PART 1 : SECTION 3

CHAPTER 9

THRUST AUGMENTATION

Introduction

1. Two methods are used to augment the thrust of turbo-jet engines while at maximum power. These are :—

(*a*) Reheat.

(*b*) Water/methanol injection.

The aim of this chapter is to give a general description of both systems: Pilots' Notes give details of the operation of any particular system.

REHEAT

Purpose and Advantages of Reheat

2. Reheat is a method of thrust augmentation used on turbo-jet engines. Fuel is injected into the gas stream from special burners after the stream has left the turbine and before it has reached the jet-pipe nozzle, so raising the gas temperature and energy. The added energy increases the gas velocity, and hence the total thrust. Reheat is primarily a method of increasing the thrust over and above that given by the engine, and is not a method of correcting the thrust of under-powered engines. Reheat is sometimes referred to as after-burning.

3. The use of reheat results in a shorter take-off and improved rate of climb and is particularly useful for carrier-borne or heavily laden aircraft. With the reheat turned on, the take-off thrust can be increased by about 45% and the thrust at 500 knots by about 80%. The specific fuel consumption (S.F.C.) rises sharply when reheat is used, but this is offset largely by the reduction in time to height and therefore in the time spent at full throttle. Since reheat raises the maximum thrust of a comparatively small engine to that of a much larger engine without reheat, the higher fuel consumption and added weight is not a high price to pay. One of the main advantages of reheat as a thrust-augmenting method is that its efficiency increases with the T.A.S. ; for example, a unit that gives 25% increase at take-off speed, produces nearly 50% increase at 600 knots and over 65% at 900 knots.

Description of a Reheat Unit

4. Reheat necessitates the use of a larger and heavier jet pipe, a two-position variable area nozzle, a separate fuel pump, and a control system. Any turbo-jet engine can be converted to take reheat by the addition of these extra items.

5. Since 66% of the air consumed by a gas turbine is for cooling purposes only, if fuel is burned with this excess air, after it has completed its cooling action, the total thrust is considerably increased. Fuel is injected into the jet pipe through burners supplied by a high-pressure turbo-pump which is driven by air taken through a tapping from the compressor delivery. The pump output is controlled by a reheat control unit which governs the supply of driving air to the pump.

6. A mechanically operated two-position nozzle is fitted to the jet pipe to increase the nozzle area and allow for the additional mass gas flow when using reheat. The purpose of the control unit is to maintain safe temperatures when reheat is used, by controlling the fuel supply to the reheat burners. If an excessive j.p.t. is generated a *temperature limiter* cancels the reheat.

7. **Nozzle Area and Exhaust Velocity.** The thrust of a jet engine is directly proportional to the weight of gas discharged from the jet-pipe nozzle multiplied by the velocity of discharge. The effective thrust-producing velocity is that relative to the surrounding atmosphere and not that relative to the jet-pipe nozzle ; only under sea-level static conditions is the effective velocity measured relative to the jet-pipe nozzle. The effect of pressure in the jet pipe is to produce velocity at the jet nozzle and not, as is sometimes stated, to "push" against the surrounding atmosphere. As the pressure in the jet pipe rises (and consequently the pressure difference between jet pipe and atmospheric pressures becomes greater) the exit velocity of the gases from the jet-pipe nozzle also increases until the speed of sound is reached ; *any further increase of pressure in the jet pipe does not produce any increase in velocity.*

8. The speed of sound in air (for the present purposes the exhaust gas can be considered as air) is about 1,100 ft./sec. at 15° C., about 1,800 ft./sec. at 550° C., and about 2,600 ft./sec.

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at 1,350° C., and is independent of pressure. Since, if the jet is to propel the aircraft, its velocity must be greater than that of the aircraft, it is of interest to note that the exhaust velocities for a flight speed of mach 1·0 are about 650, 1,010 and 1,520 knots for temperatures of 15° C., 550° C., and 1,350° C., respectively. When the pressure in the jet pipe is greater than that required to produce a gas velocity of mach 1·0 at the jet-pipe exit, the engine or the jet pipe is said to be *choked* and a back pressure is set up on the turbine which seriously affects efficiency and engine running.

9. Both the jet-pipe temperature and pressure affect the total thrust. Consider a typical jet engine having a fixed area jet-pipe nozzle and running under static sea-level conditions. As the throttle is opened, the weight of air delivered by the compressor increases, and this in turn increases the jet-pipe pressure ; the air/fuel ratio also increases to raise the jet-pipe temperature. The jet-pipe temperature has two important effects on the total thrust :—

(*a*) It affects the velocity that can be obtained at a given pressure, and the pressure in turn is related to the density of the gases. If the density is reduced by 50% (owing to temperature rise) then the velocity for a given pressure is increased by roughly 40%. The increased gas velocity which can be produced in this way can, however, only be used if the increased gas velocity at the nozzle is less than mach 1·0.

(*b*) It increases the local velocity of sound, so that higher jet velocities can be used. For example, increasing the gas temperature at the jet-pipe nozzle from 550° C. to 1,350° C. raises the choking velocity from about 1,800 ft./sec. to 2,600 ft./sec. Thus the higher temperature raises the choking velocity and total thrust by some 40%. This is enough to show that the heat energy of the gases leaving the jet-pipe nozzle is an important part of the propulsion process, and is not altogether waste-heat energy as it may at first appear to be.

From the foregoing it should be appreciated that, in order to use the full potential of reheat, some form of variable-area tail-pipe nozzle is needed.

DESCRIPTION OF A TYPICAL INSTALLATION

Jet Pipe and Two-Position Nozzle

10. The reheat jet pipe is fitted in the same way as a normal jet pipe, and is connected by a transition section to the exhaust unit of the engine (Fig. 1). The whole unit consists of a diffuser section carrying the burner assembly, parallel section, and a two-position nozzle. To combat the higher skin temperatures the jet pipe has a double skin, the space between the two being used for a slowly moving blanket of insulating air. To obtain this insulating action, an air ejector in the two-position nozzle continuously sucks cold air between the double skins.

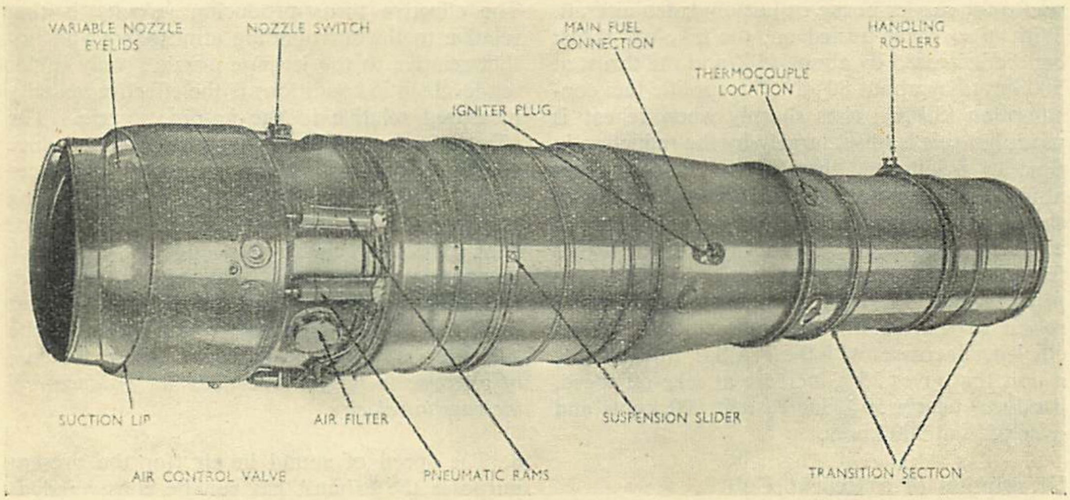


Fig. 1. Typical Reheat Jet Pipe and Nozzle.

No cooling of the very hot inner skin is possible by this or any other economical means; the main purpose of the cooling air is to insulate the outer skin. The outer skin is used as a main structural member, the inner skin being flexibly suspended inside it and carrying only the gas loads. The central parallel section of the inner skin has a sliding joint at each end to allow for thermal expansion.

11. The two-position nozzle (Fig. 2) consists of a fixed-area reheat nozzle surmounted by two moveable "eyelids" shaped like segments of a sphere. When closed, the eyelids form an elliptical nozzle of smaller area for normal running and are connected by synchronizing linkages which, when the nozzle is opening, equalize the loading to ensure that the rate of movement of each eyelid is the same.

12. The eyelids are operated by four pneumatic rams, connected in pairs to each eyelid by triangulated levers which increase the ram loading by 2 : 1 when the nozzle is closed. The rams are pressure operated by the cooling air from the turbine nozzle-box; this air passes from the nozzle-box via a filter to a solenoid-operated shuttle valve, which directs the air to either side of the ram piston and keeps the eyelids in the selected position as shown in Fig. 3.

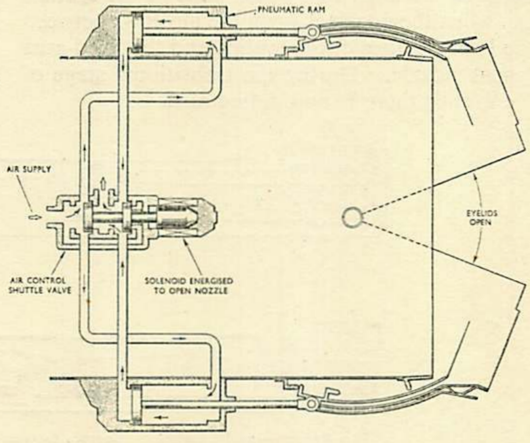


Fig. 3. Nozzle Control System.

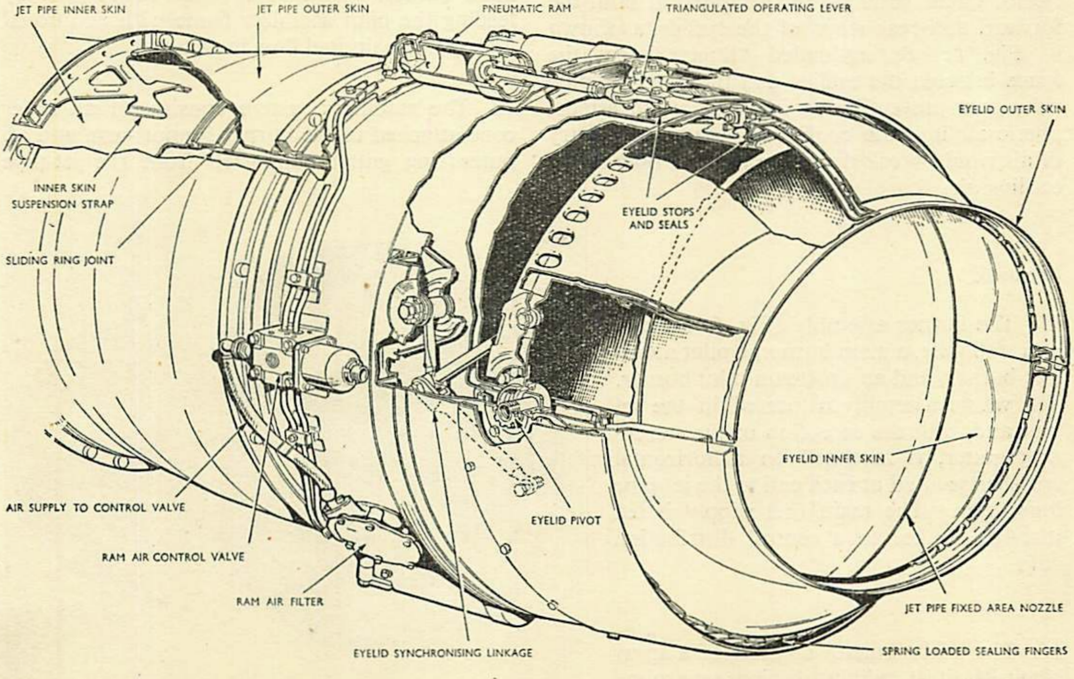
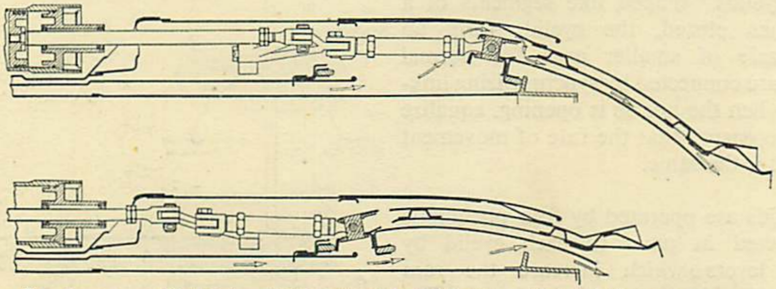


Fig. 2. Two-Position Variable Area Nozzle.

Cooling

13. To cool the inner and outer skins the double skin of the jet pipe forms an annular gap through which air is drawn by the ejector effect of the gases from the nozzle. When the nozzle is closed (Fig. 4) air is drawn through the space between the inner and outer skins of the eyelids, but when the nozzle is open the air flows between the inner surface of the eyelids and the fixed-area reheat nozzle. During the transitional stage of the eyelids there is no cooling airflow.



Top diagram—eyelid closed Bottom diagram—eyelid open Arrows indicate cooling air

Fig. 4. Diagrammatic View of Nozzle Showing Cooling Airflow.

Seals

14. To prevent a reverse flow of hot gases into the jet-pipe cooling annulus and to maintain the ejector effect, seals are incorporated at both the forward and rear stops of the eyelids, as shown in Fig. 4. Spring-loaded "fingers" seal the space between the eyelids and the outer jet-pipe skin, thus preventing an inward flow of atmospheric air into the cooling annulus. Any entry of air would break down the positive flow of the cooling air.

Burners

15. The burner assembly (Fig. 5) consists of a stabilizer, a main burner, a pilot atomizer burner, and an upstream pilot burner. The whole assembly is located in the jet pipe and, with the exception of the stabilizing gutter, is mounted on a horizontal crossbar secured at each end to the jet-pipe inner skin. The main fuel supply is led through the bar to a central distribution core.

16. The main burner consists of a spray ring with short radial stub pipes set around it at intervals. Fuel is fed to the ring through two pipes radiating from the centre feed core, and is sprayed radially through small orifices at each end of the stub pipes where it is vaporized and blown rearwards over the main reheat flame in the gutter.

17. The pilot atomizer burner, which faces downstream and is in the centre cone of the assembly, provides the pilot flame used to ignite the main fuel flow and receives its fuel from a pipe passing through the main support bar. In the apex of the centre cone on the upstream side (not seen in Fig. 5) is the upstream pilot burner which sprays fuel upstream of the main spray. Its flow increases in proportion to that of the main burner, whose combustion it supports by feeding the pilot atomizer flame with additional fuel as the main fuel flow increases.

18. The stabilizer system consists of an inner cone attached to the burner support-arm and an outer ring gutter supported from the jet-pipe

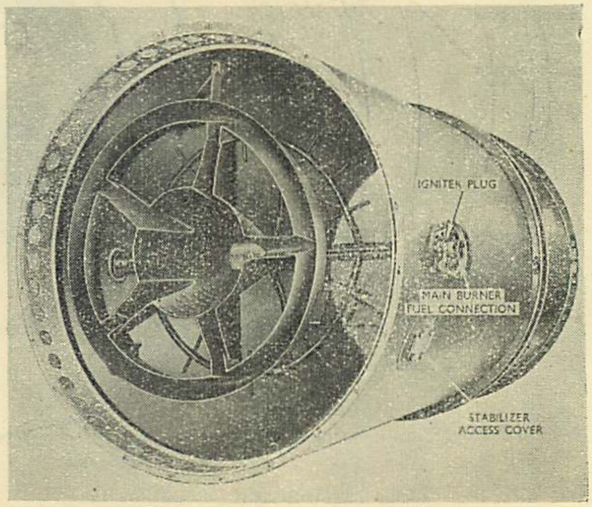


Fig. 5. Reheat Burner Assembly.

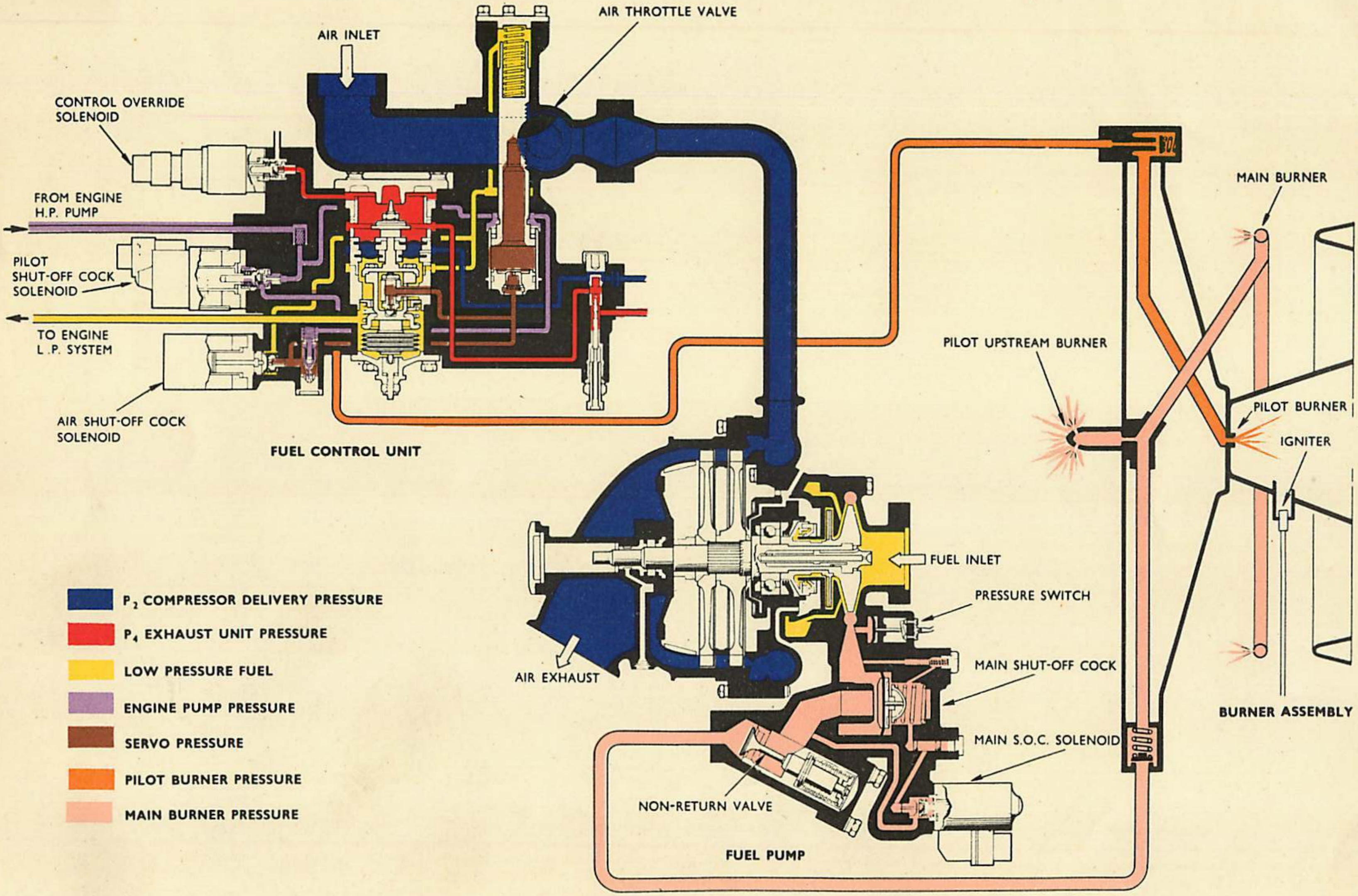


Fig. 6. Reheat Fuel System Diagram

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inner skin. The gutter forms a stabilizer for the main reheat flame, the combustion of which is supported by the pilot flame produced in the inner cone and fed radially outwards along V-sectioned troughs to the ring gutter. To reduce the resonance encountered with the ring-type burner and to smooth the boundary air layer and so prevent skin overheating, a short corrugated sleeve is riveted to the inner jet-pipe skin around the burner assembly.

Igniter

19. A high-tension igniter plug, located inside the stabilizing cone, is used for lighting the pilot atomizer fuel. It is operated by a booster-coil controlled by a 30-second time switch in the reheat circuit.

Safety Devices

20. **Nozzle-Position Warning Indicator.** A switch which controls a nozzle-position warning indicator is on the jet pipe forward of the nozzle, and is connected to the operating linkage. The cockpit magnetic (dolls eye) indicator shows black if the nozzle is in the correct position for the selected running condition, and white while the eyelids are moving between the two positions or if the eyelids are in the wrong position.

21. **Hot-Gas Warning Indicator.** The hot-gas warning indicator, an amber light, operates if the temperature between the skins of the outer and inner jet pipes rises owing to :—

(*a*) A breakdown in the cooling airflow, or

(*b*) A fractured inner jet-pipe skin allowing a leakage of hot gas.

22. **Fire Warning Indicator.** In addition to the usual fire warning device in the engine bay, another is fitted near the reheat pump and the jet-pipe diffuser section.

23. **Air-Extractor Failure Indicator.** The reheat fuel-system compartment is ventilated in flight by air taken in through forward-facing louvres ; on the ground this is done by an air extractor operated by compressor delivery air. When the system is operating correctly, the air-extractor failure indicator, in the cockpit, should show black with the undercarriage up and white with the undercarriage down.

Reheat Control Unit

24. The reheat control unit (Fig. 6) ensures that both the reheat and the engine gas temperatures are kept within safe limits. The control unit governs the fuel supply to the main reheat burners according to the pressure difference across the turbine, the pressure being greater on the inlet side of the turbine. Any variation in the pressure difference is sensed by the unit which accordingly increases or decreases the amount of driving air supplied to the reheat turbo-pump by adjusting an air throttle, thus indirectly controlling the flow of fuel to the reheat main burners.

25. To prevent the cancellation of reheat by the high pressure that occurs in the jet pipe during the initial stages of reheat light-up, a solenoid-operated override valve opens for 30 seconds and bleeds air from the control unit, thus making the unit unresponsive. The control unit also has a solenoid-operated pilot shut-off cock which controls the fuel flow from the engine H.P. pump to the pilot atomizer.

Reheat Fuel Pump

26. The air-driven reheat fuel pump (Fig. 6) supplies the reheat main burner with high-pressure fuel. The pump consists of a two-stage turbine driving a centrifugal fuel pump. The pump receives its fuel supply from the aircraft low-pressure system and delivers it, under sea-level static conditions, at a flow of about 1,500 gall. per hour and a pressure of 250 lb./sq. in.

27. A shut-off cock controls the flow of fuel from the pump. When the pump output pressure reaches a set figure, a pressure-operated switch passes current to energize a solenoid in the shut-off cock to reduce the fuel flow to the reheat main burner. A non-return valve is fitted between the pump and the burner assembly. This valve ensures that the fuel-tank booster-pump cannot pass fuel through the pump to the main burner in the event of a failure of the main shut-off cock when reheat is not in use.

OPERATION OF REHEAT

Note: The information given below applies to the Avon Mk. 108 and Mk. 114, and is an example of how a typical reheat system works. The gas flow with reheat in use is shown in Chap. 1, Fig. 1.

Selection of Reheat

28. With the reheat off, the jet-pipe eyelids are closed and the indicator shows black. When reheat is required the engine should be accelerated to maximum r.p.m. and the throttle lever moved into the position marked REHEAT. The eyelids warning indicator shows white,

indicating that the eyelids are still closed, and after two to five seconds, depending on the altitude, the indicator changes to black, showing that the eyelids have opened and that reheat is in operation. The immediate increase in thrust and noise gives a very definite indication that the system is operating. If for any reason the eyelids are open with the reheat off, a considerable amount of thrust is lost; therefore, if the reheat flame goes out, the throttle should be moved out of the reheat segment immediately.

29. When the throttle lever is moved into the reheat position on the quadrant the following sequence occurs :—

(*a*) A high-pressure fuel supply is fed to the pilot burner in the reheat burner cone.

(*b*) The igniter plug is energized by a booster-coil, and ignites the fuel to produce a pilot flame. (A time switch cuts off the current to the coil after 30 seconds.)

(*c*) The fuel turbo-pump is started by the opening of the air throttle.

(*d*) When the fuel pressure builds up to a set figure, a pressure-operated switch operates four circuits.

30. The four circuits operated by the pressure switch are those of :—

(*a*) The solenoid-operated nozzle-control valves, which therefore start opening the eyelids.

(*b*) The solenoid-operated valve in the main shut-off cock, which opens and allows pump delivery fuel to flow to the reheat main burner.

(*c*) The control-unit override, which closes and puts the reheat control unit in control of the reheat fuel flow.

(*d*) The time-switch motor, which is set into operation.

31. The eyelids should now be fully open, the indicator showing black, and the reheat in operation; at this point the time switch operates :—

(*a*) After 3 seconds, to bring the temperature limiter into operation.

(*b*) After 30 seconds, to cut off the current to the booster-coil, igniter, and time-switch motor.

32. If an excessive temperature is generated in the jet pipe the temperature limiter in the reheat system energizes a relay; this opens to break the circuit to the reheat units, thus cancelling the reheat and closing the nozzle.

Cancelling Reheat

33. When the throttle lever is moved out of the reheat position, the reheat switch opens to cut the current to the reheat units. All the control solenoids are then de-energized, allowing the turbo-pump fuel and air cocks and the eyelids to close simultaneously.

WATER/METHANOL INJECTION SYSTEMS

Principles

34. The mass of gas discharged by the jet pipe, and hence the thrust, may be increased, without increasing the jet-pipe temperature, by the injection of water or a mixture of water and methanol into the combustion gases before they enter the turbine.

35. Water/methanol injection increases thrust by raising the mass and velocity of the gas stream. If a water/methanol mixture is injected into the intake of a centrifugal compressor, the mixture immediately starts evaporating; the latent heat of evaporation reduces the air temperature by an amount proportional to the degree of compression, which is considerable at maximum pressure. As a result of the refrigerating effect before and during compression, the mass flow and pressure of the air delivered by the compressor is increased, the compressor efficiency is increased, and the temperature of the air is decreased.

36. Water alone may be used as a means of increasing thrust but, because of the marked cooling effect, the fuel flow to the engine would have to be increased at the same time. Thus undesirable complication is avoided by the use of water/methanol injection, the combustion of the methanol supplying enough heat to offset the excessive cooling effect of the water.

37. Water/methanol injection increases the maximum thrust of a gas turbine by about 15%. The additional thrust is obtained at the expense of an increase in liquid (fuel plus water/methanol) consumption. Despite this, an improved range is obtained when compared with the same aircraft using a bigger engine, since the additional liquid consumption is only needed for brief periods.

38. As stated earlier, water/methanol is used to increase the mass flow while the temperature at the turbine is kept substantially constant. The best proportion of water and methanol has been found to be 60% water and 40% methanol by volume. Injection and combustion of this mixture usually results in a slight increase in jet-pipe temperature which can be tolerated for brief periods of use.

39. The injection of water/methanol into the inlet of axial flow compressors has not proved feasible and, if used, the mixture is usually injected into the combustion chambers.

40. In a water/methanol mixture the methanol prevents the mixture from freezing at low temperatures as well as providing heat for evaporation of the water and some heat for the combustion of the air.

Description of a Typical System

41. A requirement of the system is that the pump, the control, and tanks should be installed as one unit. An air-driven centrifugal pump provides a high-pressure delivery at the injectors. A metering control for the mixture, which is dependent on engine r.p.m., is controlled manually by a switch. The process is fully automatic.

42. This method provides a virtually constant amount of thrust augmentation at take-off, irrespective of ambient conditions. When the mixture is injected into the combustion chambers, distilled water may be used since this alone provides some 16% higher thrust/weight augmentation than water/methanol. Either can be used, but if the control is adjusted for water injection, some readjustment to the overspeed governor is necessary when using water/methanol to avoid exceeding the limiting jet-pipe temperature.

COMPARISON BETWEEN WATER/ METHANOL INJECTION AND REHEAT

43. Reheat has the advantage that the overall specific liquid consumption is only about 50% of that of water/methanol. Reheat also has the advantage of relying only on the aircraft fuel and not needing a special liquid. The disadvantages of reheat are greater than the advantages : gas temperatures of 1,350° C. in the jet pipe produce significant problems with materials, cooling, and mechanical operation of the variable-area jet-pipe nozzle ; when used on the ground, the high temperature and great noise of the gases issuing from the jet pipe also present a problem. Water/ methanol injection may be used in conjunction with reheat, but presents certain difficulties.