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PART 1: SECTION 3

CHAPTER 1

BASIC THEORY AND PRINCIPLES

Introduction

1. Gas turbine aero-engines at present used in aircraft are divided into two main classes :—

(a) The turbo-jet engine, which derives its power from the reaction of a gas expelled rearwards.

(b) The turbo-prop. engine, which utilizes the greater part of its power output to drive a propeller, the residue augmenting the thrust by jet reaction.

2. A turbo-jet engined aircraft obtains its propelling motion in the same manner as a piston propeller-driven aircraft. With the propeller, a relatively large mass of air is accelerated rearwards at a comparatively low speed. It is the reaction to the rate of change of momentum of the mass of air that propels the aircraft. The turbo-jet engined aircraft is propelled in a similar manner, but the mass of air is much smaller and is subjected to greater acceleration.

3. The principle of operation of the gas-turbine engine is somewhat similar to that of the piston engine in that there are induction, compression, ignition, and expansion, and exhaust processes. However, these are continuous processes and not intermittent as in the piston engine. Fig. 1 illustrates the principle of operation from which it will be seen that air is drawn in through the intake A by a compressor B which is fixed to a shaft C. At the other end of the shaft the turbine D is fixed. Air leaves the compressor at high velocity and increased pressure and temperature, then passes through the diffuser E, which converts the velocity energy to pressure energy. The air then passes into the combustion chamber H. Of the total mass of air passing into the combustion chamber roughly 25%, known as primary air, enters the flame tubes through the flame-tube orifice G; the remainder, known as secondary air, passes along the outside of the flame tubes, entering through dilution holes J in the side of the tubes. Each combustion chamber is provided with a burner containing a swirl type atomizer, and through this atomizer fuel is injected under pressure by the fuel pump into the combustion chambers, where it mixes as

fine droplets with the incoming primary air. (Other systems, e.g. vaporizing combustion chambers, are described in Chapter 4.)

4. The combustible mixture formed is ignited by the igniters fitted to two or three of the combustion chambers. On completion of the starting cycle the igniters are cut off. At this stage the engine is said to "light up" and from this point combustion is continuous and the pressure in the combustion chambers for a given fuel flow is constant. The remaining secondary air, which passes through the dilution holes into the flame tube, mixes with the main mass of burning gas and cools it sufficiently to allow it to pass through the turbine at a temperature within the safe limits of the turbine material. Owing to the added heat energy of the fuel, the gas not only rises in temperature but also increases in volume.

5. After passing through the combustion chambers the hot gases enter the nozzle guide vanes K which direct them at increased velocity on to the turbine blades, causing the turbine disc D to rotate and so drive the compressor. Of the total energy about 60% is used to drive the compressor, so that there is a considerable drop in gas pressure and temperature across the turbine. The remaining energy, about 40%, after driving the turbine and compressor is used to form a high-speed jet, which has a substantial residual pressure; this jet passes into the exhaust cone L, to emerge at atmospheric pressure at orifice M. The jet not only has kinetic energy owing to its velocity but also considerable heat energy. The heat energy is released to atmosphere, however, and is consequently wasted.

Thrust and Propulsive Efficiency

6. An aircraft is propelled by a force known as *thrust*, this force being necessary to accelerate the aircraft and balance the drag. Piston engines are rated in *horse power* and turbine-jet engines are rated by the amount of *static thrust* they produce. The following paragraphs clarify the relationship of these three factors.

7. Anything that floats or flies and is self-propelled acquires propulsion by displacing

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something—usually a mass of the supporting medium—in the opposite direction. To make this mass move backwards it is necessary to exert a rearward-acting push on it; consequently, in accordance with Newton's third law, an equal and opposite forward reaction is set up. This forward acting force is thrust.

8. It is not necessary to use the surrounding fluid for propulsion (as with a rocket). As long as *something* is moved, there will be a reaction on the mover in the opposite direction. Familiar examples are the recoil of a gun, the rotation of a lawn sprinkler, or the reaction of a small boat as one dives from it.

9. The simple relationship between the force applied to a body, its mass, and the resulting acceleration that it experiences can be stated as follows:—

$$\text{FORCE} = \text{MASS} \times \text{ACCELERATION}$$

Consequently the thrust experienced by an aircraft depends on the mass of air passing through the propeller disc or jet pipe in unit time and the rate at which its velocity is changed.

10. To avoid confusion it would be as well to clarify the term mass, for there is a fundamental difference between *mass* and *weight*. The mass of a body is usually defined as the quantity of matter contained in it, and is constant; whereas the weight of a body is the gravitational force attracting it towards the earth, and is not constant—decreasing as distance from the earth's centre increases. Therefore the weight of a body is slightly less at the equator than at the poles. Where the force of gravity is less, the acceleration due to gravity must also be proportionately less; *i.e.* the body will not gain speed so rapidly if allowed to fall freely. Thus the weight of a body divided by the acceleration due to gravity (W/g) will always be constant, regardless of its position on earth or in space. This is the mass, and for all normal purposes is obtained by dividing the weight by 32.2 when working in ft. lb./sec.² units.

11. Returning to the equation of para. 9 and applying it to a stationary aircraft with its engine running at high power, assume that in one second W lb. of air are accelerated from rest to V_2 ft./sec. The mass of air handled by the propeller or turbine jet in that time (*i.e.* the mass flow) will be $\frac{W}{g}$ and the acceleration imparted V_2 ft./sec. Consequently the thrust acting on

the aircraft will be $\frac{WV_2 \text{ lb.}}{g}$. But as the aircraft cannot move, all the energy given to the slip-stream or jet is wasted and the propulsive efficiency is consequently zero.

12. If the aircraft is now permitted to move, it will take off and attain a certain velocity, V_1 ft./sec.; *i.e.* the air about to pass through the propeller disc or turbine has a velocity towards the aircraft of V_1 ft./sec. Assuming that the resultant velocity of this air relative to the aircraft is still V_2 ft./sec., the acceleration is now only $(V_2 - V_1)$ ft./sec.; and if the mass flow remains the same the thrust will be $\frac{W(V_2 - V_1) \text{ lb.}}{g}$. In other words, thrust falls off as speed increases.

13. At this stage a factor that favours the turbine engine makes itself evident; air pressure tends to build up in front of any object moving through it, an effect hardly noticeable at low speeds but which increases rapidly until at high speeds a considerable pressure rise is experienced. This increase in pressure, which is pronounced above about 250 knots, increases the mass flow through the engine. This is known as *ram effect*. The result is shown in Fig. 2, where it can be seen that up to about 250 knots thrust falls steadily, as would be expected from the decreasing acceleration given to the air; above this speed, however, the ram effect is sufficient not only to halt the fall but to reverse the trend, until at 500 knots the static value has been regained. The *rate* of rise of thrust with speed decreases beyond mach 1 as a result of the formation of shock waves in the entry duct unless measures are taken to counter the effect of shock waves on or in the intake.

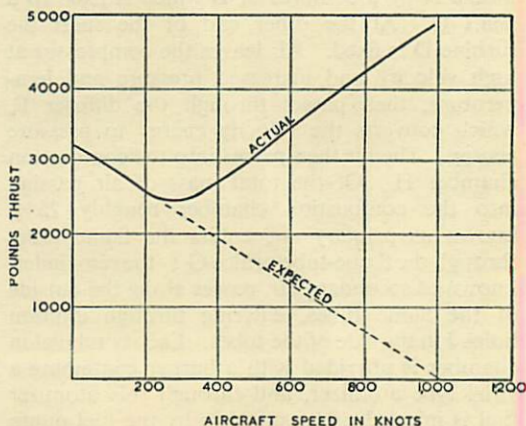


Fig. 2. How Ram Effect Affects the Thrust.

14. With the propeller the effect of compressibility is unfavourable. The pressure rise and mach-number effects at the leading edge of the blades increase drag considerably and, in turn, the engine torque required to produce a given thrust—i.e. propeller efficiency, and so thrust—increases. Furthermore, because of the combined rotary and forward movement of a propeller, its speed through the air exceeds that of the aircraft, the difference being small near the hub and considerable at the blade tips. Consequently compressibility effects become significant at the tips when the forward speed is still well below that of sound, and extend inwards as speed increases, with a resultant deterioration of the blade lift/drag ratio and so a further adverse effect on efficiency.

15. It is instructive to compare the efficiencies of the propeller and jet at various speeds. The important difference between the two is that whereas the propeller produces thrust by giving a large mass of air a small acceleration, the turbo-jet imparts a much higher acceleration to a considerably smaller mass. For example, propeller slipstream velocity relative to the aircraft is only about 5% higher than the aircraft forward speed, while jet velocity is in the region of 1,000 knots. Each type of aircraft, therefore, leaves behind it a column of air moving backwards, in the one case the column being large and slow moving, and in the other small and fast moving. Each also represents wasted energy—energy released in the engine by the burning of fuel and dissipated behind the aircraft in friction. Now the energy possessed by a moving body is $\frac{WV^2}{2g}$, W being the weight and V the velocity; i.e. kinetic energy is proportional to the mass and to the square of the speed. Thus, for a given thrust, greater efficiency is obtained by leaving behind a large slow-moving mass of air, than the reverse. It is also clear that efficiency will be zero when an aircraft is stationary and all the energy release is wasted, and would be 100% if it were possible for the forward speed to equal the jet or slipstream speed relative to the aircraft. (There would, of course, be no thrust in the latter condition.)

16. Fig. 3 shows the relative efficiencies of propeller and jet at different airspeeds. The jet lags far behind the propeller at low and medium speeds, but rises steadily as $V_2 - V_1$ decreases, until at about 450 knots it becomes more efficient because of the decreasing efficiency of the

propeller. Thus, in fuel consumption, the propeller-driven aircraft is more economical than its jet counterpart at speeds up to 450 knots.

17. In practice, the intersection of the curves in Fig. 3 occurs at a somewhat lower airspeed than that shown, owing to the extra drag caused by the propeller slipstream and the wasted energy represented by the slipstream rotation.

18. So far the conclusions arrived at have not taken into account the type of engine which drives the propeller—piston engine or turbine. A comparison should be made between the turbo-jet and the piston engine, in terms of power output. Power is defined as the rate of doing work, and is the product of force applied and the resultant velocity; it is usually expressed in horse-power, where one H.P. equals 550 ft.-lb. per sec. Thus the power applied to propelling an aircraft—the *thrust horse-power* (T.H.P.)—is equal to

$$\frac{\text{Thrust (lb.)} \times \text{aircraft velocity (ft./sec.)}}{550}$$

from which it is easy to see that, since drag

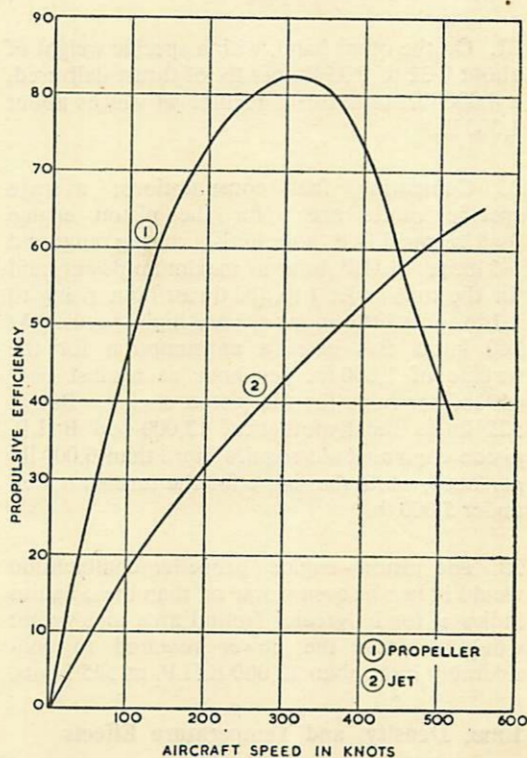


Fig. 3. Propulsive Efficiency and Aircraft Speed.

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increases as the square of the speed (until nearing the speed of sound), the T.H.P. required varies as the cube of the speed, *i.e.* to double the speed, eight times the T.H.P. must be developed.

19. The power of a piston engine is measured at the crankshaft in brake horse-power (B.H.P.), and to relate the B.H.P. developed to the T.H.P. available the propeller efficiency must be taken into account. Thus $T.H.P. = B.H.P. \times \text{propeller efficiency}$.

20. Taking as an example one of the early Spitfires which, with an engine developing 1,000 B.H.P., had a sea-level speed of about 260 knots; assuming a propeller efficiency of 80% at this speed, about 800 T.H.P. is required to attain this speed. Using the equation in para. 18, the thrust works out at 1,000 lb. To raise the speed of this aircraft to 525 knots, 4,000 lb. thrust must be produced requiring 6,400 T.H.P. Furthermore, as at this speed the propeller efficiency falls to about 53%, the engine must develop over 12,000 B.H.P. As the power/weight ratio could not be expected to be better than 1 lb. per B.H.P., a prohibitive weight and bulk of engine would be involved.

21. On the other hand, with a specific weight of about 0.32 to 0.35 lb. per lb. of thrust delivered, a 4,000 lb. static thrust turbine-jet weighs about 1,300 lb.

22. Comparing fuel consumptions, average specific values are: for the piston engine 0.45 lb. per B.H.P./hour in the cruising range and 0.5 lb. per B.H.P./hour at maximum power, and for the turbine-jet 1 lb./lb. thrust/hour rising to 1.1 lb. or a little more at very high speeds. At 260 knots this gives a consumption for the turbine of 1,000 lb. per hour as against only 450 lb. per hour for the piston engine. But at 525 knots the hypothetical 12,000-odd B.H.P. piston engine would require more than 6,000 lb. per hour, while the figure for the turbine is well under 5,000 lb.

23. The piston - engine / propeller combination would in fact be even worse off than these figures indicate, for its greater frontal area and weight would increase the power required to considerably more than 12,000 B.H.P. at 525 knots.

Ram, Density, and Temperature Effects

24. Atmospheric pressure, density, and temperature decrease with height, and together

with the ram effects, these variations have a marked effect on the performance of the gas-turbine engine. At constant r.p.m. the pressure ratio of the compressor and the temperature rise across the compressor remain constant irrespective of height; owing to the drop in air density, however, it is necessary to reduce the fuel supply to prevent a high combustion temperature resulting from an excess of fuel. In addition to the drop in density there is a drop in air temperature, and consequently the temperature of the air entering the combustion chambers will also be lower. This reduced temperature allows a slightly greater quantity of fuel to be used than would be possible if a constant temperature was maintained.

25. The increase in temperature results in a greater change of momentum of the gas passing through the engine, so that one pound of air now produces more thrust than at sea level, *i.e.* there is an improved expansion ratio through the turbine, which increases the efficiency. However, the total weight of air passing through the engine is less at height owing to the reduction in air density, and consequently the mass airflow is less; but it has been shown that one pound of air produces more power at height, so the total power output decreases at a lower rate than the air density.

26. As has been explained, the power available from one pound of air is increased if the air enters the compressor at a lower temperature. If the air at sea level is cold the density is higher. It can therefore be seen that the thrust obtainable from a gas-turbine engine is greater on a cold day, not only because of the extra power obtained from each pound of air passing through the engine, but also because the total weight of a given volume of air is greater, owing to its greater density.

27. The effect of intake air temperature on the power delivered by a gas turbine is shown in Fig. 4. It can be seen from this curve that the power increases considerably as the temperature falls; as much as 50% increase in the sea-level power is obtained at a temperature of 0°F. compared with the output at the design temperature of say 60°F. It is obvious, therefore, that with increased height and lower temperature a considerable proportion of the power will be regained by virtue of the lower temperature. As the aircraft gains height the compressor load decreases owing to the lower density and, unless the fuel flow is reduced, the turbine overspeeds. This

contingency is covered by the use of the barometric pressure control (B.P.C.) which monitors the variable-stroke fuel pumps and reduces their output as altitude is gained, resulting in a decrease in consumption. On the other hand an increase in temperature causes a loss of power, since it decreases the density (weight) of a given volume of air passing through the engine.

28. It will be appreciated that so far there has been a gain owing to the increased density at low temperatures and a loss owing to the lower density at high temperatures. At altitude the overall thrust is less, owing to the reduced density, but, also because of the reduced density, the total drag of the aircraft is less than at sea level; consequently less power is required to propel the aircraft at a given T.A.S. However, the reduction in drag is not proportional to the reduction in air density because, at altitude, the angle of attack of the wing must be increased to provide the same amount of lift, and this results in an increase in the induced drag, thus raising the total drag. Therefore the drag decreases with altitude at a lower rate than the density. If the T.H.P. of a jet aircraft decreases with altitude at the same rate as the decrease in total drag, then the T.A.S. is constant at all heights; but at height the drag is less and therefore the thrust required from the engine is proportionately less; this reduction in the required thrust is accompanied by a reduction in the fuel consumption.

If, however, power from the turbine decreases at a lower rate than the reduction in drag, then the speed *increases* with height. This gives a further increase in efficiency as a result of the increase in speed, resulting in an increase in propulsive efficiency. The increase in speed also results in greater ram effect, thus increasing the compressor efficiency which therefore absorbs less power from the turbine to do the same amount of work on the air.

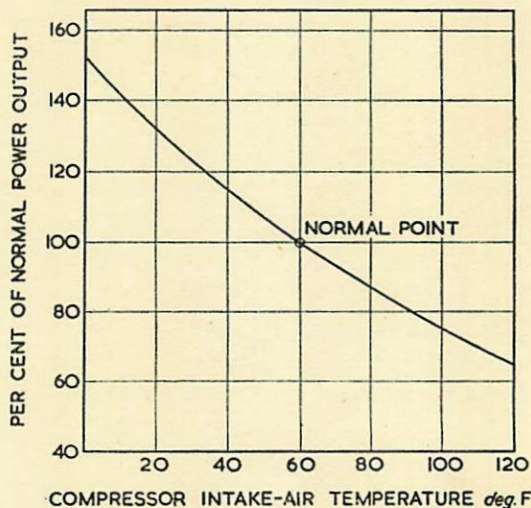


Fig. 4. Effect of Air Temperature on Power Output.

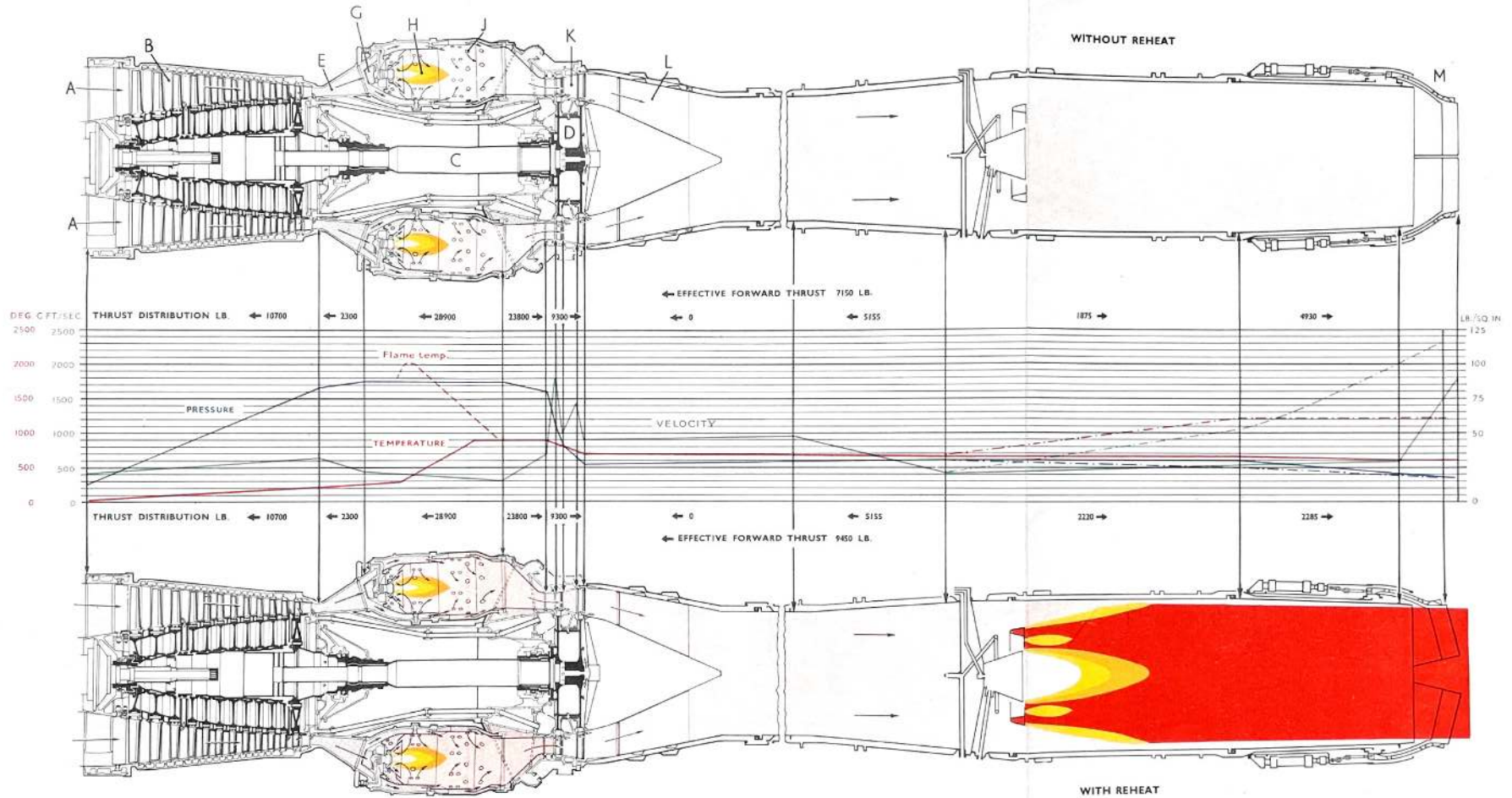


Fig. 1. Schematic Diagram of an Avon Engine showing the Gas Flow with and without Reheat

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