THE ALLEN 1000 kW GAS TURBINE ALTERNATOR

Acknowledgement is made to the Editor of the "Allen Engineering Review" for permission to reproduce the illustrations and much of the material in this article.

The possibilities of the gas turbine for driving warship generators were discussed in Vol. 3, No. 2, July 1949, *Journal of Naval Engineering*. To recapitulate briefly, the gas turbine offers the following potential advantages over existing prime movers.

Compared with steam base load generators :—

(*a*) Reduced weight and space.
(*b*) Lower fuel consumption.
(*c*) Independence of steam supply.
(*d*) Quicker starting.

Compared with diesel emergency generators :—

(*e*) Reduced weight and space.
(*f*) Less stringent head-room equipment.
(*g*) Less maintenance.

Against these advantages must be set the fact that the gas turbine so far, has only been developed to burn distillate fuels of diesel oil grade. The air consumption of the gas turbine is greater than that of the diesel, requiring increased size of inlet and exhaust ducts, and the level of airborne noise although no higher perhaps than that sometimes encountered at sea today, will have to be reduced if the gas turbine is to conform to the standards proposed by the *Noise Reduction Panel* for machinery spaces.

In view of the potential advantages mentioned above, the Admiralty placed a contract in 1948 with Messrs. W. H. Allen Sons & Co. Ltd., for the design and development of a 1,000 kW gas turbine driven alternator.

Specification

The Admiralty specification called for a set of 1,000 kW maximum continuous rating with a 20% overload for 10 minutes, to be suitable for operation all loads up to overload under temperate (60°F.), or tropical (100°F.) conditions, and capable of running satisfactorily in parallel with other steam turbine alternators, the governing requirements being 2½% speed change for 50% load change and the ability to accept or shed 100% load without the emergency gear operating. The fuel was to be diesel oil, Admiralty reference Fuel B.310, and a maximum fuel consumption of 1.27 lb/kWh. under tropical conditions in the zone 60% to 100% power was specified. Total head pressures of 14.1 lb/sq. in. abs. at the compressor intake and 15.1 lb/sq. in. abs. at the power turbine outlet were called for, thus allowing for very high inlet and exhaust trunking losses.

The engine was to be entirely self-contained and to be as small as consistent with reasonable accessibility, the maximum height available being 7 ft., and every reasonable opportunity was to be taken to reduce weight without sacrificing reliability. Shock loadings of 40 g upwards, 25 g downwards and 15 g athwartships were specified.

Finally, a life of 100,000 hours was to be aimed at, this period being made up to 65,000 hours at 80% power under temperate conditions, 33,000 hours at 80% power under tropical conditions, and 2,000 hours at full power under tropical conditions.

Type of Set

After careful consideration of the specification a simple open cycle set was designed having a two stage turbine driving an axial flow compressor of 4¼ : 1 pressure ratio, an annular heat exchanger, a multi-chamber combustion system disposed symmetrically round the engine and a single stage power turbine driving the alternator through epicyclic gearing.

The cycle is shown diagrammatically together with approximate gas temperature and pressures.

History of the Contract

The contract was placed in April 1948, and the set completed its first run March 1951.

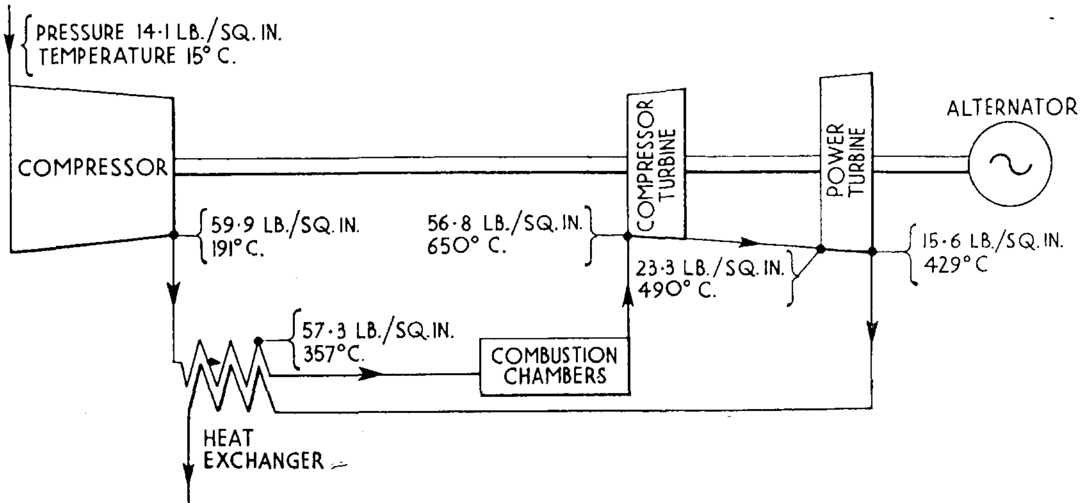
Full speed and full power were achieved in June 1951, without any major defect being revealed and the set was then stripped for examination and the inclusion of the heat exchanger, which had been omitted from the first build.

Running recommenced in December 1951, and the set is now undergoing fuel consumption and governing trials. The indications are that the designed performance will be achieved.

The description of the engine which follows has been extracted from *The Allen Engineering Review* for January 1952.

Basic Design Particulars

Continuous maximum rating at power turbine coupling, including fouling margin, b.h.p.	1512
Estimated specific fuel consumption at maximum rating, lb/b.h.p./hr.	0.745
Estimated thermal efficiency at power turbine coupling at maximum rating	19.75%
Mass flow at maximum rating, lb/sec.	37
Max. gas temperature under tropical conditions, °C.	700
,, ,, ,, temperate ,, °C.	650
Compressor speed, r.p.m. approx.	8000
No. of compressor stages	13
No. of compressor turbine stages	2
Estimated compressor adiabatic efficiency	84%
Estimated compressor turbine adiabatic efficiency	85%
Power turbine speed, r.p.m. approx.	6750
No. of power turbine stages	1
Estimated power turbine adiabatic efficiency	84%
Alternator speed, r.p.m. approx.	1500
Type of combustion chambers	Straight through
No. of combustion chambers	8
Type of burner	" Simplex "
No. of heat exchanger passes, hot gas	1
cold air	2
Heat exchanger thermal ratio	70%



DIAGRAMMATIC CYCLE

NOTE

It must be noted that the output stated is that obtained with the high inlet and exhaust losses specified. Without these abnormal losses the maximum output would be 1250 kW (temperate conditions), whilst the thermal efficiency would be 24 %, and the specific fuel consumption 0.625 lb/b.h.p./hr.

CONSTRUCTION

General

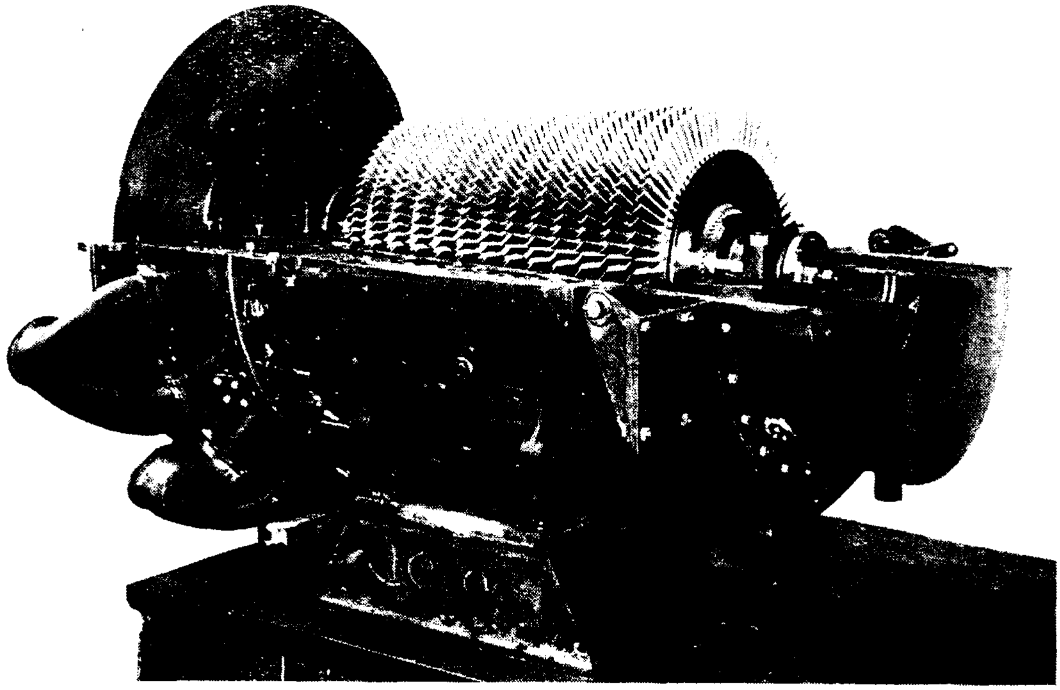
The mechanical design is based upon the component assembly principle so that each assembly is removable from the machine independently of the others.

The compressor casing is split on the horizontal centre line and the top half is easily removable for inspection purposes without breaking any pipe joints. The centre bearing can be inspected by dismantling those air pipes connected to the top half of the casing and removing the top half casing, which is also split on the horizontal centre line. The two turbines can be readily inspected after removal of the compressor air delivery pipes and the combustion chambers, by splitting the casing vertically between the compressor turbine and power turbine and moving the compressor with its associated turbine away bodily, while supporting its weight by an overhead crane. If necessary, either the power turbine or the compressor turbine assembly can be removed endwise as a unit for further dismantling.

The gear case is split horizontally and the epicyclic gear assembly can be removed vertically for inspection or dismantling.

Compressor

The compressor is of the axial-flow, multi-stage type. The rotor is of a special built-up design to reduce its moment of inertia to as small a value as possible in order to assist the speed governor during sudden large load changes. The inlet end of the shaft is manufactured from 1% chrome molybdenum steel, and the outlet end of " Nitralloy " steel hardened at the bearing journals. The rotor wheels are of 1% chrome molybdenum steel to B.S.S. En. 19, the discs being secured to each other on the faces of the bosses by means of dowel pins, through which the torque is transmitted. The complete rotor disc assembly and the shaft ends are clamped together by a special bolt passing through the centrally bored discs. Due allowance is



Bottom Half of Compressor Casing with Rotor in position

made in the design of this bolt to withstand any load due to thermal expansion, etc., during running.

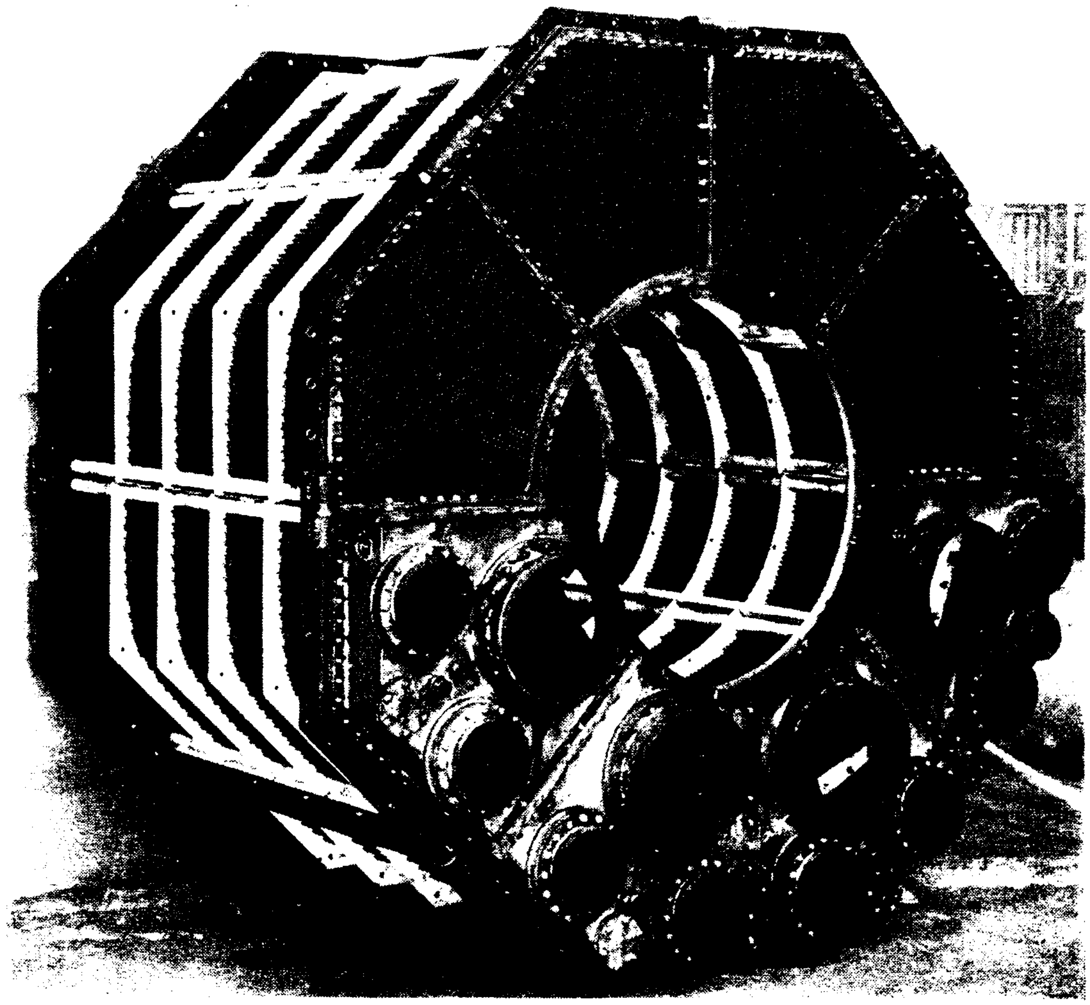
Concentricity is maintained between the compressor disc assembly and the two stub shafts under all conditions of speed and temperature since they are butted together on the faces with " Hirth " couplings.

The rotor blades, which are of aerofoil section, are each machined integral with its root from 13% chrome stainless iron bar. The blades are wired together in groups of ten each for ease of assembly and are lightly located between the rims of adjacent wheels by means of a groove machined in the roots, which engages with a corresponding register on the discs. The assembly of the discs and blades is carried out with the axis of the rotor vertical. The blade profiles were machined by Centrax Limited.

The stator blades are of monel metal rolled strip also of aerofoil section, cast into combined roots and spacers and secured in grooves in the casing. The casing is of cast steel construction, split on the horizontal centre line. Double-skin construction of the stator casing is adopted to ensure sufficient space for adequate amount of air blow-off, but it has since been found that this is not necessary.

Heat Exchanger

The heat exchanger is of the tubular, cross-flow, recuperative type arranged with a single pass on the hot exhaust gas side and two passes on the cold inlet air side. It is built of eight similar segments each containing just over 2,000 tubes, the total number being 16,500. The shell is of fabricated aluminized mild steel fitted with " Yorcalnic " tubes $\frac{5}{16}$ in. outside diameter, .020 in. thick, which are secured to the mild steel tube plates by expanded ferrules. The ferrules are expanded by means of a hydraulically operated



The Heat Exchanger with top four Headers removed

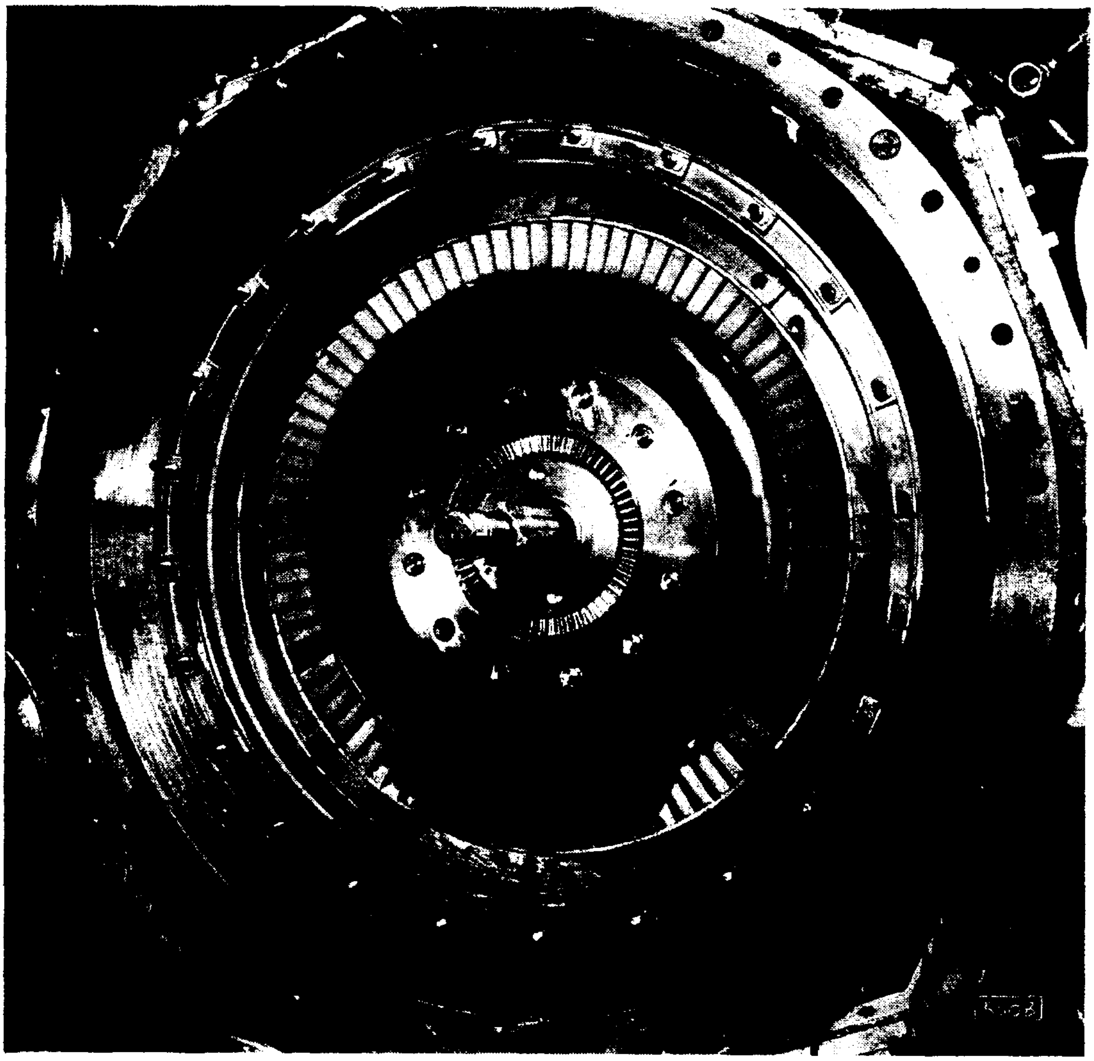
riveting gun, which was specially developed for the purpose. The ferrules are threaded on to an expanding mandrel, which is then loaded into the riveting gun. The first ferrule and the mandrel are entered into the tube and on firing the gun the mandrel is drawn back through the ferrule, expanding it and the tube into the tubeplate. After expanding, the inside diameter of the ferrule is the same as that of the tube bore. This method of tube assembly has been found to be both satistory and extremely rapid.

Combustion Chambers

The machine is provided with a multi-chamber combustion system consisting of eight chambers disposed symmetrically about the axial centre-line of the turbine shaft. The inner flame tubes are of Nimonic 75 nickel chrome alloy, cooled by the secondary air. The outer air casing is of mild steel sheet, aluminised and fitted with two bellows expansion pieces to take up the differential expansion between the turbine casing and the heat exchanger. Each end of the combustion chambers is secured by a special quick-release type of joint.

Compressor Turbine

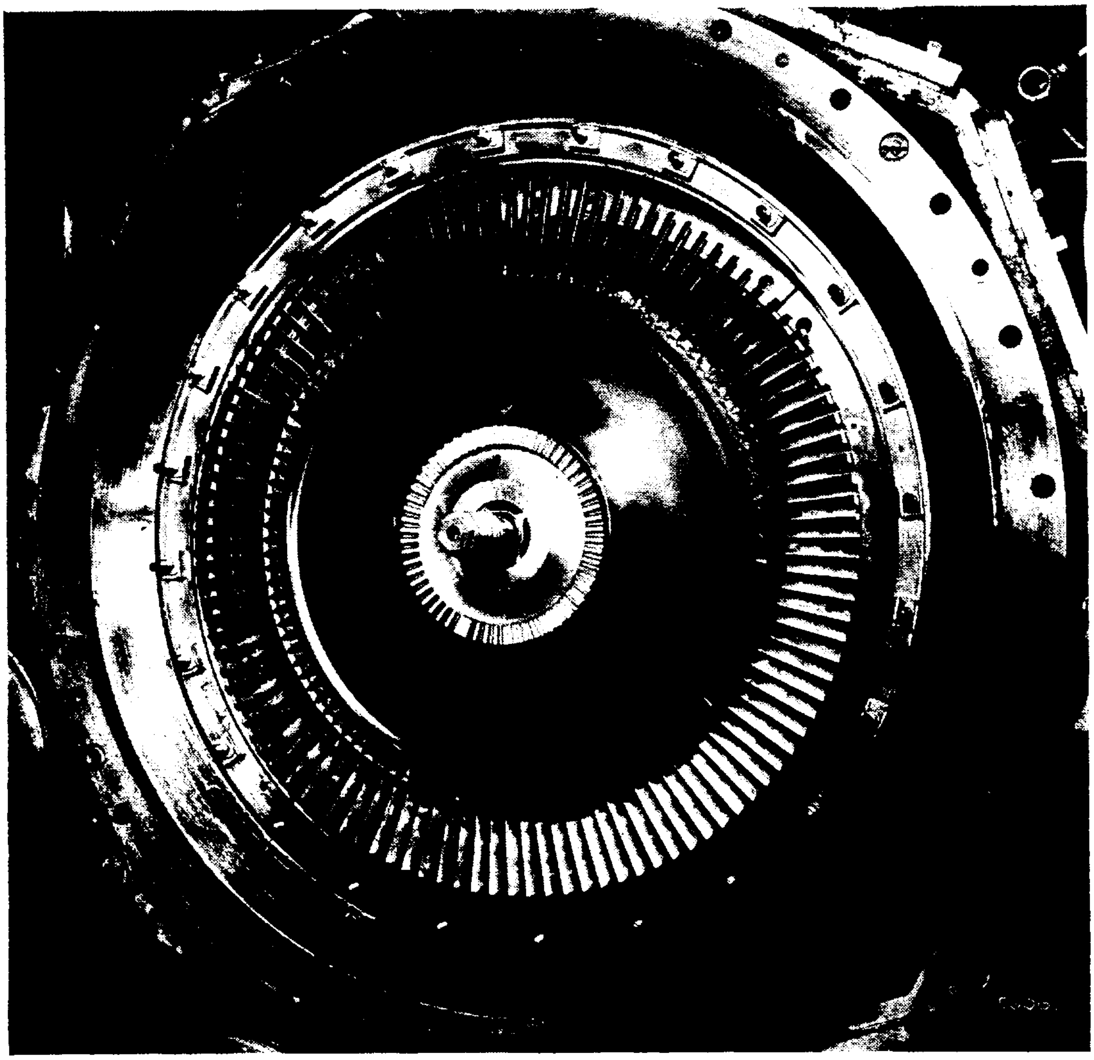
The compressor turbine is of the axial-flow type consisting of two stages.



First Stage Stator of the Compressor Turbine

The two " G18B " steel rotor wheels and the stub shafts are bolted together by means of a pre-stressed manganese molybdenum bolt passing through the centrally bored wheels, and specially designed to withstand the high expansion which occurs in the wheels themselves. " Hirth " couplings are again utilised to locate the wheels and the Nitralloy steel stub shaft. The shaft is hardened on the bearing journals.

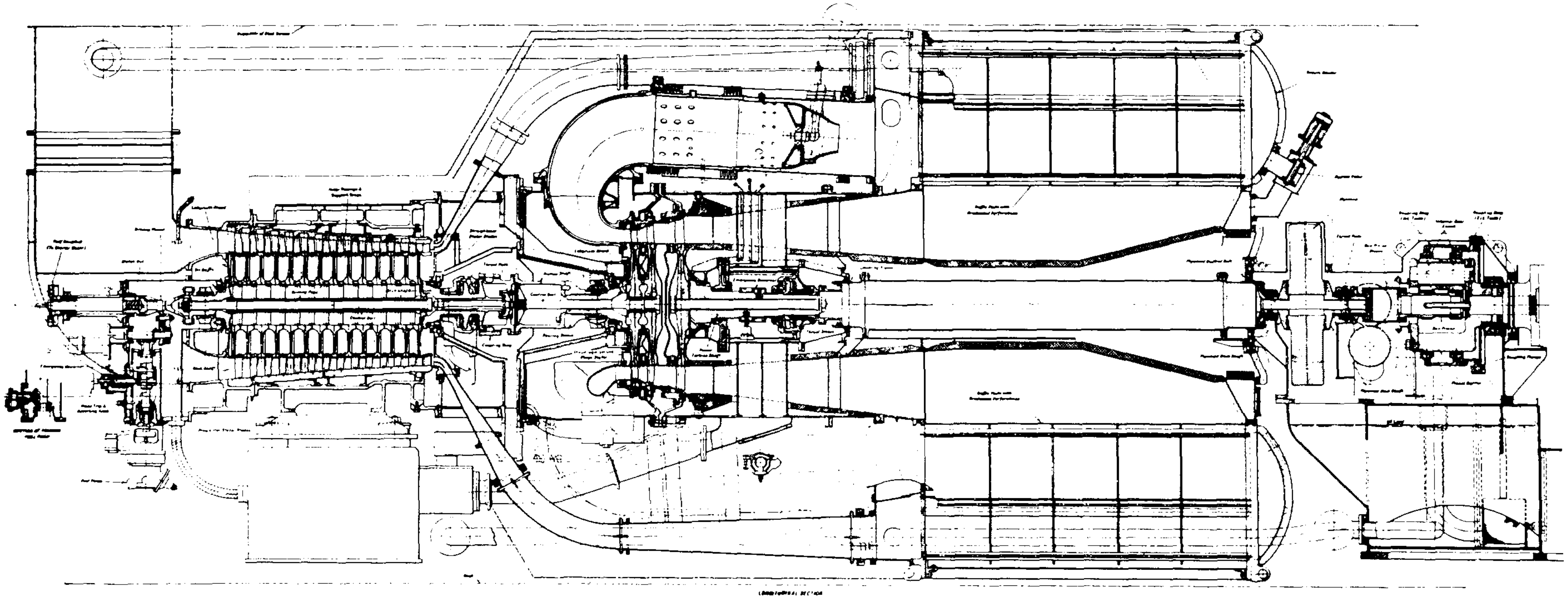
The rotor blades are of Nimonic 80A, secured in axial fir-tree type serrations in the periphery of the wheels, each blade being fixed by a locking key. All stator blades are of Nimonic 80 material produced by the lost wax process of precision casting. The first-stage blades are riveted in groups to segmented strips to form assemblies easy to handle. Each second-stage blade is secured in a groove in the intermediate casing ring and positioned circumferentially by means of two pegs. The inner end of the blades has a cylindrical projection which fits into a radial hole in the diaphragm. This engagement is such that the stator blade is free to expand radially towards the centre of the diaphragm and the diaphragm to expand radially outwards. The diaphragm is protected by heat shields designed to prevent distortion due to the temperature gradient.



SECOND STAGE ROTOR OF THE COMPRESSOR TURBINE SHOWING THE " HIRTH " COUPLING

The casing consists of an inner and outer member designed to minimise thermal stresses due to expansion and to allow all parts to expand freely and yet remain concentric. A centre casing ring of heat-resisting material is located in the main casing by means of radial keys in such a manner that it is free to expand in a radial direction at all points on its circumference. Inner segmented shroud rings of H.R. Crown Max steel are arranged to expand circumferentially in grooves in this casing ring. This arrangement maintains the blade tip clearances at all loads, thus improving the efficiency and also making it quite safe to shut down and start up quickly. Cooling air from the compressor passes around the inner casing and through passages in the centre casing ring before joining the main gas stream.

The coupled compressor and driving turbine shafts are supported in three bearings. Allowance for any malalignment of the shafts is made by connecting them by means of a quill shaft forming an extension of the turbine shaft, which is located in the bore of the compressor shaft. The driving torque is, however, transmitted through a normal gear-tooth type muff coupling.



Sectional arrangement of Gas Turbine and Gearing

Power Turbine

The power turbine is of the axial-flow type, consisting of a single stage, mechanically independent of the compressor turbine. The materials and general construction of the turbine are similar to those already described for the compressor turbine, with the exception that the rotor wheel is of Jessop's " H40 " ferritic steel. The bearing is connected radially to the outer main turbine casing by four radial fabricated struts passing through streamline airfoils, which are themselves integral with the mild steel power turbine exhaust-diffuser ducting assembly.

Turbine Cooling Systems

Great attention has been paid to the efficient cooling of the rotors and casing. There are several cooling systems so arranged that air from the compressor delivery passes through passages in the turbine casings and up both sides of the turbine rotor discs, finally joining the main gas stream.

Bearings

All main compressor and turbine bearings are of the sleeve type, the design generally following well established steam turbine practice. The bearings are of steel lined with white metal, with the exception of those which may be subjected to higher temperatures which are of mild steel, lined with lead bronze. They are lubricated and cooled by oil at a pressure of approximately 10 lb/sq. in. Ball and roller bearings are incorporated in the auxiliary drives. The thrust bearings are of the Michell type. Journal bearings are fitted with thermocouples and the thrust bearings with hydraulic wear gauges.

Glands

The casing glands of the compressor and turbine, as well as the interstage glands, are of the labyrinth type, consisting of stationary stainless iron fins working in conjunction with stepped shaft journals.

Flexible Couplings

The turbines and their driving shafts are coupled by means of continuously lubricated internal-tooth type couplings. Oil is fed by centrifugal force through internal passages to each tooth engagement.

Gearing

Speed reduction between power turbine and alternator is achieved by a double-helical epicyclic gear, which offers the maximum saving in weight and space. The gear is designed on the well-known Stoeckicht principle (which ensures equal load sharing, not only between the planet wheels, but also between the helices), and is capable of transmitting 1,800 h.p. continuously from a turbine speed of 6,750 r.p.m. to an alternator speed of 1,500 r.p.m. There are no high-speed shaft bearings in the gear unit, the sun wheel, which is supported between the three planet wheels, being connected to the power turbine by means of a flexible coupling of the double-helical-tooth type.

Mounting

The unit has no baseplate, a three-point mounting being effected by mounting the compressor independently. The supports on either side of the inlet to the heat exchanger are flexible and take care of thermal expansion.

Lubrication System

The lubricating oil system closely follows usual steam turbine practice, embodying two separate valveless gear-type oil pumps. One pump delivers oil at approximately 120 lb/sq. in. gauge to the governor oil system, whilst the other delivers oil at approximately 45 lb/sq. in. gauge for bearing and gear-teeth lubrication.

The pumps are arranged for driving in tandem either by an electric motor when starting up, or by the turbine shaft through gearing during normal running. A clutch arrangement is provided, which enables the drive to be automatically transferred from the motor to the turbine when the latter has reached a speed sufficient to maintain the pressure in the oil system.

The oil for the governor pump is taken from the lubricating system so that the oil for both systems passes through a filter and cooler.

Fuel System

The turbine is provided with a simple fuel-oil system employing Simplex-type burners. The quantity of fuel delivered to the combustion chambers is varied by the opening of a throttle valve fitted in the fuel-supply pipe to the burners and controlled by the speed governor through an oil relay. A hand-controlled throttle valve is used when starting up. The fuel pump is driven through gearing from the compressor shaft.

An emergency shut-off valve is incorporated in the fuel system, which operates automatically in the event of the turbine over-speeding or on failure of the lubricating-oil pressure. This valve is also arranged to close on manual operation of trip cocks situated both on the turbine and on the control panel.

Four of the eight interconnectors fitted between the combustion chambers are fitted with a torch igniter assembly, each assembly consisting of a thermocouple, a plug and the torch itself. Complete reliability at starting is ensured with this arrangement as each chamber is ignited directly from a torch. As a double safeguard in the event of one or more of the torches failing to ignite, the interconnectors ensure satisfactory ignition in all the chambers.

Speed Control Governor

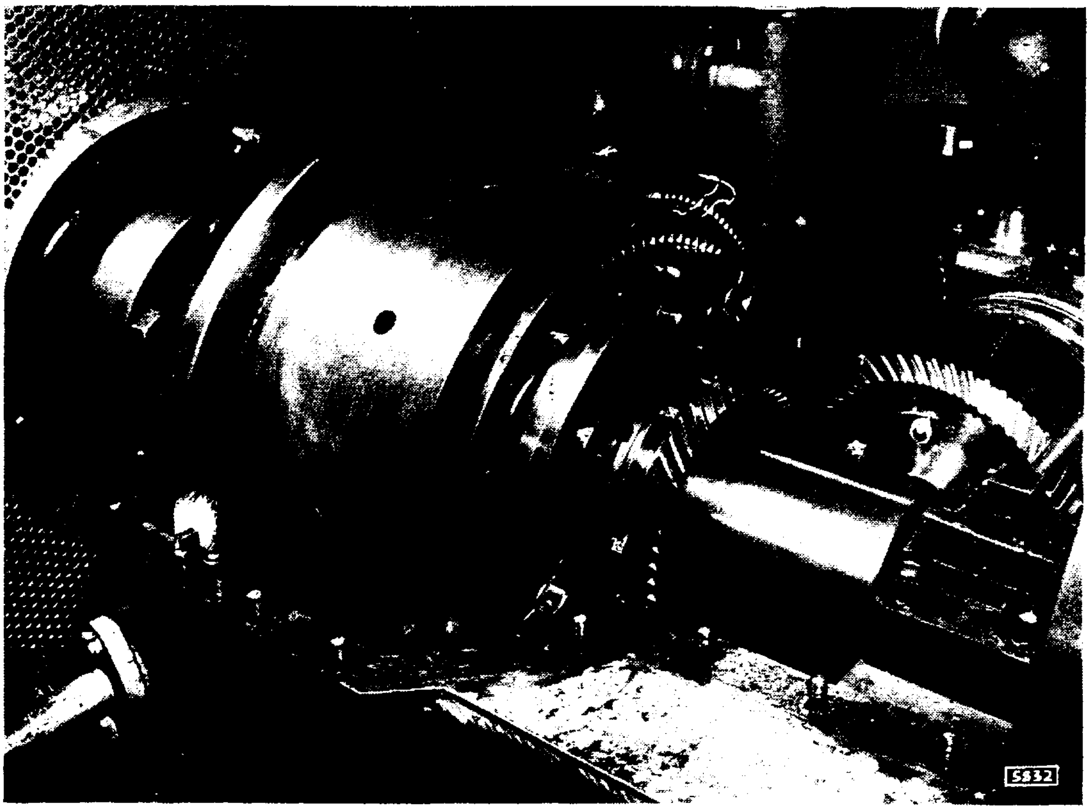
The speed control governor is the centrifugal type, driven from the power turbine shaft and operates the fuel throttle valve through an oil relay. The oil relay is supplied with high-pressure oil and is arranged so that in the event of a failure of the lubricating-oil supply the machine is automatically shut down.

To assist the speed governor during sudden load changes, a small flywheel is fitted on the high-speed shaft and housed in the reduction gear casing, whilst the compressor rotating assembly is specially designed to have a low moment of inertia.

The speed governor is provided with a manual speed-regulating handwheel positioned on the governor itself, capable of adjusting the speed of the power turbine at no-load within 5% above or below the rated speed. A small electric motor is also embodied in the governor gear, enabling this speed adjustment to be effected from both the switchboard and the control panel.

Emergency Governor

Overspeed trip governors of the shock-proof unbalanced-ring type are fitted to both the compressor and the power turbine shafts, arranged to operate an emergency shut-off valve in the fuel system by destroying the pressure in



The double helical epicyclic Reduction Gear, showing also the bevel gear drive to the Tachometer and Governor

the oil relay when the speed exceeds the rated speed by a predetermined amount.

Hand trip-cocks are fitted both on the machine and on the control panel.

Starting Procedure

The starting procedure is briefly as follows: —

The compressor is run up by an electric motor to approximately 1,500 r.p.m. (taking approximately 16 h.p.). The torch igniters are then lighted by means of an ordinary sparking plug and when the thermocouples indicate that they are operating satisfactorily, the main fuel supply is switched on to the burners. Further thermocouples indicate when each combustion chamber is alight and upon verification that all chambers are functioning satisfactorily, the turbine is accelerated on the hand throttle valve The starter motor continues to assist the turbine up to a speed of approximately 2,500 r.p.m., when the turbine becomes self-sustaining and its speed overtakes the starter motor, which disengages by means of a free-wheel clutch. As the turbine speed approaches no-load speed, the automatic speed control governor takes over control of the fuel supply through the oil-operated throttle valve. The time required to reach the no-load condition is approximately one minute. Normally, the turbine is run for five minutes at this condition for warming up before proceeding to higher loads, but if necessary, it is capable of accepting full load straight away, giving a time for obtaining full load of approximately 1½ minutes.

No barring-over of the machine is necessary after shutting down, but oil circulation to the bearings is continued for a few minutes.

Testing

The unit, without the heat exchanger, has been on test since early in 1951. Full speed, full load, and overload were achieved in the first series of tests with the minimum of mechanical " teething " troubles. A comprehensive series of performance, governing and endurance tests are now in hand.