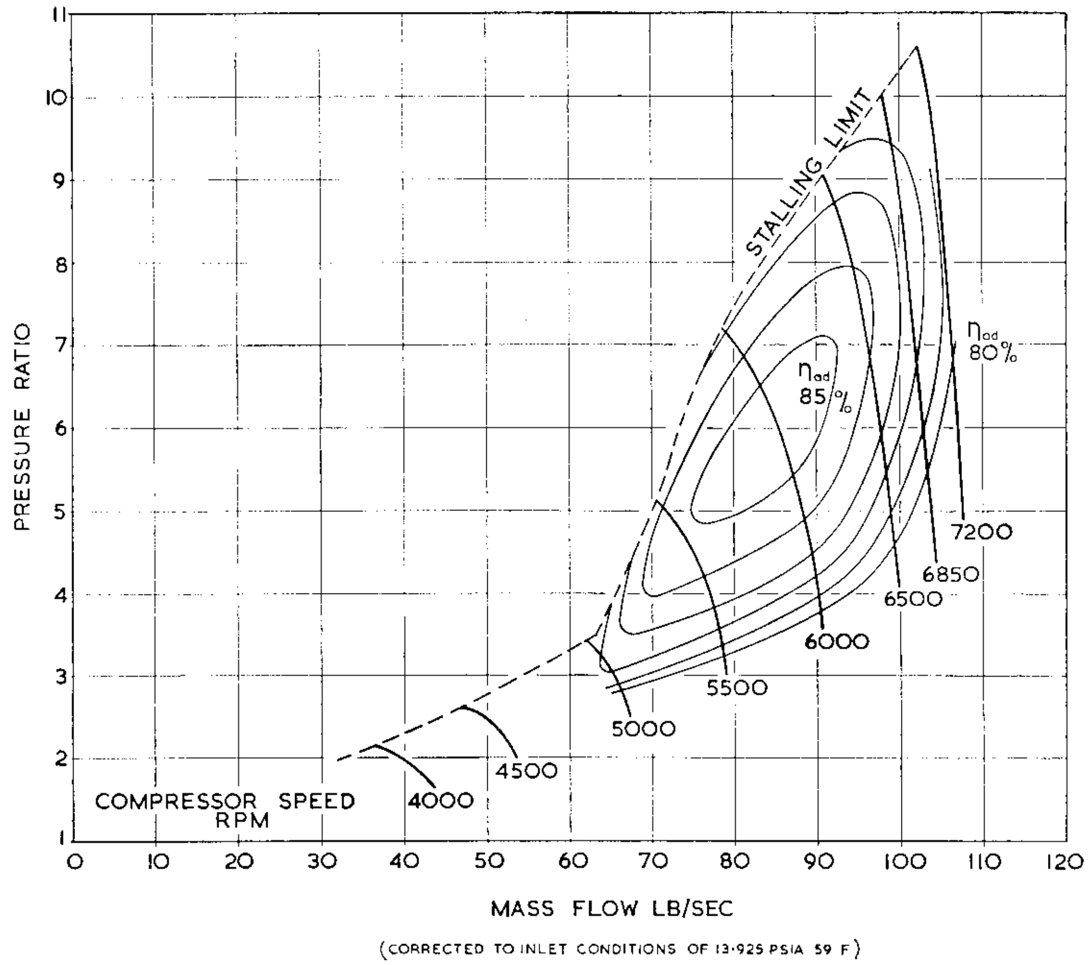

FIG. 6—COMPRESSOR PERFORMANCE

5,000 r.p.m., and the robust proportions adopted for the blading (largely on this account) were sufficient to limit the stresses to very moderate values.

The mechanical construction of the compressor rotor, with discs separated at the periphery by interstage rings, was such that a fixed blade tip rub automatically made itself worse by reason of local expansion of the rubbed (and heated) portion of the ring ; and one such rub was experienced in early testing. The short-term solution was adopted, of increasing the compressor blading tip clearances ; some price is undoubtedly paid in compressor efficiency, but reliability was put before fuel economy. (The compressor performance shown in FIG. 6 was measured on a compressor having the increased tip clearances.) There are several means of overcoming this difficulty on a long-term basis, but the time schedule laid down for installation of engines in ships did not allow the necessary design changes to be made at the time.

The initial design of combustion chamber, while allowing satisfactory operation up to full load, was unsatisfactory in that the exhaust was smoky, a most undesirable situation in a naval ship. A good deal of experimental development was carried out, in collaboration with the National Gas Turbine Establishment, involving the rig operation of an experimental chamber at full load, and, by changes to the airflow conditions in the chamber, the smoky exhaust was eliminated.

Some experimental development of starting motors has been carried out on the complete gas turbine (in addition to a good deal of initial development done by the Admiralty at the National Gas Turbine Establishment and elsewhere). Lubrication of these motors is by means of oil carried with the air

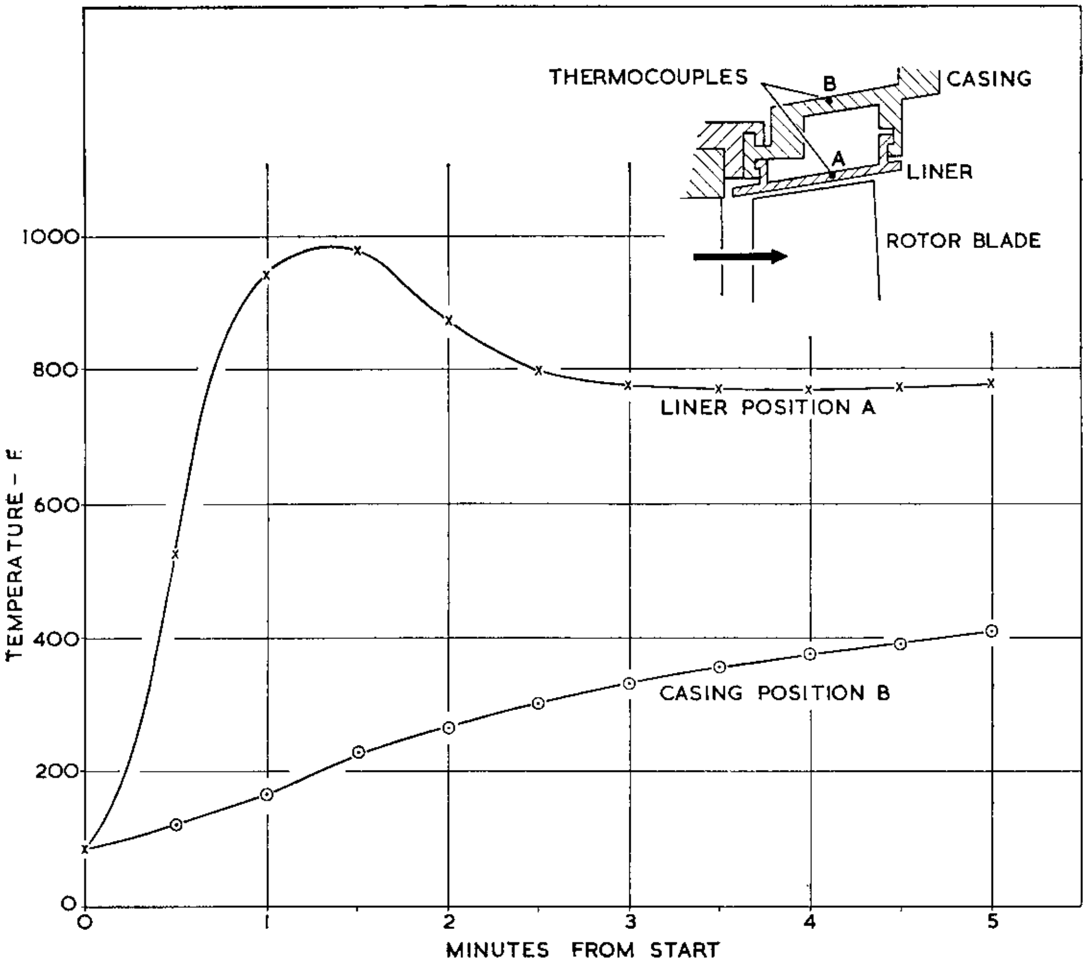

Fig. 7—Relative Heating Rates of Turbine Casing and Liner during a Normal Start

supply, and shortage of oil leads to excessive piston wear. In the final system, ‘ pre-wetting ’ of the motors is employed for an instant before the application of full air pressure, so that the motors always start in the ‘ wetted ’ condition.

The requirement for an air-tight gas turbine gave considerable trouble ; no glands leaking to atmosphere were used, and bearing space vents were piped outside the gas turbine. At first a good deal of oil escaped with the vented air, and considerable development running was necessary before a system was evolved which did not consume an unacceptable quantity of oil, and which did not cause trouble in other ways. In this scheme, most of the clean air vents (from compressor gland leaks, etc.) are piped direct to the turbine exhaust.

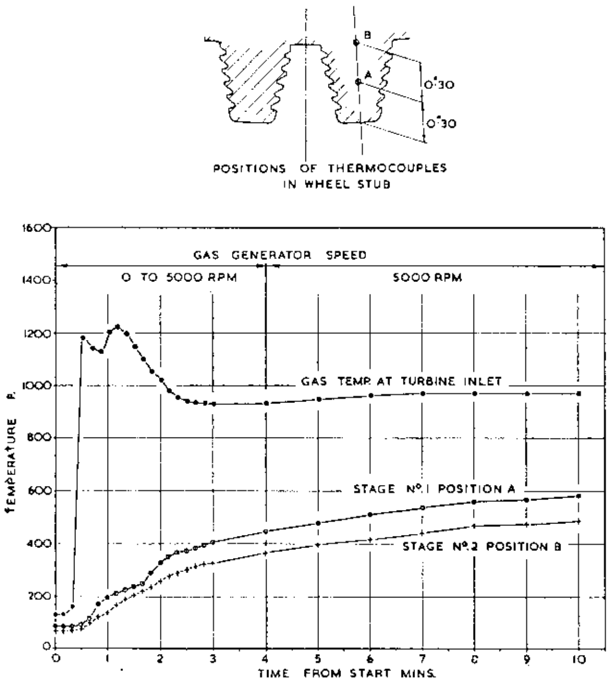

Fig. 8—Heating Rates of the L. P. Turbine Disc Rims (G.4 machine, similar to G.6) during Normal Start

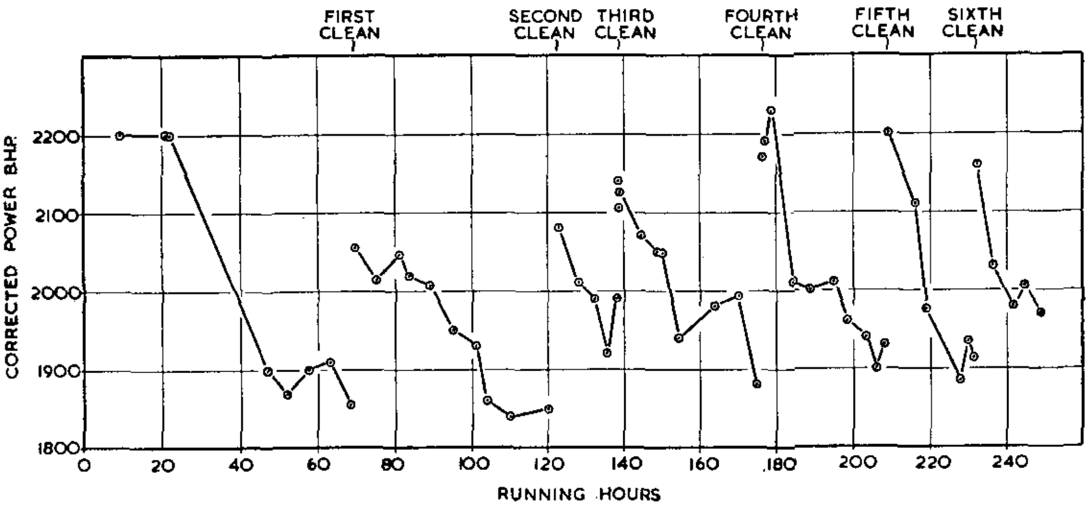

FIG. 9—POWER OUTPUT CHECKS ON A G.1 GAS TURBINE AT THE SAME COMPRESSOR SPEED (7,400 R.P.M.) OVER A LONG PERIOD OF SEA TRIALS, SHOWING THE EFFECT OF WATER-SPRAY CLEANING

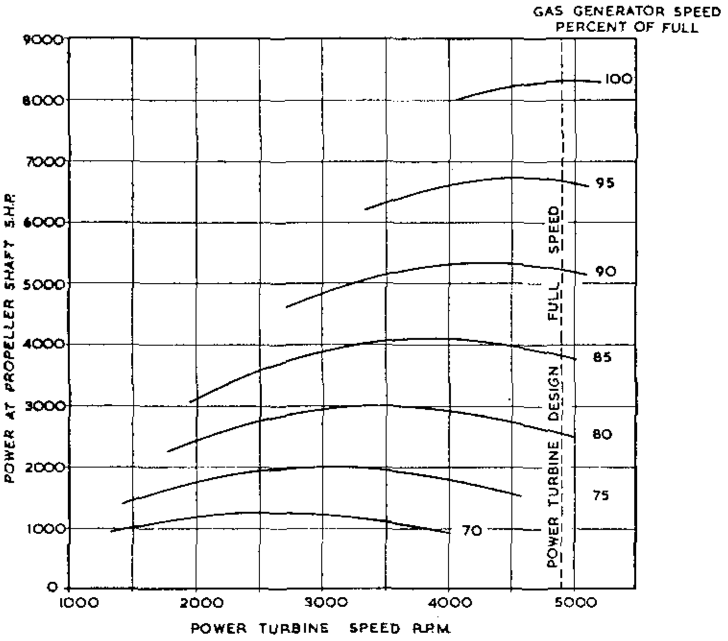

FIG. 10—POWER OUTPUT AT PROPELLER SHAFT (TEST-BED RESULTS, CORRECTED TO ALLOW FOR THE SPECIFIED SHIPBOARD DUCTING LOSSES)

while air containing oil vapour is led to a separate vent tank, which is piped to atmosphere outside the engine room.

One of the desirable features of a boost naval gas turbine is its facility for rapid starting and loading. The starter motors of the G.6 are in engagement for only about 20 seconds during a normal start, and full power has been achieved from a cold machine in 3½ minutes. Some temperature variations associated with rapid starting are shown in FIG. 7, which depicts temperatures of cylinder casing and liners of the H.P. turbine during a start. The interesting feature is the relatively slow heating rate of the casing itself, even though the liners, which are subjected to the full gas temperature, heat very quickly. Some similar measurements referring to the heating, during a start from cold, of the L.P. turbine rotor of a previous machine (G.4) are shown in FIG. 8. The rotor construction and cooling arrangements are very like those used in the G.6.

Provision is made for removing salt deposits in the compressor by washing with distilled water, sprayed into the intake at about two-thirds full speed ; this method has been used on previous naval machines and its efficiency is demonstrated in FIG. 9. This shows, for one of the Gatric machines, the power output (measured at the propeller shaft by torsion meter) at the same compressor speed over a fairly long period of operation, with occasional compressor washing. The original power is restored virtually completely after each wash.

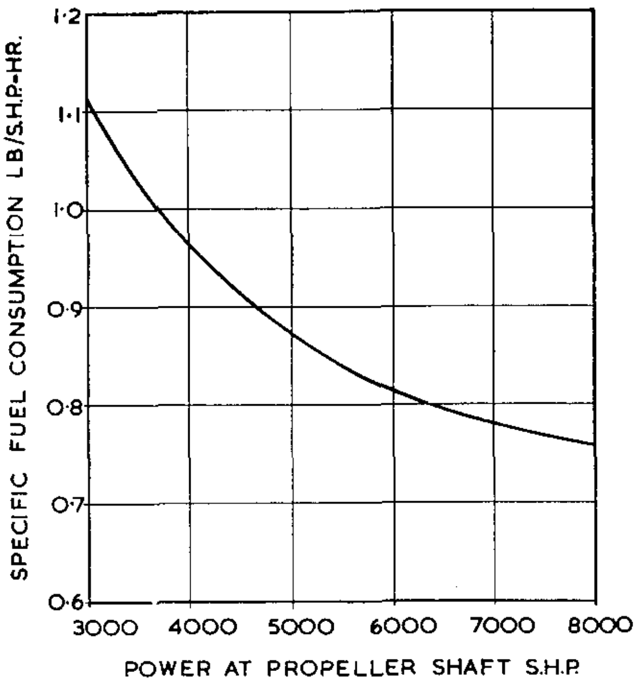

FIG. 11—SPECIFIC FUEL CONSUMPTION (TEST-BED RESULTS, CORRECTED TO ALLOW FOR THE SPECIFIED DUCTING LOSSES)

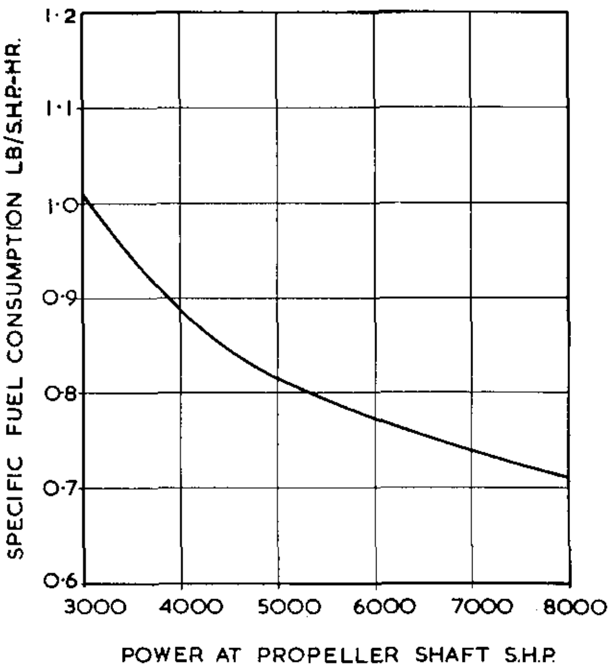

FIG. 12—SPECIFIC FUEL CONSUMPTION WITH DUCTING LOSSES OF 4 IN. WATER AT INLET AND 6 IN. WATER AT EXHAUST

This method of restoring full power is completely successful only when the deposit on the compressor blades is water-soluble, such as the salt deposited after operation in clean sea air. Test running in a heavily industrialized locality where, in spite of air filters, a black oily deposit adheres to the compressor blading has shown that spray washing with various mixtures of water and detergents will not maintain full power unless carried out daily.

Test results of the G.6 gas turbine are shown in FIGS. 10 and 11. These figures are corrected to 59 degrees F., 14·7 lb/sq in. abs., and are also corrected to the specified full power ducting losses (0·35 lb/sq in., plus a measured silencer loss of 0·4 lb/sq in., at inlet, and 0·30 lb/sq in. at exhaust). It will be seen that the originally quoted figure for specific fuel consumption at full power (0·721 lb/s.h.p.-hr.) has not quite been met (test figure is 0·77 lb/s.h.p.-hr.) Work is in hand towards effecting a recovery of this short-fall, but is at present second in priority ; the major development effort is, quite correctly, to ensure the reliability and readiness for use of the gas turbine, rather than to obtain the last ounce of efficiency from it.

Future Development

There are better creep-resisting blade alloys in existence today than in the days when the G.6 machine was first designed. This obviously allows for some benefit to be obtained by a change in alloy ; but it is not considered prudent at this stage to increase the turbine inlet temperature above about 1,520 degrees F.

Experience in an earlier naval machine (G.2) had shown that damage was caused to the turbine blading after operation in very rough weather (intended to demonstrate the sea-keeping qualities of the vessel), due to chemical attack by a mixture of sodium chloride and sodium sulphate (formed in the combustion chamber from the ingested salt and the sulphur in the fuel). Laboratory investigations showed that this attack occurred catastrophically at temperatures above about 1,560 degrees F.; a detailed study of such attack on

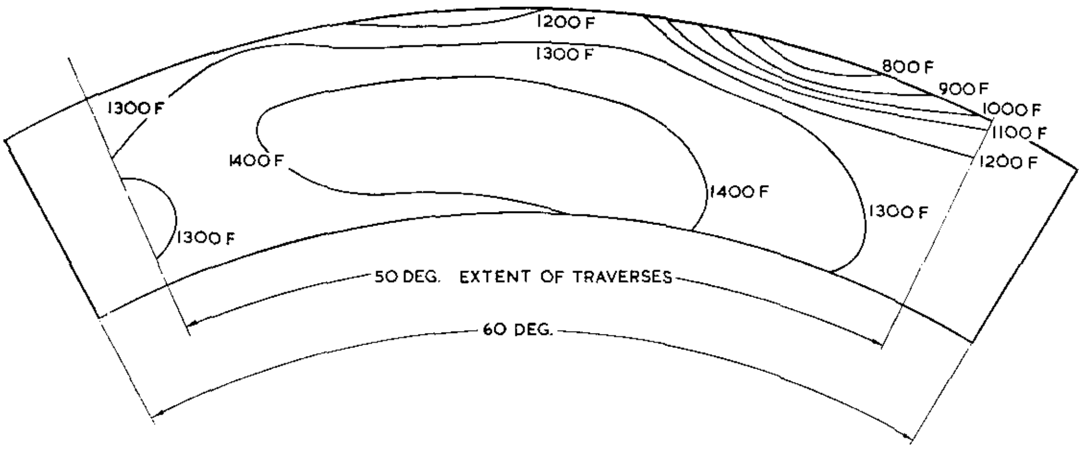

FIG. 13—TEMPERATURE DISTRIBUTION AT H.P. TURBINE INLET

GAS GENERATOR SPEED	—	6,250 R.P.M.
POWER AT SHAFT	—	6,835 S.H.P.
CALCULATED TEMPERATURE	—	1,380 DEGREES F.

many alloys has been published[3], and the experience of another British builder of naval gas turbines, where test running with deliberate salt injection was carried out, has been described[4].

Bearing this prudent figure of 1,520 degrees F. in mind, the main improvement made possible by the use of the newer alloys is in blading life. The original specification was for 1,000 hours life at full load ; the materials chosen were such that this could be achieved comfortably so that if deterioration of performance occurred in service because of compressor fouling or any other reason, the specified output could still be achieved. The newer materials make possible a blading life of at least 10,000 hours at full load, with the same facility for maintaining output in service. The performance of the machine at this condition, with ducting losses of 4 in. water at inlet and 6 in. at exhaust, is shown in FIG. 12. For an ambient air temperature of 59 degrees F., and a turbine inlet temperature of 1,520 degrees F., the output at the propeller shaft would be 8,500 h.p. (or, at turbine coupling, 9,100 h.p.).

A well-known feature of simple-cycle gas turbines is that the turbine temperature falls when load is reduced. By reducing the 'full-load' output to, say, 90 per cent of its original value, the creep life of the turbine blading can frequently be extended three or fourfold.

An important factor is assessing blading life is the possibility of peak temperatures occuring at certain points in the turbine annulus, giving rise to local hot spots in the fixed blading. FIG. 13 shows the temperature variation (measured by traversing thermocouples) near the turbine inlet, and demonstrates that the maximum gas temperature (which affects the fixed blades) and the circumferential average gas temperature (which affects the moving blades) are very close to the bulk average gas temperature (calculated from measurements of air flow and fuel flow).

Operation of the G.6 gas turbine on land now totals over 1,400 hours, of which about one-third have been at or near full load. The first frigate, H.M.S. *Ashanti*, went to sea early this year, and the first destroyer, H.M.S. *Devonshire*, commences her trials in December. Seagoing experience will undoubtedly

---

[3] Effects of Sulphate-Chloride mixtures in Fuel-Ash Corrosion of Steels and High-Nickel Alloys '
H. T. Shirley, *Journal of the Iron and Steel Institute*, Vol. 182, Part 2, February 1956, p. 144.

[4] ' Marine Proteus Engines for the *Brave* Class Patrol Boats '
B. G. Markham, *Transactions of the Institute of Marine Engineers*, Vol. 71, no. 10, 1959, p. 316, (also A.S.M.E. paper 59-A-273, Development and Sea Trials of Marine Proteus Engines for *Brave* Class Fast Patrol Boats).

reveal the possibilities of further improvements to the gas turbine design, and the operation of the plant at sea is awaited with great interest.

Conclusions

The development of the G.6 naval gas turbine, currently being installed in many ships of the Royal Navy, has been described. The concept of the gas turbine as a boost propulsion machine, first tried in coastal craft, has in Britain found application in larger ships, where reliability and ease of maintenance must stand comparison with the main steam turbine machinery.

The G.6 gas turbine represents a machine of 7,500 shaft horse-power rating, existing in a form well advanced so far as development on land can take it, and sea-going experience is awaited with confidence. Alternative applications for naval gas turbines can be reviewed in the light of such a fully developed machine being available.

Acknowledgements

Acknowlegement is due to Associated Electrical Industries (Manchester) Limited, and to Mr. Norman Elce, Director and Chief Mechanical Engineer, for permission to publish this paper.

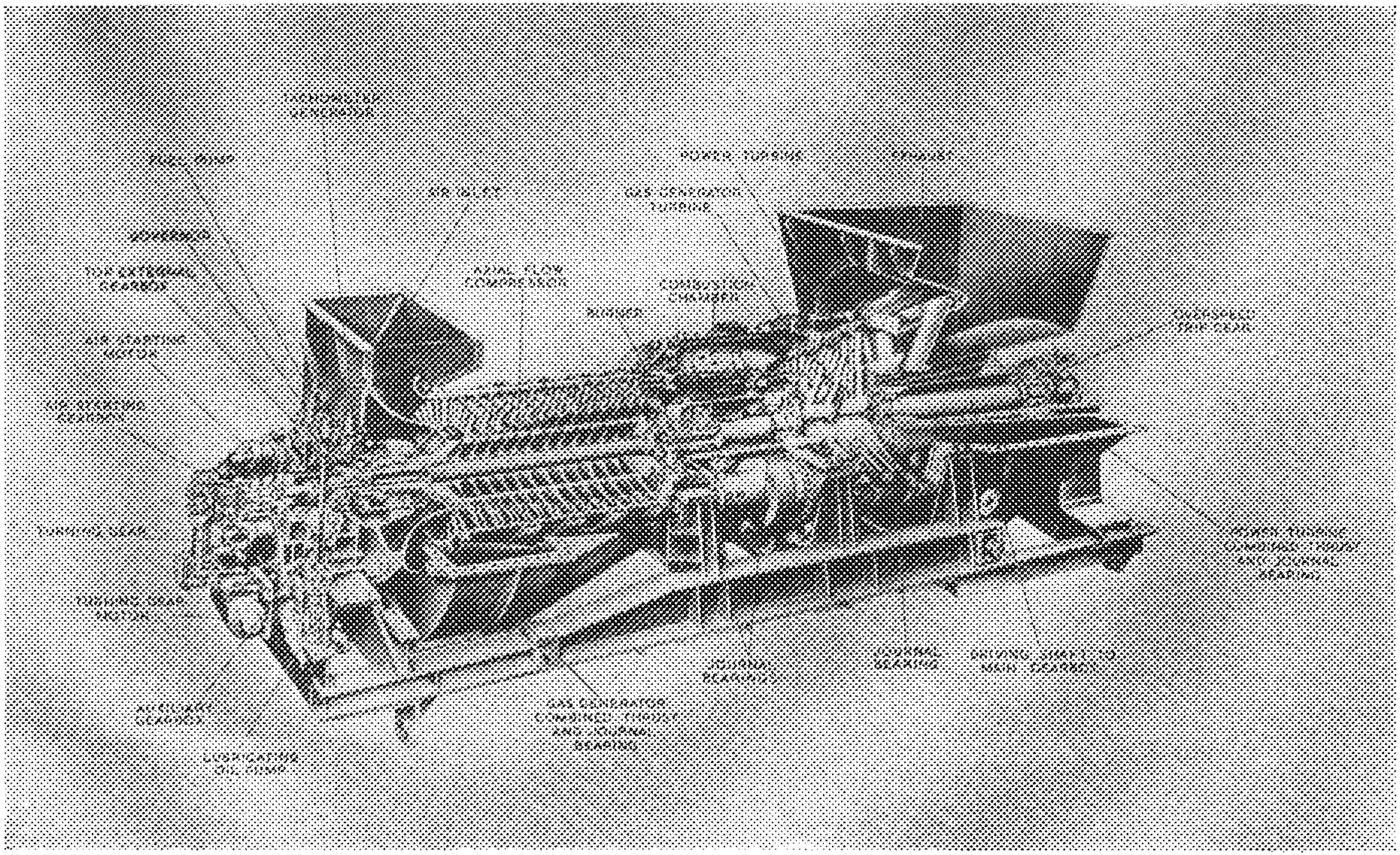

FIG. 1—CUT-AWAY SECTION OF THE G.6 TURBINE