The Present Status and Future Prospects of the Gas Turbine as a Prime Mover

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DOOR
R. W. STUART MITCHELL

UITGEVERIJ WALTMAN - HIPPOLYTUSBUURT 4 - DELFT
Mijne Heren Curatoren,
Dames en Heren Docenten,
Leden van de Wetenschappelijke Staf en Studenten,
en voorts Gij allen, die deze bijeenkomst met Uw
tegenwoordigheid vereert,

I am greatly honoured to have this opportunity, following my
appointment to the Chair of Gas Turbines, to maintain the
tradition of the Technische Hogeschool and deliver my inaugural
address to you this afternoon. I have to apologize, that being
British and only recently come from England, I am presently
unable to speak to you in your language and must needs give
my address in English. However I am taking steps to rectify
this gap in my education as quickly as possible.

The subject is "The Present Status and Future Prospects of
the Gas Turbine as a Prime Mover" and I have chosen it
because of its obvious association with the subject of my Chair
and because I hope that such a survey will help you to obtain
an appreciation of the place occupied by the Gas Turbine in
the general field of prime movers.

It is desirable to commence by defining what is meant by the
term "Gas Turbine" in the present context. A good definition
is that due to Hodge (Lately Chief Engineer of Power Jets
(Research and Development) Ltd, London) I quote:

"A mechanical device operating a thermodynamic cycle in
which the working fluid remains wholly in the gaseous phase
throughout, or if any phase change of part of the working
fluid does occur at any point in the cycle, this is not an essential
part of it but is purely incidental. The flow processes in the
cycle must be substantially continuous and not intermittent."

This definition eliminates reciprocating machines and the
"constant volume" combustion cycle whereby combustion takes
place intermittently by explosion in a closed chamber with
considerable rise in pressure. It should be clear that the definition
involves a complete power group and has not the restricted
meaning of the rotary turbine component in which mechanical power is derived from gas expansion through the machine. Nevertheless, this latter meaning, which has become established by common usage, usually and correctly prefixed by the description "exhaust", has its own importance in association with the diesel engine. Either as the power unit for an exhaust driven pressure charger, or as part of a gas-generator engine (both of which conceptions fall outside the scope of the definition) the "exhaust gas turbine unit" has a place in the motive power field which cannot be ignored.

The term "constant-pressure gas turbine" is most commonly employed to denote the type of prime mover covered by the definition, notwithstanding the fact that in 1939 Dr. Adolf Meyer of Brown-Boveri pointed out that this terminology was technically inaccurate.

Although the serious commercial development and exploitation of the industrial gas turbine as a prime mover is essentially post-war and therefore has a history of some 15 years, its technical evolution goes back very much further. Ignoring the crude turbine of Hero of Alexandria of about 150 B.C., which utilized the reaction principle so important in modern turbines and was used, we are told, to move symbolic figures in religious ceremonies, the development can be said to date from 1791. In that year John Barber, an Englishman, took out a patent describing the thermodynamic cycle of the modern gas turbine and suggesting its use for jet propulsion. Stolze, of Berlin, designed the first modern type gas turbine in 1872; on test around 1900 it failed to run under its own power because component efficiencies were too low. In 1884 Parsons suggested the engine in its modern form, but it was not until 1905, in Paris, the result of work by Armentaud and Lemiale, that the first gas turbine, capable of delivering external power, generated 25 h.p. at 4% efficiency.

Holzwarth, of Hanover, designed and built his first 'explosion' or constant volume cycle, turbine in 1908 and between then and 1928, Brown-Boveri Co., of Mannheim, built several, all of which operated with indifferent success. The 'explosion' cycle is now obsolete, and as far as I know, there is no current development.

However, it was not until modern knowledge of aerodynamics was applied to compressor design and modern metallurgy made available high temperature creep resistant alloys, that progress really began to be made. Brown-Boveri & Co. commissioned the first commercial stationary gas-turbine alternator set in 1939 at Neuchâtel, in Switzerland. The first gas turbine locomotive followed and completed its acceptance trials on the Swiss Railways in 1941.

Whittle was pioneering turbo-jet propulsion for aircraft from 1930 onwards, and the first successful testbed run on his engine took place in 1937. Rapid development followed, to a large extent accelerated by wartime requirements, and the first successful jet propelled aircraft flight in England was in 1941.

The wartime aircraft propulsion developments had taken place at an unprecedented pace, and with very heavy expenditure, and in the immediate post-war years there was great impetus in applying this aircraft engine knowledge and experience to turbines for shaft power. I will, therefore, conclude this historical summary by cataloguing a few of the more important "firsts" which resulted:

1947. First gas turbine vessel puts to sea (Metropolitan Vickers).
1950. First gas turbine automobile demonstrated (Rover).
1952. First Atlantic crossing by ship propelled solely by gas turbine power (British-Thomson-Houston).

The basic, simple open cycle gas-turbine comprises a compressor, a combustion chamber and a turbine. In the so-called constant pressure cycle, the compressor takes in ambient air, compresses it to several times its atmospheric pressure and delivers it as a continuous flow through the combustion chamber.

What is called the primary air is normally mixed with the injected fuel (liquid, gaseous or powdered solid) and the continuous burning, once ignition is started, of the fuel in the air stream raises the temperature of the latter. The primary air/fuel ratio and the temperature of combustion depend upon the characteristics of the fuel used, but for most hydrocarbon fuels, the mixture ratio is approximately stoichiometric and the temperature in the region 2000 °C—2250 °C. This is very much too high for the turbine blades and so the greater part of the air supply is used to cool the combustion gases. This 'secondary'
air makes the overall air/fuel ratio for hydrocarbon fuels very weak – between 50 and 250 : 1. Combustion theoretically takes place at constant pressure but, in practice, there is a small fall in total pressure to accelerate the flow. The mixture of the secondary air and the products of combustion is expanded in the turbine and exhausted to atmosphere. Approximately two thirds of the power developed by the expansion through the turbine goes to drive the compressor and auxiliaries and the remaining third is available on the turbine shaft to provide external power, i.e. the net output of the set.

It follows that, if either the compression or the expansion process is particularly inefficient relative to the ideal, the net output and the overall thermal efficiency will be seriously affected. In the early machines, compressor and turbine component efficiencies were low and hence the engines either failed to run "self-supporting" if the net output was negative, or produced power at very low efficiency and specific output.

The basic simple cycle, which I have just described, will give overall thermal efficiencies up to rather more than 20%. (Excluding aero engines where the total output may not be in the form of shaft power.) This compares with the corresponding value 25% for a typical spark ignition petrol engine and 40% for a modern high efficiency diesel engine. The turbine inlet temperature need not exceed 750 °C. Under these conditions, and at a pressure ratio of say 6 : 1, the specific output, which determines the air mass flow rate, and hence, for given inlet conditions, the size of the machine, would be of the order 70 b.h.p./lb. of air per sec.

The component efficiencies and the turbine inlet temperature have a marked influence on the overall thermal efficiency. The efficiencies of present day axial flow compressors and turbines (provided they are not too small) are between 85% and 90%. Radial flow machines are generally less efficient. Further advances in improvement on these figures will probably be slow. The turbine inlet temperature is mainly determined by the availability of special steels and alloys, for the turbine blades and disc, which will have sufficient strength and resistance to creep, at the inlet temperature selected, to give safe and reliable operation of the turbine. Intensive and continuous development is proceeding to produce cheaper and better alloys.

Alternatively, turbine cooling is being very carefully studied to allow inlet temperatures of say 1,100 °C to be used, but has not yet been exploited to any extent, commercially. Pametrad has a cooled turbine operating satisfactorily at 1,200 °C but this is a research machine. However, progress in cooling is expected to be marked during the next five years and ultimately turbine inlet temperatures of around 1,650 °C may well be realised. This could make the simple open cycle machine competitive in thermal efficiency with other prime movers provided the losses inherent in cooling are kept low.

One method of improving the thermal efficiency of the simple cycle is to preheat the air, before it enters the combustion chamber, in a heat exchanger or regenerator, heated by the turbine exhaust. The specific output, but not necessarily the efficiency, may be improved by adopting intercooling between compressor stages. This reduces the work input to the compressor for a given mass flow of air and pressure ratio. The limit is reached when the compression becomes isothermal, i.e. there is no temperature rise associated with the compression process.

Similarly, the work-output of the turbine may be increased, but not the thermal efficiency, by dividing the expansion into stages and 'reheating' the gas between them. The theoretical limit of reheating would, of course, be an isothermal expansion at the turbine inlet temperature.

Both the specific output and the overall thermal efficiency of the plant can be appreciably improved by a properly integrated and co-ordinated combination of the three processes, viz., regeneration, compressor intercooling and turbine reheating.

The simple cycle arrangement has a poor part load efficiency. This arises because of the high proportion of the turbine output which is needed to drive the compressor and inability to vary the mass flow through the compressor other than by varying the speed and thus the pressure ratio. Considerable improvement can be obtained by adopting a twin shaft arrangement with two turbines. One turbine drives the compressor as before, but the second turbine, on a free shaft, is used for the external power take-off. In this way the speed of the compressor and its driving turbine can be independent of the speed of the power-turbine.
Many other cycle variations are possible, and the more complex can achieve overall efficiencies of 32%, whilst there is no doubt that values of 35% are possible with the present knowledge and experience. Specific weights of the simple low efficiency machines can be as low as 1 lb./h.p. This compares with the very best high speed diesel engine practice of about 6 lb./h.p.

Gaseous fuels and distillate fuel oils have proved eminently suitable for the gas turbine but a number of problems remain unsolved in the burning of residual fuel oils and solid fuels. Good combustion can be achieved with non-distillate oils under properly regulated conditions, but ash deposition presents difficulties. For every ton of fuel burnt, between one and two pounds of ash enter the turbine, depositing on the blades and clogging gas passages. The degree of deposition may depend on the fuel characteristics, the operating conditions and the turbine design and, in general, it is highest when the ash is molten. The melting point temperature depends on the fuel composition, but increase in turbine temperature aggravates the situation and above about 675°C there will in addition almost certainly be blade corrosion. Vanadium and sodium compounds are mainly responsible for this corrosive attack. The rate of deposition is influenced by the pitching of the turbine blades and is higher, the closer the blades.

The best line of attack appears to be 1) development of additives to defeat the bonding action and raise the melting points or 2) deliberate creation of conditions that form hard carbon around the ash. The best additive so far tried is aluminium silicate or Kaolin, but there is a danger that it may clog the smaller passages in burners, etc., since it is insoluble in the fuel. Also tried with some fair degree of success have been direct cleaning methods by the injection of slightly abrasive scouring powders into the gas stream. A persistent difficulty is to achieve consistent results between different fuels, operating conditions and turbine designs and the final solution of the problem is still some way off.

The burning of solid fuels, such as coal and peat, presents its own difficulties, and until a few years ago it was receiving a great deal of development time, effort and money in the U.S.A., Canada and the U.K. Recently there has been very little published on these projects and at least three of the major ones are known to have been deferred or abandoned. Considerable progress has been made in Western Germany in burning coal and several semi-experimental plants are in service with encouraging results.

Since gas turbines have been and are being built in powers ranging from 50 s.h.p. – 40,000 s.h.p. for industrial purposes, the potential field of application is very wide indeed, covering automotive, rail traction, marine propulsion and auxiliaries and stationary power generation. In none of these, however, is the gas turbine established except for certain specialised stationary power duties which I will discuss later. In the field of aircraft propulsion the situation is entirely different. Here the gas turbine is completely established, both in turbo-jet and turbo-prop forms for practically all military 'planes and particularly in its turbo-prop form for medium and large civil air liners and long range freight 'planes. The criterion for aircraft propulsion is the speed, at which the 'plane is designed to fly. The jet turbine is usually not justified if the speed is less than say 300 m.p.h.

In nearly all western countries it seems to have been established that the most economical means of base load electrical power generation is by the large steam turbine-alternator sited in central power stations near sources of fuel supply and either coal or oil fired. Distribution is by means of the "grid" system. The trend is towards larger and larger single units and higher temperature and pressure, steam conditions. This is illustrated, for U.K. conditions, by the fact that whilst 12 years ago 50 MW was considered as the standard size of set, today 200 MW sets are being commissioned and in 1965 it is planned to be installing 500 MW sets. The thermal efficiency of these large sets is of the order 33% and for the future it is expected that the 500 MW sets will achieve 35%. Coal firing is a practical possibility and is planned for one or two new U.K. stations over the next few years.

The straight gas turbine does not really compete in this field for at least two reasons. Firstly, as we have seen, the burning of the non-distillate residual fuels, essential to the economic justification of the gas turbine for base load power generation, has not yet been developed to the point of reliable trouble-free
operation. Secondly, there is the size and power – output of individual units, - 30 MW is currently considered the upper limit and the production of units of capacity greater than 50 MW is considered improbable in the foreseeable future.

It seems, therefore, that in the central power station with "grid" distribution, the steam turbine will continue to hold its own until nuclear power supplants it, and this latter development can now be said to be proceeding more slowly than was originally anticipated. There may be an application for the gas turbine as the final mechanical power conversion in nuclear power installations but this will depend upon a variety of factors and is most likely in the smaller sized plants.

Where the "grid" distribution system is uneconomic or unavailable, there may be a requirement for relatively small base load power stations of say between 5 MW and 40 MW. Under these conditions the steam turbine, in many instances, has to give way to the diesel alternator or free piston alternator from economic considerations. The constant pressure gas turbine, unless special circumstances exist, is still unlikely to be used for this duty because of its unsolved residual fuel problem.

In circumstances where fuel costs are not the decisive operational consideration, and this is frequently the case where gas is available, or where the liquid fuel available does not give rise to ash deposition problems, the constant pressure gas turbine becomes a very competitive and attractive installation. A major contributory factor to this state of affairs is the low maintenance costs of the gas turbine. Maintenance costs for Brown-Boveri gas turbines operating over fairly long periods, in industrial service in power stations and steel works have been published. The units range between 1,600 kW and 27,000 kW and use Bunker 'C' fuel oil, blast furnace gas or natural gas as fuel. The specific maintenance costs quoted, vary between 0.00617d. per kW-hr. for the 5,400 kW set at Dudelange Steelworks, Luxembourg, burning blast furnace gas, to 0.02113d. per kW-hr. for the 13,000 kW set at Beznau power station, Switzerland, burning Bunker 'C' fuel oil.

Comparable figures for a diesel engine power station have been published. In the Peel, Isle of Man, generating station where there are 9 diesel engines of approximately 10,000 kW total installed capacity and which is the largest completely diesel station in the U.K., a figure of 0.095d. per kW-hr. has been quoted. This is 15.4 times the lower figure for the gas turbine and 4.5 times the higher figure.

If the above special fuel circumstances are combined with limited, or no supplies of cooling water, the gas turbine achieves a virtually unassailable competitive position. This situation obtains frequently, for example, in the oil fields and on pipeline pumping installations.

The cost of providing conventional generating plant to meet short term peak demand is high and it also requires qualified and experienced staff to man the power stations. A possible solution to the two problems of reliability of supply and low cost peak generation is the provision of a plant having the following characteristics:

1. Low capital cost.
2. Absolute reliability.
3. Quick starting ability.
4. Simplicity and ease of installation.
5. Automatic starting and running under remote control.

Fuel costs are a secondary consideration. This application is ideally suited to the simple open cycle, highly rated constant pressure gas turbine and such units are finding increasing use for this purpose.

I was privileged, last December, to be present at the opening ceremony of the world's first unmanned, remote controlled power station. The ceremony took place in Bristol in the S.W. of England, although the station is sited at Princetown, in Devonshire, over 100 miles away.

A version of the well tried Bristol Proteus turbo-prop aero engine, which powers the Bristol-Britannia airliner, has been adapted to a 3 MW alternator set. The dialling of a coded telephone number in the Electricity Headquarters in Bristol starts or stops the plant and complete control is effected over the public telephone system. Thus the power station can be put on load, stopped or interrogated as to running conditions for the cost of a trunk telephone call. The set can be on full load in 1½ minutes from being called. If an alarm condition develops in the station, or the plant shuts down for any reason, the control equipment will automatically put through a telephone call to the Control Centre, announce its identity in its own
pre-recorded voice and give the duty engineer information concerning running conditions or the reason for the shutdown, if such has taken place.

The plant is simple and reliable; it weighs little more than a ton and requires no cooling water. The station is completely unmanned and will only have routine visits from a service engineer four times a year. The overhaul period for the plant is expected to be once every 10 years. Although the running costs are high, (the specific fuel consumption is 0.575 lb/s.h.p.-hr. and the fuel distillate diesel fuel, i.e. gas oil), this is outweighed by the low capital cost, which is about £25 per kW, against £50 per kW for conventional steam turbine equipment and £100 per kW for nuclear power.

A second similar set is to be installed in another district in Devonshire, and Bristol Siddeley Engines Ltd. have, under development, a 15 MW emergency and peak load set based on the Bristol Olympus aero-gas turbine which powers the Vulcan bomber.

For merchant ship propulsion, marine diesel engines in the power range 4,000 s.h.p. — 20,000 s.h.p. are normally low speed direct drive engines, operate quite satisfactorily on residual fuels and are direct reversing. The past ten years have seen very substantial progress on this type of engine — the burning of residual fuels and turbocharging, using exhaust gas turbochargers, giving lower specific weights and higher output per cylinder. Notwithstanding this, the further development potential still remains high. Higher speed diesel engines requiring speed reduction gears to the propeller shaft are, for the most part, confined to the horsepower range below 4,000 s.h.p. and may or may not be direct reversing. The ability of engines to burn residual fuels reduces as the engines become smaller and the crankshaft r.p.m. becomes higher.

Steam turbines and gas turbines, even in the higher horsepower ranges, run at higher r.p.m. than the highest speed diesel and consequently a reduction gear to the propeller shaft is always necessary. Reversing in steam turbines is usually obtained by having one or more 'astern' stages on the main rotor shaft, but because of the near-vacuum conditions existing in the casing of a steam turbine, the astern stages are not 'churning' or subject to high windage losses when the turbine is operating 'ahead'. In the gas turbine, if the same method of obtaining reverse is adopted, the vacuum conditions do not exist and the windage losses could be as high as 10%. Close fitting, movable shrouds have been developed and also a damper on the astern turbine outlet can be fitted and these may reduce the losses to 2.5—3.5%, but even so it is a loss which, because of the gas turbine's already low efficiency, can be ill afforded. A reverse gear incorporated in the reduction gear is an alternative, but a very expensive one, as is also the use of the controllable pitch propeller. This latter would appear to be the technical solution to the problem but, in addition to the cost difficulty, there undoubtedly exists considerable prejudice in shipping and marine engineering circles towards the controllable pitch propeller, particularly as applied to ocean-going ships.

From the aspect of reliability and maintenance requirements the gas turbine should be satisfactory, but progress will be slow until the fuel problem is solved, together with the application of cooling to give better thermal efficiency combined with longer life. In the marine world a lifetime of 100,000 hrs. is expected from propulsion equipment.

The position for the future seems to be that for the really large ships, the steam turbine will remain the most favoured propulsion system. In ships of from 4,000—20,000 s.h.p. the gas turbine has an excellent opportunity to challenge increasingly, the diesel engine as soon as solutions to technical problems emerge. In smaller ships the situation could be equally promising, particularly since the smaller diesel engines are not so well able to burn residual fuels.

If and when nuclear propulsion becomes a commercial reality, it is quite probable that the gas turbine will find a place in such propulsion schemes. In contra-distinction to merchant vessels, naval ships cruise at about half their maximum speed thus requiring about 12% of the total installed propulsive power, and these conditions may exist for up to 70% of the vessel’s total operating life. The situation can be illustrated by considering the case of a steam turbine powered 60,000 s.h.p. destroyer with a machinery weight of 16 lb/s.h.p. If the top 42,000 s.h.p. of the steam machinery were to be replaced by relatively short life packaged gas turbine plant with specific weight between 0.75 and 2 lb/s.h.p. there
could be a saving in machinery weight of some 260 tons and perhaps a reduction in machinery length of the order of 10 ft.
The 18,000 s.h.p. of steam turbine machinery remaining, would give economical cruising. The short life aspect of the gas turbine requirements would enable higher than average thermal efficiency to be obtained from the simple open cycle machine and considerations of the combined weight of machinery plus fuel would show that the ship could have a substantially increased radius of action at full power.

This is in effect a "peak load" application of the gas turbine and all the advantages appertaining thereto remain valid. A number of ships of the British and American Navies have been modified in this way and it is understood that they are giving satisfactory service.

At first examination, the gas turbine should be potentially, very suitable for locomotive propulsion, particularly if a two shaft turbine is used so that the improved part load performance which this arrangement gives can be combined with the favourable torque characteristic of the turbine drive. The competition today comes from electric and diesel locomotives, which are now rapidly replacing the steam locomotive all over the world.

Since the torque characteristics of the diesel engine are not inherently suitable for traction purposes, electric or hydraulic transmissions are employed to provide the necessary starting effort and transmission losses reduce the efficiency throughout the load range. A straight gas turbine with mechanical gear transmission can meet the requirements, particularly if the power turbine is designed to give a high starting torque. This can be done but at the expense of a slight loss of efficiency at full load. Unfortunately, the lower gas turbine efficiency, compared with the diesel engine, is not negated by the higher transmission efficiency. This means that to be competitive under normal conditions the gas turbine locomotive should be able to burn residual fuels.

As might be expected, gas turbine locomotive development is most advanced in the U.S.A., where some 40 machines are running. These are performing with fair success, but are still far from presenting a challenge to the diesel-electric type. A disappointing aspect of the U.S.A. development is that the gas turbine is coupled to electric transmission, thus eliminating one of the principal advantages which the gas turbine has to offer for traction. One can only assume that lack of experience with high power mechanical transmission and the desire to limit the number of problems at any one time has resulted in priority being given to the development of the engine, as such.

The gas turbine as an automotive power unit has not made the progress which was confidently predicted ten years ago. The technical problems of the gas turbine application have not been solved as quickly as had been expected and, where technical progress has been made, production problems have intervened to delay the commercial exploitation.

The advantages of the automotive turbine are very similar to those for rail traction. The favourable torque characteristics simplify the transmission and for road vehicles, a two speed and reverse gear box should suffice. This is important when the trend in the vehicle field is presently towards automotive transmissions, which are expensive, complicated and frequently, when they incorporate hydraulic units, of relatively low efficiency.

A regenerator is necessary, in the automotive application, to improve the fuel consumption and at the moment nothing suitable is available and adequately developed for production. A two shaft arrangement or similar is necessary for part load operation.

In addition to high fuel consumption there are two outstanding disadvantages yet to be overcome; the provision of some substitute for the engine braking of the reciprocating engine and improvement in the response to the fuel control. This latter arises from the requirement of a road vehicle to have adequate acceleration in heavy traffic. The gas turbine is deficient in this respect because of inertia of the compressor-turbine unit and the thermal capacity in the regenerator.

In this application more than any other, economics are the predominant consideration. When it is realised that at least one engine builder in the U.K. was a short time ago producing 600 automotive diesel engines per day and the cheapest of these sells at about £3 per h.p., the magnitude of the competition will be appreciated. Again, consider a large fleet omnibus operator with say 500 buses; a 10% increase in fuel consumption could mean £35,000 higher operating costs per year – a serious consideration.
For these reasons I think that the first applications of the automotive turbine will be to heavy earthmoving equipment and off-the-road vehicles. Later, heavy trucks might follow, but I do not foresee gas turbine engined motor cars for the next ten years, if at all.

For the propulsion of fixed wing aircraft the gas turbine jet engine and the gas turbine propeller engine are steadily displacing the reciprocating piston engine in all but light and medium sized commercial aircraft. This is primarily because of the lower combined weight of engine and fuel and reduced maintenance requirements compared to the piston engine. The gas turbine is thus completely established in aviation and today in terms of annual turnover or horsepower installed this is the largest application.

With regard to the future, I can do no better than quote from a recent lecture by Dr. S. G. Hooker, the eminent British aero gas turbine designer: Thrust has increased twenty fold in the past 20 years and recently thrusts in excess of 20,000 lb. from developments of the Rolls-Royce Conway and the Bristol Siddeley Olympus engines have been announced. It does not seem likely that thrusts much larger than this will be required for subsonic aircraft in Britain but for supersonic military aircraft a boost in thrust by means of afterburning or reheat may be necessary. Thrust exceeding 30,000 lb. under sea-level static conditions can be made available from engines of the types mentioned above.

Specific fuel consumptions between 0.7 lb./lb. thrust and 0.8 lb./lb. thrust were obtained in engines with axial compressors in the early 1950s. In a design of engine later than the Conway, in which there will be three times as much by-pass air, specific fuel consumptions between 0.6 and 0.5 lb./lb. thrust developed will be achieved. By raising the compression ratio of this engine a value of less than 0.5 can be obtained. Such engines are real ducted-fan engines, and the development of this type will form the main effort of most aircraft engine companies in the next few years. The advantages of the ducted-fan engine over the conventional jet for civil aircraft are threefold: a lower noise level for a given thrust, a lower specific fuel consumption under cruising conditions, and a greater thrust output for a given weight of engine.

Thrust/weight ratio has increased from rather less than 2 lb. for each lb. of engine weight in the early Whittle centrifugal engines to between 6 and 7:1 in the Bristol Siddeley Orpheus engine in 1956.

In connection with the future of engines for supersonic flight, Dr. Hooker thinks in terms of the ramjet engine. The compression ratio of modern jet engines is of the order of 12:1, and if a similar compression ratio can be obtained by forward speed alone, then a considerable simplification can be effected by eliminating the compressor and turbine of the normal jet engine. So far ramjets have only been used for missile propulsion, but it is considered that their light weight, simplicity and inherent reliability will commend them more and more for use in aircraft as the speed of transport planes increases to three or four times the speed of sound.

If we consider, for a moment, the exhaust turbocharged, two cycle diesel engine, it has three basic components — the conventional reciprocating piston engine, an exhaust turbine fed by the piston engine exhaust gases and a rotary compressor driven by the turbine and supplying supercharging air to the pistons engine cylinders. It has been shown that, for this type of engine, there comes a supercharging air pressure whereat the power generated by the piston engine section just balances that required to drive the compressor. If, at this point, these two components are mechanically connected, the turbine then becomes free to supply the external power previously taken from the engine crankshaft, and the set constituted by the diesel engine and compressor has become a power gas generator.

The only gas generator or "gasifier" in current full scale production has taken the form of a horizontal opposed-piston two stroke diesel cylinder. Attached directly to the diesel pistons, in place of a connecting rod and crankshaft, are compressor pistons working in a cylinder larger in diameter than and co-axial with, the diesel cylinder. The compressor scavenges and charges the diesel cylinder and the exhaust gases are led to the power turbine. This combination of gasifier and turbine is called a "free piston engine", and a number of gasifiers can be connected in parallel to a single power turbine.

The arrangement has advantages over either the diesel engine
or the constant pressure gas turbine, in so far as the overall thermal efficiency is close to that of the diesel engine, whilst the operating characteristics are those of the gas turbine. The gasifier has been found insensitive to fuel quality and therefore residual fuels can be burnt, whilst the relatively low exhaust temperatures into the turbine eliminate ash deposition problems. Amongst the disadvantages is poor part load efficiency, the fairly complex control system required between the gasifier(s) and the turbine and, of course, the fact that the gasifier is a relatively heavy and complicated component which requires periodic maintenance if it is to retain its reliability.

The free piston engine shows great promise and is slowly becoming established as a competitive prime mover, particularly in stationary power generation, and, to a lesser extent, in marine propulsion.

In concluding this survey, I will endeavour to summarize the present situation and indulge in that highly dangerous activity of predicting possible future developments. The power range, presently covered by the constant pressure gas turbine, viz. 50 s.h.p. – 40,000 s.h.p. in single units, is unlikely to be extended very much at either end. Thermal efficiencies presently obtainable, range from about 20% for the simple cycle without such components as heat exchangers, intercoolers or reheaters, to 32%–35% for the more complex cycles, with these and other additional components. It should be remembered, however, that for any prime mover, thermal efficiency by itself is rarely the decisive factor in any given application. The total specific cost of power generated is normally the criterion and this involves consideration of capital cost, total fuel and operating costs, maintenance costs, etc. In respect to the first of these, the gas turbine can be very competitive with comparable prime movers, provided the simpler type of installation is chosen. If this is done, then at present the thermal efficiency will be low, and because the technical problems of operating on the cheaper residual fuels have not yet been solved, fuel costs are high. Fuel costs can also be reduced by raising the turbine inlet temperature and turbine cooling will permit very substantial increases, ultimately perhaps up to even twice the present values. Research on both these problems is currently being carried out, and there is every reason to believe that the next five years will see major advances. Maintenance costs with suitable fuels are now lower than for comparable prime movers, and it will be one of the objects of research and development to maintain these highly satisfactory conditions, whilst enlarging the fields of application of the machine. Thus, there seem to be good prospects of the gas turbine in the next five to ten years, becoming an established prime mover in the fields of stationary power generation up to say 30 MW, in marine propulsion up to 20,000 s.h.p., probably in association with the controllable pitch propeller, and in railroad locomotives with suitable mechanical transmission.

In considering the prospects of any one form of prime mover it is necessary not to blind oneself to the fact that simultaneous development will be taking place in competitive machines. This is indeed so for the diesel engine, the free piston engine and the steam turbine. For the first I foresee ever increasing specific output and higher speeds with continuous trend towards the compound engine, utilizing the exhaust gas turbine. For the second, which is really on the threshold of its development and can be regarded as a variation of the straight gas turbine, I anticipate consolidation of its attractive features and characteristics and elimination of its present "teething troubles" when it will continue to establish itself in much the same fields as the gas turbine. For the steam turbine it appears that the trend will be towards bigger individual units and higher temperature and pressure, steam conditions, which will gradually take this prime mover out of the horse power range in which it is expected the gas turbine will find its best performance.

Thus I do not think any one prime mover will dominate the field. All have their advantages and disadvantages and their special characteristics. It is my opinion that within the next five years, those of the gas turbine, existing and to be developed, will ensure its competitiveness, its fair share of the markets available and a steadily increasing number of satisfactory installations covering a wide range of applications.

Zeer Geachte Dames en Heren,

On this occasion, of entering into the duties of Professor of Gas Turbines in the Technische Hogeschool, I would express
my humble thanks to Her Majesty Queen Juliana, by whose Royal Decree I hold my office.

*Mijne Heren Curatoren,*

I have been greatly honoured by the confidence you have shown in me in recommending me to an ordinary professorship in the Technische Hogeschool. It will be, henceforth, my constant endeavour to justify that confidence and to help to maintain the dignity, traditions and reputation of this great University.

To your eminent President, Dr. Den Hollander, an engineer of great international reputation, I would say: "thank you" for his never failing courtesy and encouragement to me since I came to Delft.

*Dames en Heren Hoogleraren,*

I am privileged to be your colleague.

*Mijne Heren Hoogleraren van de Afdeling der Werktuigbouwkunde en leden van de wetenschappelijke staf,*

I have appreciated the courtesy I have received and the friendly atmosphere which existed all through the negotiations culminating in my appointment, and likewise since I came to Delft and took my place as a member of the Department.

I thank hooggeleerde Korter for the pleasant way in which, as Chairman of the Department, he conducted the negotiations, for his personal welcome to my wife and myself on our arrival in Holland and for his guidance and advice since I joined the Department.

To the members of the Mechanical Department I give my assurance that I look forward to collaborating with you in furthering the work and aims of the Department.

*Hooggeleerde De Klerck,*

It gives me great pleasure to find that my closest collaboration will be with you. It is many years since I first became acquainted with your activities in the internal combustion engine field and

I am sure that our future work together will be happy and mutually rewarding. I also thank you for the very pleasant welcome you have extended to me.

*Medewerkers van de Afdeling Personeelszaken,*

My wife and myself appreciate the help which we have had from you under the leadership of Mr. Buitenhuis, in finding us very satisfactory housing accommodation which has greatly smoothed our happy "settling in" after our arrival in Delft.

*Dames en Heren Studenten,*

It is the general impression that a University teacher, in directing the work of his students, gives a great deal and receives relatively little in return. This has not been my experience in the past and I have found stimulating my contact with young, active and intelligent minds. I am confident that this experience will continue here in Delft. Further I am quite certain that, as we proceed together with our investigations in the field of technology, the result will be mutually beneficial, and I can assure you that, for my part, I am going to enjoy very much our forthcoming association.

I must confess that my regret at my inability meantime, to speak to you in Dutch is somewhat relieved by the knowledge that in my small way I will be contributing to the improvement of your English. Fluency in other languages besides your own, and in technology particularly, in English, is almost essential in this modern world of ever increasing speed of travel and interchange of contacts.

I have spoken.