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The Forty-seventh Parsons Memorial Lecture

AERO-DERIVED MARINE AND INDUSTRIAL GAS TURBINES

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Aero-Derived Marine and Industrial Gas Turbines

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SYNOPSIS

The author traces the main influences which caused the gas turbine to begin replacing the piston engine in aircraft and the subsequent developments which have resulted in the virtual completion of this transition. Similarly, the main reasons are identified for the introduction of engines derived from aero gas turbines into the marine and industrial scenes. Some of the problems, encountered in adapting aero engines to meet the new requirements and withstand the harsher environments involved in providing power on land or at sea, are described together with the solutions. A number of typical power plants which resulted from this activity are illustrated. The escalation, relative to other commodities, in the cost of oil and other fuels which began nearly a decade ago has created new challenges for power plant suppliers and the resulting trends in gas turbine development are indicated. Finally, the author looks to the future and explains why aero-derived gas turbines will remain the best choice of prime-mover for certain duties and how new developments are likely to extend their use in some other areas.

INTRODUCTION

The concept of a better way of meeting a need is sometimes due to the inspired thinking of an inventor. However, in most cases, the basic principles involved are not novel, but the man who conceives the best way to use them, to meet a specific need, makes a major contribution. The widespread use of a concept is dependent upon the availability of the necessary technology, materials and means of production on an economic basis.

The first Parsons turbo-dynamo to run, in 1884, employed a multistage reaction turbine to achieve good efficiency while matching the speed requirements of the electrical machine, thus adapting the known turbine principle to make the first practical turbo-generator.

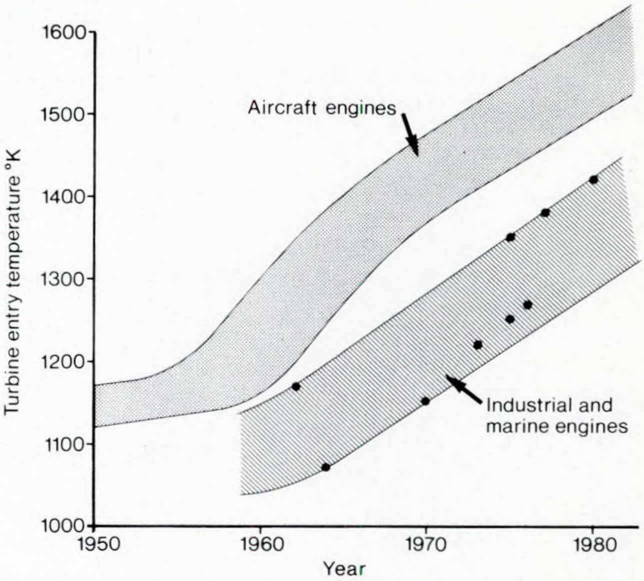
Similarly, the gas turbine concept as such was not new when the Whittle jet engine made its first flight. There were at that time a few industrial gas turbines in existence, made by the traditional builders of steam turbines. The Brown Boveri Company, which did most of the pioneering work in this field, commissioned the first gas turbine generating set in a power station at Neuchâtel in 1938 and delivered a 2000 h.p. machine to the Royal Aircraft Establishment in the following year. These heavy machines created little impact because the maximum cycle temperature to which they were limited, by the available blade materials, gave them a performance which was not competitive with other available prime movers. However, the idea of using a gas turbine as a jet engine to propel an aircraft had great merit, as subsequent events proved.

Like its rival the reciprocating internal combustion engine, the output of a gas turbine is the difference between the work in expansion and the work in compression; but, with much lower permissible maximum temperatures, the difference is far more critical. Both output and efficiency depend upon the ratio of maximum cycle temperature to intake temperature; maximum cycle temperature can be high in the reciprocating engine due to the intermittent combustion and the relative ease with which the cylinder heads and walls can be cooled.

In contrast, the turbine nozzles and blades of a gas turbine have metal temperatures much closer to the top temperature of the cycle which is therefore limited by consideration of blade strength. However, at altitude, where intake temperature is lower, better efficiency results with a given turbine entry temperature, giving the aircraft application an advantage from the start. In the Whittle engine, use of the energy as a jet minimized internal losses and helped to achieve low engine weight.

Furthermore, the jet engine appeared at a time when aircraft speeds were being pushed into an area where aerodynamically clean engine installation became a vital factor. Although ever more powerful piston engines could be made, the losses generated by the cooling system and the propeller were embarrassing. Thus, the conditions were right for the gas turbine to achieve its first significant role and it was Sir Frank Whittle who recognized the potential and caused something to be done about it. His pioneering work led to the first flight of the Gloster E28/39 aircraft, powered by a jet engine, in May 1941.

Rapid development followed, initially for military aircraft, but the performance advantages for civil aircraft were also recognized. Replacement of the centrifugal compressors used in early engines by axial flow compressors enabled more compact and powerful engines with high efficiency to be made and shaft power engines for turbo-propeller aircraft appeared. Large strides were made in the life and



The steepest part of the curve is due to the introduction of blade cooling. Also shown is the corresponding temperature trend for industrial and marine engines.

FIG. 1 Graph showing the trend in turbine entry temperatures for aircraft gas turbines

efficiency of the major components as well as solving such vital problems as the achieving of reliability and long life in anti-friction bearings in the aero gas turbine environment. In addition, important advances were made in high-temperature materials for turbine blades and the increase in maximum cycle temperature which resulted could be augmented by using air flow through internal passages to cool the nozzles and blades which are exposed to the highest gas temperatures. Figure 1 illustrates the increase in turbine entry temperature which has occurred in aircraft gas turbines since the early engines to the present.

By the late 1950s gas turbines had not only virtually replaced piston engines in military aircraft, but were also rapidly taking over in civil aviation. Furthermore, in civil aircraft in particular, where the utilization is relatively high, the new generation of engines was showing every indication of providing greater availability, reliability and longer life between overhauls than had proved possible with piston engines.

Against this background, ideas emerged for using the aero-engine technology, and the engines themselves with appropriate modifications, for marine and industrial purposes. In the following description of these developments, the author uses Rolls-Royce engines to illustrate the story because of his familiarity with this range, but similar industrial and marine applications have been pursued by other aero engine manufacturers.

AERO-DERIVED ENGINES FOR MARINE AND INDUSTRIAL APPLICATIONS

Marine

Following some experience with purpose-designed gas turbines at sea, the Royal Navy recognized the merit of exploiting the development funded from aero sources. This led first to the use of Proteus engines in the *Brave* Class fast patrol boats, which went to sea in 1958.

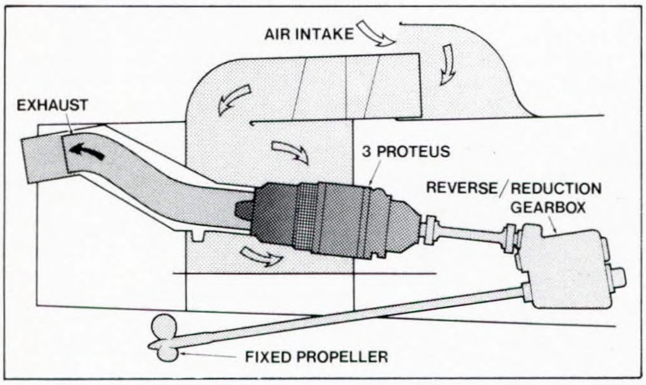


FIG. 2 Diagram showing the intake, exhaust and transmission arrangements for Proteus engines installed in the *Brave* Class fast patrol boats

The Proteus engines delivered 3500 b.h.p. each and, due to the central air intake arrangement (the air flowing forwards through the combined axial and centrifugal compressor), three engines could be fitted neatly into a plenum chamber with short exhaust pipes through the transom, as shown in Fig. 2. A new reduction gearbox was fitted to the Proteus to provide an output speed of about 5000 rev/min which was suitable for the input to the V-drive reverse reduction gearboxes.

Diesel fuel was used in place of the kerosene used in aero engines and the materials of a number of components were changed to provide greater corrosion resistance, as demanded by the salt environment. An attempt was made to reduce the ingestion of water with the intake air by means of a hood over the entry to the intake duct and drainage of water from the duct in the region of the closely spaced silencing splitters.

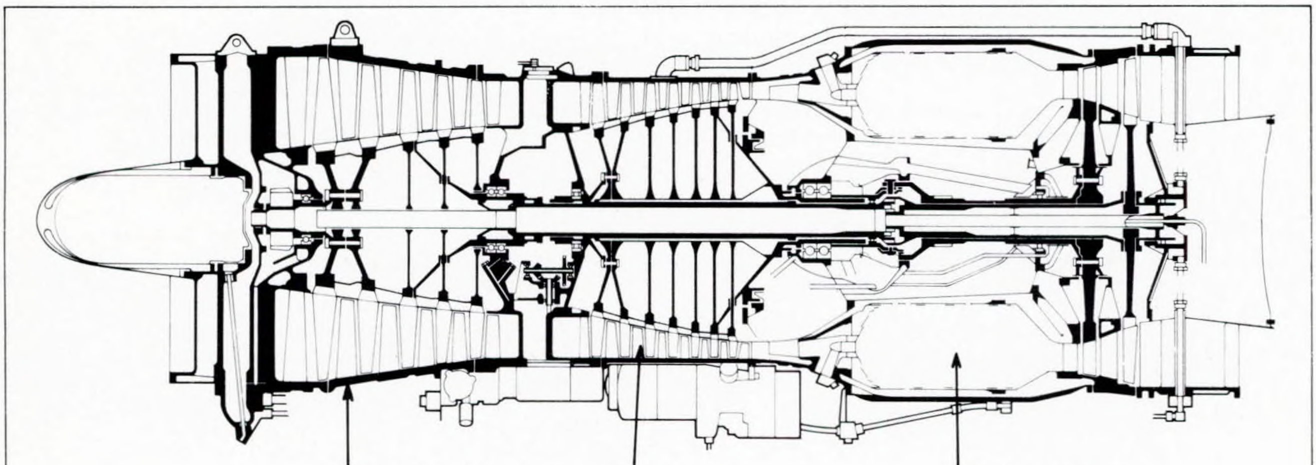
Although only two *Brave* boats were built, they resulted in a large number of Proteus-powered high-speed naval craft following their example and provided some very useful lessons about the behaviour of aero-derived engines in a sea-level environment. Much was learned, too, about the level of salt to be expected in intakes and in fuel and of the resulting rate of corrosion, particularly of turbine blading. Development was undertaken to deal with the modest number of troubles encountered, some of which seemed very obvious with hindsight. For example, it is useless to limit the salt reaching the engines with the intake air if sea water can leak directly into the plenum chamber!

Fortunately, by the time hovercraft had arrived with their self-generated storm conditions at air intakes, and were being used intensively on ferry services, sufficient was understood about blade corrosion and intake filters to enable reasonable engine life to be achieved. Development continued to extend gas turbine life for this and other hostile environments.

Meanwhile, the Royal Navy, already gaining experience at sea with the Metropolitan–Vickers G6 gas turbine in the *Tribal* and *County* Class ships, was looking for a much more powerful engine to provide boost power in projected frigates. The Olympus jet engine offered the appropriate power and was already being adapted for electrical generation duty. This engine, which is shown in Fig. 3, has mechanically independent low and high pressure compressors, each driven by a single stage turbine. The overall pressure ratio across the compressors is 10.5:1.

When an engine is used continuously at ground level, even though de-rated from the aero take-off power, it experiences loadings which are higher than the average loadings in aircraft use. Typical changes made to the engine include stronger thrust bearings and attention to many of the sliding surfaces needed to allow for expansion. Combustion chamber development is necessary to obtain a clean exhaust when burning diesel fuel and assure long life of the flame tubes. A power turbine is used to convert the exhaust energy into shaft power and the fuel control system requirements differ from those of an aero engine. Application to warship propulsion also requires consideration of the problems caused by underwater shock.

FIG. 3 The marine version of the Olympus jet engine



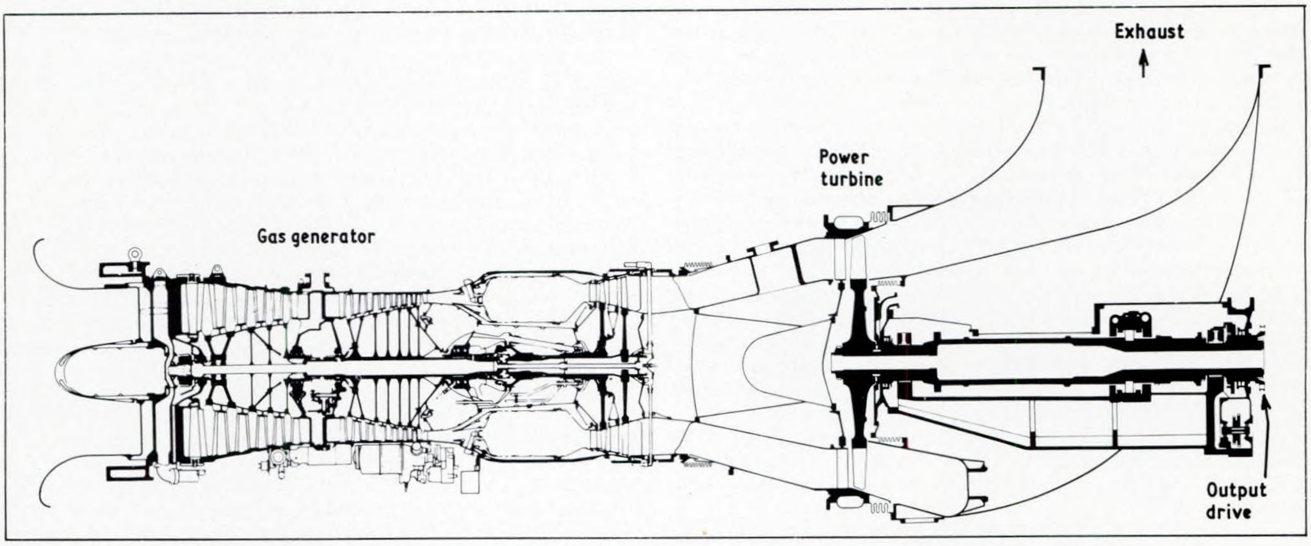


FIG. 4 The Olympus gas generator and single-stage power turbine with upswept exhaust

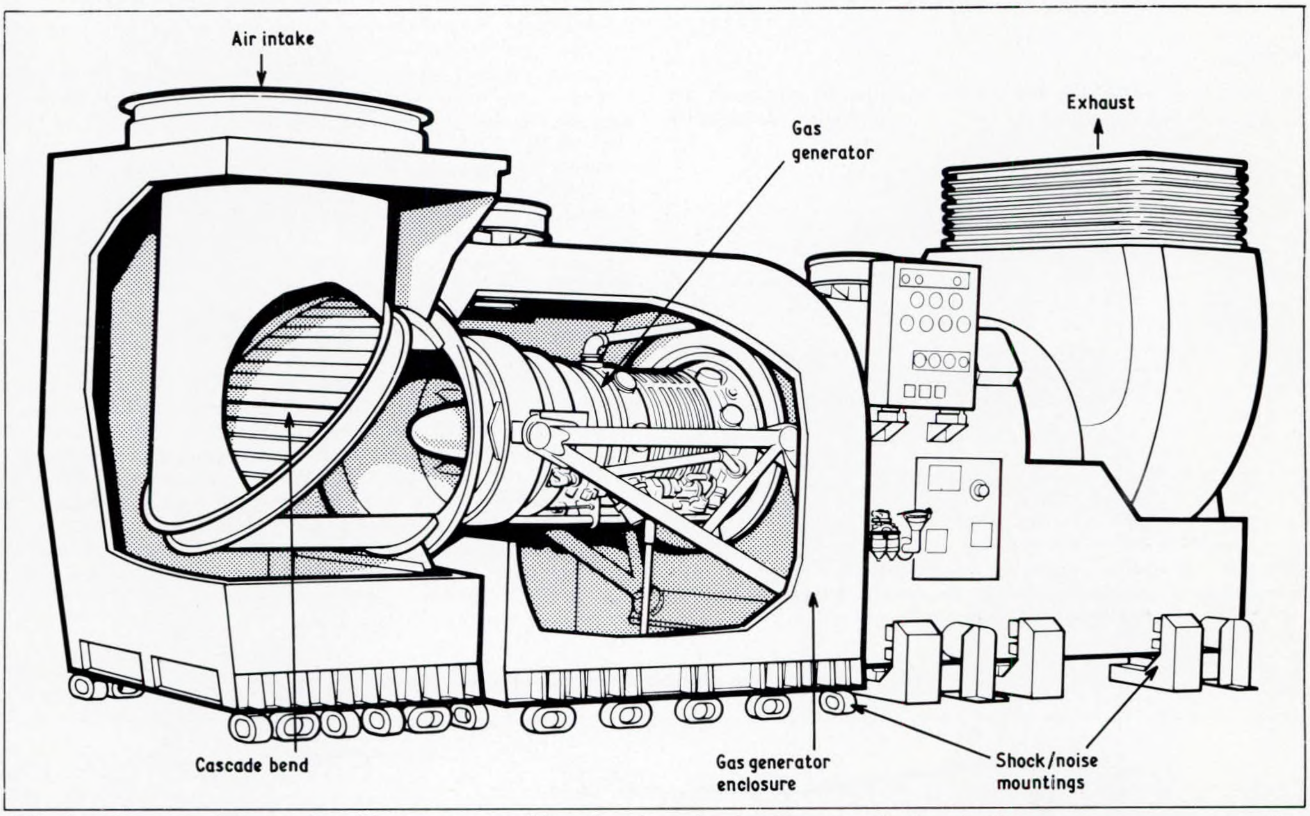


FIG. 5 The complete marine Olympus assembly, showing the intake cascade bend, the gas generator mounting arrangement and enclosure which reduces noise and the escape of heat into the engine room

For the marine Olympus, it was decided to design a single-stage power turbine of modest diameter and an upswept exhaust duct was evolved, as shown in Figs 4 and 5. These arrangements kept the width of the unit below 8 ft overall, enabling two engines to be accommodated side by side, with adequate access, in a frigate.

To deal with shock, the casings of the Olympus itself (now known as the gas generator) were strengthened and the mountings changed to enable the unit to withstand 30 ***g*** acceleration. It was supported from the robust bedplate under the power turbine. Shock attenuating and noise suppressing mounts could now be fitted between the bedplate and the ship seatings to limit the engine acceleration experienced under shock to 30 ***g***. The shock attenuation results in movement of the engine relative to the seatings and consequent misalignment of the shaft coupling the power turbine to the main reduction gear. Limitations in the deflection permissible at the shaft flexible couplings largely determined the choice of 30 ***g*** for the shock resistance of the power unit.

Despite a considerable amount of testing, a few unexpected problems were encountered and the most serious example is of interest. The Royal Navy put the Olympus to sea in 1967 in HMS *Exmouth*, converted from steam propulsion. After 65 hours of operation, a blade failed in the first stage of the compressor and detailed investigation followed this setback.

The Olympus drew air from the rectangular downtake duct in the ship through a flare and it was argued that any non-uniformities in the relatively low velocity flow in the duct would be smoothed out by the acceleration of flow into the engine intake. It transpired that a small step on one side of the downtake duct, needed to avoid a structural member in the ship, caused a flow detachment and the formation of a vortex upstream of the flare. The acceleration in the flare concentrated the vortex into a really vicious disturbance in the air flow with consequent excitation of the compressor blades. This incident resulted in the fitting of the cascade bend upstream of the flare seen in Fig. 5. The cascade prevents the generation of a vortex in front of the engine intake and ensures that the flow into the compressor is sufficiently uniform to avoid causing excessive vibration of the rotor blades.

Furthermore, it was realized that, while new ships would be unlikely to have a step in the wall of the downtake, a similar effect might easily be generated by battle damage and so the cascade bend remains a feature of subsequent installations. While this failure inevitably earned a black mark at the time, some important lessons were learned and more attention was paid henceforth to problems which can arise from unwanted flow patterns in ducts.

The original concept of a very long-life rugged power turbine employing plain bearings, which are accessible, and a gas generator, which can be quickly replaced for overhaul via the intake duct, has been shown to be sound by experience in service. The complete module concept illustrated in Fig. 5, with the gas generator enclosure and other features, has done much to make the engine room more habitable and to ensure ready accessibility where it is likely to be needed.

The Royal Navy desired all-gas turbine propulsion to give reduced on-board maintenance compared with either steam or diesel plant, and reduced underwater noise compared with diesels to minimize the risk of detection by submarines. It was recognized that it would be uneconomic in fuel consumption to operate the 28 000 b.h.p. Olympus engine at the low cruise powers at which naval vessels spend much of their time and, therefore, a small gas turbine giving high efficiency at these powers was required. A marine version of the Tyne engine rated at 5340 b.h.p. was developed for this purpose along very similar lines to the Olympus and these engines are used in the current Royal Navy ships as well as by a number of other Navies.

Perhaps the main departure from the Olympus pattern was due to the fact that the Tyne, being a much smaller engine, has much higher rotational speeds than the Olympus, the power turbine running at 14 000 rev/min. This speed was deemed too high for the interface between separately mounted units and a primary reduction gear was incorporated into the Tyne module. Advantage was taken of this feature in two ways, however. By fitting an idler gear as required, opposite-handed rotation of the propellers could be obtained, whereas with the Olympus this was achieved with handed power turbine blades. Secondly, by appropriate choice of the primary gear reduction ratio, the Tyne could feed its power into the same pinion in the main reduction gearbox as the Olympus, thus avoiding additional complexity in the main gearbox.

The main improvement expectations from gas turbine propulsion in warships, of high ship availability and reduced manning, appear to have been fully justified by service experience. It is evident that the pioneering of the Royal Navy and Rolls-Royce has now been followed by most other major navies, each acknowledging the advantages of gas turbine propulsion to warship design and operation.

Electricity generation

The first Rolls-Royce generating set employing an aero-derived engine was commissioned for the South West Electricity Board at Princetown on Dartmoor in 1959. This location, at the end of a grid system spur, required reinforcement to meet peak demand and there was opposition to heavier overhead transmission lines in the National Park. Furthermore, the tariff arrangements by which the Central Electricity Generating Board (CEGB) sold electricity to the Area Boards meant that use of the Proteus-powered 3 MW set for quite short periods would reduce the peak demand charge sufficiently to offset rapidly the cost of the set.

A number of sets of this size were built, both in static and mobile installations. The main advantages were seen to be low cost per kilowatt, a relatively short time from ordering to commissioning, and the ability to start and accept load quickly: the feasibility of remote operation was also demonstrated.

This activity was relatively short-lived due to a threat to alter tariff arrangements but, meanwhile, the CEGB agreed to assess the merits of a larger unit to be assembled at Hams Hall power station. The Olympus engine, being the largest available Rolls-Royce aero unit, was chosen and a two-stage power turbine designed to run at 3000 rev/min, thus permitting direct coupling to a 2-pole alternator. It was guaranteed to produce 15 MW.

The first Olympus set, which was built in the loading bay of an existing power station, is shown in Fig. 6 and was commissioned in

FIG. 6 The first Olympus generating set which was installed in a loading bay at Hams Hall power station
The intake duct and gas generator enclosure are brick built.

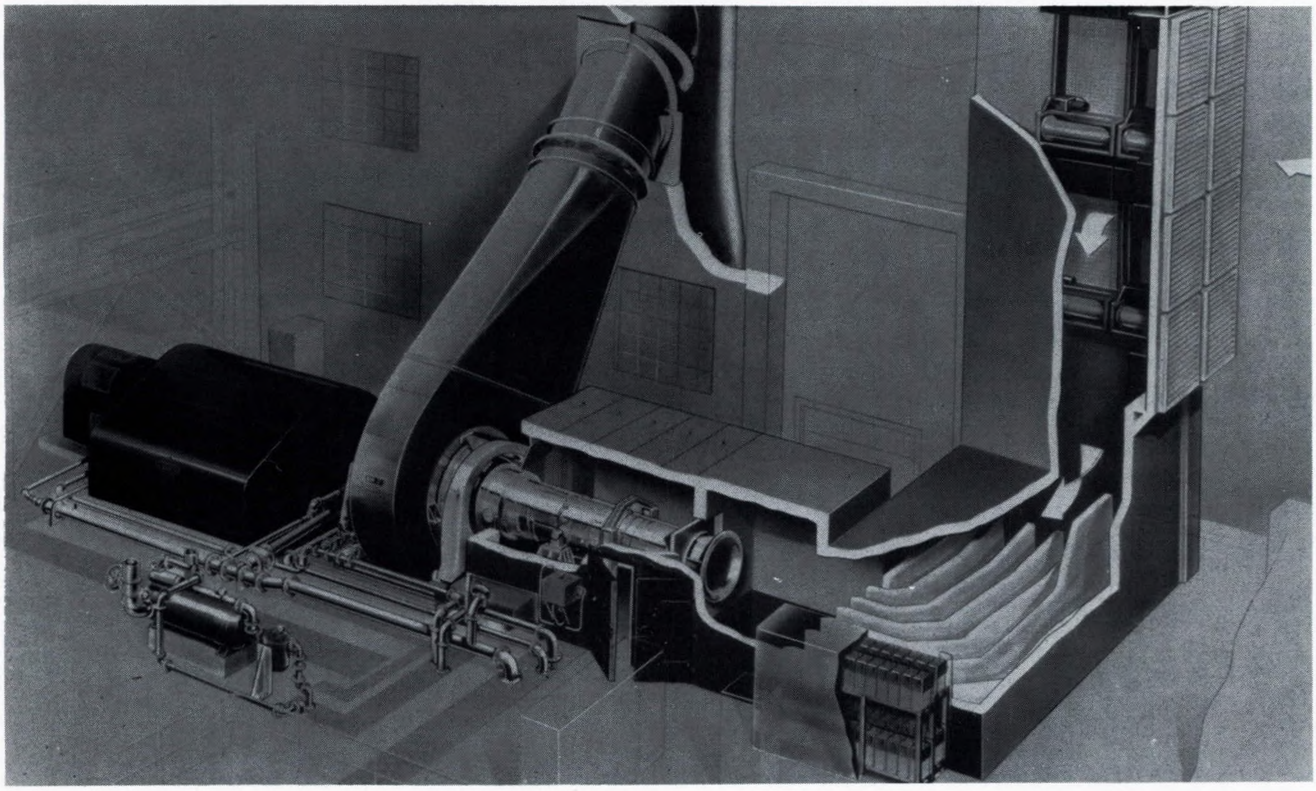


FIG. 7 A typical Avon gas pumping station on a natural gas pipeline in Alberta, Canada

1962. It quickly showed its ability to start, automatically synchronize and run up to full output within two minutes and it produced 17.5 MW.

Shortly afterwards, there occurred a major blackout in the South East of England due to a sudden upsurge in demand exceeding the capacity of the generating sets which were operating, resulting in a cascade of trips. This event, coupled with a shortage of capacity, led the CEGB to equip each of the new 500 MW steam sets with a standby gas turbine set arranged to take over the driving of the steam set ancillaries in the event of frequency falling due to overloading. The gas turbines, with other multiple Olympus units, would also be available for coping with sudden load peaks.

This kind of application of aero-derived gas turbines soon involved the Avon engine as well as the Olympus and was not confined to this country. While enabling the lightweight gas turbine to fulfil an important role in electricity generation, it placed excessive stress on the use of the highest possible ratings and the ability to run up to load very quickly. Running time between starts was often remarkably short and, while ongoing development dealt with the most serious wear and tear effects of this rough treatment, the aero-derived unit tended to gain a reputation of relatively short life between overhauls in the power generation industry. The installation of gas turbine sets in urban environments at load centres was shown to be entirely acceptable, thus saving transmission losses, and the lightweight units encouraged the design of mobile generating sets; these and other considerations led to some units enjoying greater utilization with correspondingly improved life between overhauls.

Base load applications grew in number more slowly, limited by the relatively high cost of distillate oil and gas in many areas, but in such duties the units were able to show long lives much closer to those already being achieved in another role, the pumping of gas in pipelines.

Gas and oil industry

The Avon jet engine, modified to an industrial 'gas generator', entered service on the Trans Canada natural gas pipeline in 1964, the power turbine and gas compressor being provided by Cooper Industries. The engine was conservatively rated at 16 000 h.p. as it was recognized that, although the gas generator could be quickly exchanged when overhaul became necessary, long life with almost continuous operation would be needed. The fuel was ideal, in the form of clean natural gas from the pipeline, and the environment was also clean though with obvious low temperature and icing hazards in winter. A typical gas pumping station is shown in Fig. 7.

While aero engines are worked extremely hard at take-off, they tend to enjoy much lower component loadings and temperatures when cruising at altitude. Thus, despite changes made to the Avon initially in adapting it for industrial use, some problems, which did not appear or did not limit the life in aircraft, turned up as the reasons for requiring overhaul in pumping duty. However, improvements were introduced as the shortcomings appeared and the life increased rapidly, enabling some units to achieve over 40 000 hours between overhauls, equivalent to 5 years of almost continuous running.

There were fears in some quarters that such lives would never be achieved by ball and roller bearings but the bearings in fact were never a serious problem. Despite precautions, icing did cause some compressor failures and research showed that blocks of ice entering the intake did not themselves cause blade failure but could deflect a first-stage blade elastically far enough to hit the neighbouring stator vanes. The problem was eliminated by cutting back the blades at the tip to avoid interference and, later, by the introduction of titanium blades in place of aluminium alloy. The use of titanium alloy for compressor blades not only results in greater blade stiffness but also provides greatly enhanced corrosion resistance.

Fuel control unserviceability problems were dealt with by the use of an electronic system in place of the original hydro-mechanical fuel metering system. The oil pumps and other ancillaries were originally engine-mounted and engine-driven through a built-in accessory gearbox as in the aero engine. Troubles with the gearbox and its drive proved difficult to eliminate completely to match the long life achieved by the gas generator and, eventually, the ancillaries were floor-mounted and electrically driven.

As a result of the long lives achieved and the ease with which the gas generator could be replaced quickly when necessary, the use of aero-derived engines became widely accepted as the best way to provide power for pumping gas and oil, both at pipeline booster stations and also on offshore platforms where it is essential to minimize both the size and the weight of the power plant.

NEW REQUIREMENTS AND THE RESULTING DEVELOPMENTS

By the early 1970s, derivatives of aero engines had become accepted on a wide scale for the propulsion of naval ships, for gas and oil pumping duties and were in use for certain limited roles in electricity generation. New challenges gradually appeared and the most significant were the result of the following needs:

1. While distillate diesel oil or natural gas were acceptable fuels for the majority of users, the desirability of being able to use a wider range of gases arose. In addition, a dual-fuel capability was wanted in some applications.
2. Fuel costs escalated rapidly from 1973 onwards, stressing the importance of higher efficiency.
3. Units of larger power were needed for some industrial purposes.
4. Pollution regulations were becoming more stringent in many areas.

Other fuels and dual-fuel operation

It was found relatively easy to accept gases other than natural gas, such as ethane or refinery tail gases, although minor changes to the combustion system were sometimes necessary.

Sour gases with a high hydrogen sulphide content did not create a combustion problem but caused turbine corrosion problems, especially as they usually occurred in salty environments. The arrival on the scene of new cast blade materials, with enhanced corrosion resistance compared with the previously used Nimonic alloys, helped enormously in dealing with this problem and also, of course, in improving blade life in marine duties.

The need to be able to change over at any time from gas to liquid fuel and vice versa required the design, within the limited space available, of fuel injectors or burners embodying discrete passages for both types of fuel. Furthermore, it was found that when running on liquid fuel, a small quantity of the liquid was inclined to migrate into the gas manifold and eventually ignite. This placed a further restraint on the design of the dual-fuel injector and required a small purge flow of air through the gas manifold to eliminate the problem.

The metering of liquid and gas fuel flows to permit controlled change-over at any engine running conditions, while preserving all the normal limitations of maximum speed, temperature and acceleration, resulted in a highly complex hydro-mechanical system. Fortunately, the adoption of an analogue electronic system provided a much more acceptable solution. No difficulty was encountered in running on liquid and gaseous fuels at the same time.

The use of crude or residual oils requires fuel treatment plant to remove most of the sodium, the introduction of a vanadium corrosion inhibitor and heating of the fuel if the viscosity is high. This requires careful monitoring and, even then, significant performance deterioration rapidly occurs due to deposits forming on turbine blades. Use of such fuels is unlikely therefore with lightweight aero-derivative engines, except possibly in circumstances where no other fuel is available.

Effects of fuel cost escalation

Higher fuel costs direct attention to the achievement of higher efficiency. In the aero scene, the jet engine had given airframe designers really low powerplant frontal area which they were reluctant to see jeopardized and this attitude delayed further advances, at least in civil engines; but the combined needs to attack the jet noise problem and improve propulsive efficiency led first to the bypass engine and later to the modern fan engine. In both these types, air at modest pressure is passed around the outside of the gas generator and is ejected with the hot exhaust to give, effectively, a high mass flow, low velocity jet.

These developments encouraged further improvement in the basic gas turbine efficiency by the pursuit of higher pressure ratios and higher turbine entry temperatures. In recent years, to these trends have been added further efforts to improve component efficiencies and to reduce blade tip and seal leaks. All these efforts have been of corresponding benefit to the industrial and marine derivatives.

It became clear that an industrial version of the RB211 engine (Fig. 8) would provide a gas generator of about 30 000 h.p. which would be attractive for gas and oil pumping and some electrical tasks. Similarly, a version of the Spey, with the bypass deleted, would provide a more efficient engine for applications previously met by the Avon and would also satisfy the Royal Navy wish for an engine of about 16 000 h.p. and good fuel consumption for future ships. Both these engines have pressure ratios at industrial ratings in excess of 18:1, both embody cooled turbines and they have an efficiency of 34% in comparison with about 28% for earlier engines.

The complete Spey marine unit which has been developed for the Navy is shown in Fig. 9. Many of the features of the Olympus module have been retained, as can be seen in the illustration. A two-stage power turbine was designed to provide enhanced efficiency over a wide range of speed with the higher power turbine expansion ratio provided by the Spey. An electronic fuel control system was adopted, following the successful application of electronic controls to industrial engines.

Demand for units of larger power and lower cost per KW

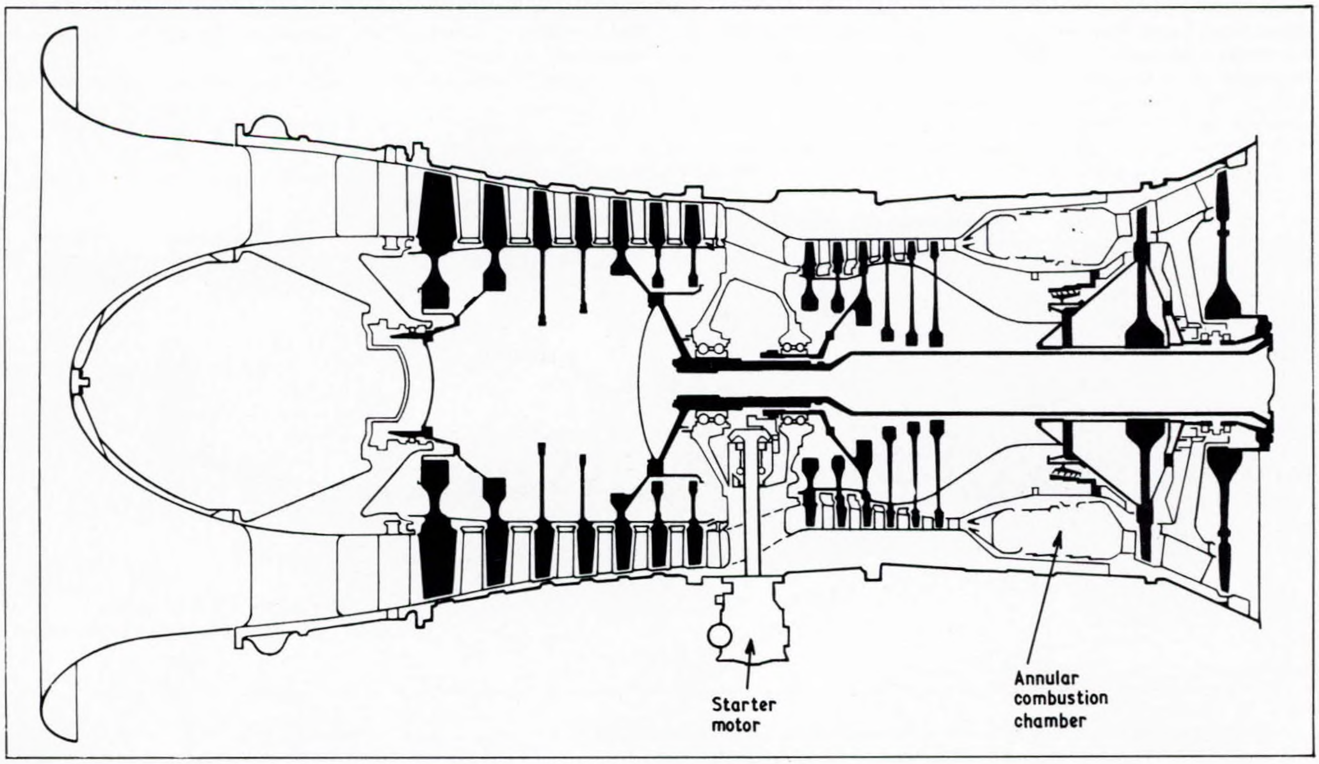
For large gas pipelines, the most economical solution to the pumping power requirement is for a gas turbine of around 30 000 h.p. and this need is met by the RB211 which is used, for example, in the British Gas system and on offshore platforms.

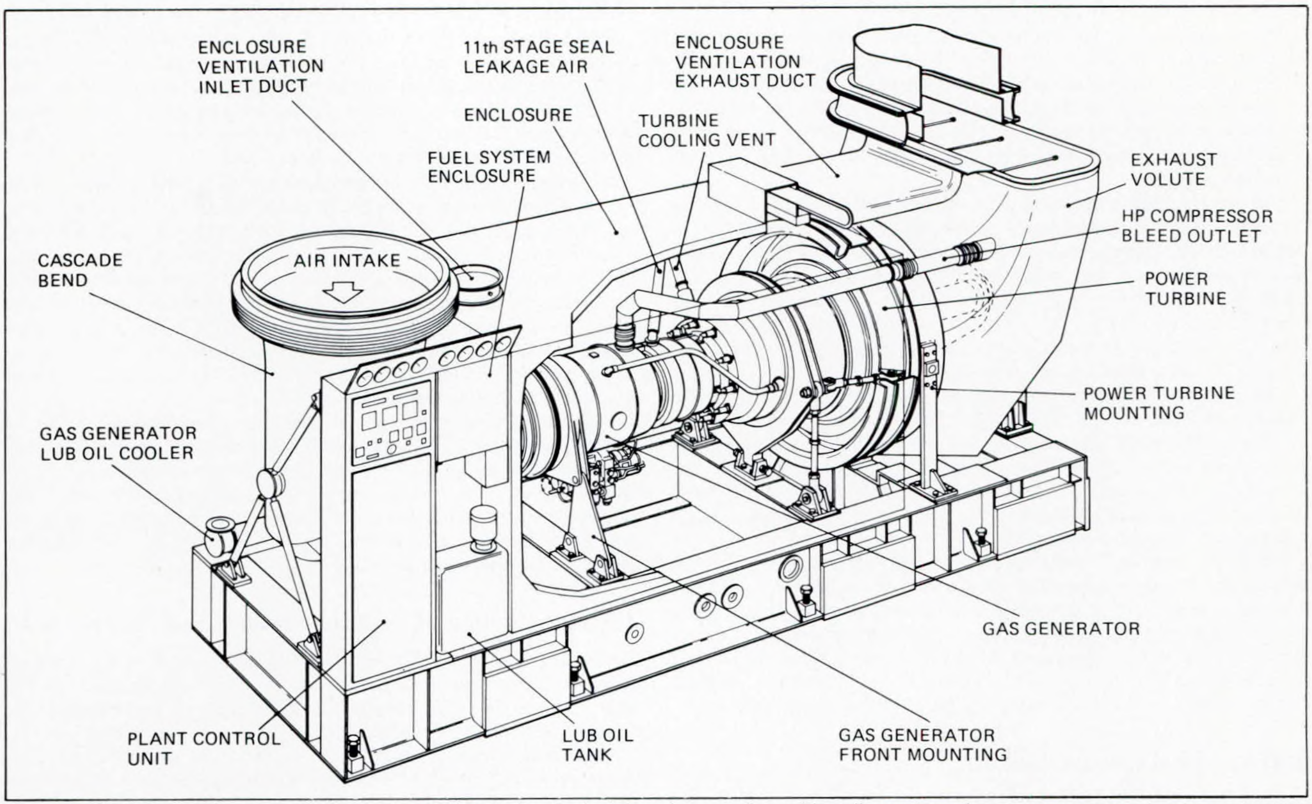
At power stations, steam sets of 500 MW upwards are now common. As mentioned earlier, larger gas turbine sets can be provided by using a multiplicity of gas generators, but most gas turbine sets of around 100 MW in use are single-shaft heavy machines and not aero derivatives.

Consideration was given to the use of the Olympus 593 Concorde engine, the most powerful aero engine available, which would have provided an industrial unit of 48 MW. However, insufficient advantage was seen, compared with further developing the existing Olympus engine for electrical generation, to justify proceeding.

FIG. 8 The industrial gas generator derived from the RB211 engine by removal of the fan and the turbine which drives it

The pressure ratio is more than 18:1, an annular combustion chamber is employed and abradable tip seals are fitted opposite every row of blades.





The assembly including the gas generator enclosure is carried on the bedplate shown and, as with earlier engines, the gas generator can be changed quickly when required.

FIG. 9 The Spey marine propulsion module, showing the main features

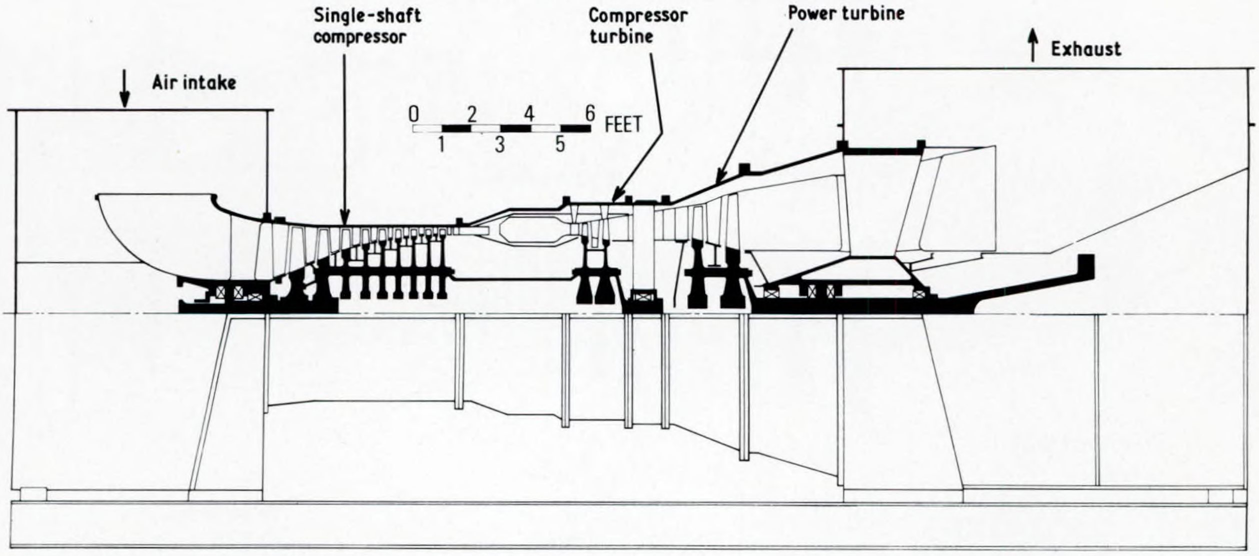
A design for a gas turbine of about 100 MW was undertaken and is shown in Fig. 10. Although not strictly an aero derivative, this unit employed aero techniques wherever appropriate. As can be seen from the illustration, the design employed a single-shaft gas generator and a separate power turbine. This enabled it to satisfy both 50 Hz and 60 Hz output speeds with 2-pole alternators and the engine size and power were limited by stress considerations in the last stage. The use of a mechanically independent power turbine provided the added advantages of greatly reduced starting power requirements and improved part-load efficiency. However, this machine did not proceed beyond a design study and effort was concentrated on improving the Olympus.

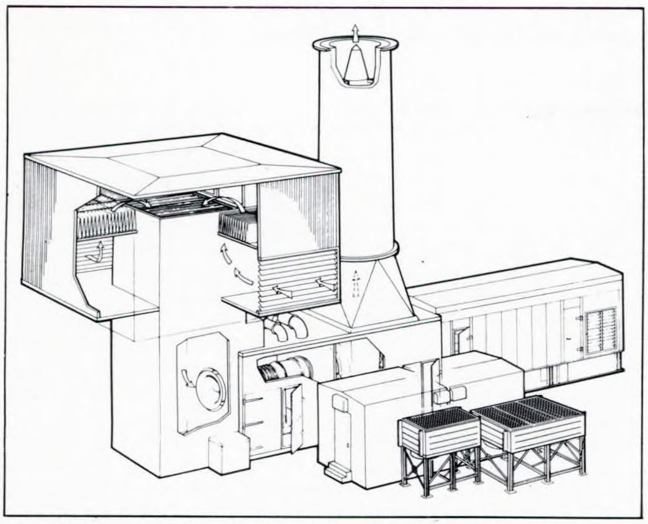
The Olympus industrial engine was substantially uprated by designing a new turbine with cooled blades. A new flame tube was also developed to enable the turbine entry temperature to be increased by more than 150°C. This engine is currently rated at 28 MW.

The specific cost was reduced by designing a packaged concept of generating set, as shown in Fig. 11. Among the merits of gas turbine generating sets are the modest cost per kilowatt and the relatively short time from receipt of order to commissioning when compared with steam plant. Both these features are assisted by the packaged design, which enables a number of sub-assemblies to be delivered to the site where they are bolted together on a simple prepared foundation. Thus, for example, the power turbine, fully assembled on its baseplate and

FIG. 10 The design of an industrial gas turbine of 100 MW output

The single-shaft gas generator pressure ratio was 15:1.





The Olympus embodies cooled turbine blades and a three-stage power turbine is used. In the foreground are the coolers and control room.

FIG. 11 An SK30 28 MW packaged generating set

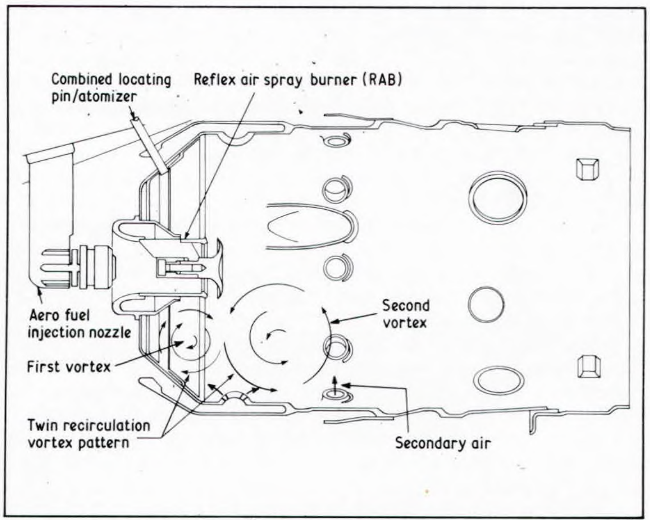


FIG. 13 Flame tube incorporating reflex airspray burner, showing the double vortex airflow pattern in the primary zone

complete with enclosure containing various auxiliary systems, is shipped to the site as a unit. By avoiding re-assembly on site and minimizing civil work, both time and cost are saved.

By the use of handed power turbine blading, two gas turbine units can be arranged to feed power into each end of a 56 MW alternator. While a single gas turbine of twice the power might save some cost, this arrangement confers benefits in flexibility of operation, greater reliability and better part-load efficiency.

To meet the specific needs of power generation on offshore platforms, a compact version of the packaged set mounted on a single bedplate was produced. Two of these assemblies are shown in Fig. 12 on a barge, being conveyed to a platform in the North Sea. After testing the complete set on-shore, each unit is lifted into place on the platform, where it is carried on a three-point mounting; this ensures that any movement of the platform under the influence of wind and waves will not upset the alignment of the machine.

Reduction of pollution

Gas turbines can create pollution in the form of a dirty exhaust and noise. The desire to reduce pollution is one we all share and, although there are setbacks from time to time because the solutions usually increase costs, there can be little doubt that improvement in this area will continue.

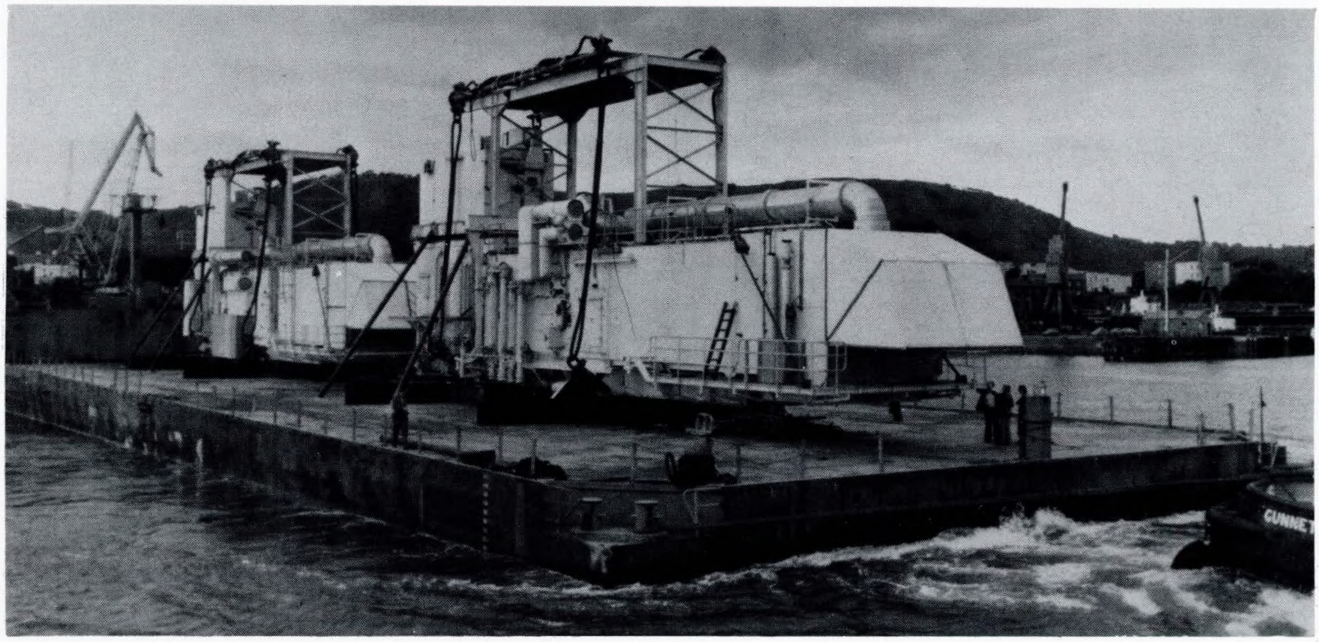
Gas turbines, while noisy, do not produce loud discrete noise at the low-frequency end of the spectrum, which is the area most difficult to deal with by sound reduction techniques. Thus, by providing an enclosure for the machine and appropriate sound-attenuating systems in the intake and exhaust ducts, the desired level of quietness can be achieved at modest cost.

With regard to the exhaust, the main constituents which it is necessary to address are smoke and oxides of nitrogen. Exhaust smoke is caused by incomplete combustion and black smoke is unburnt carbon resulting from incomplete combustion of a small fraction of 1% of the fuel. Eliminating smoke completely is a difficult problem, bearing in mind the need to retain freedom from flame-out, adequately cooled flame tube walls and an acceptable outlet temperature distribution to avoid excessive local temperatures in the turbine.

An indication of the way in which the problem is solved is given in Fig. 13, which shows the reflex airspray burner arrangement developed for the marine Spey. Particular features to note are the injector outside the flame tube, spraying fuel into a pre-mix chamber and the double

FIG. 12 Two SK30 compact generating sets on a barge en route to a North Sea platform

Note the air intake snow hoods and anti-icing hot air feed pipe to the intakes. Each set weighs a little over 200 tons.



vortex airflow configuration in the primary zone of the flame tube. The small fuel injector combined with the locating pin shown on the diagram is used only for starting. The fuel–air ratio at high power is arranged to be rich in the first vortex and combustion is completed in the second vortex after the admission of more air. Under conditions of rapidly throttling back the engine, the fuel–air ratio in the first vortex is still sufficiently near to stoichiometric to avoid a flame-out problem. This combustion system results in an exceptionally clean exhaust over the full range of operation from idling to full power.

The art of keeping flame tube walls at a temperature consistent with long life, without the use of an excessive amount of air for this purpose, has kept pace with the increasing demands caused by higher compressor delivery temperatures (higher pressure ratio) and high turbine entry temperatures.

The production of oxides of nitrogen is a function of residence time of combustion gases at very high temperature and also of the constituents of the fuel. Fortunately, combustion developments to eliminate visible smoke have also helped in reducing NO_x formation, but, again, the problem is aggravated by increasing pressure ratio. While engines of modest pressure ratio can now meet the most stringent current regulations, development is continuing to achieve this situation with the higher pressure ratio engines and, in the meanwhile, NO_x levels in the exhaust can be reduced, as needed, by water injection into the combustion chamber.

The level of sulphur dioxide in the exhaust is directly related to the sulphur content of the fuel and this is either non-existent or quite modest for most of the fuels consumed by aero-derivative engines. Coal and heavy oil burning plants are much greater offenders with regard to sulphur dioxide discharge unless sulphur removal equipment is provided in the exhaust stack.

FUTURE PROSPECTS

In today's cost-conscious world, it usually appears that minimum total cost takes precedence over all other forms of usefulness or excellence. The total cost of ownership of a piece of plant embraces first cost, cost of the fuel used and maintenance and it is relevant to consider where aero-derived gas turbines stand in these respects.

First cost

The use of many aero-engine parts which are already tooled for quantity production assists in minimizing first cost. Furthermore, the intense competition in the aero-engine field ensures the exploitation of modern manufacturing methods and the use of computers in design, planning, manufacture and inspection of components.

Maintenance

Repair by replacement, made practicable by the relatively small size and weight of aero derivative gas generators, is likely to be of increasing importance. A further aid to maintenance which the more recent gas generators provide is that they are designed to be easily separated into about five or six 'modules' and each of the modules is interchangeable with an equivalent assembly. This feature frequently permits repair on site by replacement of the appropriate module and also reduces spare unit holding requirements.

Health monitoring arrangements are already assisting maintenance and continue to be developed. The use of digital systems for sequencing, control and data logging will expand and further assist in easing the task of maintenance and achieving a high level of availability.

Fuel cost

With regard to the fuel bill, aero-derived units lead the field in efficiency relative to other simple-cycle gas turbines and we can expect to see full power efficiency rise to about 38% as a result of further improvements in component efficiency over the next few years. However, this still leaves the gas turbine below diesel engine efficiency, especially at part load. Furthermore, the typical fuels used such as distillate diesel oil or natural gas are inevitably more expensive than, say, residual oil or coal.

While modest additional gains in efficiency will be possible by continuing the process of development to higher pressure ratios and turbine inlet temperatures, this would be at the expense of increased first cost and aggravation of the pollution problem. Fortunately, more dramatic attacks on the fuel bill are available by departing from the simple cycle concept and by pursuing ways of being able to use coal without either detracting from the reliability of gas turbine operation or creating an unacceptable pollution problem.

More complex cycles

Simple cycle gas turbines, unlike other prime movers, discharge virtually all the waste heat in the exhaust at quite high temperature. One way of recovering some of this energy is by the use of a heat exchanger (recuperator) feeding heat back into the compressor delivery air ahead of the combustion chamber. However, the portion of the exhaust heat which can be used in this way falls as compression ratio is increased because of the increase in compressor delivery temperature. Thus it becomes more attractive to employ an intercooler during the compression process in association with a recuperator.

By such means, the efficiency can be raised to over 40% and part-load performance can be improved considerably despite the pressure losses incurred by the heat exchangers and the associated ducting. The compactness of the gas turbine tends to be lost and there are difficult, though probably not insuperable, problems in the design of the heat exchangers to withstand vigorous thermal cycling without cracking.

The alternative way to employ exhaust heat is to feed the exhaust to a waste heat boiler. The advantages of the resulting combined cycle plant are best illustrated by briefly describing the installation nearing completion in The Hague which employs two Rolls-Royce Olympus generating sets burning natural gas.

The layout of the plant is indicated by the diagram shown in Fig. 14. Each Olympus generating set is rated at 26 MWe and the exhaust from each is passed through a waste heat boiler. The steam raised is used to drive a steam turbine generating set of 26 MWe capacity and, in addition, low-grade heat in the exhaust is used to heat water for a district heating scheme.

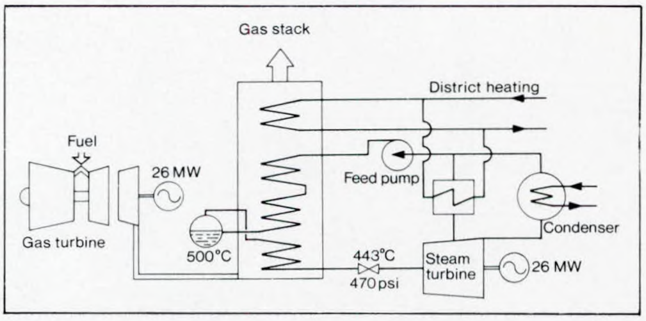
The efficiency of conversion from energy in the fuel to electricity is 44%. If the heat available for district heating is included as useful output then almost 75% efficiency results. The main difficulty with combined heat and power schemes is that the demand for electricity and heat often does not match the relative output of these commodities which the plant produces, but this problem can be largely overcome in the manner shown in Fig. 14. By bleeding steam from the steam turbine and using it to augment the heat input to the district heating water, reasonable flexibility in the relative amounts of heat and electricity can be achieved with only a small penalty in the efficiency of electricity generation.

Still higher thermal efficiency is possible with combined cycle plant by moving to greater complexity in both the gas turbine and steam plant cycles but a balance needs to be struck between the first cost of the plant and the resulting saving in fuel.

Use of coal

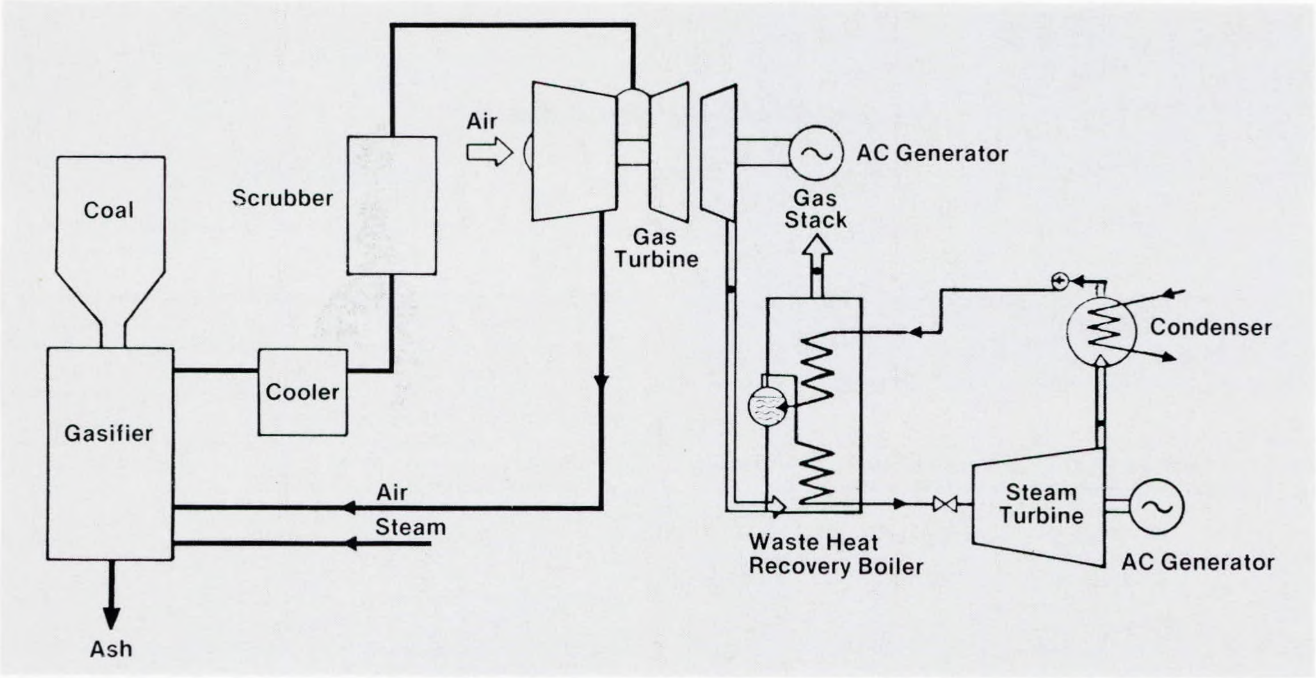
Coal can be used directly in a fluidized bed to provide the heat input to a gas turbine but the turbine inlet temperature is severely limited by the need to avoid slagging of the coal ash. In addition, it is difficult to clean up the combustion products adequately to ensure that the particulate content is acceptable both in the turbine and in the exhaust.

Alternatively, coal can be gasified or used to produce oil. Gasification involves far less loss of heat energy than the process of conversion to a liquid fuel and the resulting gas can be used in a gas turbine with only minor modifications to the combustion system. A



The exhaust heat from two Olympus generating sets produces steam, in waste heat boilers, which powers a separate steam turbine driven generator. Low-grade heat is also supplied to a district heating scheme.

FIG. 14 Diagram showing the combined cycle plant in Holland



Much of the sensible heat in the gas leaving the gasifier should be used to augment steam production.

FIG. 15 Simplified diagram of a coal gasification plant used in conjunction with combined cycle electricity generating set

FIG. 16 HMS *Invincible*: powered by four Olympus gas turbines

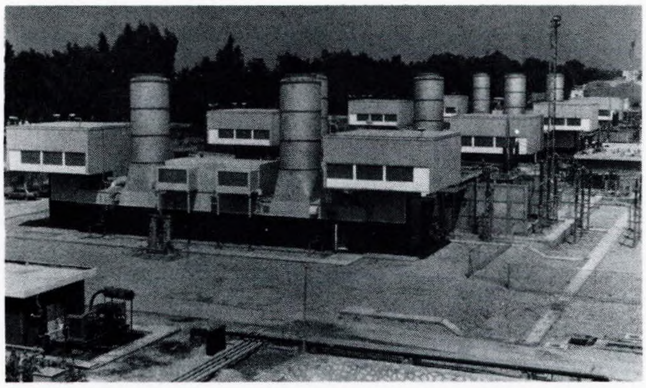


FIG. 17 Four double-ended generating units installed in Egypt

plant employing a gasifier in conjunction with a combined cycle generating set is shown diagrammatically in Fig. 15.

As indicated, the gas leaving the gasifier is scrubbed before passing to the gas turbine and, if desired, the sulphur can also be removed at this stage. This is a more economical process than removing sulphur from the flue gases of a coal-fired steam plant.

A number of pressurized gasifier systems are being developed, both air and oxygen blown. All the indications are that plant of this type will be capable of dealing with the pollution problem and providing higher efficiency than conventional power stations: in addition, cost per kilowatt is expected to be lower, certainly for medium-sized plant.

Thus with prospects of further substantial improvements in overall efficiency, continuing developments to minimize pollution and the ability to use the world's most prolific fossil fuel, where appropriate, the gas turbine is likely to be used in wider fields in the future. While aero-derived units, because of limited power output, will not satisfy all needs, the technology developed for aero engines will certainly be an asset to engineers concerned with marine and industrial gas turbines of all sizes.

CONCLUSION

The tremendous developments in the gas turbine aero engine over the past 40 years have resulted in this type of prime mover dominating air transport and making possible the enormous expansion in this form of travel which has occurred.

In the second half of this period, aero-derived units have become firmly established in warship propulsion, gas and oil pumping and some areas of electricity generation. Examples are shown in the accompanying illustrations.

Figure 16 shows HMS *Invincible* which is powered by four Olympus units, two per shaft, all four engines being used for full power, whilst one engine on each shaft is used for cruise. The four double-ended Olympus generating sets installed at Mahmoudiya in Egypt are seen in Fig. 17 and the use of aero-derived units for pumping duties is typified in Fig. 18 by the British Gas site at St Fergus in Scotland where both Avon and RB211 engines are employed.

In naval ships, future developments to higher temperatures will reduce downtake and uptake sizes and the adoption of more complex cycles appears probable as it becomes essential to limit the proportion of operating cost attributable to fuel. The reduced exhaust temperature accompanying the higher efficiency would be a useful by-product. While the diesel engine is likely to remain the first choice for most

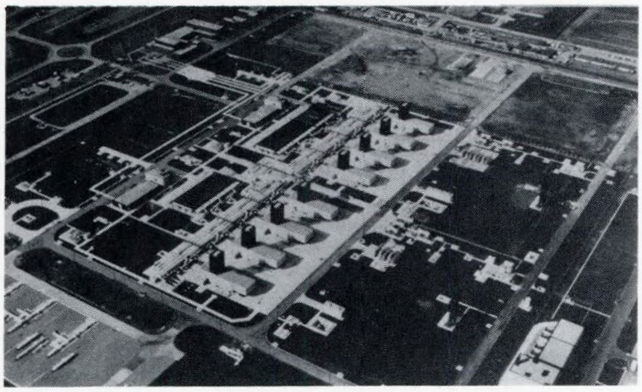


FIG. 18 Avon and RB211 powered pumping sets installed at the British Gas site at St Fergus in Scotland

merchant ships, gas turbines, possibly in combined-cycle plant, appear to have merit for certain applications such as LNG carriers and ice breakers.

The enormous disparity between the speed of ships and the speed of aircraft continues to create interest in higher speed seaborne craft but developments such as the hovercraft and hydrofoil have not achieved widespread success so far. Possibly the SWATH (small water-plane area twin hull) ship or the invention of some more direct means of propulsion than the propeller will result in higher speeds at sea which would favour the use of gas turbines.

Gas turbines can make important contributions to the efficient use of fuels in electricity generation. They can also assist in minimizing pollution and have merit in combined heat and power schemes which are likely to be used on a wider scale in future to conserve fuel supplies.

In the gas and oil industry, aero-derived units are already the first choice for most pumping duties. In this application, where operation is usually virtually continuous, the cost of the fuel consumed in a year can be greater than the first cost of the prime mover: it seems clear that the adoption of more complex cycles must be advantageous.

Sir Charles Parsons, who adapted the design of his steam turbine to meet the particular requirements of electricity generation, naval ships and merchant ships, would surely have applauded the efforts of gas turbine engineers in similar directions.

ACKNOWLEDGEMENT

The author wishes to thank colleagues at Rolls-Royce Ltd, Industrial and Marine, for helpful suggestions and assistance in producing the typescript and illustrations.

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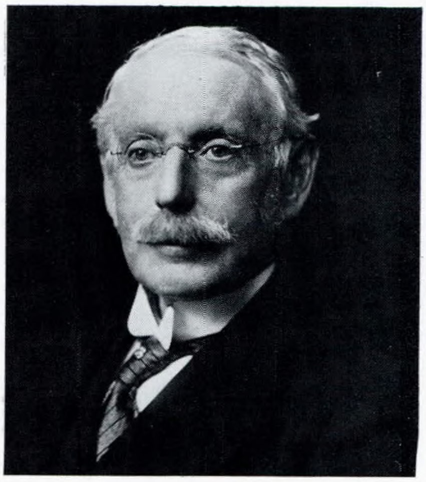
After graduating from Manchester University, Mr Slatter joined Armstrong Siddeley Motors and was involved in the development of jet and turbopropeller engines such as the Sapphire, Viper and Mamba. He began working on gas turbines in 1941, flew with the Company's first jet engine and was, at various times, responsible for performance, flight development and research. In 1959, following the formation of Bristol-Siddeley Engines, he transferred to industrial and marine activities, becoming Chief Engineer in 1963 of the department concerned with the design and development of gas turbines in this field. He continued in this capacity when Rolls-Royce acquired Bristol-Siddeley and was appointed a Director of the Industrial and Marine Division in 1973. Thus, for the second half of his career, he has been responsible for adapting aero gas turbines and the associated technology for application to ship propulsion, electricity generation and pumping duties. Mr Slatter retired last year but is retained as a consultant to Rolls-Royce Limited.

PARSONS MEMORIAL LECTURES 1936–1981



Sir Charles Parsons

1936 'Sir Charles Parsons and steam' by Sir Frank E. Smith (North East Coast Institution of Engineers and Shipbuilders).

1937 'Scientific activities of the late Hon. Sir Charles Parsons, O.M., K.C.B., F.R.S.' by G. Stoney (Institution of Electrical Engineers).

1938 'Sir Charles Parsons and marine propulsion' by S. S. Cook (Institution of Mechanical Engineers).

1939 'Some researches on steam turbine nozzle efficiency' by Dr. H. L. Guy (Institution of Civil Engineers).

1940 'The engining of highly powered ships' by Sir Stephen J. Pigott (North East Coast Institution of Engineers and Shipbuilders).

1941 'Sir Charles Parsons and the Royal Navy' by Sir Stanley V. Goodall (Institution of Naval Architects).

1942 'Reduction gearing for marine steam turbines' by S. F. Dorey (Institute of Marine Engineers).

1943 'Optical topics in part connected with Sir Charles Parsons' by Lord Rayleigh (The Physical Society).

1944 'The determination of critical speeds, natural frequencies and modes of vibration by means of basic functions' by Professor C. E. Inglis (North East Coast Institution of Engineers and Shipbuilders).

1945 'High voltage research at the National Physical Laboratory' by R. Davis (Institution of Electrical Engineers).

1946 'Recent developments in optical glass manufacture' by Sir Hugh Chance (Institution of Civil Engineers).

1947 'Parsons—the man and his work' by Sir Claude Gibb (Institution of Mechanical Engineers).

1948 'British marine gas turbines' by T. W. F. Brown (North East Coast Institution of Engineers and Shipbuilders).

1949 'Progress in marine propulsion, 1910–1950' by K. C. Barnaby (Institution of Naval Architects).

1950 'Sir Charles Parsons and cavitation' by Professor L. C. Burrill (Institute of Marine Engineers).

1951 'Sir Charles Parsons and optical engineering' by F. Twyman (The Physical Society).

1952 'From Stodola to modern turbine engineering' by C. Seippel (North East Coast Institution of Engineers and Shipbuilders).

1953 'Continuity of electricity supply' by H. Leyburn (Institution of Electrical Engineers).

1954 'Factors influencing the continuing development of the steam turbine' by F. Dollin (Institution of Mechanical Engineers).

1955 'The development of the gas turbine' by Sir Harold Roxbee Cox (Institution of Civil Engineers).

1956 'A review of naval propulsion engineering progress in the last ten years' by Vice-Admiral Sir Frank T. Mason (North East Coast Institution of Engineers and Shipbuilders).

1957 'Aspects of propellers for the Royal Navy' by R. W. L. Gawn (Institution of Naval Architects).

1958 'Some recent progress in nuclear engineering' by Sir John Cockcroft (Institute of Marine Engineers).

1959 'Atmospheric imaging systems' by Dr C. R. Burch (The Physical Society).

1960 'Sir Claude D. Gibb—Engineer' by A. T. Bowden (North East Coast Institution of Engineers and Shipbuilders).

1961 'Magnetohydrodynamics' by Professor M. W. Thring (Institution of Electrical Engineers).

1962 'The duty and development of modern power station plant' by F. H. S. Brown (Institution of Mechanical Engineers).

1963 'Spadeadam rocket establishment' by A. B. Mann (Institution of Civil Engineers).

1964 'The high-speed generator—eighty years of progress' by W. D. Horsley (North East Coast Institution of Engineers and Shipbuilders).

1965 'Sir Charles Parsons and the naval architect' by Professor E. V. Telfer (Royal Institution of Naval Architects).

1966 'The prospect for steam propulsion' by Captain N. J. H. D'Arcy, RN (Institute of Marine Engineers).

1967 'The measurement and control of small displacements' by Professor R. V. Jones (Institute of Physics and the Physical Society).

1968 'Sir Charles Parsons and astronomy' by G. M. Sisson (North East Coast Institution of Engineers and Shipbuilders).

1969 'Large turbine-generators—a survey of progress' by Dr A. Frankel (Institution of Electrical Engineers).

1970 'Designing warships for cost-effective life' by Vice-Admiral R. G. Raper (Institution of Mechanical Engineers).

1971 'The linear motor and its application to the tracked hovercraft' by Professor E. R. Laithwaite (Institution of Civil Engineers).

1972 'The development of large wet steam turbines' by N. C. Parsons (North East Coast Institution of Engineers and Shipbuilders).

1973 'The impact of the gas turbine on warship design' by S. J. Palmer (Royal Institution of Naval Architects).

1974 'Eighty years with the steam turbine' by Dr A. W. Davis (Institute of Marine Engineers).

1975 'Light and movement—a lecture demonstration in statistical optics' by Dr E. R. Pike (Institute of Physics).

1976 'Warship design: new concepts and technology' by R. J. Daniel (North East Coast Institution of Engineers and Shipbuilders).

1977 'Power generation in the future' by Dr R. Hawley (Institution of Electrical Engineers).

1978 'Economics of scale in electricity generation and transmission since 1945' by Sir Francis Tombs (Institution of Mechanical Engineers).

1979 'Optics and structural measurement' by Dr J. M. Burch (Institution of Civil Engineers).

1980 'The present status and likely future prospects of the steam turbine' by J. M. Mitchell (North East Coast Institution of Engineers and Shipbuilders).

1981 'Designing ships for fuel economy' by D. G. M. Watson (Royal Institution of Naval Architects).

Presentation of Parsons Memorial Medal

DR J. H. HORLOCK FRS (Vice-Chancellor, The Open University): It is a great pleasure for me to present the Parsons Memorial Medal on behalf of the Royal Society. The history of this Lecture shows a very happy association between the engineering institutions and the Royal Society. Perhaps, as a member of the new Engineering Council, I might wryly comment that the Royal Society appears to have had more success in grouping the Institutions in the 1930s, for the purpose of this Lecture, than the Engineering Council is having in the 1980s.

It is a particular pleasure to me to present this Parsons Medal. I was brought up in the shadow of Parsons. First of all at St John's College, Cambridge, where, surprisingly, this great engineer, Sir Charles Parsons, took the mathematical tripos and became a senior wrangler. Second, at Rolls-Royce, where I worked as a design engineer on axial flow compressors, only to learn that the first axial flow compressor had been designed by Sir Charles at the begining of the 20th century. Strangely, this was one of Parsons' rare failures—his compressor achieved a very low efficiency, and presumably some of the blade rows were stalled.

More recently, I have been privileged to give a television lecture on Sir Charles Parsons and I am now involved in writing a biographical memoir about him for St John's College.

Parsons was a remarkable man. For me he has always illustrated the romance of engineering. What engineer can fail to be moved by the picture of *Turbinia* charging through the fleet at the Spithead Review, with Sir Charles Parsons FRS at the helm and Dr Stoney FRS stoking the boiler down below. Dr Stoney was the second Parsons Lecturer and his lecture, published in the Institution of Electrical Engineers' proceedings, is a great source of information on Parsons' work.

Many distinguished lecturers have followed Stoney and the list includes names such as Guy, Rayleigh, Gibb, Inglis, Seippel and Cockcroft. That distinction has been maintained by Mr Slatter this evening. I offer him warm congratulations and thanks on behalf of the Royal Society and I am pleased to present him with the Parsons Memorial Medal.

MR SLATTER: I thank Dr Horlock most sincerely for being present at the meeting and for presenting the Parsons Memorial Medal. Dr Horlock is obviously a most appropriate person for this task due to his various associations with the work of Sir Charles Parsons in addition to many other activities.

Discussion

CDR J. M. KINGSLAND RN, MIMechE (Head of Marine Gas Turbines, NGTE): In considering the future prospects of the aero-derived gas turbine in marine and industrial applications, Mr Slatter has emphasized the importance of total costs and has addressed at length the reduction of fuel cost by the use of complex cycles. It is perhaps worth further discussing first cost and maintenance, as these must be significant factors affecting the prospects for the aero-derived gas turbine.

It appears that a fundamental problem has arisen in recent years, in that aero requirements have resulted in engines that require very much greater modification to make them suitable for industrial/marine applications. They are far more complex than the early conversion engines, such as the Olympus and Avon, and are therefore more expensive in first cost and upkeep cost.

Higher pressure ratios have given improved efficiency but have also introduced the need for complications, such as handling air bleed and variable compressor geometry, while higher temperatures have further complicated the specialized art of blade manufacture by requiring elaborate cooling passages. Pressure for even marginal reductions in fuel consumption in civil aero-engines has led to many refinements, for example in blade tip and other seal designs. The advantages of reduced fuel consumption have been offset to a large extent by penalties of increased complexity and cost, affecting both first cost and upkeep costs.

It seems possible that a gas turbine designed from the outset for industrial/marine use, without the constraints imposed by aero parentage, could be cheaper and better suited to its application. For example, the industrial/marine engine must have long installed life, and more extensive facilities for *in situ* inspection and upkeep could be incorporated. More difficult fuels must be burned, and such an engine would allow greater freedom to design the combustion system for this purpose.

The description in Mr Slatter's paper of a design study for a 100 MW industrial gas turbine designed on aero lines is very interesting, particularly the features of single compressor/turbine shaft configuration and moderate pressure ratio. Recent divergence of the respective requirements for the aero-engine and for the industrial/marine gas turbine suggests that a parting of the ways is now inevitable; it would be interesting to hear Mr Slatter's views on this; and whether such an approach would be feasible for marine propulsion.

B. M. HUGGETT (Manager, Machinery Dept, British Gas Corporation): The author refers to the role that the aero-derived gas turbine has played in the gas industry. In the UK, the British Gas Corporation has installed to date 45 Rolls-Royce based aero-derived gas turbines on the national gas transmission system. The following comments and observations on the paper are based on the experience gained from the installation and operation of these units in some 15 gas pumping stations built in the last 12 years.

'Unexpected problems'

On page 4 Mr Slatter comments on the emergence of the 'unexpected problem' in his reference to the damaging effect of vortices entering the compressor intake of the Olympus unit installed in HMS *Exmouth* back in 1967. This problem was successfully resolved. It is interesting to note, however, that we are still experiencing the unexpected. At two of the British Gas compressor stations commissioned in 1974, vortices visible to the naked eye, emanating from the plenum chamber/silencer splitters, are believed to have led to considerable inlet guide vane bush wear.

Although this has not caused serious problems to date, maintenance costs are incurred due to frequent bush replacement and there is always the worry that the bush wear will lead to failure elsewhere. Once an installation has been designed and built, it is not easy to resolve the problem without a lot of expense. Therefore it would seem prudent to persuade both the gas turbine manufacturer and the packager of the gas turbine equipment to get together early enough to avoid such problems.

Titanium blades

On page 6 the author refers to the particular advantages of titanium blades that were helpful in overcoming the problems of ice ingestion on Avons. Unfortunately, what looks like a simple remedy for one symptom very often introduces secondary problems. Before the change to titanium blades could be considered successful, Rolls-Royce had to overcome blade lug fixing-pin defects and '00' stage disc-cracking problems. I am glad to say that these have, in the main, been dealt with successfully.

Gas turbine noise

Turning to page 9, the statement on noise from gas turbines appears to be somewhat optimistic. In practice, our experience of installing gas turbines at quiet rural locations in the UK has involved a fair amount of expenditure on noise reduction. The unsilenced noise from a gas turbine does include a characteristic whine from the gas generator and, sometimes, a low-frequency rumbling noise from the power turbine exhaust. I agree that these, and other sources of gas turbine noise, can be silenced by conventional passive means.

British Gas are, in conjunction with Cambridge Consultants Topexpress Ltd, carrying out experiments in active attenuation of low-frequency rumble at one of the British Gas compressor stations. (Active attenuation is the process whereby sound waves of equal and opposite amplitudes are superimposed, such that they cancel each other out and result in noise reduction.) So far these experiments have demonstrated successfully that such a system is technically feasible and could provide an additional technique for dealing with low-frequency noise in future.

Condition monitoring

On page 10 the author predicts expanded use of data-logging and condition-monitoring systems. From a user's point of view, the need for continual improvements in unit availability, and also for maintenance of the maximum unit performance, certainly justifies the development of such systems.

However, the main effort and expenditure in this field appears to have come from the engine users and, of course, the suppliers of specialized data acquisition equipment.

Perhaps Mr Slatter would comment on whether the engine manufacturers should take a more positive lead in this field and, possibly, develop condition-monitoring equipment with inbuilt diagnostic capabilities which they could market as an additional engine feature?

Fuel cost

I agree with the author that even the relatively high efficiency of the current simple-cycle gas turbines leaves the gas turbine at a disadvantage compared with other prime movers and that further improvements in component efficiencies should be made. The implication is that this high efficiency is to be achieved by such features as burnishing of compressor rotor blades and 'superpolishing' of turbine rotor blades, together with other mechanical changes. Would Mr Slatter comment on the extent that such an approach would have in making deterioration in gas turbine efficiency even more sensitive to hours run?

Incorporating gas turbines in combined cycle plant, thus achieving thermal efficiencies in the order of 45%, is becoming increasingly attractive. British Gas are planning to add waste-heat recovery on compressor stations where the load factor and power requirements are appropriate.

CDR R. D. F. COLBY RN, MIMarE (MOD(PE)): In the section headed 'Other fuels and dual-fuel operation', the author argues that the use of crude or residual oils is unlikely for lightweight aero-derivative engines because significant performance deterioration arising from blade deposits would occur, despite the use of fuel-treatment plant. In the next section he points out the influence of increasing fuel costs.

Recent experience in the Falklands indicates that, in periods of tension, supplies of clean water-free fuel will by no means be assured. Equally, there is no guarantee that future warships can be fitted with bulky fuel-cleaning plant nor that it would always run at peak efficiency in the heat of battle.

Would it not be advisable to recognize that financial and practical pressures will make gas turbines that depend on high-grade distillate fuels increasingly unattractive, and to develop combustion and blade systems accordingly?

CDR P. W. W. RIDLEY RN (DG Ships, MOD(PE)): During his excellent lecture Mr Slatter said he hoped that, in the succeeding discussion, some information would be given on how aero-derived gas turbines performed in the South Atlantic. So, rather than asking a question, I am answering one.

During the 4-month period between April and August 1982, 19 ships powered solely by aero-derived gas turbines were deployed in the area around the Falkland Islands. The main engines of all ships fully met their staff requirements; availability remained high throughout the period, and no ship was withdrawn at any stage as the result of a defective main propulsion system.

A number of problems had been expected which, in practice, did not surface. For example, weather conditions, including icing, had little or no effect on the gas turbines, except possibily when stirring up sediment in fuel tanks. It had also been thought that the need to shut down gas turbines to allow routine maintenance to be carried out (including engine changes) would prove debilitating. In practice, however, it was found that the inherent redundancy of both the COGOG and the COGAG fits was such that virtually all maintenance could be completed at, or very near, the specified intervals without interfering with operational availability.

The lessons learnt have been legion: about fuel cleanliness; about logistics; about access for maintenance; and about the need for Marine Engineering Officers to be able to repair in an emergency anything on the engines, including sensitive items in the fuel-control system which would normally be replaced with spares under the 'upkeep by exchange' philosophy. All these are being analysed in detail; but it is reassuring that, in many ways, the design of the next RN marine gas turbine (the SM1A) appears to have anticipated the main problem areas.

Finally, I must mention the varying claims of the 'gas' and 'steam' lobbies. The fact is that both systems performed admirably during the Falklands campaign, and it is difficult to promote the case for one of them without seeking merely to diminish the successes of the other. Nevertheless, when considering the question of vulnerability to action damage, a relatively direct comparison may be made between the experiences of HMS *Glasgow*, a COGOG Type 42 destroyer, and HMS *Argonaut*, a steam-driven Y100 *Leander* Class frigate. Both suffered severe bomb damage in an engine room but, whilst *Glasgow* retained main propulsion power and full manoeuvrability even immediately after being hit, *Argonaut* suffered a main steam failure and shock damage to pipework that put her propulsion machinery out of action for some hours.

Perhaps the most telling example of the redundancy available from a fit of four gas turbines (and of the robustness of the engines themselves) is the experience in HMS *Sheffield*, in which not only were both Tyne engines still fully operational but one was actually running when she finally had to be abandoned, 6 hours after having been struck by an Exocet missile.

J. NEUMANN FEng (Managing Director, YARD Limited, Consulting Engineers): The author's excellent review of aero-derived marine gas turbine development brings into sharp focus the speed of development and application of this means of propulsion: less than 30 years from the first wartime flight of a gas turbine-powered aircraft to the sea trials of an Olympus gas turbine in HMS *Exmouth*. The subsequent development certainly appears to deny the statement by the late Captain Farquhar Atkins that 'The gas turbine is a bird, not a fish'.

Since the mid-1960s, all major RN surface warships have been powered by various combinations of aero-derivative gas turbines in lieu of steam plant. An interesting corollary of this change has been a whole new approach to the design of the propulsion power plant. With steam plant it was customary to design turbines, boilers and propulsion auxiliaries specially for each particular ship application. On the other hand, the gas turbine was available only in one or two discrete power outputs; and the tendency has been to accept these, to tailor the overall propulsion schemes to suit, and to develop and use a range of standard auxiliary machinery which did not need to be developed afresh for each new succeeding class of ship.

The benefits of standardization are obvious; but of course the danger of stultifying progress must be guarded against. It is often a nice judgement whether to accept a tried and proven equipment or to pursue something new and as yet untried but offering better performance and reliability or lower costs.

Regarding the Olympus engine as used in the RN ships, it would be very interesting to hear Mr Slatter's views in respect of the power turbine speed and bearing arrangement; the considerations which led to their adoption, and a comment in hindsight on whether they are still considered to be the best solutions.

The author has been too modest in his reference to the gas turbine assembly (module) shown in Fig. 5 of the paper. Following the early naval application of the gas turbine it seemed evident that the way ahead was to have a complete module with all engine services standardized and integral with the module, rather than to design these specifically for each particular application. The module approach was pioneered by Rolls-Royce and YARD on behalf of the Ministry of Defence and has since been followed by all other manufacturers of propulsion gas turbines. The development of compact module designs for the engines (in which maintenance and removal facilities have been designed in from the beginning) contributed substantially to the appeal of the aero-derivative for power generation in the congested machinery spaces of naval and many offshore applications.

In his conclusions Mr Slatter looks to the continuing expansion in the use of aero-derivative gas turbines in industry and in warship propulsion and outlines hoped-for developments, to some of which he may yet contribute personally. Mr Slatter is to be envied to a considerable extent, since few engineers have been fortunate enough to be involved at the first stage of a new engine development and to see it, in their working life, achieve such world-wide application in so many fields of engineering.

J. HEPPER (Engineering Manager, Industrial and Marine Division, David Brown Gear Industries Limited): I would appreciate the author's comments on the choice of power turbine type and speed for the various engines discussed, particularly with regard to marine applications.

The industrial variant of the Olympus has a two-stage power turbine designed to run at a speed of 3000 rev/min, which is understandable considering the application, but the marine variant has a single-stage power turbine and runs at a much higher speed. It is worth noting that the major US competitor to the marine Olympus has a multi-stage power turbine and operates at 3600 rev/min.

The Tyne engine operates at 14 000 rev/min and the newly developed Spey is still designed to run at a relatively high speed.

This request is made in consideration of the effect of these speeds on the design and performance of the gear units which are being driven by the engines. The number of gear stages, the pitch line speeds, unit efficiency, the frequencies of airborne and structureborne noise are all speed-dependent to some degree. A further area of the installation where engine speed is important is concerned with the achievement of high-speed line assembly balance and vibration limitations when considering the length of coupling assembly, to allow the engine and gear unit to be installed in separate compartments, and the degree of flexibility required to allow for movement of the engine on its mounts during running and under shock conditions.

Author's Reply

In reply to Cdr Kingsland, the pursuit of higher efficiency, through increases in pressure ratio and maximum cycle temperature, inevitably tends to result in greater complexity and engine cost. However, the saving in fuel cost can be much larger, especially where utilization of the engine is high.

While it is difficult to cover all cases, the number of modifications to convert a modern engine, such as the RB211, for industrial and marine use was probably no more than for the earlier Olympus. Although design *ab initio* of an industrial and marine gas turbine, using aero-technology, should result in the best possible machine for the purpose, a large investment is involved for the design, development and tooling for production. This expenditure would not be justified and would increase the product cost unless there was certainty of selling a large number of engines.

In the particular case of the 100 MW gas turbine briefly described in the paper, there is no aero-engine large enough to achieve this output. To be competitive in performance, a purpose-designed engine would need the same basic features, e.g. similar pressure ratio and degree of turbine cooling, as an aero-derived machine. Thus, it seems unlikely that specially designed engines will be produced for applications where a suitable aero-engine exists which can be adapted to meet the requirement.

Regarding Mr Huggett's comments on intakes, the problem experienced in the early operation of HMS *Exmouth*, which is described in the paper, taught the lesson that model testing of an intake duct is a wise precaution unless the configuration is similar to one which has already been used successfully. Certainly, this aspect requires early consideration by all concerned.

The silencing of noise by passive means is least effective at the low-frequency end of the sound spectrum because the length of the silencing system has to relate to the wavelength of the sound for effective attenuation. The development of an active silencing system by generating a noise of equal amplitude and opposite phase appears to offer an attractive solution to this problem. However, every effort should be made to minimize the creation of very low-frequency noise, which is caused by turbulence in the exhaust duct, by care in the design of the exhaust system.

The engine manufacturer certainly should take the lead in health-monitoring arrangements and, indeed, has already given much thought and effort to this subject. While making progress with arrangements which can undoubtedly contribute to the achievement of high availability and minimum maintenance cost, it is also desirable to avoid the introduction of complicated instrumentation which, although practicable, is unlikely to prove cost-effective.

The small but worthwhile advantage in performance which can result from good surface finish of blading is unlikely to be lost in service if the environment is clean or where intake filtration is provided to collect particles larger than about 5 microns.

Mr Huggett is to be congratulated for planning combined-cycle plant where it is justified by a sufficiently high load factor. This surely must be a step in the right direction for the future.

In answer to Cdr Colby, while real advances have been made to render gas turbines and their fuel controls less susceptible to malfunction caused by lapses in fuel quality, the effort along these lines needs to be maintained. This is necessary for the reasons given by Cdr Colby and also because the properties of readily available distillate fuel are changing.

Endeavours over the past 40 years to enable gas turbines to use really low-grade fuels satisfactorily have achieved only a modest degree of success. It has not proved possible to avoid a loss in performance, increased maintenance and sophisticated fuel-treatment plant, all of which are most undesirable in a warship. Furthermore, as refineries strive to obtain the maximum output of clean fuel from each barrel of crude oil, the quality of residual oil will become worse and attempts to use this type of fuel in warships are unlikely to be rewarding.

I am very grateful to Cdr Ridley for the information he presented about the behaviour of the gas turbines in HM ships in the South Atlantic.

The experience related was of great interest and I feel sure that others present would also wish me to thank Cdr Ridley for his stimulating contribution to the discussion.

I thank Mr Neumann for his kind remarks and agree with his comments about marine gas turbines.

I should like to pay tribute to the work done by Mr Neumann and his colleagues in the design of the complete machinery installations using gas turbines and also in providing guidance in the design of the engine modules.

Mr Hepper questioned the choice of power turbine rotational speed and Mr Neumann also raised this issue together with the associated power turbine bearing arrangement. To some extent, the speed is determined by the power of the engine but there is still considerable freedom of choice at the design stage.

The simple single-stage robust power turbine chosen for the Olympus appears to be justified by its requiring minimal attention in service. An alternative is to employ a multi-stage turbine of lower speed with bearings fore and aft supported through the main gas flow passage. As Mr Hepper pointed out, the lower speed can confer advantages in the gearbox and coupling shaft areas. However, such a design almost certainly requires the use of anti-friction bearings which are not readily accessible and the blading has a high aspect ratio and is much less robust. There is unlikely to be much difference in cost between the two approaches, provided that a multi-stage design of turbine is available in the form of the fan turbine of an aero-engine such as the RB211.

Thus, the best choice for the future can only be made by considering these and other factors in relation to a given gas turbine and the type of installation for which it is intended. The optimum solution may lie between the extremes, along the lines of the 2-stage design of power turbine for the marine Spey.

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