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MARINE AUXILIARY GAS TURBINES

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SYNOPSIS

A considerable amount of attention has been focussed in the recent past on the application of gas turbines as propulsion prime movers for warships and, to a more limited extent, for certain specialised merchant vessels. The problems encountered, and the experience being gained, in the marinisation of both aero-derivative and industrial type gas turbines in the 3000 to 30,000 h.p. range have been recorded in some detail, in papers to this Institute and other articles in the technical press. It is therefore surprising by comparison how little attention has been given to the possible application of gas turbines as prime movers for marine auxiliary machinery in merchant vessels, in the power range 500 to 4000 h.p.

This paper therefore sets out to:

a) examine the case for utilising gas turbines for auxiliary drives.
b) report the conception and development of a radial gas turbine designed as a marine auxiliary prime mover of approximately 2100 h.p.
c) outline the types of sea-going installation in which this gas turbine has been utilised and report on service experience.
d) survey the future likely applications of this type of equipment.

THE CASE FOR THE DEVELOPMENT OF A MARINE AUXILIARY GAS TURBINE

In the early days of the evaluation of gas turbines for propulsion duties, the advantages over competing types of prime mover were claimed to be:

a) low maintenance requirements and ease of basic maintenance operations.
b) simplicity of operation, reliability, and suitability for automatic or remote control.
c) small size, and low weight, for the power developed.
d) low support system requirements.

The experience that has now been gained in the operation of main propulsion has shown that, although these advantages may not have manifested themselves in quite the manner originally expected by the installation designer, they have in the main verified the original expectation.

In evaluating the case for auxiliary gas turbines, the same advantages must therefore be considered. But before deciding on the type and size of auxiliary gas turbine to be developed specifically for marine applications, there are some additional considerations. The largest single type of auxiliary duty is electrical power generation. The high degree of development achieved by the diesel engine for power generation, coupled with the

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differences in the basic thermodynamic cycles between gas turbine and diesel engine, result in the gas turbine being at a disadvantage when comparing fuel consumption, particularly if the design of gas turbine is kept very simple to capitalise on its other advantages in terms of ease of maintenance, small size, and simplicity of operation. The rising cost of fuel, and emphasis on economy of ship operation, therefore normally militates against the concept of gas turbo-generators as base load electrical generators at sea. The advantages of the gas turbine are therefore more likely to find themselves best utilised where the auxiliary power requirement is for high power from a restricted space in, for instance, a 'peak-lopping' mode, and in locations or environments where the application of alternative types of prime mover are impractical. Before finally establishing the basic design philosophy of the marine auxiliary gas turbine, however, some of the criticisms that have been levelled at some of the previous main propulsion gas turbines had also to be considered. These included:

a) unsuitability of design and materials for the marine environment.
b) need for specially qualified staff to operate and maintain the gas turbine.
c) need for special gas turbine fuel.

and it was obvious that any gas turbine to be developed as a marine auxiliary would have to seek not only to capitalise on the stated advantages, but also to avoid the above pitfalls.

THE DESIGN PHILOSOPHY FOR A MARINE AUXILIARY GAS TURBINE

As a result of the foregoing considerations, the following are the components of the design philosophy of a marine auxiliary gas turbine:-

a) Suitability for a marine environment. This influences selection of cycle temperatures, selection of materials and general robustness of the design, and must also extend to the ability to burn typical marine fuels of only average standards of purity, as well as the capability of operating in high salt-in-air concentrations.
b) Simplicity. The requirement for reliability, and low and easy maintenance, indicates the adoption of the simplest solutions in terms of mechanical design, turbine arrangement, etc.
c) Size and weight. The design must be such as to achieve an overall size and weight considerably less than competing prime movers.

Any design is inevitably a compromise between the conflicting basic requirements, but in any such conflict the above considerations might be regarded as being in order of priority.

THE APPLICATION OF THE DESIGN PHILOSOPHY

In order to test the validity of the foregoing design parameters, it is necessary to study their application to the design of a specific gas turbine, and then to evaluate the resulting machine in the light of the service experience gained in the various types of marine installation in which it has been utilised.

The gas turbine selected for this study is the Kongsberg KG-2 (or Viking 2), the current rating of which is 2100 h.p. under I.S.O. conditions at 15°C ambient temperature.

The brief history of its development is that following the formulation of the concept of a specifically marine auxiliary gas turbine, a world market survey was conducted in 1964 to determine the approximate power required from the first frame size. The design development and testing which followed lead to the construction of the first prototypes in 1967 and 1968, and general production in 1970. In a welcome reversal of the trend whereby marine equipment is adopted and adapted from other disciplines, about two-thirds of the 330 machines installed or under construction are for non-shipboard applications, either in industrial installations or in the oil-and-gas producing industry. However many of the latter, on production platforms offshore, experience an environment very similar to installations on board ship. To date more than 70 sets are in service on board ship with a further 30 either under construction or on order.

THE DESIGN OF A 2100 H.P. MARINE AUXILIARY GAS TURBINE

Introduction

It is not the purpose of this paper to describe in detail the design of the gas turbine, but the following are the main characteristics, in order to evaluate whether or not the basic aims for the machine stated above have been achieved. Some figures for speeds, power, air mass flow etc. for the machine are listed in Appendix I to the paper, and Appendix II contains a list of the standard materials used in its construction.

Basic Arrangement

The KG-2 gas turbine is a single shaft open cycle machine, (see Fig. 1) with a single-stage radial compressor and single-stage radial turbine, mounted back-to-back and supported in two bearings so that the rotor is cantilevered. In the radial or centrifugal design of turbine or compressor the direction of flow of the gas is predominently in a radial direction as opposed to the axial machine where the predominent direction of flow of the gas is parallel with the axis of rotation. The choice of an all-radial gas turbine, as opposed to the more conventional axial machine results in:-

a) a compact design, with low unit length for the power developed.
b) substantial compressor and turbine blading, which is less prone to damage in service due to erosion, corrosion, or foreign bodies, and which also has larger gas passages with correspondingly less sensitivity to loss of performance due to fouling.
c) less sensitivity, compared with an equivalent axial machine, to air inlet pressure and temperature profile variations. This makes possible the installation of the machine in constricted locations where the inlet air flow is asymetrical.

Rotor

The overhung or cantilevered rotor support arrangement is achieved using two bearings of the tilting pad hydrodynamic type, specifically designed and developed for this machine. (see Fig. 5) The normal rotor speed is 18000 r.p.m. The overhung arrangement results in:

a) the support bearings being located in the 'cold' end of the engine, with consequently reduced demands on the bearing lubrication system; this also minimises heat soak to the oil on shutdown of the machine.
b) a simple axial exhaust flow with consequent flexibility of choice of exhaust ducting arrangement.

Cycle of Operation

The cycle of operation may be summarised as follows (see Fig. 2):

i) air is drawn into the compressor through a static contoured annulus.
ii) on leaving the compressor, the air passes through a static four-stage annular diffuser which progressively converts the velocity energy of the air into pressure energy.
iii) air is admitted to the combustion chamber: primary air through the nozzles, and secondary and tertiary air through the liner. The combustion system is a single reverse flow combustor tangentially mounted on the pressure vessel. The combustor head is of multi-nozzle design and is secured by a quick release clamp.
iv) the lower end of the combustion liner is located in the entry to the volute, which directs the hot gases into the turbine nozzle guide vanes.
v) the gases enter the turbine and turbine exducer, which are solidly coupled together, and then exhaust from the machine through an axial exhaust diffuser.

Gearbox

The reduction gearbox which forms an integral part of the machine is a two stage straight spur reduction gear and also contains the auxiliary gear train, providing drives for the engine-driven fuel and lube oil pumps, and also carries the bevel gear arrangement for the starter motor input. A variety of reduction ratios can be achieved with variations of arrangement inside the standard gearbox casing, the most common, of course, being those to achieve suitable speeds for generator drives such as 1500 and 1800 rpm.

Controls

Regardless of the simplicity and robustness of any prospective item of marine equipment, the successful and reliable operation of its control and protection system will often determine its acceptability for application in marine installations. Superimposed on this general requirement, two additional considerations in the case of the auxiliary gas turbine have a further bearing on the control and monitoring system design:-

i) by the nature of many of the applications to which it is put, the auxiliary gas turbine is often located outside the regular machinery spaces, and is often required to operate at high power after relatively long periods of inactivity, perhaps in an emergency situation.
ii) because of the often sporadic nature of its operation, and its relative rarity, to date, as an auxiliary prime mover, the auxiliary gas turbine will frequently be operated by staff who have had no opportunity of familiarising themselves, over a lengthy period of steady operation, with the characteristics of the machine.

These characteristics place on the designer of the controls-and-monitoring system the following requirements for the system:-

a) it must function satisfactorily independent of the operator. Push button operation, automatic interlocks and shutdowns must be utilised in place of relying on the skill of the operator to carry out complex checking and monitoring functions.
b) it must function satisfactorily with a minimum of system maintenance. This produces the requirement for system simplicity, and for module replacement in the event of failure.
c) the system must wherever possible be failsafe, so that any uncorrected malfunction shuts the turbine down, and double system protection must be provided in critical areas to cover for the failure of one part of the monitoring or control system in that area. This requirement must,

however, be balanced with ship safety in, for instance, emergency generator installations, when a manual override is included in order to be able to run the turbine with only the most essential monitoring during an emergency situation.

d) the characteristics of the control and governing system on the machine must be compatible with those of other prime movers with which the gas turbine may be called upon to operate in parallel.

e) the control system as a whole, and the control cabinet in particular, must be physically tested before adoption to ensure their continued operation when subjected to high humidity, salt laden atmosphere, vibration, and shock.

The system which was designed to satisfy these requirements and which has now been in operation at sea for up to six years is outlined in Appendix III to the paper.

Fuel and Lubricating Oil Systems

The gas turbine is suitable for operation on gaseous fuel, a wide variety of liquid fuels, or as a dual gas-or-liquid fuel engine. The normal marine liquid fuel system, suitable for burning standard Class B2 marine diesel fuel, as a self-contained system with the fuel pump driven from the auxiliary power offtake on the gearbox. Fuel is drawn through the suction filter by the pump which then delivers to the high pressure fuel filter and the electro-mechanical control system. Duplex filters are fitted to allow on-line change-over. During turbine run up, in order to achieve controlled acceleration, the fuel valve controls the fuel flow in response to a signal from the compressor discharge pressure. At full speed the lube oil driven actuator takes over control. This actuator compares the actual speed with the correct preset speed at all loads and produces an output based on the difference. The excess fuel is spilled back to the pump suction, while the correct amount of fuel is passed through:-

- an on/off solenoid valve
- a non-return valve
- a primary/secondary distributing valve

to the fuel nozzles in the combustor head. The lube oil system operates with any one of a number of the standard mineral oils available on board ship. The main components are:

i) main lube oil pump, driven from the auxiliary power take off on the gearbox.
ii) lube oil cooler which may be sea water or air cooled, depending on the installation.
iii) full flow filters, normally arranged in duplex, of 5 micron size.
iv) pressure modulating relief/reduction valve.
v) thermostatic 3-way control valve of the wax element type.
vi) auxiliary lube oil pump, which may be driven by electric, air, or gas motor depending on the installation.

During the start cycle, the auxiliary lube oil pump primes the main pump ready for the turbine run-up and also provides the turbine lubrication until the main pump takes over. Similarly during the run-down cycle, the auxiliary pump ensures adequate lubrication when the engine-driven main lube oil pump output falls off.

During normal running, the main lube oil pump supplies oil from the integral drain tank in the turbine underbase to the bearing systems and gear trains via the oil cooler and full flow filters. The system pressure is regulated by the relief /reduction valve which spills the excess back to the drain tank. The temperature is regulated by the thermostatic valve which mixes cooled and uncooled oil.

Such are the modest duties of the lube oil system and the limited size of the system, that lube oil consumption in operation can be regarded as negligible.

Starting System

A variety of starting motor types can be fitted, according to the type and location of the installation. Standard types of start motor which have been fitted to existing installations include:

i) compressed air or gas pneumatic motor
ii) D.C. motor supplied from, for instance, a bank of batteries.
iii) A.C. motor supplied from an adjacent A.C. system (such as the ships distribution system) driving through a fluid coupling.
iv) an industrial petrol engine, which is started from a car battery and then in turn used to run up the gas turbine through a standard torque converter.

The starter motor runs the turbine up to the speed at which ignition commences, and then assists acceleration above the turbine self-sustaining speed (approximately 50% full speed), when the starter motor is stopped and the sprag clutch disconnects. The turbine takes over and the starter sequence is concluded when the turbine has accelerated up to 100%.

Typical time required from initiation of the start sequence to full load can be 45 seconds in compliance with the SOLAS requirement, and recorded starting reliability is now of the order of 99.6%. In emergency standby installations the Classification Societies have accepted starting air storage capacity for only 3 starts, as opposed to the more normal 6.

The Resulting Gas Turbine

The machine which results from the realisation of the design aims outlined above, and the system considerations described:

a) has a nominal rating of 2100 h.p. at 15°C under marine conditions on liquid fuel.
b) is 2.02 metres (6.47 ft) overall in length, by 1.38 metres (4.42 ft) wide, by 2.19 metres (7.01 ft) high.
c) weighs 2.6 tonnes complete with underbase and oil drain tank at working level.
d) operates on marine diesel fuel and standard marine-type lube oil,
e) is now approved by the Classification Societies on a Type Approval Basis.

THE APPLICATION OF THE MARINE AUXILIARY GAS TURBINE IN MERCHANT SHIPS

Characteristic parameters

The types of installation which can benefit from the application of the gas turbine described above will have one or more of the following requirements for an auxiliary power source in common:

a) high power to space ratio, for instance due to restricted machinery space, or a transportability requirement.
b) high power to weight ratio, for instance due to a vessel's stability problem, or the need to mount the equipment high in the vessel.
c) uneven or 'peaky' power demand profile which has short periods of high power requirement superimposed on the basic or everyday load.
d) high starting reliability, even after relatively long periods of inactivity, and with minimal day-to-day maintenance, for instance such as is required from an emergency generator.
e) simple remote or automatic starting arrangements, for instance for emergency generators mounted outside the main machinery spaces and arranged for automatic start-up on failure of the main generators.
f) remote or difficult location where support services such as electrical power, cooling water, and/or compressed air are not available.

Some of the installations in which the auxiliary gas turbine has been utilised have more than one of the above characteristics, and in some cases, some ship operators after initial experience of the gas turbine in a modest or relatively limited role, have in subsequent ships considerably extended its sphere of operation. The following are some of the applications in which the machine has been utilised.

Combined emergency/standby generator

Although the statutory requirements covering a specific vessel may require only a very small generating capacity specifically delegated as the emergency supply, a number of shipowners believe that the safety of the ship is more adequately served by installing a larger generating capacity outside the machinery spaces. Hence the capability of the emergency generator, which may statutorily be required to cover only:

- emergency bilge pump
- emergency lights in a restricted number of locations.
- ships navigation lights
- communications equipment
- and other small consumers such as signalling equipment, watertight doors etc.

can with relative simplicity, be extended to cover additional loads, the availability of which in an emergency may be vital, such as

- steering gear
- full lighting throughout the vessel
- deck machinery
- bow thruster if fitted

This extension of the role of the emergency generator is feasible because of the gas turbo generator's

i) small size and weight for the power developed. A 1500 KW gas turbo generator is approximately 4 metres (13.12ft) in overall length and weighs 10 tonnes. (see fig. 4). The generator can therefore be mounted relatively high in the vessel (e.g. on the funnel deck abaft the funnel, with consequent simplification of air intake and exhaust arrangements).
ii) low ancillary system requirements. The provision of, for instance, an air cooled lube oil cooler, and D.C. motor-and-battery start system, can render the generator set independent of ancillary systems, except for a supply of fuel. Alternatively, a compressed air starting system can be supplied from an emergency air storage bottle, and this also allows the provision of auto-start facilities for the generator in the event of a black-out.
iii) low vibration and noise signature. Being essentially a high speed rotary machine, the vibration and noise characteristics of the machine are either lower, or more easily attenuatable, than might be the case with slower speed reciprocating machinery. Experience has shown that it is quite feasible to mount the gas turbo-generator in an emergency generator

room contained, for instance, in the accomodation block of a large tanker, with only modest acoustic insulation in the compartment.

iv) ease of installation: this is really a subsiduary advantage of the size and weight of the machine, allied with the simplicity of the three point support arrangement of the common underbase of the set. It makes possible a single lift installation of what is a relatively large capacity generator set, and also allows it to be installed in the vessel, without complex alignment or seating check procedures, at a relatively late stage in the vessel's construction.

To gain full advantage of the concept of a 1200 to 1500 KW gas turbo-generator mounted outside the machinery spaces, however, it is necessary to go a step further. The conventional arrangement of, for instance, a large tanker is as shown in Fig. 6 with three generators in the machinery spaces, where one of these sets is a steam turbo-generator for base load generation, one of the remaining two (diesel) generators is utilised during peak loading or standby conditions, and the second diesel generator is available as standby in the event of failure of either of the other two. The emergency diesel generator outside the machinery spaces is a small capacity set, fitted predominently in compliance with the basic statutory requirements.

If this emergency diesel is replaced by a gas turbo-generator set of say 1400 KW capacity, one of the standby generator sets in the machinery spaces can be dispensed with, without in any way compromising the generating or standby capability of the vessel. The resulting generating arrangement, comprising two generators in the machinery spaces (one for base load, and one for peak-lopping and standby) with one gas turbo-generator outside the machinery spaces as a combined standby and emergency set, offers a solution to the question of generator selection and arrangement which:

- is lighter
- is less consuming of engine room space
- requires less maintenance
- offers greater emergency generating capacity
- and is, at worst, no more expensive in combined capital and installation costs than the alternative all diesel generator installation.

Since the first of the standby/emergency sets of the type described in this paper was installed in 1970, a total of between 35 and 40 sets have been installed as single emergency/standby generators (some in configurations which are separately described later in the paper involving, for instance, inert gas production, or a containerised generating set) on vessels ranging in size from a 5750 TDW product carrier to 330,000 TDW VLCC's and including ferries, OBO ships and an LNG carrier.

Extension of standby/emergency generator concept

The prospective advantages claimed above for the concept of the emergency/standby gas turbo-generator coupled with experience in service, have proved sufficiently attractive for a number of installation designers and shipowners for the concept to be extended to the fitting of two gas turbo-generators outside the machinery spaces, with further reduction in the number or capacity of the generators fitted in the machinery spaces. As a result of this, a further 30 sets are installed in pairs on vessels ranging from 9x18,500 TDW container ships to 6x98,000 TDW OBO carriers and, as before, covering both steam turbine and diesel propelled ships.

The steam turbine propelled container ships represent an interesting extension of the peak-lopping concept in the application of the gas turbo-generator. The basic parameters of the vessel are:

L.O.A.: 210,60 metres
Capacity: approx. 1,700 containers in combinations of 20 foot and 40 foot sizes.
Deadweight: 18,500 tons
Main machinery: 36,000 SHP, AG Weser/General Electric MST14 steam turbine.
Generators: 2 x 2000 KW steam turbo-generators (Blohm and Voss SHT 50/40)
2 x 1500 KW gas turbogenerators (Kongsberg KG-2)

Each of the steam turbogenerators is of sufficient capacity to carry the basic load at sea. However, a characteristic of the vessel's electrical power profile is the occurrence of a high peak load in the early stages of many loaded voyages, caused by the refrigeration load from containers carrying perishables, which have to be brought down to transit temperature within a relatively short time of being brought on board. Once the contents of these containers has achieved transit temperature, the electrical load returns to a more normal level, since the refrigeration load is only such as to cover thermal leakage. The fitting of the two gas turbogenerators, in a small generator room on the Bridge Deck, aft of the machinery casing, provides:

i) an 'all turbo-machinery' generating plant arrangement with consequent advantages for both ease of remote control and reduction in maintenance.

ii) a compact 'peak-lopping' generating plant arrangement, the alternative to which would be a marked increase in the number or size of the generators in the engine room with the probable involvement of diesel generators.

iii) an extensive standby/emergency generating capacity outside the engine room, covering for the protection of the cargo if engine steam plant is shut down for some reason, and for the provision of a large electrical power capacity to preserve the safety of the ship in the event of 'black-out'.

The Gas Turbine and Inert Gas Plant

The provision of equipment on board tankers which produce on inert gas with which to fill empty cargo tanks, to minimise the risk of explosion and corrosion, has become a statutory requirement on new vessels over a predetermined cargo capacity. Inert gas plants are also frequently utilised on L.P.G. and L.N.G. carriers, and have in the past been used on a variety of other types of vessel, including some for instance involved in the carriage of fish-meal in bulk, the cargo apparently being prone to spontaneous combustion in transit.

For inert gas capacities up to about 10,000 Nm^3/hr. the usual type of plant utilised is a purpose built oil burning inert gas generator. For larger gas capacities, for instance of 20,000 Nm^3/hr. required for a 233,000 TDW tanker, a plant utilising boiler flue gas is often employed. This system is attractive from the point of view of 'getting something for nothing' since it uses the boiler exhaust gases and, after washing, cooling and compressing them, passes them directly to the cargo tanks. There are, however, some inherent disadvantages:

i) the boiler exhaust gases are liable to contain a relatively high level of sulphur contaminants which may not be completely eliminated by the washing process in the scrubber, with the consequence that the gas passed to the tanks is corrosive, thereby defeating one of the objectives of fitting the plant.

ii) the sulphur contaminants that are removed in the scrubber lower the pH value of the water used for washing the gas, and this is discharged overboard. Regulations governing the discharge of effluents in harbours or inshore waters which have been , or are in the process of being, framed by various authorities usually call for the pH value of thos effluents to be maintained between approximately 5.0 and 9.0 (clean sea water is around 8.0 and clean fresh water around 5.5). The overboard discharge from a flue gas plant may be about 2.5 - 3.5 and although this can be rectified by the use of additives before discharging the water overboard, this not only increases the operational costs, but may also contravene that section of the regulations in respect of either the chemical content of, or suspended solids in, the effluent.

iii) fluctuations in the steam load on the boiler may result in marked fluctuations in the oxygen content of the inert gas output. Since the objective of generating the inert gas is to exclude oxygen from areas prone to explosion or corrosion by maintaining the oxygen level of the inert gas at or near 1%, fluctuations in the inert gas oxygen content up to, say, 10% reduces its effectiveness.

iv) additional electrical generating capacity is required to drive the gas circulating fans.

With these problems in mind, the author's company, in conjunction with Moss Verft, developed the concept of using the gas turbine exhaust on vessels fitted with gas turbogenerators, as the source of a high quality inert gas. The gas turbine exhaust contains approximately 15% by volume of oxygen and is low in other contaminants. The gas turbine acts as the compressor for the inert gas system and eliminates the need for gas circulating fans for normal operation. The oxygen level is lowered by burning it off in an afterburner, using the same low sulphur fuel as the gas turbine.

The operation of the plant is as shown in Figure 9. The hot gas emanating from the afterburner is cooled by sea water spray in the cooling tower. The demister effectively dries the gas before it leaves the tower. An oxygen analyser monitors the gas passing from the cooling tower and controls the fuel supply to the afterburner and also a dump valve to atmosphere. A pressure sensor in the same gas flow can also control the by-pass of the gas up the funnel in the event of overpressure.

Using a gas turbine of 2100 h.p. nominal output, up to 31,000 Nm^3/hr. of inert gas can be obtained. The turbine can circulate the gas against system total heads of the order of 3.5 metres water gauge (including the afterburner/cooling tower, and the dry type deck seal through which the gas is passed to the vessel's tanks) and at this back pressure the gas turbogenerator can still generate approximately 600 KW. This is more than sufficient for the system electrical requirements, which are limited to the power for the cooling tower sea water circulating pump and for the small fresh water circulating pump for the afterburner combustion chamber cooling system. The remaining generated power is available for ship systems, since the gas turbogenerator can readily be operated in parallel with other types of generator.

During the gas freeing of the tanks, for instance to enable staff to gain access to the tanks for maintenance or inspection, up to 25,000 Nm^3/hr. of fresh air available by utilising a compressor bleed from the gas turbine to drive an air ejector. The fresh air is distributed to the tanks by the same gas piping system used for the inert gas.

An interesting adaptation of the basic inert gas system was utilised to provide the high quality, low dew point inert gas required for L.N.G. carriers. A number of L.N.G. carriers operated by Shell regularly running to Tokyo Bay are supplied with inert gas at their destination by an inert gas barge. The system consists essentially of the system as described above, to which has been added the necessary refrigeration and drying plant to produce an inert gas of approximately 1% oxygen content and -45° C dew point. The source of electrical power for the whole inert gas system including the refrigeration and drying plant, and for the barges own electrical requirements, is the gas turbogenerator.

A total of thirteen gas turbine generator/inert gas plants are currently installed.

The Containerised Gas Turbogenerator

One of the early land-based applications of the 2100 h.p. gas turbine described in this paper was the construction of a mobile 1 MW generator set suitable for towing behind a standard road vehicle. At about this time, a need arose with a number of shipowners for easily transportable generator sets to be available at short notice for fitting to existing vessels which had experienced a major main generator breakdown or a shortage of electrical generating capacity. The basic requirements were for:

a) a self-contained generator package of 1000 to 1400 KW capacity in an all weather outdoor enclosure.
b) capability for 'single lift' installation with a minimum of alteration to the vessel, and a minimum of other additional equipment on board, to restrict vessel down time for fitting.
c) capability for swift transportation to a suitable port of embarkation.

The solution to the requirement consisted essentially of adapting a standard 20 foot x 8 foot x 8 foot container to enclose the gas turbogenerator set. The circuit breaker is built onto the generator, and a small control room provided in one end of the container to house the gas turbine and generator control cabinets and the switchgear operating equipment. A module combining the gas turbine air intake and the air cooled lubricating oil cooler is mounted on top of the container, as is a small fuel header tank, and the gas turbine exhaust silencer and duct forms the only other projection outside the I.S.O. 20 x 8 x 8 standard dimensions.

This packaged generator, landed as a single lift on a simple seating at any convenient location such as the funnel deck, can successfully operate in a fore-and-aft or athwartships position. When the emergency which caused the requirement for the additional generating capacity has passed, some owners have elected to leave the container as a permanent part of the vessel's equipment, and some have removed it to maintain it as a depot spare against a similar eventuality on other ships.

An air transportable version of the containerised generator has also been constructed for military use as portable shore power for warships, in which the fuel tank, air inlet/lube oil cooler module and exhaust stack are also containerised. This second container rides 'piggy-back' on the first in operation, but in transit is removed and separately loaded into the transport aircraft.

There are twelve containerised 1000 to 1400 KW sets in service. The containerised concept has been extended to inert gas systems to enable the generator/inert gas system to be retrofitted on existing ships, the fitting out and commissioning if necessary being carried out at sea with minimum interruption to the vessel's operation. In addition to the containerised generator set, the afterburner/cooling tower is also enclosed in a second package for mounting on deck in a convenient location.

Gas Turbo-electric Cargo Pump System in Tankers

The power required for the discharge of cargo in any type of tanker is a good example of the peaky auxiliary power requirement profile to which the auxiliary gas turbine concept can very profitably be applied. The product carrier, which may be involved in several small parcel cargo discharges at relatively short intervals, is a particular case in point. Furthermore, the conventional steam turbine driven cargo pumping system suffers from the disadvantages that it:

a) is relatively costly in terms of fuel
b) requires an extensive boiler and low pressure steam system, which is a source of maintenance load.
c) requires considerable preparation by ship's staff prior to and after each cargo discharge (flashing up, warming through, draining etc).

In a group of three 30,000 TDW products carriers, the last of which is nearing completion, the alternative installation of the type shown in figure 11 has been adopted, utilizing electrically driven cargo pumps, supplied by two gas turbogenerators mounted abaft the funnel.

The normal operation for cargo discharge of such a system is as follows:

a) ship's harbour load is carried by the diesel generator.
b) the two gas turbogenerators are started remotely, from the cargo discharge control room. These two generators are run in parallel but isolated from the normal ship's distribution system, and are available for full load approximately 60 seconds after initiation of the start procedure.
c) the cargo pumps are started in turn as required from the cargo discharge control room.

A variety of electrical arrangements are feasible for such an installation, including standard low voltage or high voltage transmission with transformers, and covering direct on-line starting or phased starting. The simplest arrangement, involving the minimum additional equipment, and no additional expertise on the part of the operating staff, is a standard low voltage system with direct on-line cargo pump motor starting, and this is perfectly feasible on, for instance, the 30,000 ton products carrier chosen as an example. The cargo pump motors are of the order of 650 KW each, and the voltage drop and frequency dip which occur when starting each cargo pump is not experienced by the ship's electrical system and is within acceptable limits. The one operational mode in which the gas turbogenerators and the ship's system are connected when cargo pumping is when the Harbour Diesel is out of commission. In such circumstances, provided only 3 out of the 4 cargo pumps are used, the voltage and frequency variations, which are experienced by the ship's system, are within Classification Society requirements, and this is largely attributable to the single shaft configuration of the gas turbine which provides for good load response.

The gas turbo-electric cargo pumping system, when compared with the conventional steam system, can be shown to be:

a) at least competitive on capital and installation costs, the extent of steam raising plant required for cargo heating often being the deciding factor.
b) lighter and less bulky
c) simpler to operate and maintain
d) less costly to run. Savings of the order of 30% are feasible even when account is taken of the cost per ton differential between residual fuel and Class B diesel.

Gas Turbine Driven Pumps for Offshore Service

Considerable attention has recently been focussed in the offshore oil industry on the provision of an adequate firefighting capability on board supply, standby, service or support vessels to augment, or in an emergency replace,the on-platform fire protection system. The primary requirement is for very large quantities of water capable of being projected to a sufficient height and distance to reach the platform from sea level. On vessels of restricted size, the provision of powerful pumping capability for an emergency duty, utilising equipment which will interfere with the day-to-day work of the vessel as little as possible, is a tailor-made application for the gas turbine.

Figure 12 shows the general arrangement of a gas turbine driven fire pump capable of pumping 4000 m^3/hr, of water at a discharge pressure of 110 metres W.G. This can be utilised in remotely controlled monitors to project jets 50 metres high to distances of 150 metres. Variations in the pump can of course produce different combinations of quantity and pressure and consequently of height and range of jet.

Gas turbine driven pump sets of this type are at present in service in the North Sea and have already been instrumental in the control and extinguishing of two platform fires. With a skid-mounted pump set unit weight of approximately 7.5 tonnes and an overall length of 4.16 metres, the application of the gas turbine in this type of vessel offers an effective solution to the problems of:

high power, small size and weight,
high starting reliability, even in intermittent use, with limited maintenance.

SERVICE EXPERIENCE AND DESIGN MODIFICATIONS

The peak-lopping, emergency, or standby nature of the duties for which the marine auxiliary gas turbine described in this paper has been employed results in the machines accumulating running hours in service at only a modest rate, with a relatively high number of starts: hence the ratio of 4670 hours operation and 1650 starts accumulated by late July 1976 by one of the sets delivered in late 1973 is not uncommon.

It is in the industrial and oil and gas applications of the machine that higher utilisation has occurred. One base load machine installed in 1972 had run 23200 hours by late 1976. Hence it is installations such as this that show up areas requiring design modifications.

A continual programme of improvement to increase the reliability and output of the turbine has been carried out. The basic rotor, the bearing system, and the reduction gear has remained unchanged, however. Improvements which have been made include:

a) combustion chamber and nozzle design development to enable some of the more difficult fuels encountered in service to be burned satisfactorily. These fuels had caused coking and hard carbon formation due to lack of fuel cleanliness or the contamination of the fuel with heavier fractions.

b) increasing the turbine volute thickness and altering the volute material from Nimonic 75 to Hastalloy X to cope with the higher inlet temperatures as the turbine rating was increased. The method of supporting the volute was also improved, based on service experience.

c) introduction of modest air cooling of the turbine nozzles and the turbine shroud to maintain the low metal temperatures which are so important even when the best cobalt based alloys are used. The shroud material was changed from FV Crown Max to Haynes 188.

d) introduction of sacrificial anti-corrosion coatings in the compressor and inducer, since experience has shown that good stainless materials like FV520 and 17-4Pn require such protection in a marine environment.

e) modification of the control system in the light of experience to provide greater reliability and improved ability to withstand adverse environmental conditions such as vibration and humidity. Modifications include utilising lubricating oil instead of fuel as the working medium, and the introduction of hermetically sealed plug-in relays,and the resultant control system underwent stringent environmental, vibration and reliability testing.

FUTURE PROSPECTS

For the Development of the Marine Auxiliary Gas Turbine

For an engine of the type described in this paper, the general aims for further development are self evident, namely, continued component and system development to further increase reliability and life. More specifically, research into the burning of lower grades of fuel continues. The engine is capable of burning even crude now, but the aim of the research is to reach the point, for successively lower grades of fuel, where the combination of any fuel treatment necessary together with the rating at which the turbine can be operated for extended life represent an economical proposition. For the majority of marine applications of this engine, however, the case for burning lower grade fuels is harder to make, since the peak lopping or emergency nature of the duty militate against the provision of an off-engine fuel treatment system, which may be used only for short periods. The initial acceptance of the radial gas turbine by shipowners, and by operators in other fields, together with the initial operational experience, has been such that there is a good case for extending the concept to other power ranges. Consequently, in 1976/77 the first engines of two further gas turbine types will enter service. These engines:

- the Viking 831 at 600 - 700 h.p. which is adaptation of an industrial gas turbine which has been in service for 13 years
- the KG-5 at 3800 - 4500 h.p. which is a newly designed machine similar in concept to the KG-2.

are generally similar to the KG-2 described in this paper in design philosophy, construction and intended utilisation.

For Further Applications of the Marine Auxiliary Gas Turbine

Application of the new gas turbines referred to above in the fields in which the 2100 h.p. engine has already proved successful is an obvious prospect. In particular, the smaller engine, with a nominal 500 KW rating, brings the possibility of marine auxiliary gas turbine to a whole range of ship sizes for whom the 1000 to 1400 KW machine is too large. In particular, an attractive concept is the containerised 500 KW gas turbo generator set, approximately 4 metres long, for use by fleet owners as a depot spare for transportation by air to any ship in trouble.

There are, however, a number of feasible applications of the established machine which further illustrate the wide variety of installation types to which the marine auxiliary gas turbine can effectively be applied.

a) Advantage can be taken of the characteristics of the exhaust gases of the radial gas turbine
- quantity (13 Kg/sec for a 2100 h.p. gas turbine)
- temperature (550°C approx. at full power)
- oxygen content (15 to 16% by volume)

Considerable promise is shown by the concept of utilising the gas turbine as a combined turbogenerator and air heater/forced draught fan for the boiler installation on a steamship particularly if coupled with the gas turbines' gas burning capabilities on an L.N.G. carrier as referred to in (b) below. (see figure 13). The gas turbine can operate as a conventional standby generator, exhaust

-ing direct to atmosphere. Alternatively under normal full power operation at sea, the exhaust gases are used to augment or replace the combustion air supplied to the boiler, while the gas turbogenerator is still capable of acting as one of the vessel's main generators, at a modestly reduced output due to the increased back pressure from the boiler combustion system. The advantages of the system over a conventional arrangement are:

i) fuel economy: detailed independent heat balance evaluations show prospective fuel economies of the order of 3%.

ii) reduction in equipment, or equipment complexity. The utilisation of the gas turbogenerator for combustion air heating and circulation allows the reduction in size or elimination of the air preheater, if fitted, and the forced draught fan.

b) The 2100 h.p. gas turbine described in this paper has, in its industrial and oil-and-gas applications, achieved considerable successful experience running on various grades and types of natural gas. A marine gas turbogenerator is already at sea fitted with a dual fuel system capable of burning either diesel or natural gas fuel, and the application of this capability in L.N.G. and L.P.G. vessels will be readily apparent. The following are attractive possibilities:

   i) dual fuel gas turbogenerator for standby or base load generation capable of burningcargo boil-off.

   ii) as in (i) but with the additional capability of utilising the gas turbine exhaust in an inert gas plant.

   iii) as in (i), but in this case utilising the exhaust gas as the combustion air supply to the vessel's boilers, as described in (a) above.

c) When, and indeed if, the demand for V.L.C.C. and U.L.C.C. vessels revives, there are attractive possibilities in the extension of the gas turbo-electric cargo pumping arrangements described for a products carrier earlier in this paper. This extension may well include the combination of electrically driven and direct gas turbine driven pumps.

CONCLUSIONS

The marine auxiliary radial gas turbine offers a viable solution to installation design problems requiring a prime mover with high power-to-weight and power-to-volume ratios, good reliability and low maintenance requirements, with particular emphasis on peak lopping, standby and emergency applications.

Initial operating experience has justified the application of the research and development effort which has been and is being expended, and indicates that there should be a continuing and expanding requirement for this type of prime mover.

ACKNOWLEDGEMENTS

The author wishes to thank members of the staff of Kongsberg Ltd, and of the Gas Turbine and Power Systems Division of the parent company, A/S Kongsberg Vaapenfabrikk, Norway, for their assistance in the preparation of this paper.

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APPENDIX I

Some figures relating to the 2100 H.P. gas turbine

Performance: 2100 h.p. - I.S.O. Standard condition - 15°C ambient

Compressor: pressure ratio across compressor and diffuser assembly 4:1

: air mass flow at normal full power 13 Kg/sec (22400 c.f.m.)

Turbine : normal turbine rotor speed 18000 r.p.m.

Standard reduction gear outputs 1500 r.p.m.
1800 r.p.m.

Governing : electrical generation; typical performance:
Steady state frequency $\pm$ 0.25%
Transient frequency (full load application or shedding) $\pm$ 1%
Recovery to steady state 4 seconds

Fuel system :
1) (Liquid fuel) suction filter size 40 micron
High pressure filter 10 micron
Max. pressure 70 Kp/cm^2
Minimum pressur at inlet to on engine system - 1m W.G.
Max. pressure 15m W.G.
Fuel valve limiter type: Woodward 1907
Actuator type: Woodward EG3P
Fuel consumption at full load : 8 x 10^6 Kcal/hr. ± 5%
2) Other options: gaseous fuel system.
: dual fuel system

Lube oil system : main pump capacity 185 1/min at 13.5 Kp/cm^2
Aux. pump capacity 60 1/min at 2 Kp/cm^2
Main filter size 5 microns
Lube oil tank volume: 320 litre

Start system :
1) compressed air: consumption per start 25 Nm^3 minimum starting air pressure 7 Kp/cm^2
2) A.C. electric motor, motor rating 50 KW
3) Other options: D.C. electric, (petrol engine).

APPENDIX II

Materials of Construction of 2100 H.P. radial gas turbine

Inlet housing : Welded steel construction - aluminium coated

Compressor cover : Salt water resistant aluminium alloy casting

Diffuser : The blade segments are precision cast in aluminium broze alloy. The rear support plate is machined from steel. The forward support plate is nodular cast iron. The support plates are surface treated with a corrosion resistant coating.

Plate diffuser : Fabricated from 1.5 mm steel blades - aluminium coated.

Turbine casing : Welded steel construction - aluminium coated.

Combustion chamber : Consists of a flame tube and a combustor head. Welded heat resistant nickel base alloy. NIMONIC 75.

Volute : Welded fabrication in heat resistant nickel base alloy: HASTELOY X.

Turbine housing assembly : This is a bolted assembly of the following components:
- front nozzle ring
- nozzle guide vanes
- cooling segments
- turbine housing

The front nozzle ring is machined from a centricasting in F.V. HR CROWN MAX material. This is a high temperature chrome nickel alloy steel.

The turbine nozzle guide vanes are precision cut from cobalt-base alloy : X40 (HS31).
The cooling segments are precision cast from F.V. HR CROWN MAX material.

The turbine housing is manufactured as one part from either a centricasting in NIMOCAST PE-10 or from HAYNES 188 Hydroformed welded plate.

The complete turbine housing assembly is secured by means of NIMONIC 90 bolts and Waspaloy nuts.

Compressor seal plate : Machined steel plate with a corrosion resistant coating. Three compressor seal rings on the front face.

Heat shield : 7 segments of high temperature chrome nickel alloy steel: F.V. HR CROWN MAX (type 309) machined from a centricasting.

Exhaust casing and diffusor : Made of heat resistant stainless steel.

Compressor inducer wheel : Precision cast 13% chromium - cobalt steel

Impeller : Machined F.V. 520 (B) chromium - molybdenum steel

Turbine wheel ; Machined by EDM and milling process, chromium-cobalt nickel 'WASPALOY'

Exducer wheel : Precision cast alloy 713 LC

Rotor clamp bolts and pressure rings : Machined from forgings in nickel base alloy NIMONIC 90

APPENDIX III

Gas Turbine Control and Monitoring System

The 24 V DC control system functions primarily to sequence operating systems during start/stop and normal operation; to provide necessary protection during all phases of operation, and to provide indication of critical parameters during operation.

During normal operation alarm, without shutdown, is given when there is:

- increasing vibration level
- increasing lube oil temperature
- increasing exhaust temperature
- decreasing lube oil pressure
- pick-up failures

To ensure protection of the turbine, shutdown will occur when there is:

- overspeed
- low lube oil pressure
- high lube oil temperature
- high exhaust temperature *
- flame-out
- high vibration level *
- low lube oil reservoir level *
- pick-up failures *

* not for emergency sets.

The sequencing system controls the turbine during start/stop and normal operation by measurement of overspeed, vibration and exhaust temperature. The measurements are compared with pre-set reference values, which represent alarm limits. When alarm limits are exceeded, this is shown by a first out indication on the front of the control panel.

This light will indicate the cause of the alarm. The system is based on relays for ease of maintenance. The relays are hermetically sealed and of plug-in type.

Printed circuits are used in the monitoring system and a testcard can be inserted for testing/simulating purposes.

The following three parameters are electronically monitored:

a) Speed: magnetic pick-ups for speed sensing are fitted at the end of the turbine rotor. The system has two independent circuits, each with separate speed pick-ups.

b) Vibration: the sensor is an accelerometer, built into the end of the rotor bearing housing and signals for alarm, shut-down, system failure and indication are provided.

c) Exhaust gas temperature: thermocouples are fitted in the exhaust outlet, for sensing the exhaust gas temperature, and signals for alarm, shut-down, light up, system failure and indication are obtained.

Lube oil temperature is monitored by two switches, one for alarm and one for shut-down. These switches are fitted into the lube oil inlet line, up-stream of the turbine bearings. Lube oil pressure is monitored by means of three switches, which ensure correct oil pressure in the system before starting and also correct operation of alarm and shutdown signals. Lube oil level is monitored by a level detector which is situated in the lube oil reservoir, and which provides the signal for alarm or shutdown when the oil level is too low.

In addition to the Woodward governor the fuel system has double shut-off valves operating independently to protect against overspeed and the lube system has continuous lube oil pressure level and temperature monitoring.

The lube and start systems are interlocked to prevent start before the auxiliary lube pump has built up pressure.

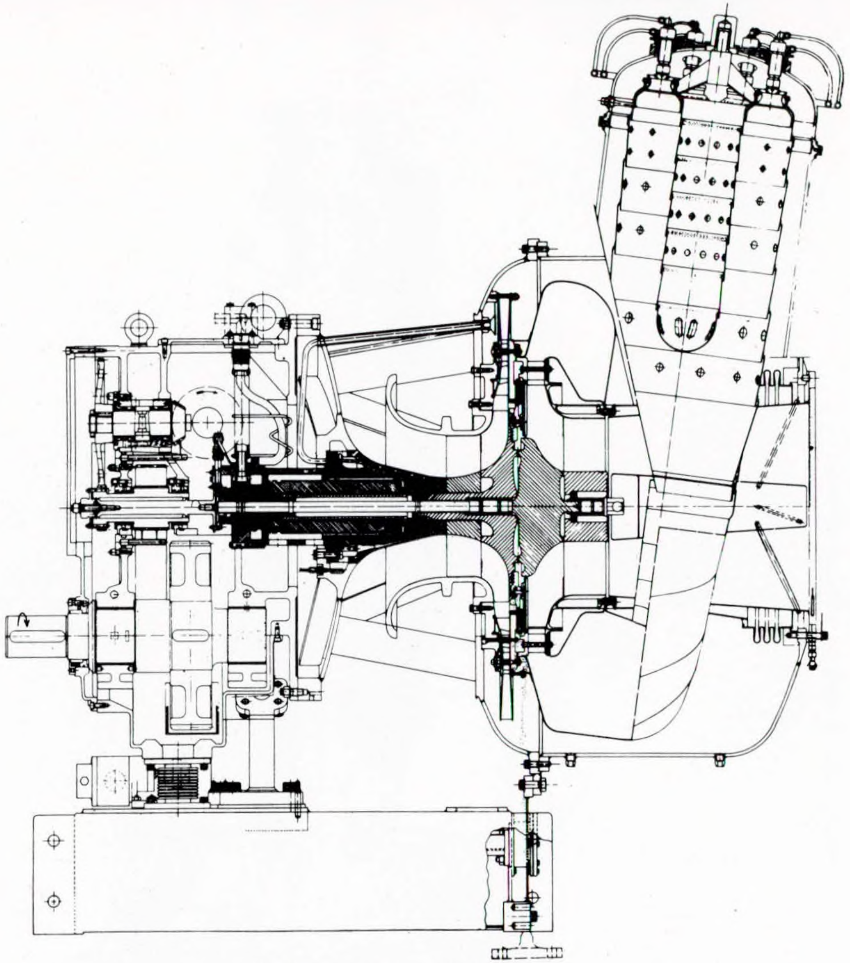


Fig. 1 — Cross-section of KG2-3 engine

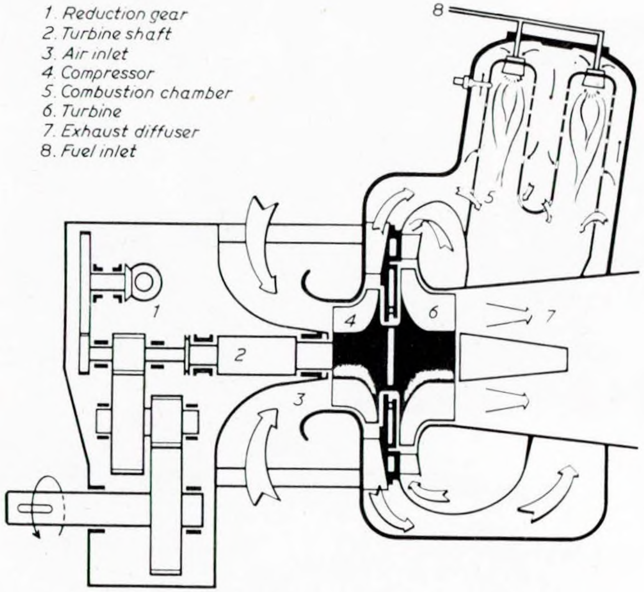


Fig. 2 — Principle of operation of 2100 hp all-radial gas turbine (Kongsberg KG-2)

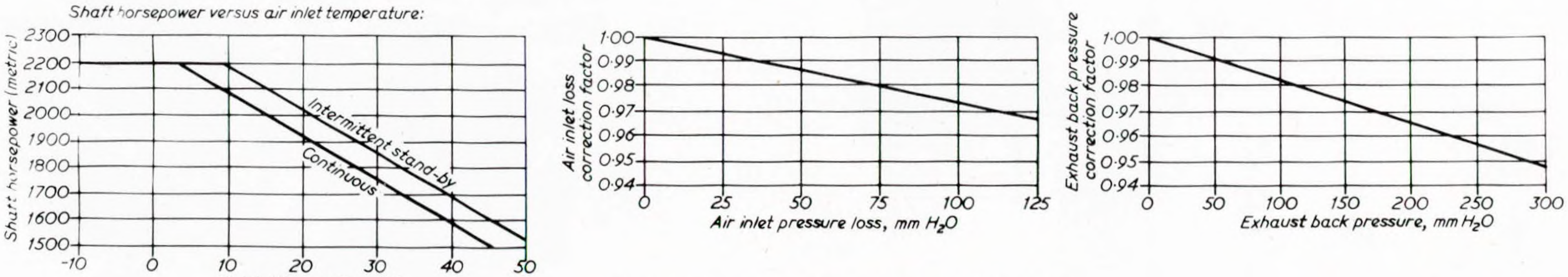


Fig. 3 — KG2-3 engine performance and correction factors

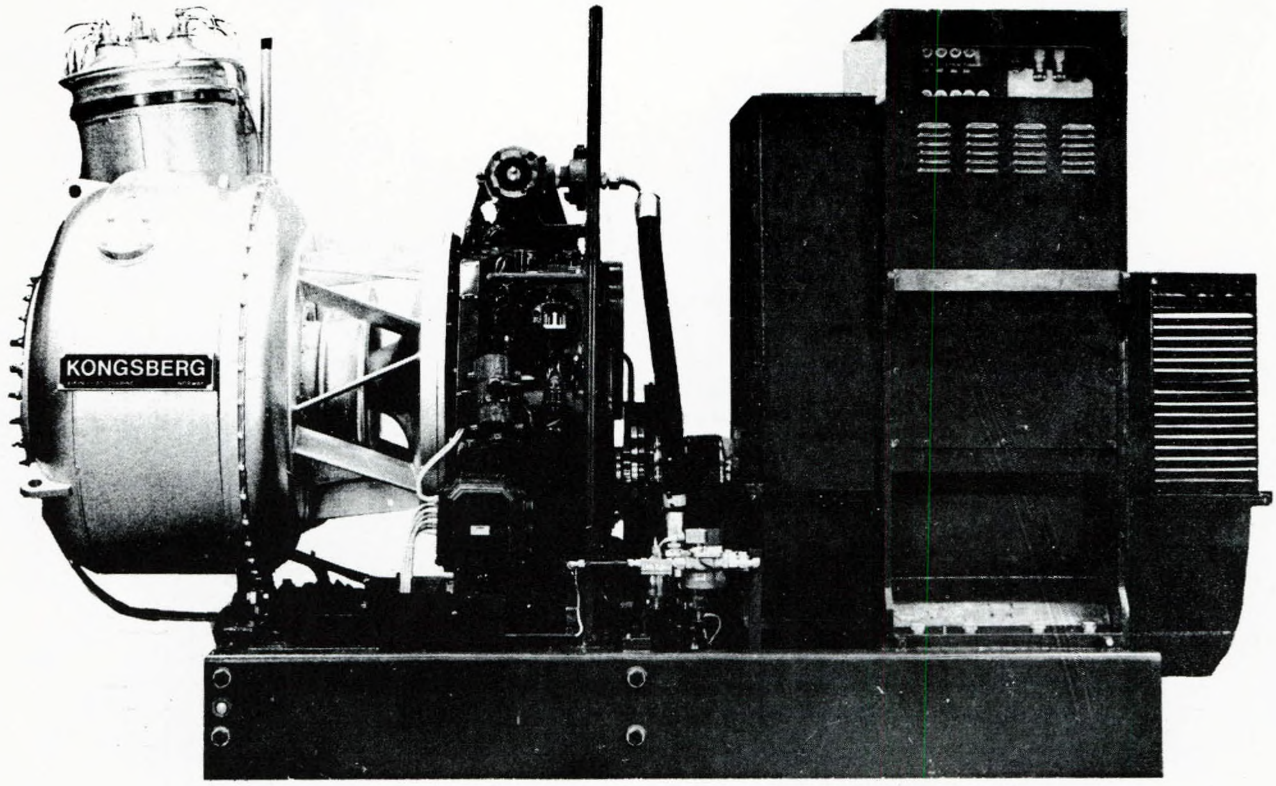


Fig. 4—External view of KG2-3 engine with generator

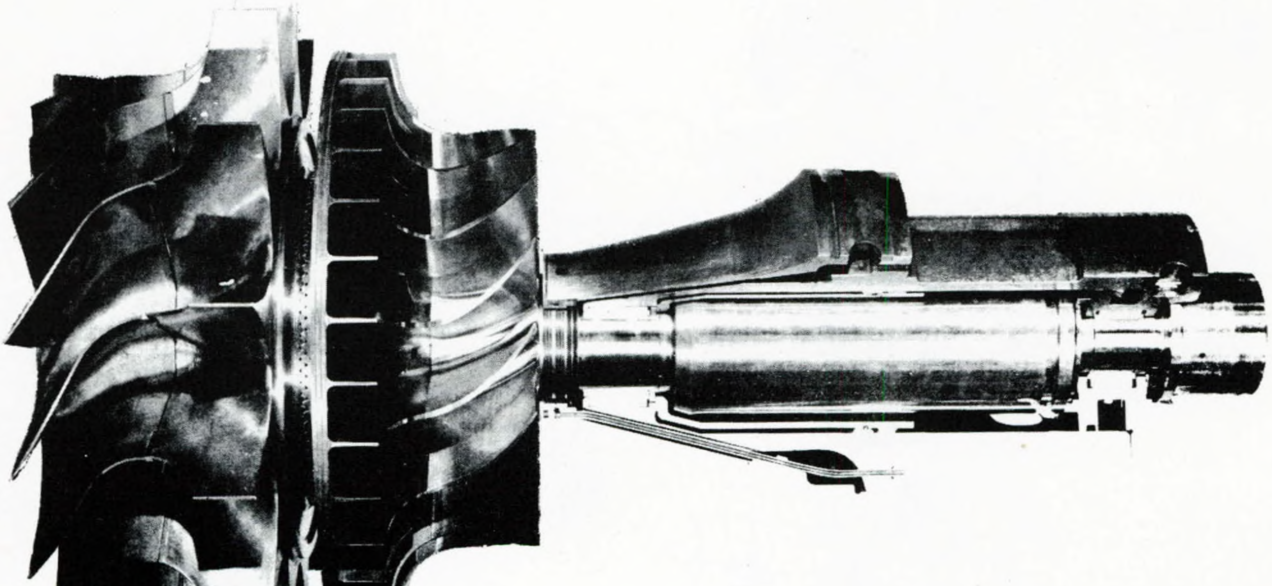
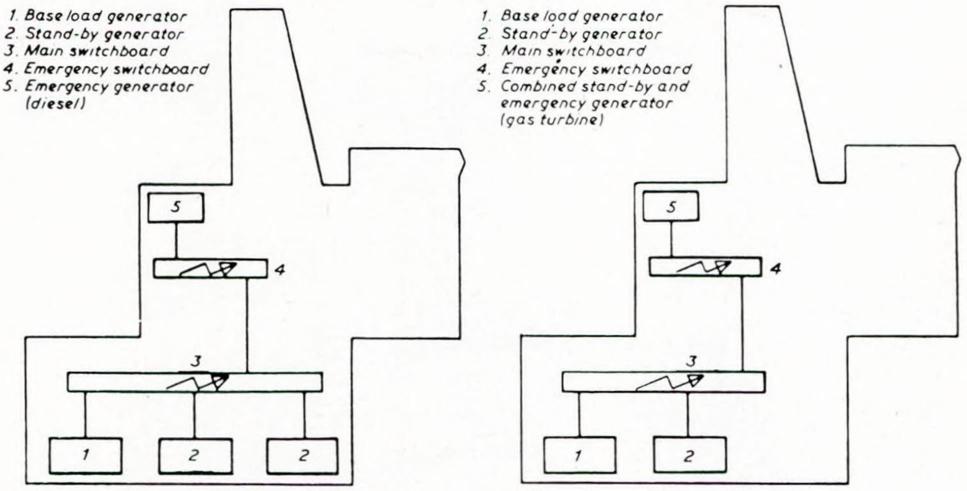


Fig.5—KG2-3 rotor



(a) (b)

Fig.6—Generator arrangement for large tanker with (a) diesel generators (b) diesel generators and gas turbo-alternators

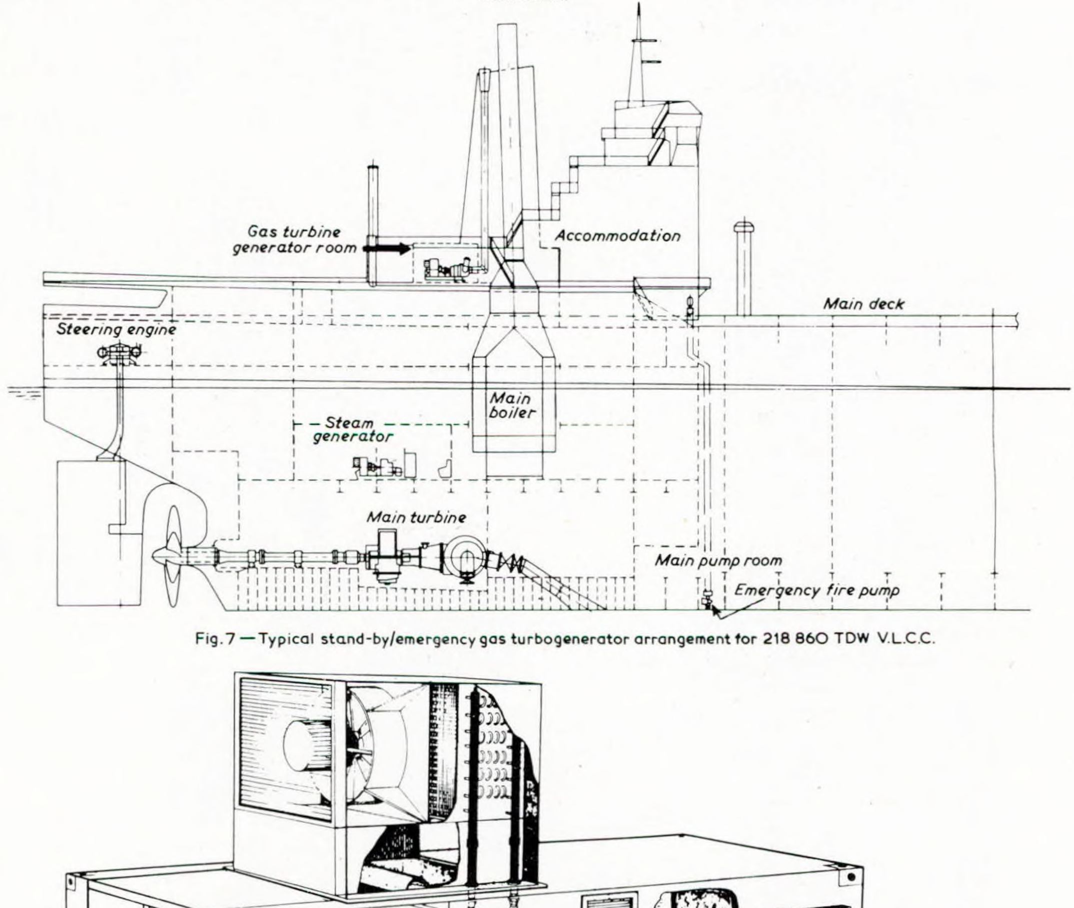


Fig.7—Typical stand-by/emergency gas turbogenerator arrangement for 218 860 TDW V.L.C.C.

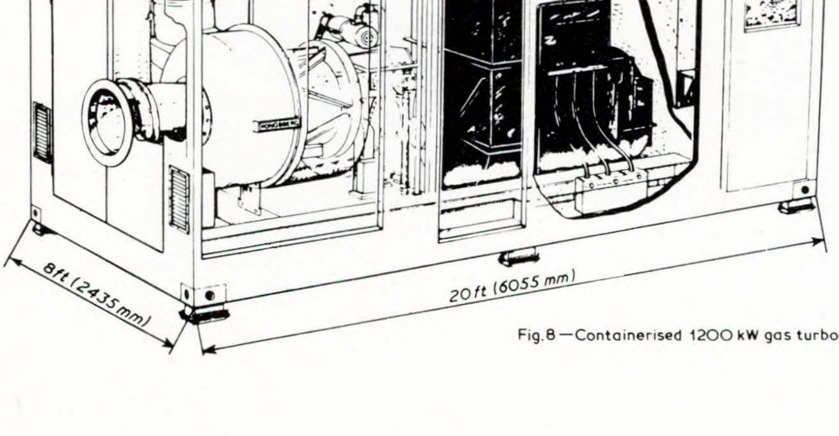


Fig.8—Containerised 1200 kW gas turbogenerator

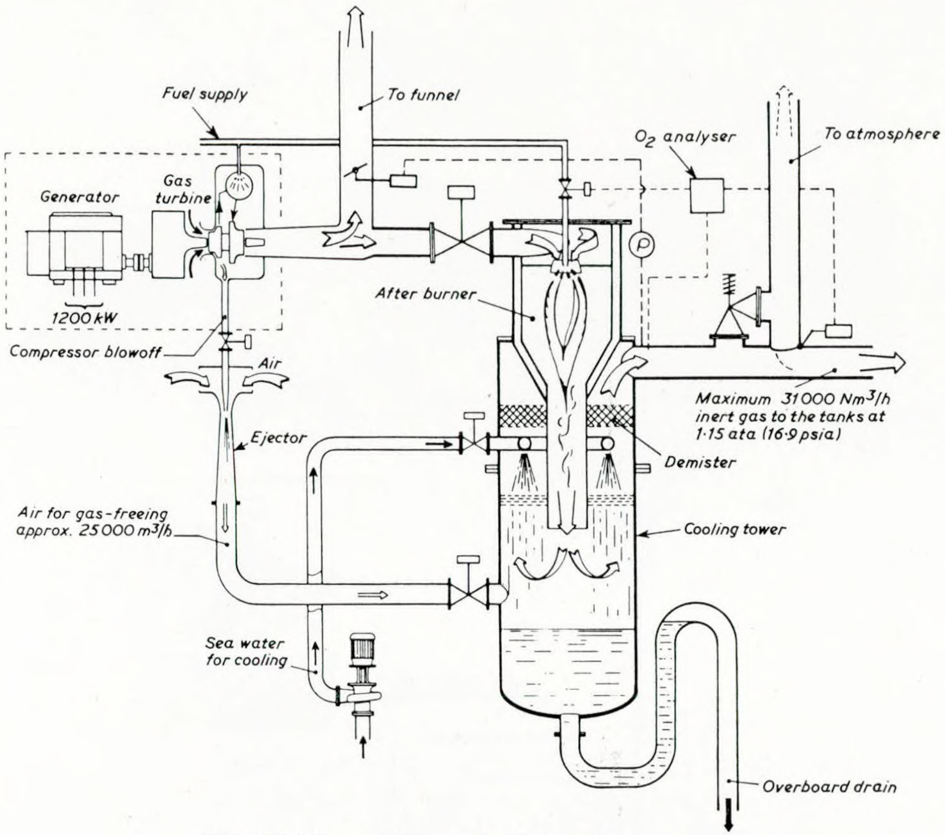


Fig. 9 — Principle of gas turbine generator/inert gas plant

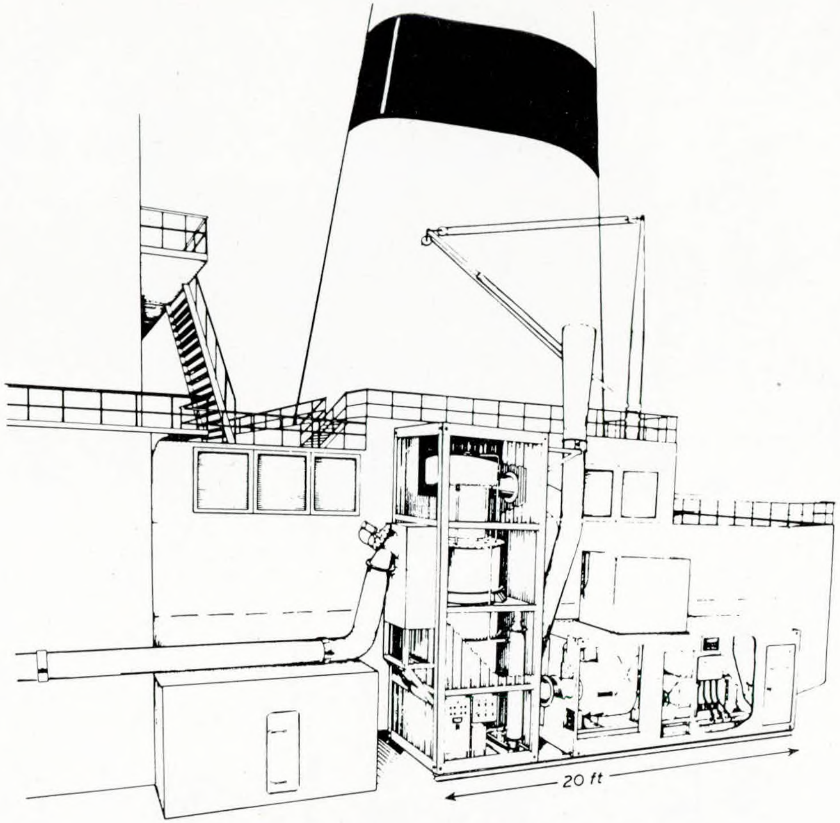
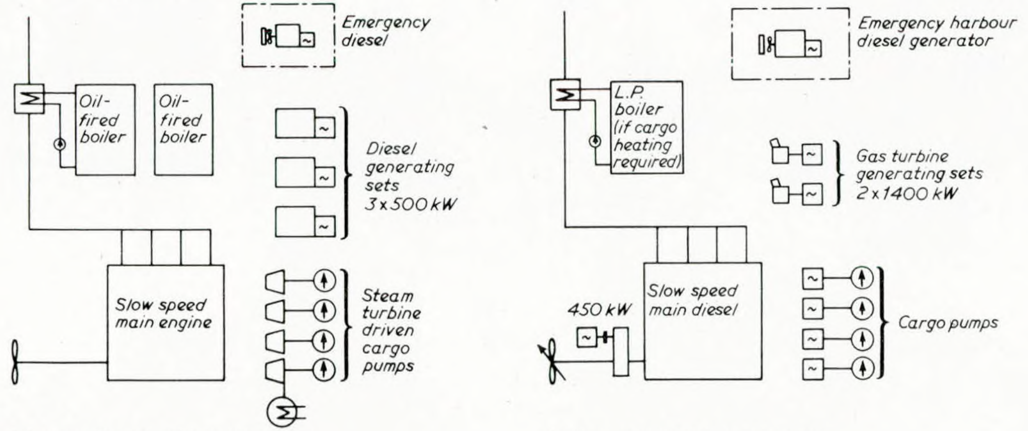


Fig. 10 — Containerised gas turbogenerator and inert gas plant



(a) Steam turbine driven cargo pumps *(b) Gas turboelectric cargo pumps*

Fig. 11 — Alternative arrangements for cargo pumping system for 30 000 TDW products carrier

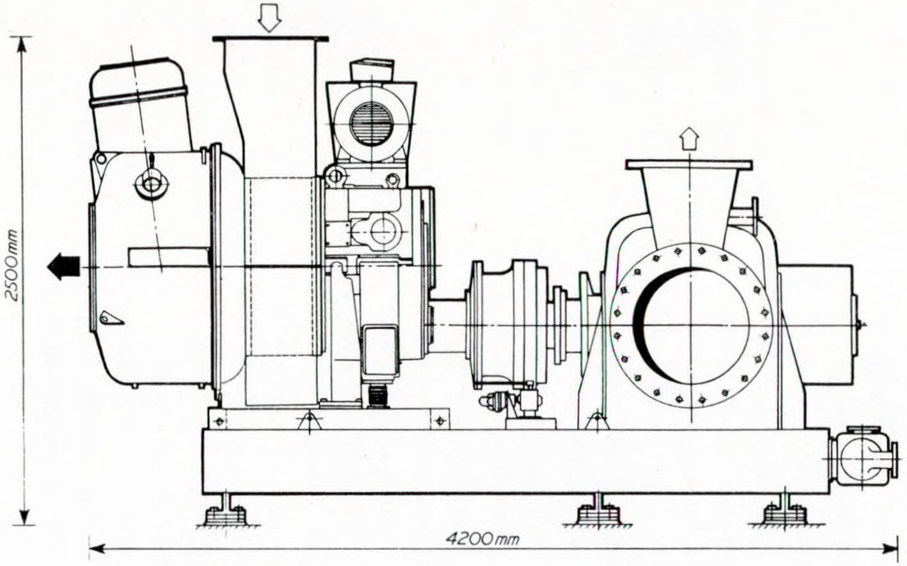


Fig. 12—Gas turbine driven fire pump 4000 m³/hr at 110 metres W.G.

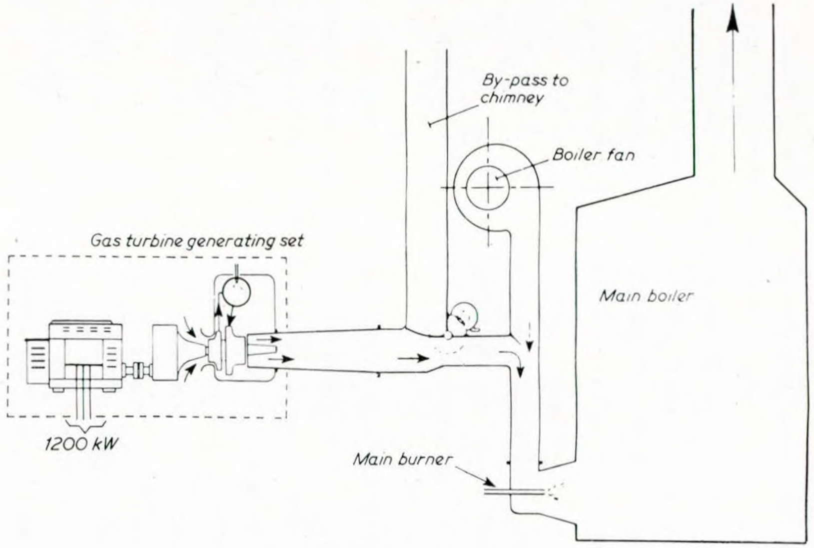


Fig. 13—Gas turbine as generator drive and boiler air heater and forced draught fan

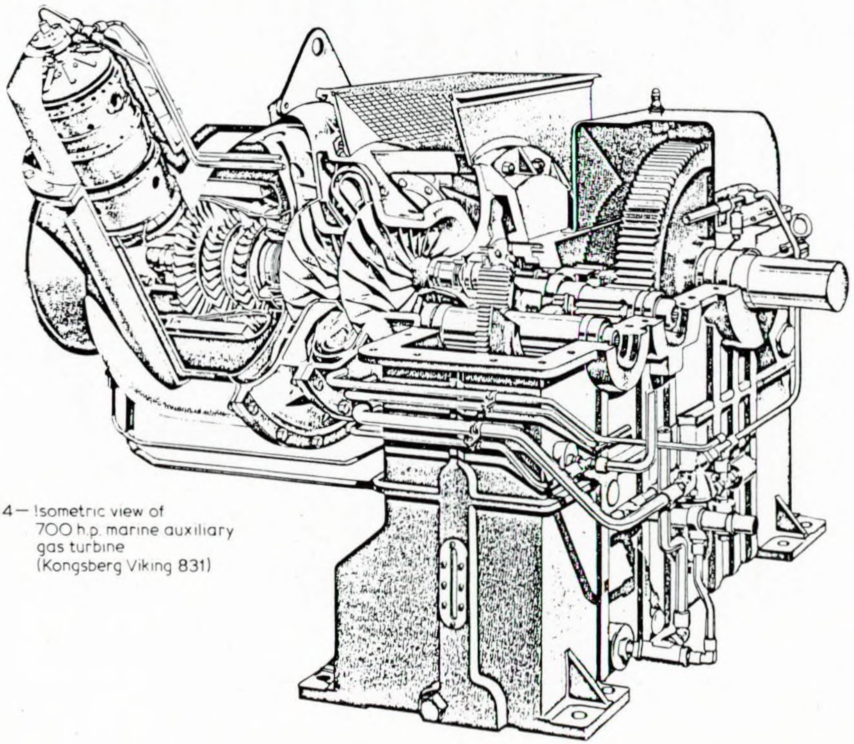
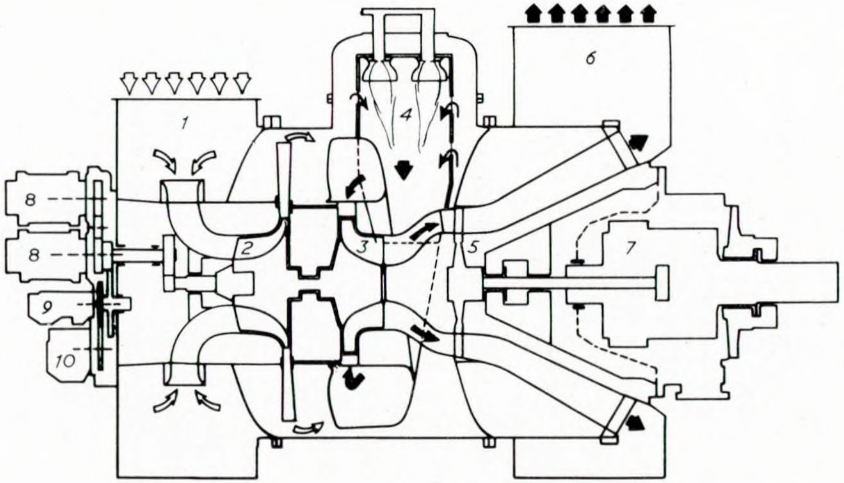


Fig. 14—Isometric view of 700 h.p. marine auxiliary gas turbine (Kongsberg Viking 831)



1. Air intake 3. Gas generator turbine 5. Power turbine 7. Reduction gear
2. Compressor 4. Combustor 6. Exhaust outlet 8. Starter motors
9. Fuel pump 10. Lub. oil pump

Fig. 15—Principles of operation of 4000 h.p. marine auxiliary gas turbine (Kongsberg KG-5)

DISCUSSION

MR. E.W. ARMSTRONG said that a good account had been given of the concept, design and application of a class of engine designed from the outset to cope with a marine environment. Regarding applications, the paper had brought out the importance of seeking market opportunities where the particular attributes offered by the gas turbine, i.e. compactness, rapid and reliable starting, air bleed capability, etc, would be of maximum value. However, he would like to have heard more about the costs associated with this form of powerplant, in relation to alternative solutions such as diesels. It was well known that one of the problems of the gas turbine in the smaller size range was that of achieving a competitive first cost. A typical small gas turbine would also have had a considerably higher fuel consumption than a diesel engine. Alternatively the attributes to which he had just referred, could be important in off-setting these disadvantages. Would the author discuss this question of the balance of costs further ?

The paper was essentially concerned with the commercial field, where the use of gas turbines as the main propulsion units of merchant ships had so far been very limited. By contrast, in many navies the gas turbine was increasingly used for main propulsion, although it appeared not to be spreading as quickly as an auxiliary powerplant. Therefore, what were the author's views on the prospects for gas turbines for auxiliary duties in naval applications ?

Correspondence

MR. C.J. LINNELL said that the author had provided an interesting and valuable paper for reference on the use of gas turbines as marine auxiliaries.

However, the writer thought it must be remarked that this was not a complete summary of the state of the art on marine or industrial gas turbines, nor the only method of achieving the required result for the application engineering. As this paper should be read by all the marine engineering fraternity, the writer would appreciate the author's comments so as to allow for a more balanced comparison of the excellent virtues and capabilities of gas turbines versus any other method of creating rotary power.

The many other types of simple cycle gas turbines, other than the radial gas turbine, seemed to have been given poor coverage. From the author's assumptions that the KG2 and KF5 were purpose built for the aforementioned applications, Mr. Linnell found the appearance of the Viking 831 Combined Centrifugal (radial) axial unit, somewhat out of place, if any validity could be attached to the previous assumptions. Given that there was validity for this machine, and therefore for other methods of constructing gas turbines, would the author comment on them ?

Further to the author's noted existence of units of 500 h.p, 2100 h.p. and 45 000 h.p. there had been and still were a large number of other powers, both below and between the aforementioned, available should any engineer require them. Whilst it could be controlled more precisely than vice-versa, what were the author's comments concerning the introduction of complexities such as clutches, into a single shaft machine, in applications of high torque starting loads, i.e. fire pumps ?

Whilst the three sizes of gas turbines were recorded, would the author comment on the use of more than one turbine into a gearbox to provide the required single shaft output power/rev/min the effect on the efficiency of such a system in the area appertaining to fuel consumption and control. Would there be a possibility of partial versus full machine downtime for service/redundancy ? Would the author compare radial versus axial turbine, overall thermal efficiency ?

Regarding future development, while the burning of lower grade fuels could be an apparent cost benefit on the fuel side, what was the resulting service life and overhaul cost in comparison with that of a machine run on a higher grade, distillate fuel ? Could the author give his views on the future development for the marine industry of a compact, high overall thermal efficiency, low maintenance, low initial cost, high reliability, rotary power source ?

CDR. P.W.W. RIDLEY, M.I.Mar.E, said that electrical generators in the Royal Navy were peculiar, in that they were sized to absorb essential electrical loads, thrown over in the event of the loss of another of the ship's generators. Under normal conditions, generators were run at 60 per cent or less; a situation in which the specific fuel consumption of all but the most highly complex cycle gas turbines compared poorly with those of equivalent diesel engines. Calculations for operations in a typical Royal Navy frigate showed that annual fuel consumption for electrical generation would double at least if a change was made from diesels to any of the simple, marine auxiliary, gas turbines at present available. Nothing in the paper refuted this argument.

Of course the s.f.c. characteristics could be greatly improved by the adoption of a complex cycle such as a combined gas turbine and waste heat supplied steam turbo alternator. However, the Royal Navy's view was that such plants as might be suitable for its purpose required considerable development before the penalties of increased complexity and maintenance, coupled with reduced reliability, would make them competitive with diesels of similar specific fuel consumption. In an age where balances always had to be struck, and those in a warship were more intricate than most, the overriding attraction of the gas turbine appeared to lie in its fundamental simplicity. Compromising this simplicity only served to weaken the case for the gas turbine itself. Nevertheless, the R.N. continued to monitor developments in the field of auxiliary marine gas turbines and would certainly investigate any promising new design.

AUTHOR'S REPLY

In thanking Mr. Armstrong for his contribution, the author agreed that the comparative costing of the competing diesel and gas turbine auxiliary systems was very important in any evaluation of the feasibility of either system for merchant marine installations. A generalized direct comparison between the capital costs of the two prime movers was not easy since:

a) for the gas turbine, until it was more widely accepted as an auxiliary prime mover, the number of frame sizes of machine was limited. Hence the capital cost of the installation, if expressed as a £'s/horse power figure, would be radically affected by whether the particular power being considered fell on or near a specific gas turbine frame size;

b) for the diesel, the capital cost of the engine would be radically affected by the type and, more particularly, by the rated speed of the diesel being used in the comparison.

As a very broad generalization, if comparing a specific frame size of gas turbine with the equivalents in a variety of diesel engine types, the gas turbine in terms of capital costs was about equal to a medium speed diesel generator drive, cheaper than a slow speed and more expensive than a small high speed machine.

However, as Mr. Armstrong suggested the direct comparison of capital costs alone was not strictly relevant, as it was the through-costing of the installation over the operating life of the vessel which was important, covering as it did the capital, the installation, the operation and maintenance costs for the system. Nor was it simply a question of comparing a diesel driven auxiliary system with the same system in which the diesel had been substituted by the gas turbine: to take full advantage of the particular attributes of either type of prime mover would probably require re-design of the whole auxiliary system. It was, therefore, important to ensure that the whole system costs were compared. The fact remained that, with reference to the specific 2100 h.p. gas turbine which had been considered in the paper, no shipowner chose the gas turbine in the 100 plus installations for which it had been selected because he had an altruistic desire to be a technical innovator. For each installation which represented a new type of installation for that gas turbine, an economic evaluation was carried out to identify the financial advantages and ensure that the chosen system maximized these. The author would be happy to discuss any of these studies, suitably disguised to preserve commercial confidentiality, with Mr. Armstrong or any other interested engineer. Part of the problem of providing a generalised comparison was that one of the important factors influencing the overall costs was the cost of installation, covering the labour and facilities involved in lifting and positioning the equipment, the weight and costs of the supporting structure, and the care and time involved in alignment. Although clearly less expensive for the gas turbine, estimates from shipyards and repair yards for the costs of labour and material involved did vary very widely.

With reference to Mr. Armstrong's query about naval auxiliary gas turbines, the author was indebted to Cdr. Ridley for his clear and concise statement of current R.N. policy regarding the feasibility of gas turbogenerators in warships. The following points were, the author believed, relevant background:

a) The R.N. had had perhaps more experience than anyone else in the operation of marine gas turbogenerators, before abandoning them in the current new classes of warships. Operating experience, bearing in mind the state of the art at the time of their installation, was, after some fairly extensive teething troubles had been overcome, quite successful, and they were ultimately popular with the operators themselves.

b) By rejecting gas turbogenerators in, for instance, the current group of new frigates (Type 42, Type 21 and Type 22) the R.N. were by no means following a universal trend. The US Navy, in the "Spruance" Class, and the Canadian Navy in the DDH 280, both utilized gas turbogenerators, with waste heat utilization for steam generation. It was the waste heat boiler which offered the simplest and most effective method of rendering the gas turbogenerator a very efficient machine. With specific reference to R.N. installations, however, there appeared to be a further problem in achieving a balance between steam demand and electrical power demand. To the best of the author's knowledge, in the various studies carried out for the R.N. of auxiliary prime mover waste heat utilization, diesel or gas turbine, it never proved possible to achieve a satisfactory compromise in recent projected installations, with the possible exception of HMS "Exmouth" where, perhaps significantly, a gas turbogenerator/waste heat boiler package was adopted.

c) It seemed clear that, with the exception of the "total energy" approach referred to above, there were two ways in which gas turbogenerators might once more find favour with the R.N. One was the discovery of an adaptation of the gas turbine which improved its s.f.c. without, as Cdr. Ridley had pointed out, compromising the basic advantage of simplicity. Investigation of various possibilities was a continuous activity including, in the case of the author's company, some studies in conjunction with MOD(N). It would be misleading to suggest an imminent breakthrough but progress was promising although some complication of the machine was inevitable. The second possibility for the re-introduction of gas turbogenerators is a re-appraisal of the warship electrical generation philosophy. The current arrangement had all generators arranged for either base load or standby duties, with no generators specifically designated as emergency. If the philosophy was revised to have certain generators designated as base load and others as emergency, action load, or standby, the adoption of compact and simple gas turbogenerators for the latter duty could

- reduce machinery space and weight requirements
- reduce maintenance load

without adversely affecting reliability and probably with an improvement in frequency/voltage control on sudden load variation.

With reference to Mr. Linnell's lengthy and valuable contribution, he had almost raised a sufficient number of points for a full reply to constitute a new paper to the Institute. The author was the first to agree that the paper was not a complete study of the state of the art of marine gas turbines, and that there were many other types of simple cycle gas turbines which could have been included although none, the author would suggest, that had found so extensive an application in specifically marine auxiliary installations as those covered in the paper.

The author appreciated Mr. Linnell's puzzlement, after reading the case made in the paper for radial gas turbines which were originally specifically designed for marine installations, in finding reference to a 500 kW gas turbine which was not entirely radial nor originally marine. The explanation was basically one of compromise: the author's company, in utilizing its main research and development resources on the 4500 h.p. machine to augment the 2100 h.p. machine, also had a need to achieve to a shorter timescale a 500 h.p. frame size. The adoption of an existing engine which had already achieved a very extensive record of running hours and reliability in a wide range of environments, and the application to this engine and its packaging of all the experience of the design and material selection acquired from other specifically marine engines and applications, was a swift way of achieving a marinized gas turbine in this power range. To this extent, the three stage axial turbine and a two stage radial compressor configuration was an already established fact. However, it was worth noting that, with reference to this particular configuration, the small size of the gas turbine itself, in relation to the reduction gear by which it was supported, resulted in any variation in length of the turbine, due to the selection of a radial or axial form for either the compressor or turbine having only a second order influence over the overall size of the turbine/gearbox prime mover package. The selection of a two stage radial compressor also illustrated the same point.

Obviously had either of these particular configurations been selected for the 2100 h.p. gas turbine, the size of which relative to its gearbox was considerably greater, the effect on unit size would have been correspondingly increased. As always, the process of design was a compromise, in this case between

- for the radial configuration, shorter machine length, more robust rotor construction, larger gas passages and,
- for the axial configuration, longer machine length;
- for multi-stage arrangement but probable better overall efficiency depending on the application.

The basic gas turbine design choice between single shaft or twin shaft (separate power turbine) construction was similarly a choice between the identifiable advantages of each option for specific applications, as witnessed by the decision by the author's company to design the new 4500 h.p. machine as either a single or twin shaft machine. The relative characteristics were:

for the single shaft machine, a high degree of output speed and power control, shorter engine, fewer bearings but virtually constant speed operation and low starting torque capability;

and for the two shaft machine, greater operational flexibility in terms of speed variation, power turbine output variation (e.g. stalled operation etc.) but more complex design arrangement and less immediate power output control.

With reference to Mr. Linnell's query regarding the use of more than one turbine in, for instance, a twin engine/single driven unit application, was of course a feasible proposition and had been employed with success. The advantages in terms of flexibility of operation and improved part load fuel consumption would be self-evident, since the fuel consumption of one 500 kW machine on full load in a 2 x 500 kW twin installation was obviously considerably better than a single 100 kW set at 50 per cent load. Although the system standby or redundancy capability of the twin engine set was no doubt theoretically better, the proven reliability of the single gas turbine set was high enough to make this gain a second order consideration.

It was not necessary of course to employ a gearbox to combine the outputs of the two machines. The author's company was building generator sets with twin 2100 h.p. gas turbine imputs to a single generator, in which the gas turbines, which were "handed", would drive into opposite ends of the generator.

With reference to the requested statement on the comparative efficiencies of axial and radial turbines: tests by the author's company and several published data confirmed that there was no significant difference in the design point efficiency of radical and axial turbines. The off-design efficiency characteristic of radial turbines matches the propeller load curve well, and offered in certain cases an advantage over the axial turbine. For other applications where linear characteristics were important (e.g. traction) the axial turbine characteristic was better suited.

The question of burning lower grade fuels revolved largely around the composition of the specific lower grade fuel and what proportion of the constituents were the ones most liable to have deleterious effects in the turbine. The gas turbines described in the paper were, in general, capable of burning almost any grade of fuel down to crude, by a combination of the provision of fuel treatment and the de-rating of the engine to maintain the cycle temperatures within the range acceptable with respect to that particular fuel composition. Once the nature of the fuel was known, the relevant ancillary system, de-rating, and operational regime to maintain reliable operation could be determined. However, in marine applications, it was not often that the additional costs represented by:

- the fuel treatment system
- the de-rating of the engine
- any additional compressor washing, or turbine maintenance periods

were counterbalanced by the saving in fuel costs, particularly in those many marine installations where the gas turbine was performing a peak lopping, standby, or emergency duty with correspondingly low annual running hours.

Mr. Linnell's listing in his last paragraph of the desirable characteristics for the future development of the marine gas turbine was an apt one, and it could be argued that among the gas turbines currently available there were several which achieved any two or three of these targets. In respect of the (predominently) radial machines described in the paper, for instance, they represent achievement of compactness, reliability, and low maintenance and, with increased acceptance and greater quantity production, would hopefully pass from their reasonable initial cost to the desired "low" rating. We were then left with the problem previously discussed and assiduously pursued, of improving the thermal efficiency without, by increasing complication, compromising any of the targets already achieved.

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