PART 1 : SECTION 3

CHAPTER 10

TURBO-PROP ENGINES

Introduction

1. The turbo-prop engine consists of a gas-turbine engine driving a propeller. Most of the energy of the gas flow is used to drive the propeller and compressor, leaving a small amount of residual thrust. Turbo-prop engines are most useful in transport or maritime aircraft having a comparatively long range and operating speeds up to about 450 knots. These engines fall into the following classes :—

(*a*) Direct drive turbine.

(*b*) Free turbine.

(*c*) Ducted-fan engine.

(*d*) Bypass engine.

(*e*) Compounded engine.

Types of Turbo-Prop Engines

2. **Direct Drive Turbine.** The gas flow is fully expanded across a turbine which drives the compressor, the surplus horse-power developed being transmitted through a reduction gear to the propeller.

3. **Free Turbine or Work-Turbine.** A separate turbine, in addition to that driving the compressor, is used to drive the propeller. Irrespective of the propeller pitch and r.p.m., the compressor and its turbine run at a near-constant r.p.m. In another form of this engine, some compression may be undertaken by a secondary compressor on the propeller work-turbine shaft. The engine characteristics are slightly changed, but from the control system point of view the engine may be regarded as a work-turbine.

4. **Ducted-Fan Engine.** The ducted-fan engine (Fig. 1) was developed to increase propulsive efficiency by decreasing the mean speed of the exhaust gases and at the same time increasing the total mass flow. Further energy is taken from the main gas flow to drive an additional turbine coupled to a fan running in an annular duct. The fan compresses air taken from a separate atmospheric source to provide a *cold jet* of greater mass flow and comparatively low speed. The cold jet is then fed into the hot jet at the propelling nozzle, thus reducing the temperature and raising the overall mass flow through the engine and, consequently, the engine efficiency. Ducted-fan engines were intended to fill a gap which existed between the propeller-type engine and the pure jet engine, but owing to the increasing propulsive efficiency of propellers, this gap now scarcely exists.

5. **Bypass Engine.** The bypass engine (Fig. 1) also uses separate cold and hot streams in its operation. After leaving the compressor, the air is split into two flows, a primary which passes through the engine in the usual way, and a secondary flow which bypasses the combustion zone to flow around the engine and rejoin the

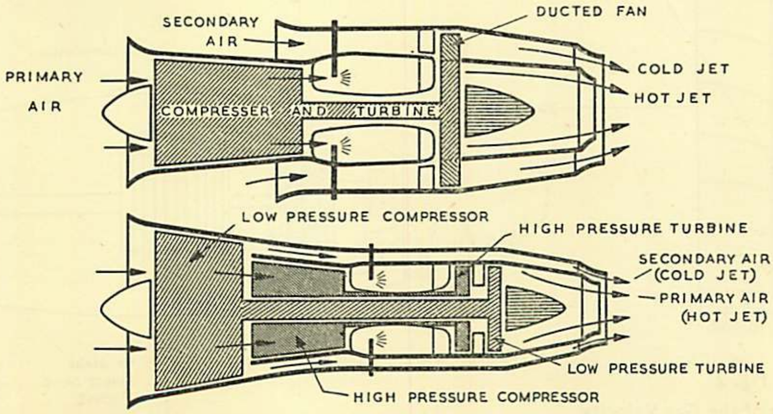


Fig. 1. A Ducted-Fan Engine Compared with a Bypass Engine.

hot jet at the jet nozzle. The amount of bypassed air is smaller than the primary flow. The propulsive efficiency is higher than in the pure turbo-jet, since the cold bypass air reduces the temperature and increases the mass flow. Bypass engines can use the twin spool arrangement of compressor (Fig. 1) in which the rear compressor is used to further compress the primary air.

6. **Compounded Engine.** The practice of fitting a centrifugal compressor downstream of an axial compressor is known as *compounding*. This is not so much to increase the overall compression ratio as to assist the axial compressor when running outside its relatively narrow operating range (particularly during starting) thus adding to the flexibility of the engine.

Shaft Horse-Power (S.H.P.)

7. The nozzle guide vanes lead the gas flow to the turbine, at a set direction to the plane of the turbine rotor. The velocity (V) of the gas flow has two components (Fig. 2), V_1 which generates shaft energy and acts in the direction of turbine rotation, and V_2 which generates propulsive energy and which acts rearwards. In a turbo-prop engine the aim is to increase the magnitude of V_1 and minimize the value of V_2 (in pure jets the reverse applies). Therefore the basic design of the engine is different from that of a pure jet. To drive a propeller the total work of the gas turbine is taken out as shaft horse power (S.H.P.) instead of kinetic energy as in a turbo-jet. The propulsive efficiency is at its maximum at speeds below about 450 knots : above this speed propeller efficiency falls off (see Chap. 1). The proportion of thrust between propeller and jet is about 90% propeller to 10% jet. The weight is about half that of a comparable piston engine.

Advantages of the Turbo-Prop over the Turbo-Jet

8. By using a propeller the following advantages are gained :—

(*a*) The amount of power available for propulsion is largely independent of the forward speed of the aircraft, so that more power is available during the initial stages of the take-off run.

(*b*) A slipstream is produced which improves elevator and rudder control at low speeds.

(*c*) The engine can be run under more efficient and economical conditions at low and medium altitudes and retain these two qualities at low aircraft speeds.

(*d*) With the use of interconnected engine and propeller controls the power response to throttle movement is more rapid than that of a turbo-jet engine.

Turbine Assemblies

9. **Direct Drive Turbine.** Most engines use either a two-stage (direct drive) or a three-stage (free) turbine assembly. The two-stage turbine (Fig. 3) consists of two coupled turbine discs on which are mounted the turbine blades. Between the discs is a ring of guide vanes. The two rotating discs are connected to the main drive

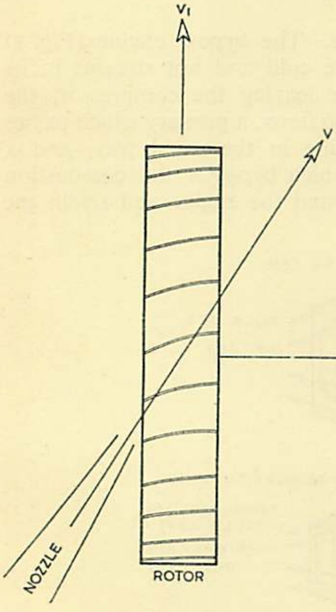


Fig. 2.
Components of the Gas Velocity through a Free Turbine.

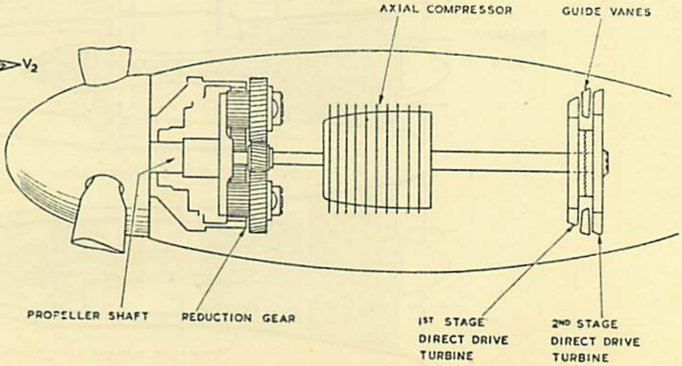


Fig. 3. Simplified Two-Stage Direct Drive Turbine.

shaft, on the forward end of which is the compressor, the compressor in turn driving the propeller through a reduction gear. This system is known as a direct-drive turbine.

10. **Free Turbine.** The three-stage turbine assembly (Fig. 4) uses two stages to drive the compressor and the third to drive the propeller. There are thus two rows of guide vanes ; one between the first two stages, and a second between the second-stage turbine and the free turbine. The chief advantage of the free-shaft turbine is the reduction of torque loads when starting, since the starting mechanism does not have to rotate the propeller and reduction gear, but only the compressor and its turbine, whereas with a direct drive unit the starter must rotate not only the gas generating components but the reduction gear and a heavy propeller.

Direct Drive Turbines

11. During the passage of the gas through the two-stage turbine it gives up roughly 97·5% of its energy, the remaining 2·5% leaving the jet pipe as thrust. About 58% of the turbine energy is extracted by the first stage of the turbine and 42% by the second stage.

12. Assuming the total gas energy to be, say, 6,100 H.P., and ignoring combustion and turbine losses, the turbine develops 6,100 H.P. The first commitment of the turbine is to drive the compressor, which, in the majority of gas turbines, absorbs about 65% of the total turbine output, so that of the 6,100 H.P. roughly 3,965 H.P. is used for this purpose, leaving a net 35%, say 2,135 H.P.

13. About 90% of the net power is used to drive the propeller, leaving 10% residual energy which passes out of the exhaust as jet thrust. Therefore, of the 2,135 H.P. net amount which is available for work, 1,922 H.P. will be S.H.P. for driving the propeller and 213 H.P. will be jet thrust. In this example, mechanical losses in the reduction gear which amount to 3% to 4% have been ignored.

14. The net energy required for driving the propeller depends on general design factors, but there has been a tendency to increase the power available to the propeller and reduce the jet thrust.

Free-Shaft Turbines

15. The main difference between direct-drive and free-shaft turbines is in the transmission of the power. Fig. 4 shows that the first two stages are connected direct to the compressor, while the third stage is connected to a separate shaft which turns concentrically through the bore of the main shaft and drives the propeller through a suitable reduction gear. The first two stages absorb 65% of the power, the remaining 35% being passed on to thethird-stage turbine which drives the propeller independently of the compressor.

Propeller Control

16. **Reduction Gears.** Since the operating r.p.m. of gas-turbine engines is 8,000 to 10,000 and more, a reduction gear must be used between the engine and the propeller to obtain the much lower r.p.m. required by the propeller. The reduction gears are generally similar to those

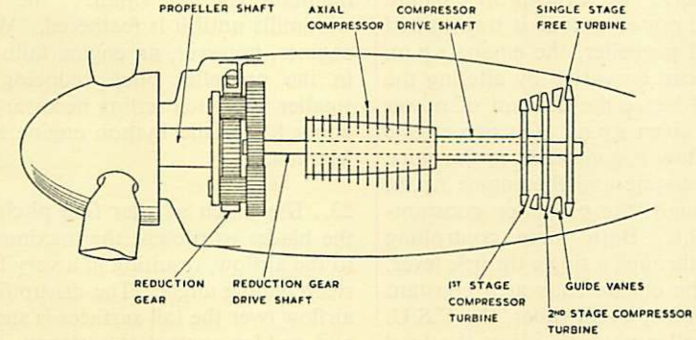


Fig. 4. Simplified Three-Stage Free Turbine.

used on piston engines but, because of the greater reduction, epicyclic gearing (Fig. 5) or a combination of this and spur gearing is used. On engines which use a counter-rotating propeller, spur gears are used to transfer the driving torque to the rear and front propeller shafts, some of the speed reduction being obtained in this way.

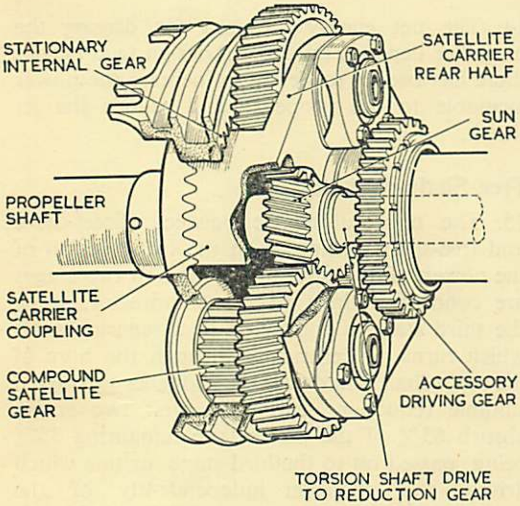


Fig. 5. Typical Epicyclic Reduction Gear.

17. **Pitch Setting for Starting.** An important requirement of the direct-drive turbine is that the propeller must be able to move to a very fine pitch setting (8° to 12°) before starting, so that the power required to turn it while the engine is idling is kept to a minimum.

18. **Controlling the Power Output in Cruising Flight.** In turbo-jet engines the power output is determined and controlled by the rate of fuel flow into the burners. In turbo-prop engines, however, where the power output is transmitted to a constant-speed propeller, the engine r.p.m. and power output can be varied by altering the propeller pitch and hence the amount of power it can absorb at a given r.p.m. On one engine (Mamba) the fuel flow is controlled in the same way as a turbo-jet engine and the engine r.p.m. is controlled through the propeller constant-speed unit (C.S.U.). Both these controlling functions are done through a single throttle lever. In cruising flight the engine runs at a constant r.p.m. (max continuous) at all times, the C.S.U. governing the propeller pitch to adjust the load on the engine and maintain this speed. When the throttle is opened, the fuel flow is increased and at the same time the pitch is coarsened to absorb the higher power. Closing the throttle reduces the fuel flow and, to maintain the same engine r.p.m., fines off the pitch.

19. **Increasing to Take-Off Power.** When the throttle is opened past the maximum cruising position to take-off power, the fuel flow is increased and the C.S.U. setting is altered to allow the engine constant speeding r.p.m. to increase to the take-off figure.

20. To reach take-off r.p.m., the C.S.U. reduces the pitch, and hence the power absorption of the propeller, to allow the engine to accelerate rapidly to the new figure. There is a tendency for the engine r.p.m. to overshoot the take-off figure but this is taken up by the engine overspeed governor which limits the r.p.m. by reducing the fuel flow, and thus the power.

21. **The Anticipator.** To prevent this reduction in power at a time when the throttle is being opened, an anticipator mechanism is put between the fuel control unit and the governor. The anticipator delays any alteration to the basic C.S.U. setting when the throttle is opened rapidly, and its effect is to ensure that, when increasing power, the r.p.m. *selected* by the C.S.U. is slightly lower than the instantaneous (*indicated*) r.p.m. (*i.e.* the pitch setting is kept slightly coarser than the optimum), so ensuring a steady increase in pitch until at full throttle the correct pitch is obtained to absorb the take-off power.

Engine Failure

22. When a failure occurs on a piston engine, the C.S.U. moves the propeller pitch to fully fine—an angle of about 25°—in an attempt to maintain the set r.p.m.; the propeller then windmills until it is feathered. With turbo-prop engines, however, an engine failure would result in the propeller pitch reducing to the much smaller fine pitch setting necessary for starting—about 8° for the Python engine and 12° for the Mamba.

23. The much smaller fine pitch setting causes the blades to present the maximum frontal area to the airflow, resulting in a very high drag and a steep gliding angle. The disrupting effect on the airflow over the tail surfaces is such that elevator and rudder control is seriously impaired. The propeller is sometimes said to be *discing* when this occurs.

24. **Reverse Torque Switch.** To prevent this very undesirable state of affairs, a reverse torque switch in the reduction gear operates whenever the normal torque reverses, *i.e.* when the overspeeding propeller tends to drive the engine. The reverse torque switch overrides the C.S.U and causes the feathering motor to feather the propeller. On occasions a momentary period of reverse torque may be encountered (as when throttling back quickly). This is indicated by the flashing of the reverse torque warning light ; however, when the pitch adjusts itself after a second or two the feathering action is halted and normal operation is resumed. If the fully feathered position is reached before power returns, the engine stops and will have to be re-lit. The propeller can be feathered at any time by the pilot ; this usually entails closing the H.P. cock and energizing the feathering motor or closing the H.P. cock through a feathering gate ; Pilots' Notes detail the method for each type of aircraft.

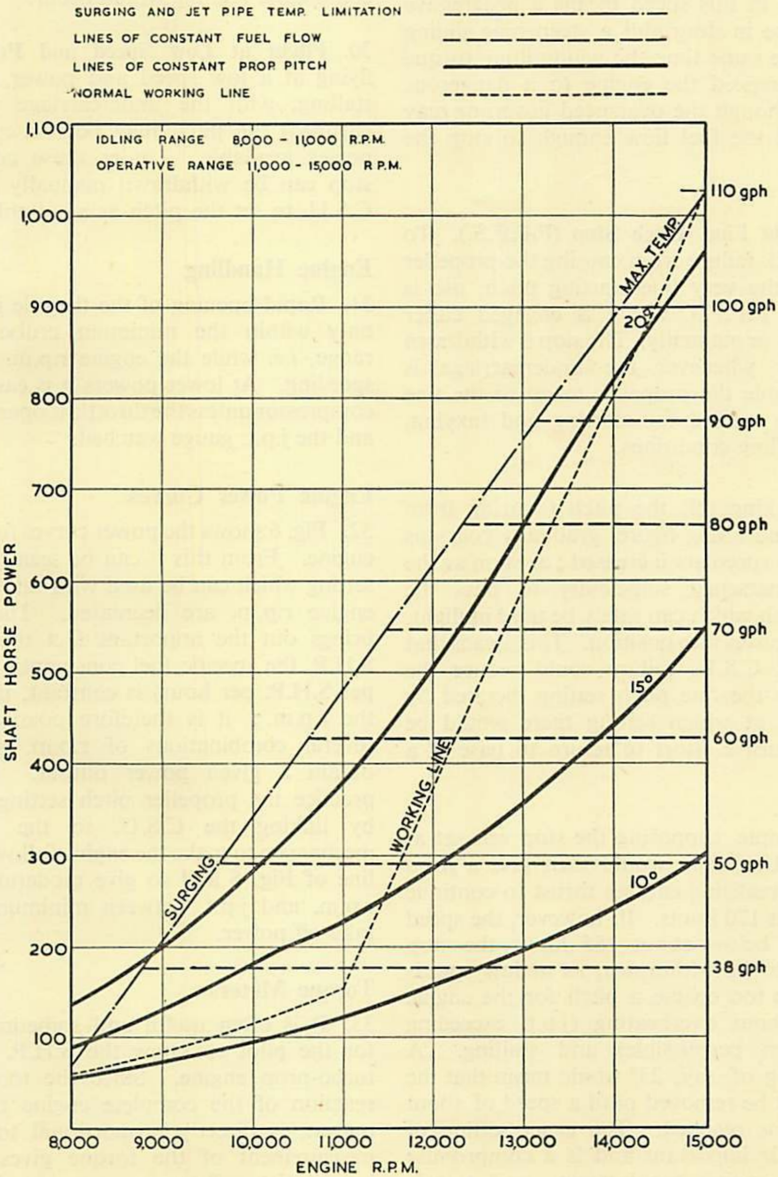


Fig. 6. Power Curves (Mamba Engine).

Propeller (C.S.U.) Failure

25. If the C.S.U. fails, the propeller blades move to the fully-fine position by virtue of the inherent centrifugal twisting moment on the blades (see Sect. 1, Chap. 15). Since the engine is still under power there will be an immediate increase in engine r.p.m. until restricted by the engine overspeed governor, which reduces the fuel flow to an extent that will probably stop the engine. In the very fine pitch position (say 12°) 100 knots is the highest speed at which no drag occurs. Any increase in this speed means a progressive and rapid rise in drag and a steepening gliding angle ; at the same time the windmilling torque tends to overspeed the engine to a dangerous extent even though the overspeed governor may have reduced the fuel flow enough to stop the engine.

26. **The Flight Fine Pitch Stop (F.F.P.S.).** To prevent C.S.U. failure from causing the propeller to move to the very fine starting pitch, use is made of an F.F.P.S. which is engaged either automatically or manually. The stop is withdrawn automatically whenever the undercarriage is down, to enable the propeller to go to the fine pitch settings needed for starting and taxying, *i.e.* ground idling conditions.

27. When taking off, the pitch (starting from the fine ground idling figure) gradually coarsens as power and speed are increased ; as soon as the pitch has coarsened sufficiently to pass the minimum pitch which can safely be used in flight, the F.F.P.S. moves into position. This means that a subsequent C.S.U. failure could reduce the pitch only to the fine pitch setting dictated by the F.F.P.S., at which setting there would be enough propulsive effort to return to base at a low I.A.S.

28. For example, supposing the stop was set at 28° ; a C.S.U. failure would then give a *fixed* pitch of 28°, realizing enough thrust to continue flight at about 170 knots. If, however, the speed was reduced below about 155 knots the stop would have to be withdrawn, as at low speeds 28° would be too coarse a pitch for the engine to drive without overheating (j.p.t. exceeding the maximum permissible) and stalling. A smaller setting of, say, 23° would mean that the stop need not be removed until a speed of about 115 knots was reached. The exact setting of the F.F.P.S. is important and is a compromise between the engine requirements and a safe approach speed.

29. Since the F.F.P.S. is withdrawn when the undercarriage is lowered, this would mean that when lowering the undercarriage after returning to base following a C.S.U. failure the pitch would go to the ground idle setting with all the resultant dangerous control difficulties. To prevent this, the action of the undercarriage on the F.F.P.S. can be overridden so that the stop remains engaged. However, when the aircraft touches down, the engine must be stopped by turning off the H.P. cock, otherwise overheating and compressor stalling would occur.

30. **Flight at Low Speed and Power.** When flying at a low speed and power, *e.g.* practice stalling, with the undercarriage up (F.F.P.S. engaged) the pitch may be too coarse for the power available. Under these conditions the stop can be withdrawn manually to allow the C.S.U. to set the pitch at a suitable value.

Engine Handling

31. Rapid opening of the throttle is permissible only within the minimum cruise to take-off range, *i.e.* while the engine r.p.m. are constant speeding. At lower powers it is easy to stall the compressor unless the throttle is opened cautiously and the j.p.t. gauge watched.

Engine Power Curves

32. Fig. 6 shows the power curves for the Mamba engine. From this it can be seen that the pitch setting which can be used with safety falls as the engine r.p.m. are decreased. The figure also brings out the important fact that at a given S.H.P. the specific fuel consumption (lb. of fuel per S.H.P. per hour) is constant, irrespective of the r.p.m. ; it is therefore possible to run at several combinations of r.p.m. and j.p.t. to obtain a given power output. However, in practice the propeller pitch setting is governed by linking the C.S.U. to the fuel control mechanism to make the engine follow the working line of Fig. 6 and so give moderate changes in r.p.m. and j.p.t. between minimum cruise and take-off power.

Torque Meters

33. It is often useful and sometimes necessary for the pilot to know the S.H.P. output of a turbo-prop engine. Since the torque, *i.e.* the reaction of the complete engine to the power output, is directly proportional to the S.H.P., measurement of the torque gives the desired information. Torque meters can be calibrated to read either torque (lb./sq. in.) or S.H.P.

There are many ways of measuring torque and the simplified method described below shows the principle.

34. A typical torque meter (Fig. 7) consists of two or three pistons moved by bell crank levers which are operated by movement of the floating (freely mounted) annular gear of the epicyclic reduction gear assembly. The oil pressure in the piston cylinders restrains the movement of the annular gear and prevents it from rotating.

35. The planet gears, inside the annular gear, mesh with teeth on the inside of its circumference, thus driving themselves around the inside periphery of the annular gear, on the S.H.P. output transmitted to them by the central sun gear.

36. The greater the S.H.P. and the torque, the greater is the tendency for the annular gear to be driven in the opposite direction of rotation to that of the circling planet gears; this torque force on the annular gear is taken up by the oil in the cylinders, and the oil pressure is indicated on the torque-meter gauge.

37. If the engine fails in flight, the propeller pitch fines off causing the engine to overspeed and drive the windmilling engine, *i.e.* torque is reversed. This has the effect of reversing the direction in which the annular gear is *attempting* to rotate; movement of the bell crank then closes the reverse torque switch to operate the feathering motor.

Propeller Brakes

38. The engine compressor and turbine assembly of a turbo-prop is free to rotate. Consequently if the aircraft is parked in the open when a wind is blowing the propeller windmills. Some form of brake is therefore needed to keep the propeller stationary. A typical propeller brake is of the internal expanding type and is hydraulically actuated by an oil accumulator. Control of the accumulator, and therefore of the propeller brake, is linked to the H.P. cock. Closing the H.P. cock operates a valve in the accumulator; the propeller feathering pump then automatically delivers feathering oil to the brake accumulator, the pressure in the brake system increasing until it is sufficient to apply the brake. When the propeller stops, non-return valves close and trap the oil in the brake-operating system. When the H.P. cock is reopened, the brake accumulator control valve is rotated and the oil under pressure is discharged from the system and the brake released. The released oil is returned to the normal lubrication system.

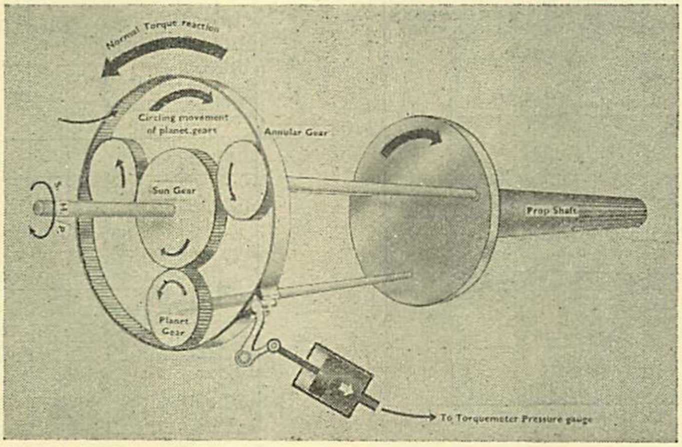


Fig. 7. Principle of the Torque meter.

Fuel Consumption

39. **Comparison Between Turbo-Jet and Turbo-Prop Engines.** Comparing the fuel consumption of a two-stage centrifugal compressor engine driving a propeller with that of a single-stage centrifugal compressor turbo-jet, it can be seen from Fig. 8 that at sea level and 400 m.p.h. (347 knots) the turbo-jet engine with a compression ratio of 4 to 1 produces 3,900 lb. of thrust and has a specific fuel consumption (S.F.C.) of 1·42 lb./hr./lb. thrust. On the other hand, the two-stage compressor with a ratio of 6 to 1 and driving a propeller produces 3,400 lb. of thrust and has an S.F.C. of 0·71 lb./hr./lb. thrust, which is half that of the turbo-jet. At 36,000 feet the turbo-jet power output is 1,450 lb. thrust with an S.F.C. of 1·25 lb./hr./lb. thrust, whereas the turbo-prop has a power output of 1,400 lb. thrust with an S.F.C. of 0·66 lb./hr./lb. thrust, showing an improvement in fuel consumption in favour of the turbo-jet. If the forward speed of these two engines is increased to 500 m.p.h. (435 knots) at sea level, then we have an S.F.C. of 1·46 lb./hr./lb. thrust for the turbo-jet and 1·0 lb./hr./lb. thrust for the turbo-prop, thus showing that with an increase in speed the turbo-jet engine gradually improves its position.

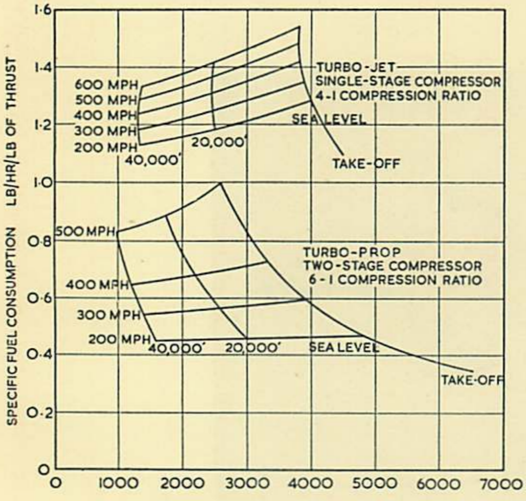


Fig. 8.

Comparison of Specific Fuel Consumption and Thrust of Turbo-Jet and Turbo-Prop Engines.

40. **Comparison Between Piston and Turbo-Prop Engines.** It is interesting to compare the turbo-prop engine with the piston engine. To simplify the example a speed of 300 m.p.h. (260 knots) is assumed, because at this speed and with a propeller efficiency of 80%, 1 lb. of thrust equals 1 H.P. Referring again to Fig. 8, it can be seen that at sea level and 300 m.p.h. the turbo-prop engine produces 3,900 lb. of thrust, which equals 3,900 B.H.P. and has an S.F.C. of 0·58 lb./B.H.P./hr. At 20,000 feet it develops 2,500 B.H.P. with an S.F.C. of 0·56 lb./B.H.P./hr. Comparing this with a piston engine, which would have an economical cruising S.F.C. of 0·44 lb./B.H.P./hr. and at full throttle a consumption of, say, 0·6 lb./B.H.P./hr., the consumption of the turbo-prop engine can be considered as very satisfactory. The power/weight ratio of the turbo-prop engine is also considerably better than that of the piston engine.

41. **Axial Compressor Turbo-Props.** Assuming a speed of 400 m.p.h. (347 knots) at sea level, it can be seen from Fig. 9 that the power output at 8,000 r.p.m. continuous cruising is 3,800 S.H.P.

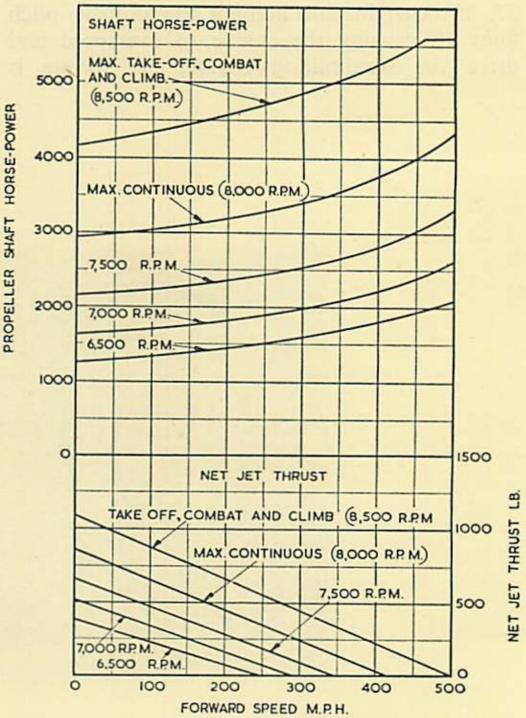


Fig. 9.

Typical Sea-Level Power Curve for a Turbo-Prop Engine.

plus 50 lb. net jet thrust. The fuel consumption under these conditions (Fig. 10) is 0·82 lb./T.H.P./hr. At 36,000 feet the power output is 1,850 S.H.P. plus 140 lb. net jet thrust, giving an S.F.C. of 0·612 lb./T.H.P./hr.

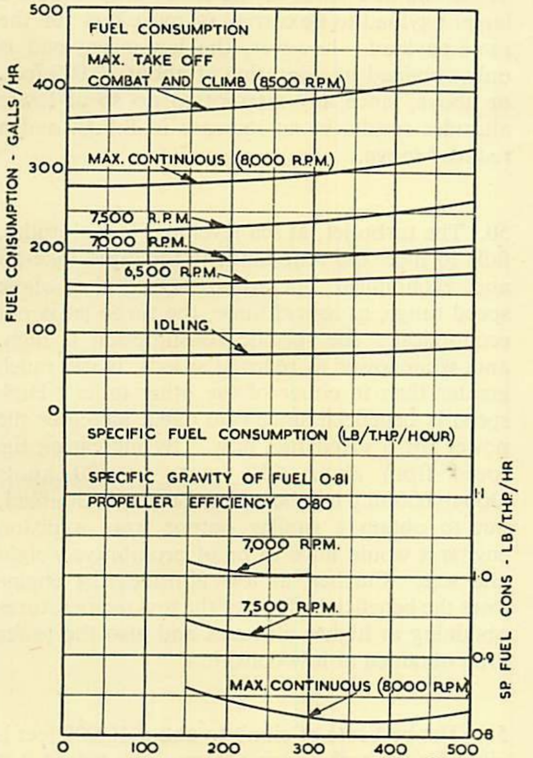


Fig. 10.

Typical Sea-Level Fuel Consumption Curves for a Turbo-Prop Engine.

42. If these S.F.C. figures are compared with those of the two-stage centrifugal compressor turbo-prop, the centrifugal compressor engine would appear to be slightly better at sea level, but at height the position is reversed, thus indicating that the axial compressor is more efficient at higher altitudes. It must, however, be remembered that the hypothetical centrifugal compressor has been given a compression ratio of 6 to 1, while the figures for the axial compressor are empirical figures based on an actual engine having a compression ratio of 5 to 1 ; with an increase in compression ratio to 6 to 1, there is an improvement in fuel consumption at sea level and at all heights.

Power/Weight Ratio

43. The average power/weight ratio of a turbo-prop engine is about 50% better than that of the piston engine at sea level. Up to its rated height the power of the piston engine remains virtually constant (so that the power/weight ratio does likewise) whereas the power of the gas turbine falls off linearly. Above the rated height, however, the power of the piston engine falls off more rapidly than that of the gas turbine. It must be appreciated that the power of the gas turbine at sea level is much greater than that of the piston engine so that at, say, 36,000 feet, the relative advantage of the gas turbine will not be greatly different from its value at sea level. The power output of the turbo-prop engine also varies slightly with speed, but, ignoring this variation, the following example is given to illustrate the importance of high power/weight ratio.

44. Assuming a turbo-prop engine of 4,000 S.H.P. at sea level and 300 m.p.h., then its weight will be in the region of 3,000 lb., giving a power/weight ratio of 0·75 lb./S.H.P. A piston engine of, say, 2,200 B.H.P. at sea level will weigh about 3,300 lb., giving a ratio of 1·5 lb./B.H.P. At the rated height, say 20,000 feet, the power/weight ratio of the piston engine is unchanged, but the power of the gas turbine will have dropped to 2,600 S.H.P., giving a ratio of, say, 1·1 lb./S.H.P. At 36,000 feet the power output of the piston engine will have dropped to 800 B.H.P., giving a ratio of, say, 4·1 lb./B.H.P., while the gas turbine will have dropped to 1,800 S.H.P. giving a ratio of 1·6 lb./S.H.P., which approximates to the piston engine ratio at sea level.

45. From the foregoing it can be appreciated that the turbo-prop engine permits the aircraft to fly at greater heights for the same weight of power plant, and therefore to have a greater cruising speed while carrying the same payload as the piston-engined aircraft. It can also be appreciated that the higher fuel consumption has a slightly adverse effect on the payload, but it can be taken that an aircraft fitted with piston engines and cruising at 220 knots at 20,000 to 25,000 feet will, when fitted with turbo-prop engines, be able to cruise at 300 knots at 30,000 to 40,000 feet. It may appear invidious to compare the power/weight ratio of a 4,000 H.P. engine with one giving only 2,200 H.P., but it is this high power output of the gas turbine that justifies its existence, apart from its freedom from vibration.

Fuel Control of the Turbo-Prop Engine

46. Temperature control is from many aspects an ideal method of controlling the engine, since both the turbine and jet-pipe temperatures are the governing operating factors. It is, however, difficult to provide control at low power, because under these conditions the turbine and compressor efficiencies are low ; this causes a rise in engine temperatures and consequently a misleading signal is transmitted to the controlling mechanism. There are, however, several types of control available, either automatic or manual, which largely fulfil the necessary requirements. These systems are based on the spilling (bypassing) of a measured amount of fuel from the flow control unit to keep the fuel flow to the engine such that the indicated j.p.t. is equal to the ideal j.p.t. for the particular power. The automatic control unit is operated electrically while the manual type is a simple direct rheostat control, the spill being set to the desired value manually. In both cases the indicated temperature is obtained from the output of four jet-pipe thermo-couples connected in parallel. Chapter 8, paras. 14 to 17, contains details of a typical temperature control system.

Summary of Performance Characteristics—Basic Types of I.C. Engines

47. The graphs in Fig. 11 summarize the main characteristics of the turbo-jet, turbo-prop, and piston engines under the following headings :—

(*a*) Variation of T.H.P. with speed.

(*b*) Specific weight with speed, power, and height.

(*c*) Rate of climb.

(*d*) S.F.C. with speed and height.

The various curves show the characteristic trends of each type of engine under the various headings. The curves are hypothetical but are assumed to apply to one type of aircraft carrying the same payload. The following discussion should be read in conjunction with Figs. 11 and 12.

48. From the viewpoint of rapid take-off, high initial rate of climb, and moderate cruising speeds up to about 220 knots, the piston engine is the most effective unit. At these speeds the piston engine can be run efficiently at a low power setting and in weak mixture conditions ; any form of gas turbine which is run under the same set of conditions experiences a considerable loss in efficiency and greatly increased S.F.C.

49. However, if a combination of good take-off performance and a fairly high cruising speed is required, the turbo-prop is the best engine by virtue of its better power/weight ratio (*i.e.* specific weight), lower drag through smaller frontal area, and increase in power with speed. These characteristics of the turbo-prop enable a larger payload to be carried or more fuel for the same payload ; however, the larger payload is only obtained by operating at about 30,000 feet, or above, since any attempt to do so at lower altitudes results in an increase in S.F.C. and a reduced range.

50. The turbo-jet, at sea level and low altitudes, fails to meet the requirements for rapid take-off and economical operation. Over the whole speed range, at low altitude, the turbo-jet is not economical ; the specific consumption is high, and, while lower at reduced speeds, is still much greater than in either of the other units. High speed is beneficial since ram effect increases the power for a given fuel flow. By increasing the speed from about 250 knots to 520 knots (300 to 600 m.p.h.) the power output is doubled, but to obtain a similar output from a piston engine it would have to be of prohibitive weight and size. Further, at low altitudes the engine loses the beneficial effects of the low temperatures obtaining at higher altitudes and also the lower drag obtained at low densities.

51. The best rate of climb to about 10,000 feet is given by the turbo-prop ; above this height it is bettered first by the piston engine and then by the turbo-jet. At about 25,000 feet the piston engine is again overtaken by the turbo-prop, owing to the piston engine fall in power once the rated altitude is exceeded. Since the turbo-prop is not supercharged the power tends to fall with the air density, but this is offset by the improvement due to ram effects at high airspeeds and the increased mass flow due to the lower temperature. Added to these effects is the better power/weight ratio and lower drag ; the final result being that the rate of power fall-off is ultimately slower than that of the supercharged piston engine.

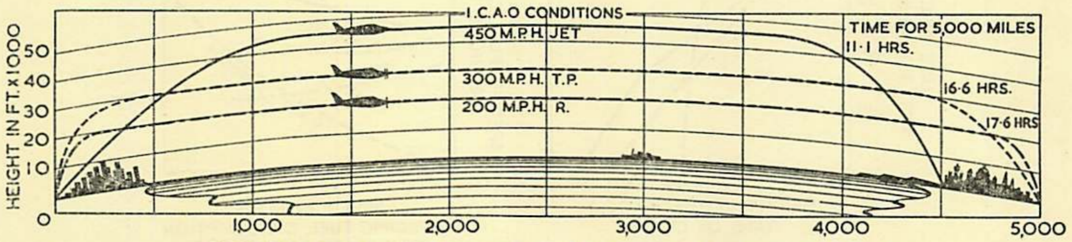
52. The rate of climb of the turbo-jet eventually exceeds that of the other engines and gradually improves, in relation to its rivals, up to the tropopause. Above this height, having lost the advantage of the decreasing temperature gradient, the power falls off at a similar rate to the turbo-prop.

53. The piston engine, at high speed and altitude, fails in all respects because of its dependence on high air density which cannot be supplied by the supercharger. Any attempt to increase the speed under these conditions causes a high S.F.C. and so greatly reduced range, apart from the stresses imposed by having to run the engine at maximum power.

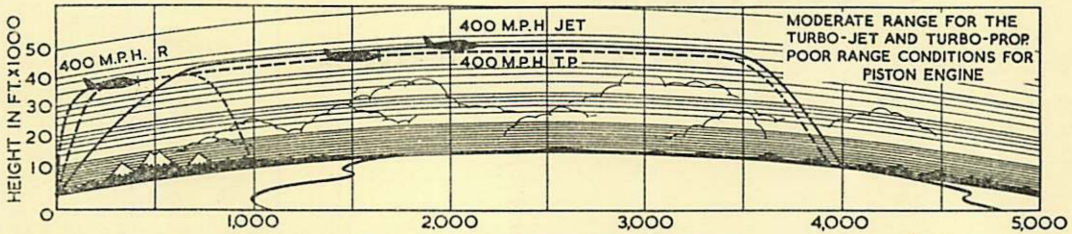
54. The turbo-prop has many of the advantages of the turbo-jet but its maximum speed is limited by compressibility effects on the propeller. However, the cruising speed and operating altitude are greater than those of the piston engine with very little penalty in fuel consumption.

55. At the highest altitudes the turbo-jet is the best engine; it permits the use of high cruising speeds with an S.F.C. hardly less economical than that of the other units when operated at their optimum conditions. The maximum operating height is much greater than those of the other types of engine.

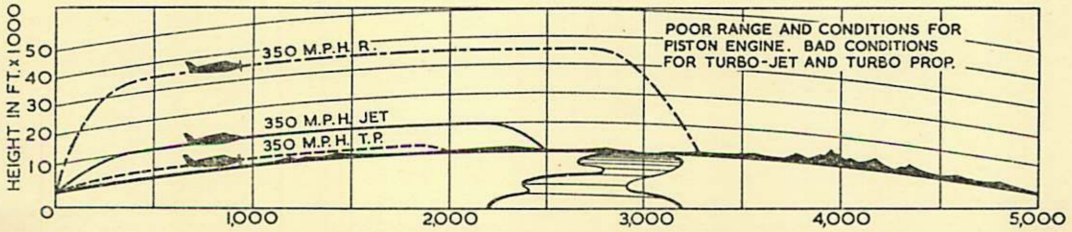
56. It can be seen from this brief summary that there is no engine that has a good all-round performance in terms of speed, height, and range. Each unit has its own limitations and its own peculiar requirements for maximum economy. The type of engine selected for an aircraft depends on the role of the aircraft and is the type best suited to the performance framework within which the aircraft is to operate.



OPTIMUM CONDITIONS OF SPEED AND HEIGHT FOR MAXIMUM RANGE



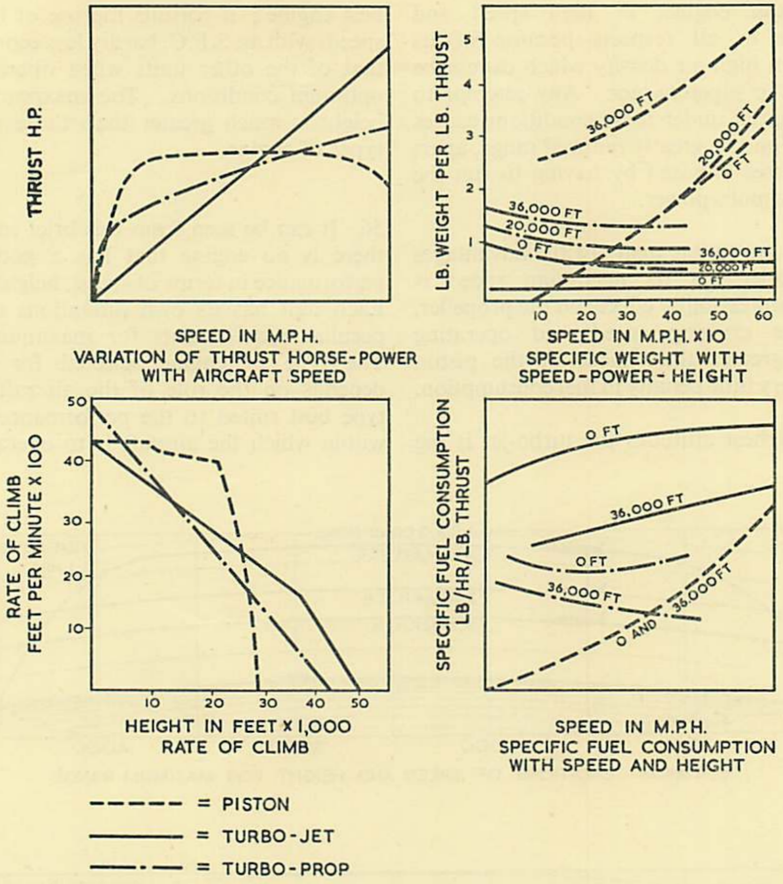
RANGE AT 35000 FT. AND 400 M.P.H.



RANGE UNDER INEFFICIENT CONDITIONS

LONG RANGE BOMBER
10% PAYLOAD. STILL AIR

Fig. 11. Comparison between Aircraft using Different Basic Types of Engine.



VARIATION OF THRUST HORSE-POWER WITH AIRCRAFT SPEED

SPECIFIC WEIGHT WITH SPEED-POWER-HEIGHT

RATE OF CLIMB

SPECIFIC FUEL CONSUMPTION WITH SPEED AND HEIGHT

Fig. 12. Typical Performance Curves.

(*A.L.*4, *May* '55)


XA699