

SECTION 9, CHAPTER 1

GAS TURBINE FUNDAMENTALS

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Introduction

1. Gas turbine power units are a relatively modern development which, since their development to the fully operational stage, have been widely applied. Initial development was aimed at the production of aircraft propulsion units which would enable aircraft makers to obtain better performance than was being obtained by the use of piston engines. Intensive development has resulted in the large piston engine being almost entirely superseded by the gas turbine as an aircraft propulsion unit.
2. Although the gas turbine power unit is particularly suitable for aircraft operating at high speeds and high altitudes, it has various other applications such as railway, marine, electricity generation and other stationary uses (Fig. 1). At present considerable research is taking place directed towards its use as a power unit for road transport vehicles.
3. An advantageous feature of the gas turbine unit is that within a considerable range it can quite readily be scaled up or down in size and output. A result of this, and one with which the general engineer will come into close contact, is the use of a small gas turbine

mounted on a trolley to provide a mobile unit for starting the large gas turbines used for aircraft propulsion.

4. Gas turbines are engines which produce power smoothly and continuously in a similar way to the early wind and water wheels (Fig. 2). Compared with the reciprocating type and its intermittent power impulses, the gas turbine has inherent advantages such as freedom from vibration and high power/weight ratio. Why then was the reciprocating type developed in preference to the turbine? The broad answer is that metals which would withstand the high temperature conditions met within the turbine were not available at that period.

5. Briefly, the gas turbine produces power continuously in the following manner. The working medium is air, which is compressed and then heat is added by the burning of a liquid hydrocarbon fuel. Expansion of the compressed and heated air through a turbine produces mechanical power (Fig. 3). The design of the engine varies with its particular application; one important factor is whether the requirement is for maximum thrust or for mechanical energy at the output shaft.

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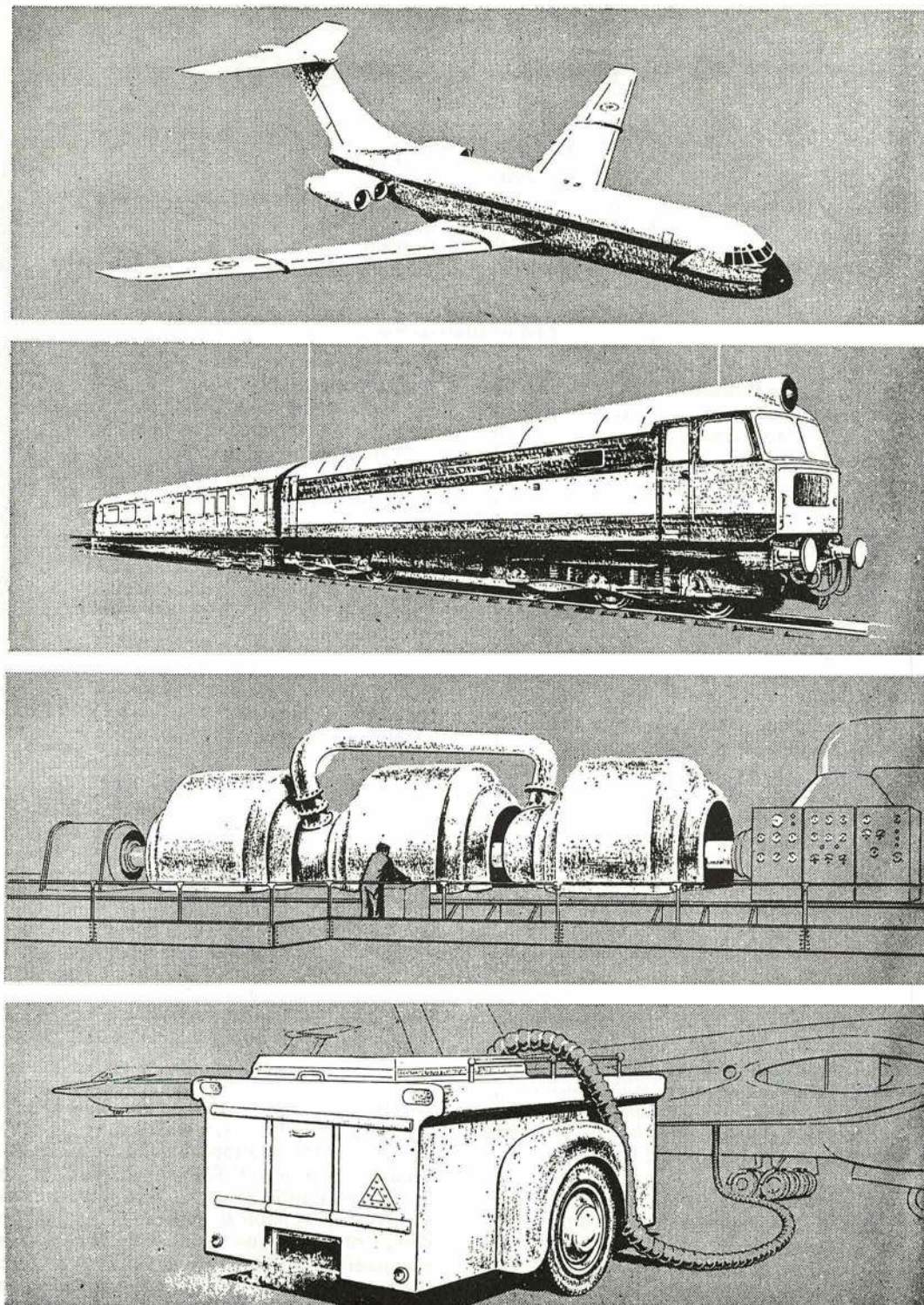


Fig. 1. SOME GAS TURBINE APPLICATIONS

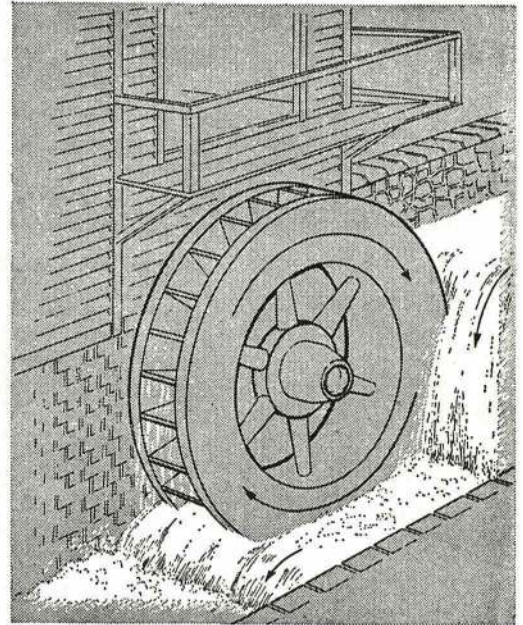
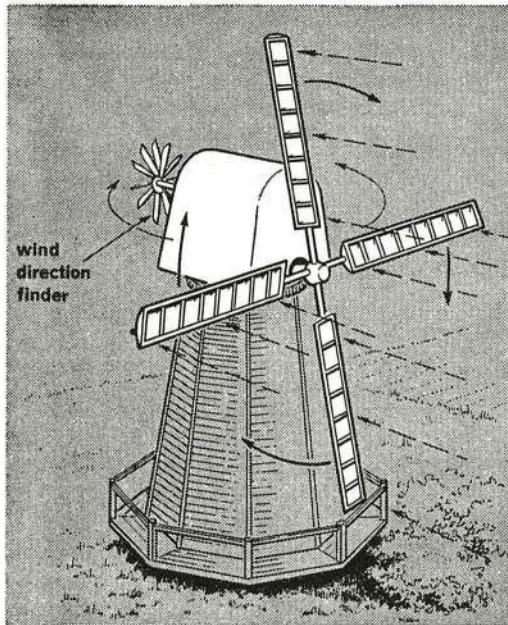


Fig. 2. WIND AND WATERWHEELS

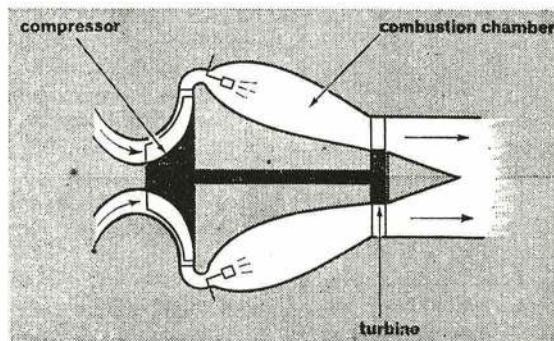


Fig. 3. SIMPLE TURBINE

Principles

6. Understanding of the principles on which turbine engines work can best be obtained from a study of the development of the jet propulsion engine. Firstly, we must remember Newton's third law of motion which states that "for every force acting on a body there is an equal but opposite reaction" because jet propulsion is a practical application of this law. A jet engine produces thrust in much the same way as a propeller/piston engined unit. They differ in that the propeller produces a small acceleration of a large weight of air, whilst the jet engine achieves a large acceleration of a small weight of air (Fig. 4).

7. The equal but opposite acting force to the force required to produce the rearward acceleration of the air is the force which, in the case of the jet engine, acts on the inner parts of the engine and thus produces forward motion.

8. This action can be shown with the aid of a toy balloon. Inflate the balloon and whilst the opening is sealed the pressure will exert an equal force in all directions on the inside wall. When the air is released the balloon moves rapidly away in the direction opposite to the outlet where the jet of air issues. The rotating sprinkler that is often seen at work

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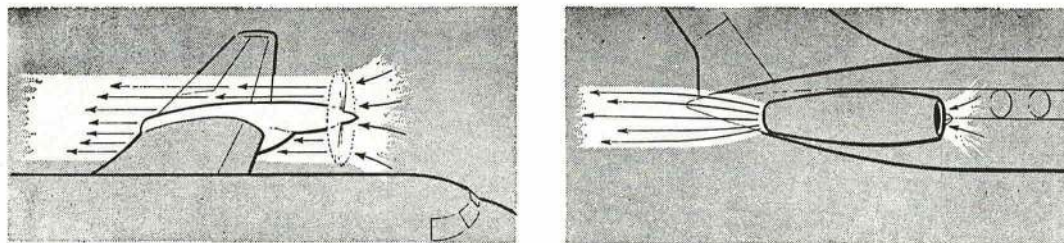


Fig. 4. PROPELLER/JET COMPARISON

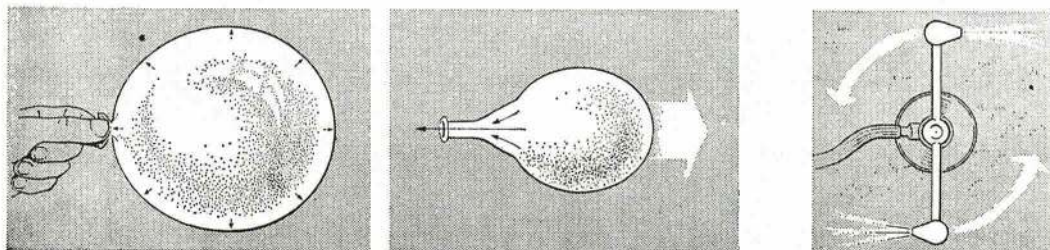


Fig. 5. PRINCIPLE OF REACTION

watering lawns and gardens is another practical example of this principle. Rotation occurs because of the reaction to the jets of water (Fig. 5).

Methods

9. There are various types of jet engine which differ only in the way in which the engine supplies and converts the energy into power.

10. **Ram Jet.** This type (Fig. 6) is the simplest of all jet engines. It has no rotating or reciprocating parts and consists of an aerodynamic duct having a divergent forward

end (entry) and a convergent or convergent/divergent rear end (exit). This construction causes the air which enters to decrease speed and increase pressure. Heat energy is then added by the burning of fuel, and the expanding gases accelerate out through the convergence at the rear to atmosphere. It will be realised that the ram jet needs initial forward movement before it can produce any thrust and thus it is impracticable for ground equipment usage.

11. **Pulse Jet.** This type of engine (Fig. 7) is similar to the ram jet but produces power intermittently. Because higher pressures than

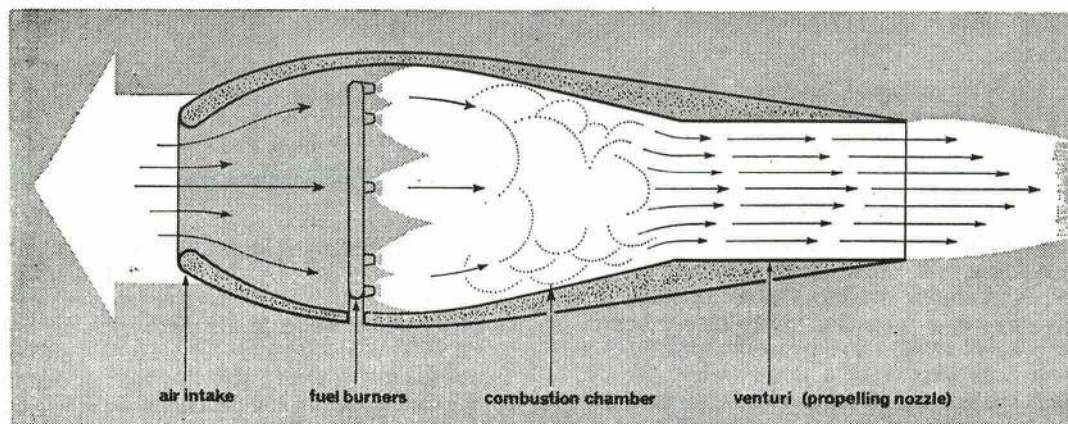


Fig. 6. RAM JET

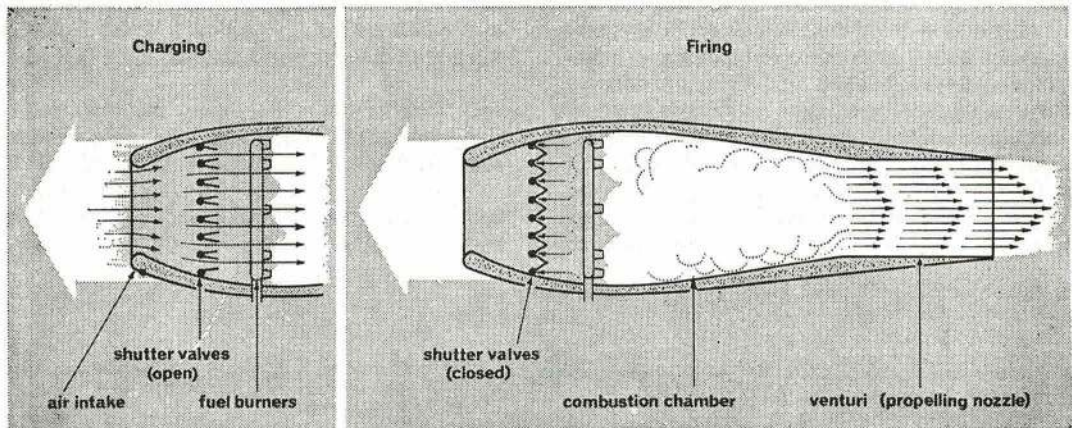


Fig. 7. PULSE JET

those which occur in the ram jet are achieved the construction is more robust. Non-return valves which are spring-loaded in the open position are fitted at the inlet to the duct. Air passes through the open valves into the combustion chamber where it is heated by the burning of fuel. The consequent expansion and rise in pressure closes the valves and the expanding gases are ejected rearwards. This ejection causes a depression which allows the valves to re-open and admit a fresh charge and so the cycle is repeated. The frequency is dependent on the design of the duct, one particular example being 2,800 cycles per minute. Among other disadvantages this type has a high fuel consumption and its performance is inferior to that of a modern gas turbine engine.

12. Gas Turbine. The main drawback of the ram and pulse jets is that forward movement is required to induce a flow of air into the intake and this is overcome by the use of a gas turbine (Fig. 8). This type of engine is able to run while stationary by using a turbine driven compressor which creates an area of low pressure to exist at the air intake and causes air to flow into the engine. The engine consists of two main rotating components, a **compressor** and a **turbine**, and one or more **combustion chambers**. This is the basic layout and there are quite a few detailed mechanical arrangements for particular applications.

GAS TURBINE ENGINES

Compressor Assembly

13. The purpose of the compressor is to induce a continuous flow of air into the air

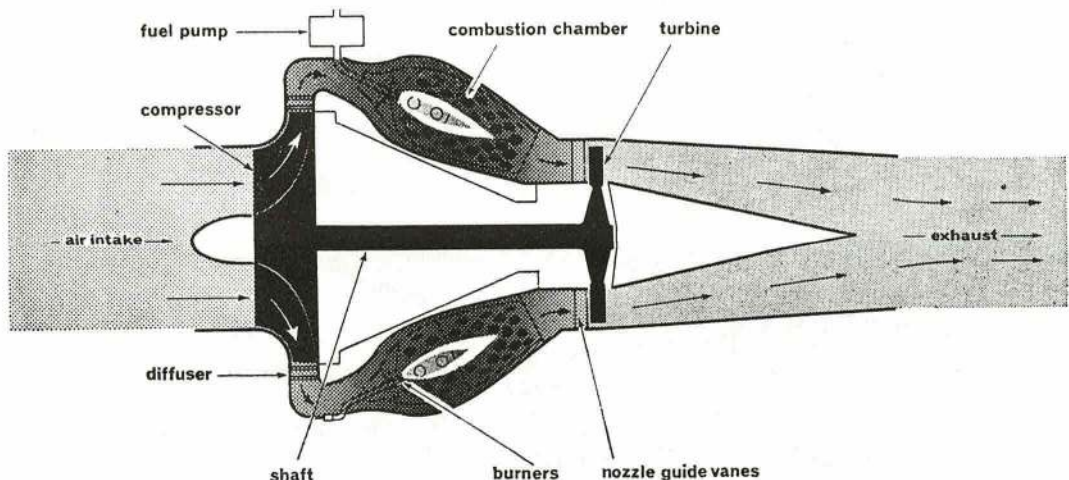


Fig. 8. BASIC GAS TURBINE

intake and then to increase the pressure of the air before combustion takes place. The compressors with which we have come into contact so far have been of the reciprocating positive displacement type but these are not suitable for use in gas turbine engines. Consequently rotary compressors of two types will be found in common use, differing in the line of flow. The **centrifugal** type imparts a radial flow whilst the **axial** type produces a flow that

is parallel to the axis of the engine. Either type or a combination of both may be used according to the design requirements.

14. **Centrifugal.** This may be a single- or two-stage unit using an **impeller** to accelerate the air flow and a **diffuser** to produce the required pressure rise (Fig. 9). Air is continuously induced into the eye or centre of the impeller which is rotated by the turbine.

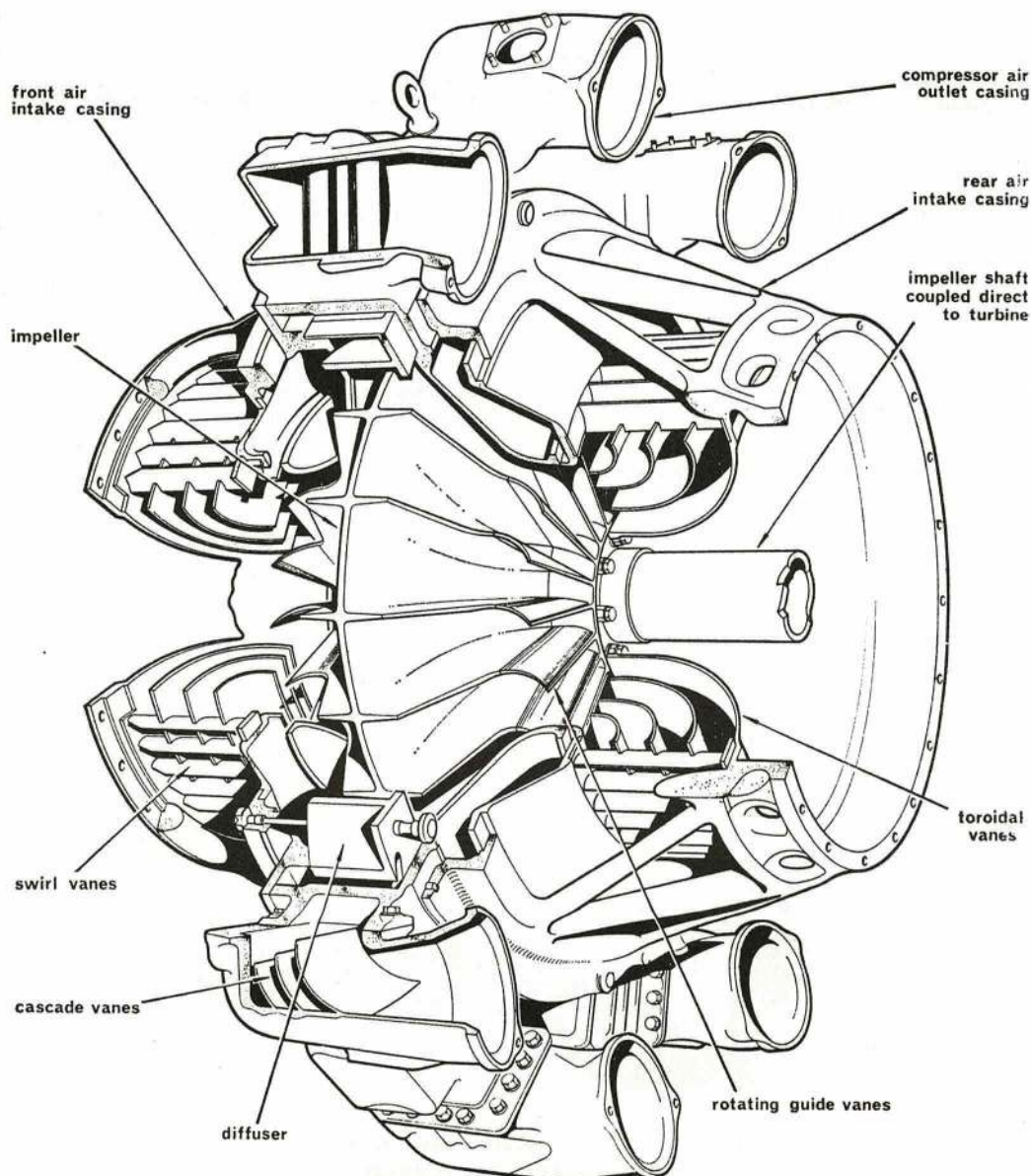


Fig. 9. TYPICAL CENTRIFUGAL COMPRESSOR

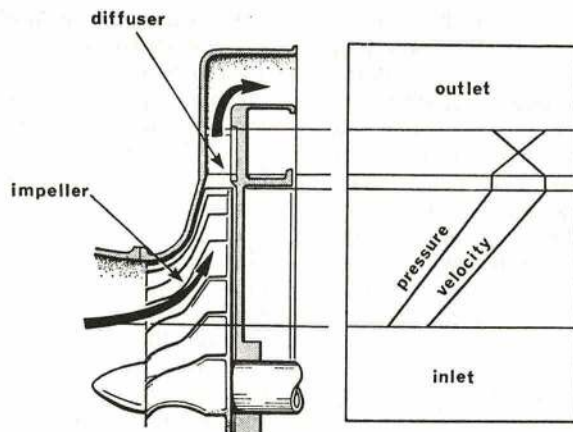


Fig. 10. PRESSURE/VELOCITY CHANGES—CENTRIFUGAL

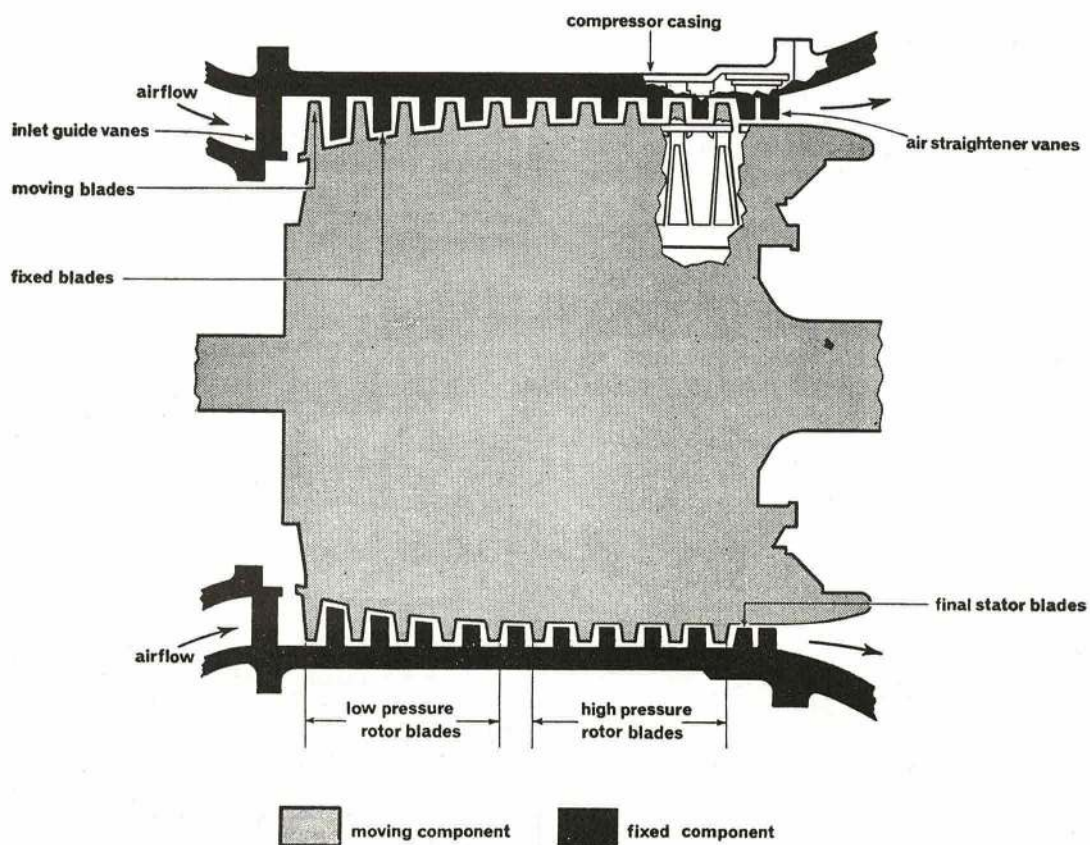


Fig. 11. AXIAL COMPRESSOR

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Centrifugal force causes the air to flow along the vanes to the tip of the impeller where it leaves at approximately 90 deg. to the point of entry, and at an increased velocity and pressure that is dependent upon the rotational speed. On leaving the impeller the air passes through the divergent passages of the diffuser, the purpose of which is to reduce its velocity energy and increase its pressure energy (Fig. 10). In practice it is usual to design the compressor so that about half of the pressure rise occurs in the impeller and half in the diffuser.

Note.—If a double-entry impeller is used, the airflow to the rear side is reversed in direction and thus a plenum or stabilizing chamber is required.

15. Axial Flow. An axial flow compressor (Fig. 11) may be a single or twin-spool rotor assembly which carries rings of aerofoil section blades and alternating rings of stationary blades fixed in the casing. Air entering the compressor is directed by the **guide vanes** to the alternate sets of moving and fixed blades (Fig. 12). The **rotor blades** are driven by the shaft and because of their aerofoil section they increase the speed of the air rearwards. The compressor is a multi-stage unit because the pressure increase at each stage is relatively small, each stage consisting of one row of rotating blades followed by a row of **stator** (stationary) blades. The stator blades influence the angle at which the air approaches the rotor blades and act as diffusers by reducing the air velocity and increasing the pressure. As the air passes through the compressor its density is increased; therefore, in order to maintain a mean constant velocity, the dis-

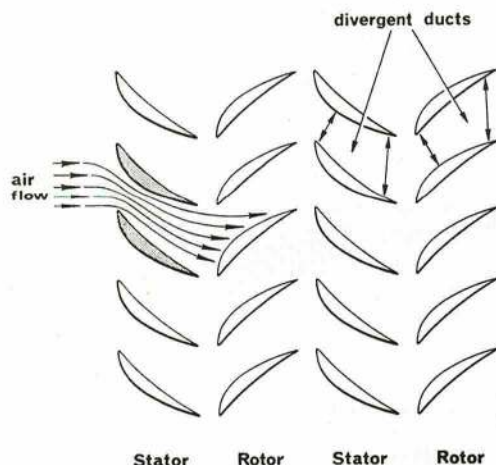


Fig. 12. AXIAL COMPRESSOR AIRFLOW

tance travelled between each stage and the annular air space available must be decreased. This is achieved by decreasing the width of the blading and by tapering either the casing or the rotor or by a combination of both (Fig. 13). At the rear of the compressor is a final row of stator blades and a row of air straightener vanes.

16. Depending upon the number of stages in a compressor, and ignoring temperature variation, there is an overall pressure increase through the compressor with an overall constant velocity as shown in Fig. 13. The compression ratio depends upon the number of stages and the speed of the rotor. At times the airflow around the compressor blading instead of being smooth becomes very turbulent. If this disturbance is confined to one or two stages only the airflow is said to have **stalled**. If this stalled condition spreads to all the stages then the airflow will **surge** to and fro within the compressor. These faults can be overcome by separating the early stages from the later ones; this separation led to the development of, amongst other factors, the **twin spool** type of compressor.

17. Twin Spool Compressors. When compression ratios of 9:1 or more are required, two axial flow compressors in tandem but driven by separate turbines are frequently employed (Fig. 14).

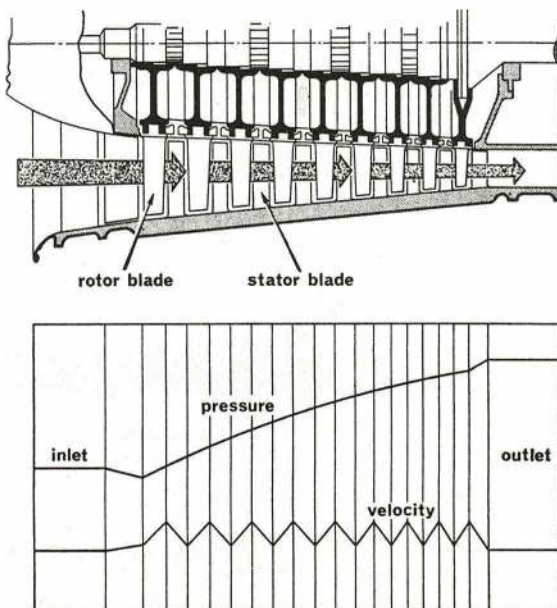


Fig. 13. PRESSURE/VELOCITY CHANGES—AXIAL

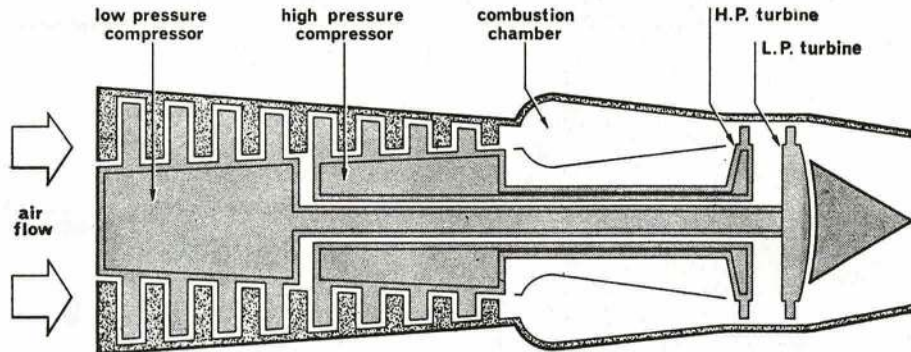


Fig. 14. TWIN SPOOL LAYOUT

18. The relative characteristics of centrifugal and axial compressors are as follows:

Feature	Centrifugal	Axial
Cost	Cheaper. Simple to construct. Less man hours to produce.	Expensive. Difficult to construct.
Strength	Robust. Can stand some shock from "icing up".	Easily damaged by solids in the airstream.
Drag	Large overall diameter but short length. Airflow deviations absorb energy.	Small diameter. Airflow in a straight line increases efficiency.
Compression Ratio	Approximately 4:1 maximum. Little tendency to surge. Flexible and relatively efficient over a wide range of engine speed. Can take full advantage of 'ram' effect.	Up to 8:1. More efficient at high r.p.m. than centrifugal type, but tends to surge at low r.p.m. and is less flexible. The higher compression ratio gives lower specific fuel consumption and cheaper running costs.
Maintenance	Simplicity of design reduces need for maintenance	Complexity needs more engine components such as bleed valves, variable swirl vanes and acceleration controls, thus increasing maintenance.

Combustion Systems

19. The difficulty of satisfying combustion requirements was responsible for some of the delay in the production of the gas turbine engine. Solution of the problems involved has resulted in the present use of three types of system namely **multiple chamber**, **annular** and **tubo-annular (cannular)**, which may be arranged for **direct flow** or **reverse flow**; the main reason for using reverse flow is to restrict the overall length when an axial compressor is employed.

20. **Multiple Chamber.** A typical combustion chamber is illustrated at Fig. 15; it is one of a number comprising the complete system (Fig. 16). The flame is contained in a **flame tube** supported centrally in an **air casing**. Approximately 18 per cent of the mass air flow passes into the primary combustion zone and the remainder passes into the annular space between the flame tube and the air casing.

21. The primary zone air is used to combine
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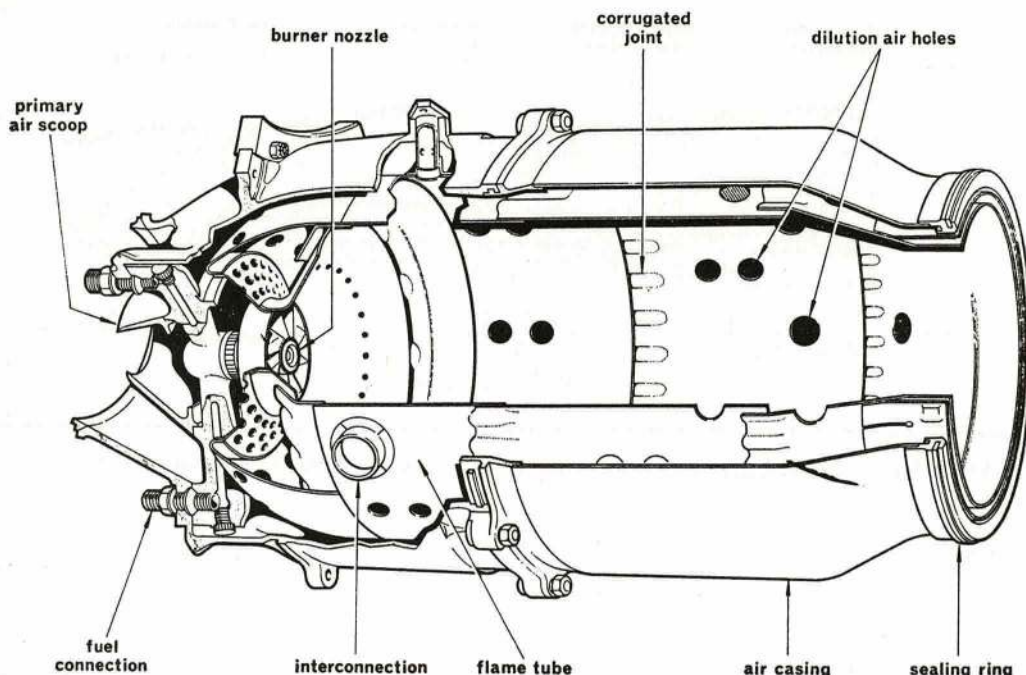


Fig. 15. TYPICAL COMBUSTION CHAMBER

with the fuel from the burner to form a combustible mixture and it is admitted in such a manner that it will:

- (a) Cool the burner head and also prevent carbon formation.
- (b) Hold the flame back on to the burner.
- (c) Control the shape of the flame.

22. About ten per cent of the air passing between the flame tube and the air casing passes through the primary air holes in the flame tube and so enters the primary zone. The remainder of the air not required for combustion amounts to about 72 per cent of the total airflow, and this is introduced progressively, via dilution holes, into the flame tube. Approximately half is used to reduce the temperature of the gas before it reaches the turbine, and the other half cools the flame tube (Fig. 17).

23. Two chambers are fitted with **igniter plugs** from which an electric spark starts combustion. All the chambers are interconnected so as to obtain a simultaneous "light up" and to maintain pressure balance.

24. **Annular.** This type of combustion system (Fig. 18) consists of four tubes posi-

tioned concentrically around the axis of the shaft. The inner and outer tubes form the casings which contain the airflow; this is received from the compressor at one end and passes to the turbine at the other end. The annular space between the other two tubes forms the flame tube, at the compressor end of which a ring of burners injects fuel downstream; in some engines however the burners are arranged to inject the fuel upstream.

25. The annular combustion chamber has the following favourable features:

- (a) Reduced chamber area exposed to the gas results in a lower pressure loss.
- (b) A continuous sheet of gas at uniform temperature over the whole area instead of a number of outlets results in better pressure and flow distribution around the nozzles.
- (c) Ease of servicing and simplicity of manufacture.
- (d) Smaller overall diameter when used with an axial flow compressor.

26. **Tubo-annular.** The tubo-annular combustion chamber (Fig. 19) is often referred to as the **cannular** type and it is a combination of the two previously mentioned types. It over-

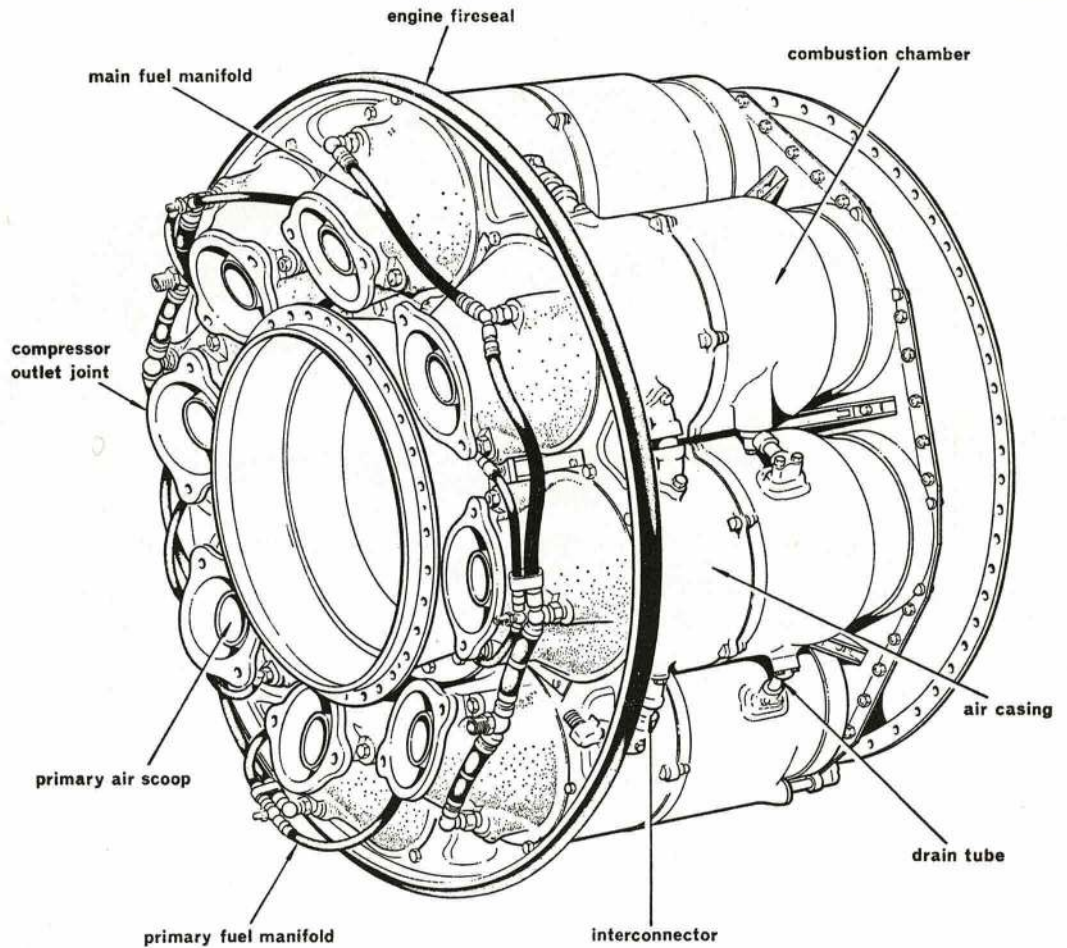


Fig. 16. MULTIPLE COMBUSTION CHAMBERS

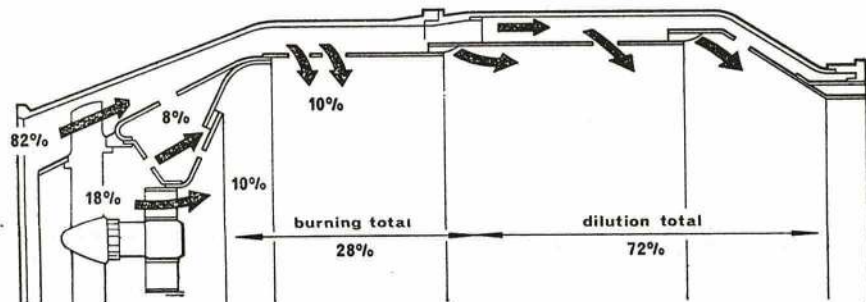


Fig. 17. AIRFLOW APPORTIONING

comes the difficulty of keeping a stable flame shape in an annular system by the use of a number of separate flame tubes in an annular casing, the flame tubes having separate

burners and interconnectors. This type combines the ease of overhaul and testing of the multiple system with the compactness of the annular system.

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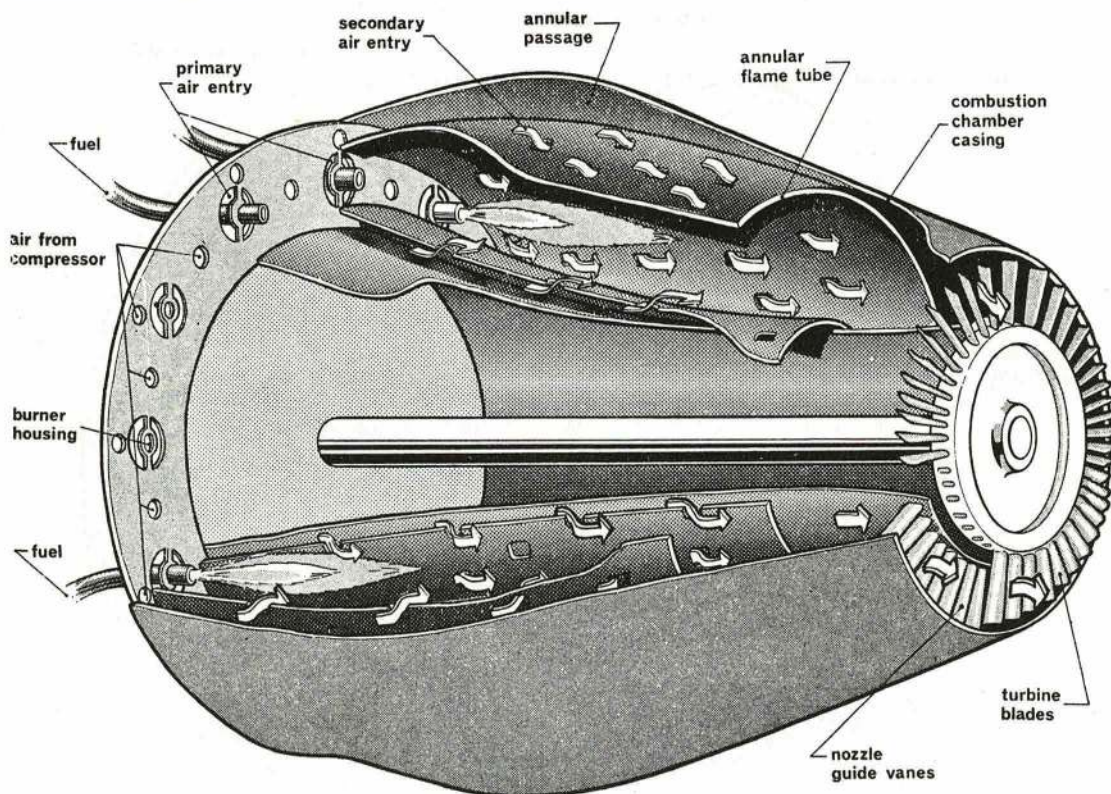


Fig. 18. ANNULAR COMBUSTION CHAMBER

Burners

27. Burners are used in various forms, either injecting fuel under pressure downstream in the form of spray or pre-vaporized upstream. A typical burner is illustrated at Fig. 20. They are designed to give good atomization, complete combustion within a well-shaped flame and freedom from flame extinction. The major difficulty is to achieve this within a wide fuel flow range using short lengths of flame tube, because any extension of the combustion zone leads to a longer and heavier engine.

Turbine Assembly

28. The purpose of the turbine (Fig. 21) is to provide the power to drive the compressor and any accessories and, in the case of engines not designed for jet propulsion, providing power for the turbine shaft. It satisfies these requirements by extracting energy from the hot gases flowing from the combustion system, expanding the gases and lowering their pressure and temperature.

29. One or more stages are used to produce the driving torque or turning moment. Each

stage consists of a row of stationary **nozzle guide vanes** situated in front of the **blades** of the moving **turbine disc**. The guide vanes increase the speed of the gas and direct it onto the turbine blades at the angle required to produce a torque. The number of stages included in the design of a turbine will depend upon the power output of the engine, the general design requirements such as frontal area and whether it is to provide pure jet thrust or shaft horse power.

30. The blade design combines two basic principles in varying proportions according to the particular application of the turbine. The shape of the blades provides that the turbine functions partly under impulse and partly under reaction conditions.

31. **Impulse section blades.** (Fig. 22) cause torque by the direct impact of the gas flow onto the blades. With the constant straight flow speed of the gas flow and the difference in speed between the root and the tip of a rotating blade, only the root or inner part of the blade can take full advantage of the velocity of the gas-flow.

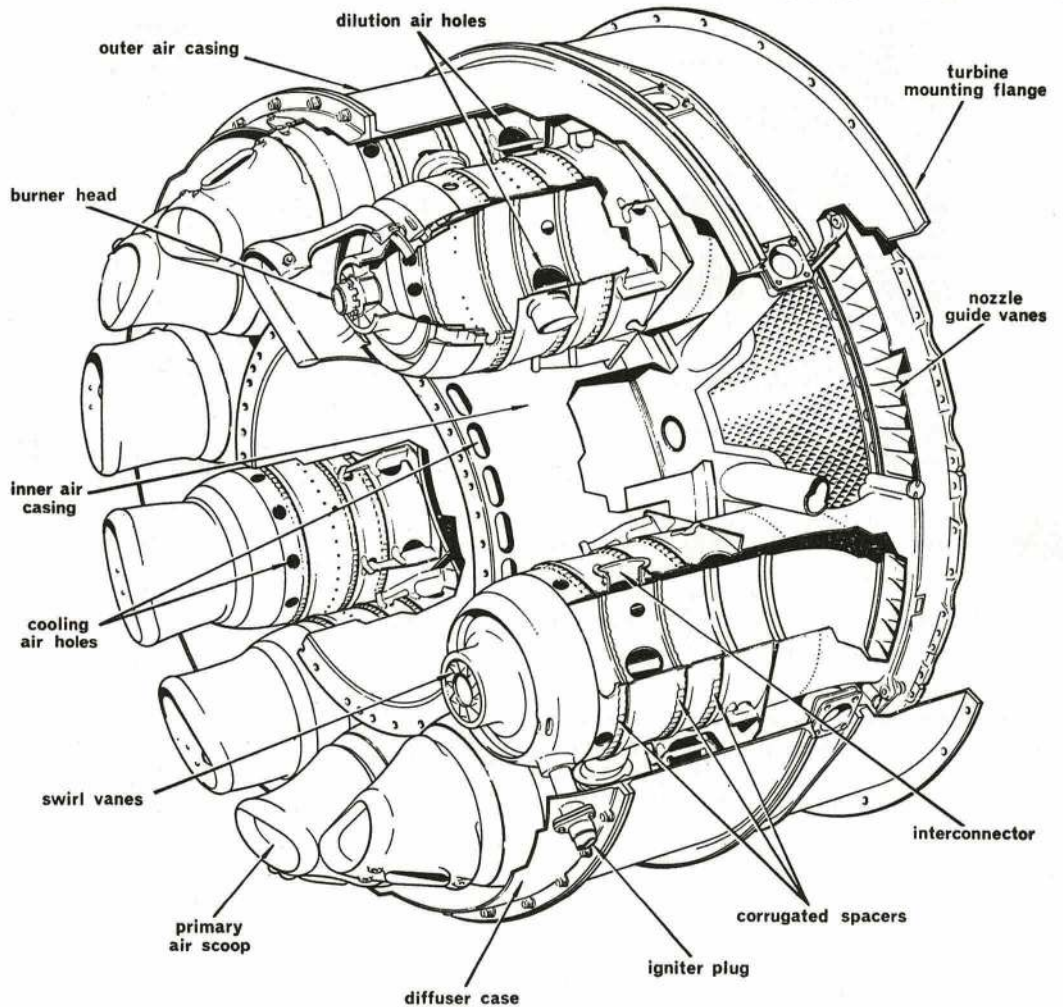


Fig. 19. TUBO-ANNULAR SYSTEM

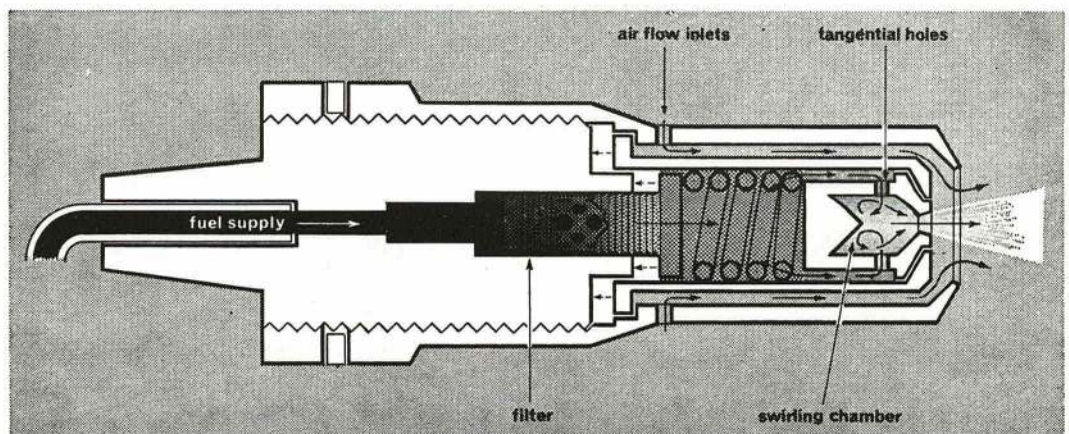


Fig. 20. TYPICAL BURNER

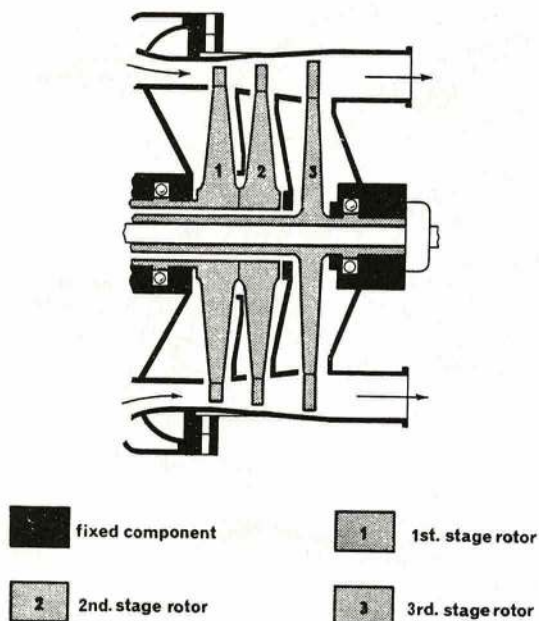


Fig. 21. TYPICAL TURBINE (3-STAGE)

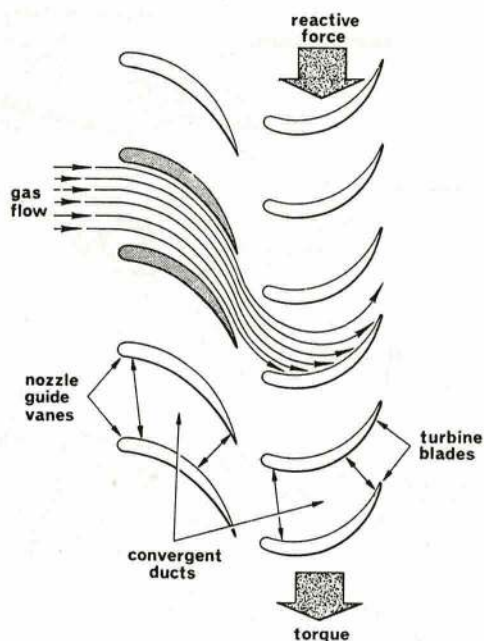


Fig. 23. REACTION BLADING

32. **Reaction blading** (Fig. 23) produces torque from the reaction resulting from the expansion and acceleration of the gas flow through the convergent passages formed by the blades.

33. Thus, shaping a blade to a suitable section at each place produces the typical

impulse/reaction type as illustrated in Fig. 24, where the whole blade from root to tip will apply an even torque. Consequently it is essential that the blades are not damaged or their section changed in any way. Uneven aerodynamic forces acting on the turbine

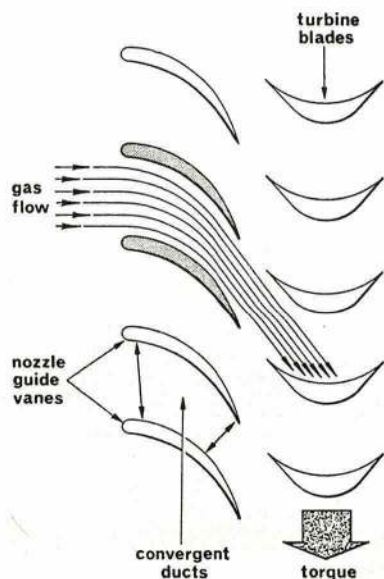


Fig. 22. IMPULSE BLADING

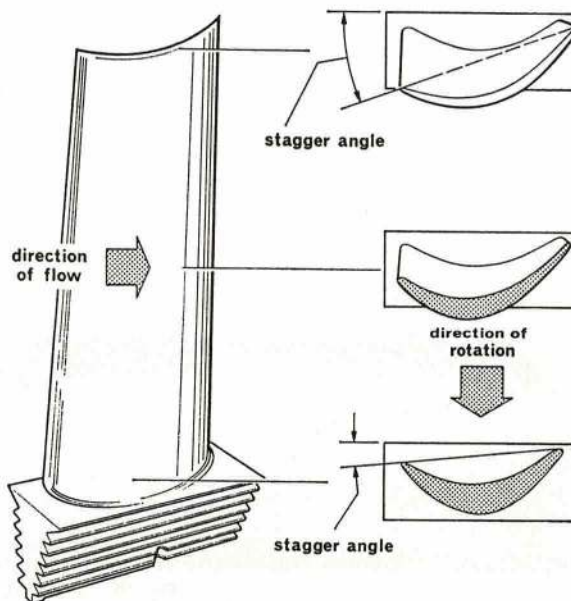


Fig. 24. TURBINE BLADE

blades would lead to inefficiency, heavy vibration and probable fracture.

34. The temperature of the gas flow at the turbine is such that it restricts the materials that may be used for turbine blades to those having the following qualities:

- (a) Oxidization and corrosion resisting. Scaling or corrosion would destroy the essentially accurate blade section.
- (b) Strength at high temperature. A temperature rise reduces the strength of a material.
- (c) High resistance to fracture and thermal shock. Sudden changes in speed of the gas flow or quick cooling and heating puts heavy loads on the blades.
- (d) Inherent damping action. The changes in loads acting on the blades must not set up vibration that is likely to cause stress or fatigue.
- (e) Fatigue resisting. To give long life.
- (f) Resistance to 'creep'. Creep is a grad-

ual change of shape in the direction of the load in material subjected to heavy loads at high temperatures for a long time, and which eventually leads to fracture. Turbine blades stretch gradually during service, thus reducing the blade tip clearance.

35. We can see that the design of the engine will be such that the temperature of the gas stream entering the turbine is limited and so does not exceed a figure at which the vanes, blades and discs can be subjected to very arduous conditions for a satisfactory period of working life. Research will doubtless produce materials which will enable higher temperatures to be used in the future.

36. **Balance.** This is an important factor in turbine production. Because of the high rotational speeds and the mass of the materials, any unbalance would seriously affect the rotating assembly bearings and engine operation. Very accurate balancing of the rotating assemblies is therefore essential.

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