PART 1 : SECTION 3

CHAPTER 3

TURBINES

Introduction

1. A simple turbine consists of an arrangement of stator vanes (termed the nozzle guide vanes) and moving vanes, about 80 in all, attached to the periphery of the turbine disc. Through the nozzle guide vanes the airflow is turned to strike the turbine vanes at the optimum angle of attack. The rotating turbine drives the compressor by absorbing a high proportion of the energy of the gas flow and converting this to mechanical energy. The gas flow leaves the turbine at a lower speed, temperature, and pressure, proportional to the energy given up to the turbine.

Types of Turbines

2. Turbines are axial flow in design, *i.e.* the flow is parallel to the axis of rotation. There are two basic types of turbines: the *impulse turbine* and the *reaction turbine.* In practice all turbines are combinations of both types, the individual design factors being adjusted to obtain the best combination. They are then known as *reaction impulse turbines.* Any turbine consists of one or more stages, each stage consisting of one set of stator blades and one rotor. The greater the number of stages the greater the energy taken from the gas flow. Fig. 1 shows several typical turbine units.

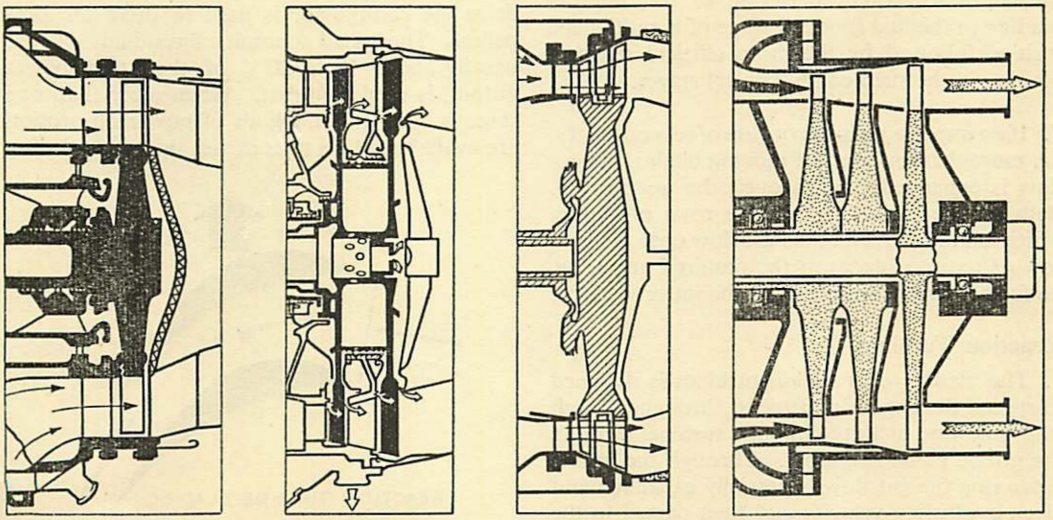
Impulse Turbines

3. As its name implies, the impulse turbine transfers the energy of the gas flow to the turbine wheel by an impulse or impact. When the gas flow reaches the nozzle guide vanes it has a certain temperature, pressure, and velocity. The nozzle guide vanes are designed to :—

(*a*) Change the direction of flow to give it a whirling velocity and to enable it to meet the moving blades at the optimum angle of attack.

(*b*) Expand the gas flow so that on emerging from the turbine, the temperature is lower, the pressure is reduced, and the velocity is higher.

4. The pressure drop through the nozzle vanes results in the pressure falling to that on the immediate downstream side of the turbine disc, *i.e.* no further pressure energy is lost through the turbine disc.



Single Stage (Turbo-Jet) Two Stage (Turbo-Jet) Two Stage (Turbo-Prop) Three Stage (Turbo-Prop with a Separate Stage for the Propeller)

Fig. 1. Types of Turbines.

5. The accelerated flow then strikes the turbine rotor ; the blades (Fig. 2) are so designed that the passages through which the air flows are of constant area, and the entering angle of the air is about equal to the leaving angle on the other side of the rotor. As a result, the flow undergoes no further expansion in the constant area rotor flow passages.

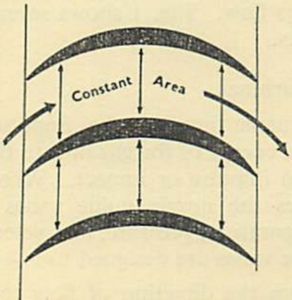


Fig. 2.
Gas Effect on the Blades of an Impulse Turbine.

6. The velocity of the gas flow leaving the nozzle ring of an impulse turbine is greater than that from a reaction turbine. Since the greater the velocity the greater the temperature drop, an impulse turbine rotor is therefore working at a lower temperature than a reaction turbine rotor (described in para. 8). Because a small difference in blade temperature has a marked effect on blade life, it is sometimes desirable to use impulse blading in the first (hottest) stage of a multi-stage turbine followed by the more efficient reaction blading in the succeeding (cooler) stages.

7. If an impulse turbine consists of several stages, *i.e.* more than one row of moving blades, the gas flow is expanded only through the nozzle ring. Between the turbine rotors are rows of stators which act only to direct the gas flow onto the next row of moving blades at the required angle, *i.e.* no further expansion occurs in the stator sections.

Reaction Turbines

8. The blading on reaction turbines is designed to spread the expansion process throughout each stage and not, as in the impulse turbine, through the nozzle guide ring only. Through the nozzle guide ring the gas flow is partially expanded and given a whirling velocity and then passed to the rotor. The passages between the rotor blades are convergent, having a larger cross-sectional area at the upstream entry point than at the downstream exit (Fig. 3). In the rotor the thermal energy is converted to mechanical energy by an increase in the gas flow velocity due to the convergent form of the passage. Thus the blades experience a reaction (similar to the lift force on any wing) which, added to the impulse force, causes a greater driving force than that obtained from a pure impulse turbine.

9. If all the blades throughout the stages have identical cross-sections the same expansion process occurs in each row of blades. Such an arrangement is said to have symmetrical blading and to operate with 50% reaction.

Power Absorption

10. Since the turbine absorbs energy from the gas flow to drive the compressor, the thrust is obtained from the remaining energy in the gas flow. Therefore, the turbine is designed to absorb just enough power to drive the compressor, leaving the greatest possible amount for propulsive purposes. The velocity of the gas flow is kept high so that the turbine diameter, and hence engine size and weight, is kept to a minimum. The driving power (torque) of the turbine is obtained by using one or more stages. If a two-stage turbine is used, the two rows of moving blades are usually fitted on a single rotor disc, the intervening stators being fixed to the outer casing.

11. **Turbo-Prop Engines.** In turbo-prop engines, gas-flow energy in excess of that required to drive the compressor is used to drive the propeller. The small amount of residual energy, usually about 10 to 20% of the total power output, is used as thrust. When more than one stage is used, two methods of power absorption are available. One type carries the rotor blading

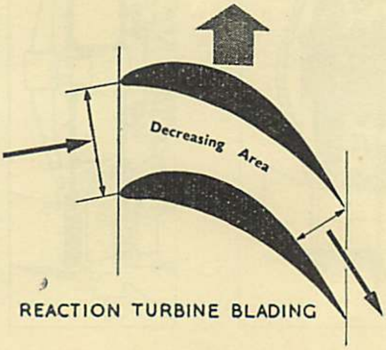


Fig. 3.
Gas Effect on the Blades of a Reaction Turbine.

on a single disc which drives both the compressor and the propeller, the whole rotating as a single unit. The second type has two separate rotors, the front driving the compressor and the rear the propeller shaft, independently of each other. Usually the compressor is driven by a two-stage turbine, and the propeller by a single stage.

12. The turbine must be designed to match the performance of the compressor. If the mass flow through the compressor is too low, surging occurs, and if it is too high, efficiency falls rapidly. Therefore the turbine must be designed to drive the compressor at its optimum r.p.m. for a given set of conditions. When the compressor is designed to operate at its maximum possible pressure ratio, it is very sensitive to small variations in mass flow, *i.e.* changes in r.p.m. In practice, however, some departure from the ideal conditions is made to avoid having an over-sensitive engine and to give some degree of flexibility.

Basic Requirements of a Turbine

13. The main requirements for a turbine are :—

(*a*) Light weight.

(*b*) Small frontal area.

(*c*) High efficiency.

(*d*) Ability to operate at high temperature (power) for sustained periods.

(*e*) Reliability and serviceability.

Light weight is ensured by running the turbine rotor at the highest permissible rim speed, using a small diameter rotor. Since the stresses in a turbine disc increase approximately as the square of the rim speed, the maximum speed is limited by the stress characteristics of the disc and blade materials at the operating temperature.

14. With centrifugal compressors the frontal area of the driving turbine is much smaller than that of the compressor and combustion chamber assembly and has little influence on the overall size of the engine. In axial compressor designs, however, the frontal areas of the turbine and compressor are nearly equal, so the turbine diameter can affect the overall diameter of the engine.

15. The design of the turbine passages is based on aerodynamic considerations, using heavily cambered blades. For a desired thrust output and mass flow through the engine, the speed of flow velocity must be subsonic throughout the engine, otherwise the smooth flow breaks down and heavy losses are incurred.

16. Rotor failures, which often occurred in early jet engines, have been overcome by improved gas seals, better methods of cooling the disc, and by the use of more suitable materials. Turbine blades are exposed to a temperature of some 700° to 800° C. The high temperature in itself is not serious, but when, at the same time, a tensile stress of up to 15 tons/sq. in. is applied to the material because of centrifugal force, it becomes necessary to use alloys capable of retaining their properties under these stringent operating conditions. It is the difficulty of producing alloys capable of withstanding very high temperatures, thereby permitting an increase in the maximum temperature of the gas entering the turbine, that sets a limit to engine efficiency.

Metallurgical Requirements

17. The properties required of turbine blade material are exacting, some of the more important being :—

(*a*) Resistance to corrosion and oxidization.

(*b*) High tensile strength at high temperatures.

(*c*) High resistance to fracture.

(*d*) High creep resistance.

(*e*) High resistance to fatigue.

Creep Resistance

18. A characteristic of all metals at high temperatures is that the strength properties change over a period of time and they tend to lengthen (creep) under tensile loads. In most metals the tensile properties at high temperatures differ from those at low temperatures in that the time factor is much more important at high temperatures. For most materials there is a limiting stress below which they will not fracture, irrespective of the time for which the stress is applied. At high temperatures, however, there is a point above which it is not possible to state with certainty that a given metal or alloy will not fracture under a certain stress, if that stress is applied long enough.

19. Blade materials operate under creep conditions, and tests are made to determine their behaviour under these conditions. The normal creep curve (Fig. 4) is one in which strain is plotted against time, and the curve shows the progressive extension of the test piece when a given strain is maintained at a fixed temperature.

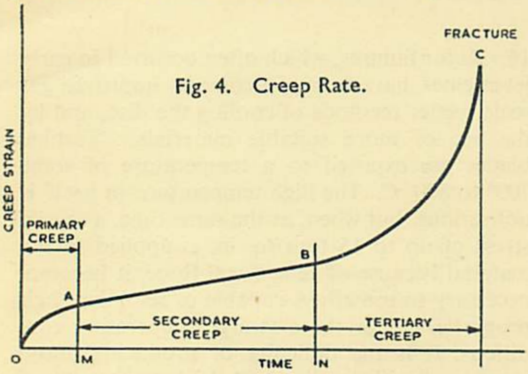


Fig. 4. Creep Rate.

20. The creep curve may be divided into three parts showing :—

(*a*) The primary creep stage, when relatively rapid extension takes place but at a decreasing rate.

(*b*) The secondary period, during which creep occurs at a more or less constant rate.

(*c*) The tertiary creep stage, when the rate of extension accelerates and finally leads to fracture.

21. The primary stage OA of the curve is mainly of interest for the part it forms of the total extension reached in any given time. Since clearances between the blade tip and its stator have to be kept to a minimum, the smaller the value of AM, the better.

22. Rapid and fundamental changes are in progress in the tertiary stage and materials subjected to creep conditions should not be allowed to enter this stage. For this reason, the service life of any component subject to creep should be limited to a period which does not approach ON.

Rotor Disc

23. The operating temperature of the centre of the turbine disc is lower than the temperature of the rim, which again is somewhat lower than the temperature of the blades. As a result of these radial temperature differences, stresses arising from the thermal expansion of the material are superimposed on those arising from the high speed of rotation, the most severe stresses occurring at the centre of the disc. Stresses in the hot rim of the disc reach levels where creep may occur and the material of which the disc is made must, therefore, have satisfactory creep resistance.

Nozzle Guide Vanes

24. The stresses in nozzle guide vanes are relatively low, but additional stresses arise from thermal expansion effects. The thin section blades are heated and cooled very quickly and the uneven temperature distribution during rapid heating and cooling leads to stresses which may cause cracking or buckling of the vanes and their supporting structure. The operating temperature of the guide vanes is higher than that of the rotor blades, and whereas the latter are subjected to a mean temperature, an individual group of nozzle guide vanes may operate above the mean temperature because of uneven balance between the various flame tubes. As a result of these conditions, the material used for nozzle guide vanes must have a high resistance to scaling, cracking, and distortion under the sudden and uneven rapid rates of heating and cooling. (Scaling is the tendency for the surface to flake off owing to oxidization effects.)

Cooling and Sealing

25. The heat from the gas stream passing over the turbine blades is conducted through the turbine disc to the bearings and shaft. This necessitates a cooling system (Fig. 5) to keep the

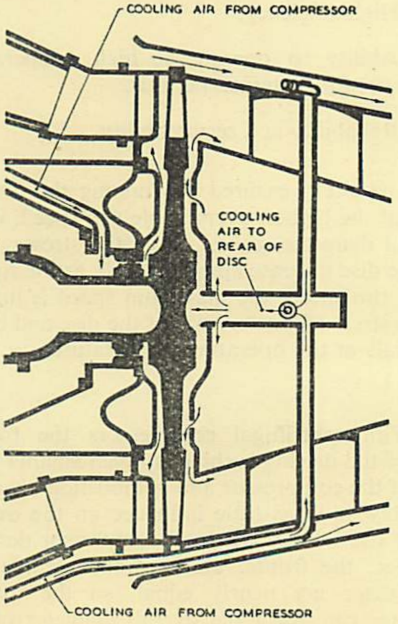


Fig. 5. Pressure Cooling.

temperature of the disc and bearings at a reasonable level. The forward side of the disc may be cooled by air bled from the compressor or by a small fan on the shaft forward of the disc face. Additional air may be led over the rear face by pipes in the jet pipe cone fairings ; this air helps in reducing the inequality in temperature distribution, should the jet pipe cone be slightly eccentric with the disc. The space between the nozzle guide ring and the disc is sealed against the entry of hot gases at rotor blade pressure by a supply of cooling air at a higher pressure than the gas pressure. The necessary gap is formed by a thin sharp-edged (labyrinth) seal to ensure the minimum damage if expansion and distortion reduce the clearance so that contact occurs.

26. If the cooling air over the front face of the rotor disc is supplied at a sufficiently high pressure to ensure that it is spilled out into the hot gas stream immediately before the turbine blades, there is no possibility of back leakage of hot gas, thus eliminating the need for particular accuracy in seal clearances and in some designs dispensing with the labyrinth seal completely. A built-up multi-stage turbine wheel can be cooled by passing high-pressure air from the compressor through the space between the front and rear discs of the wheel and out to the gas stream past seals at the blade roots (Fig. 6). Both faces of the wheel can be cooled in this way.

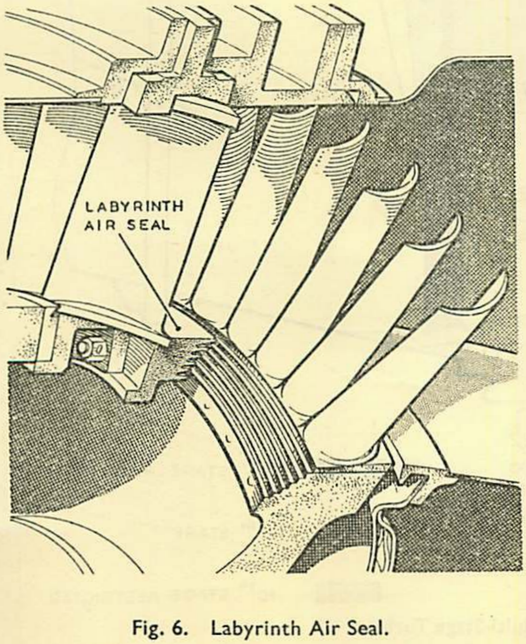


Fig. 6. Labyrinth Air Seal.

Blade Manufacture

27. There are three methods of blade manufacture :—

(*a*) Machining from bar.

(*b*) Forging.

(*c*) Casting.

Since the performance of the turbine is very sensitive to small differences in the blades, the production of efficient blades is not easy. Machining methods give the most consistent results since good bar stock can be reliably produced, but the process is costly. Forging is a good method, but the dies for forging turbine blade metal at high temperature are expensive and require frequent replacement, while some machining is still required to finish the blades to the close tolerances required. Casting has received much attention owing to speed of manufacture and finishing operations ; the drawback is the difficulty of producing batches of blades without internal flaws.

Rotor Construction

28. The method of attaching the blade to the disc is very important, since the stress either in the disc around the fixing or in the blade root itself reaches a limiting value which determines the number of blades which can be fitted. The *fir tree* type of root fitting is used in most turbine wheels. The sections carrying maximum stress are the base of the fir tree at the edge of the disc and the root portion of the blade. This arrangement of root fixing is generally satisfactory, since the blade root can be made an easy push fit in the disc serration because thermal expansion and disc compression load at high rotational speeds ensure a tight fit in operation. On some types of engines the loose fit of the blades is made apparent by the slight rattling noise heard when the engine has almost come to rest after shutting down.

29. Rotor construction for a single-stage turbine is comparatively straightforward, consisting of a single disc running on an air-cooled bearing. Multi-stage rotors are a different matter, since cooling arrangements are not easy and the manufacture of large forgings from the special steels or alloys is a difficult problem. Fig. 7 shows the cooling arrangements of a two-stage built-up turbine wheel.

30. **Shrouded Turbines.** Most turbine wheels in use are open at the outer perimeter of the blades.

However, another type called a *shrouded turbine* is sometimes used. The shrouded (T-shaped) turbine blades, in effect, form a band around the outer perimeter of the turbine wheel. This improves efficiency and vibration characteristics, and permits lighter turbine weights, but on the other hand it limits turbine speed and requires more blades. To give additional strength the blade shrouds are sometimes welded together in pairs.

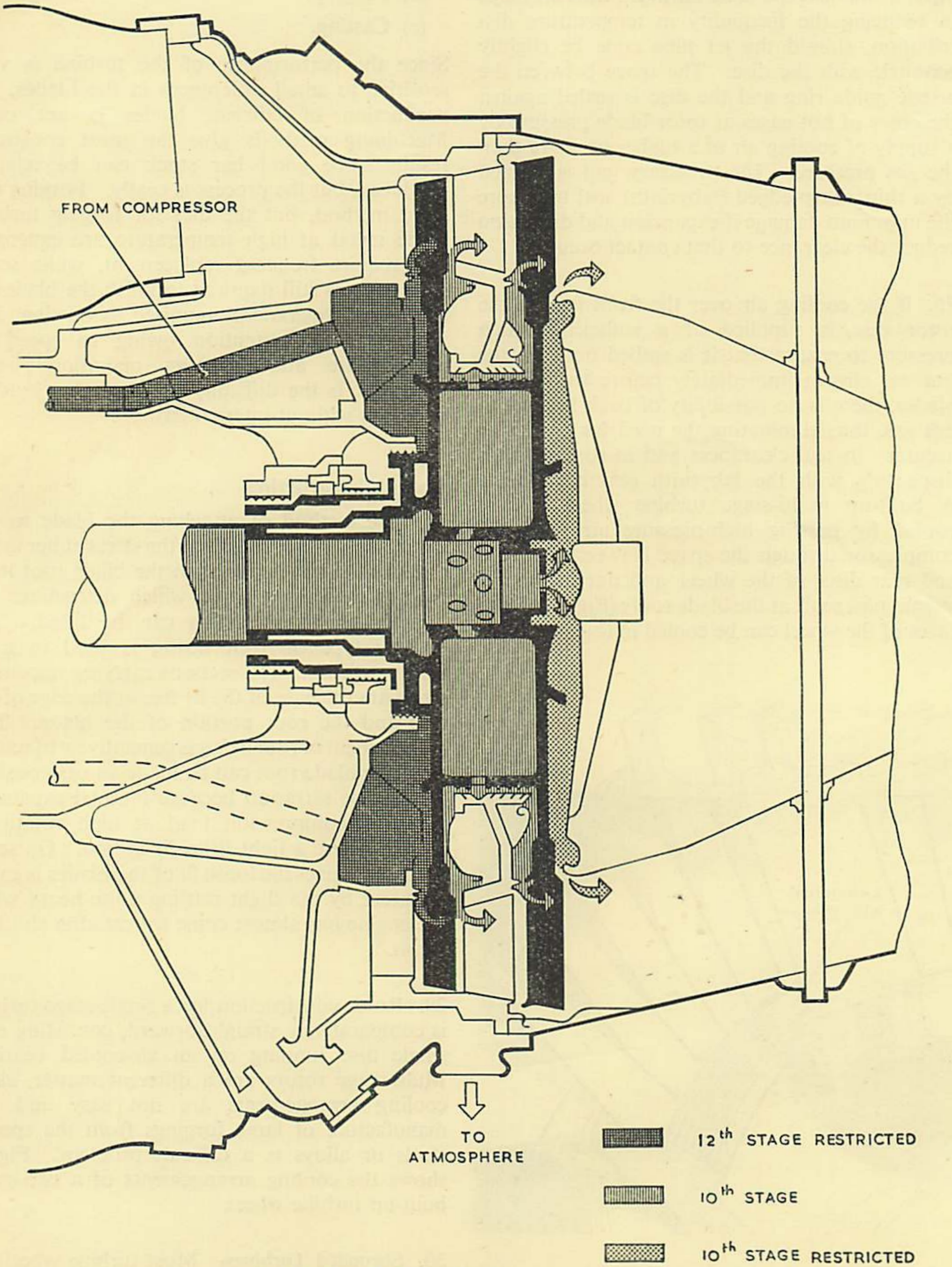
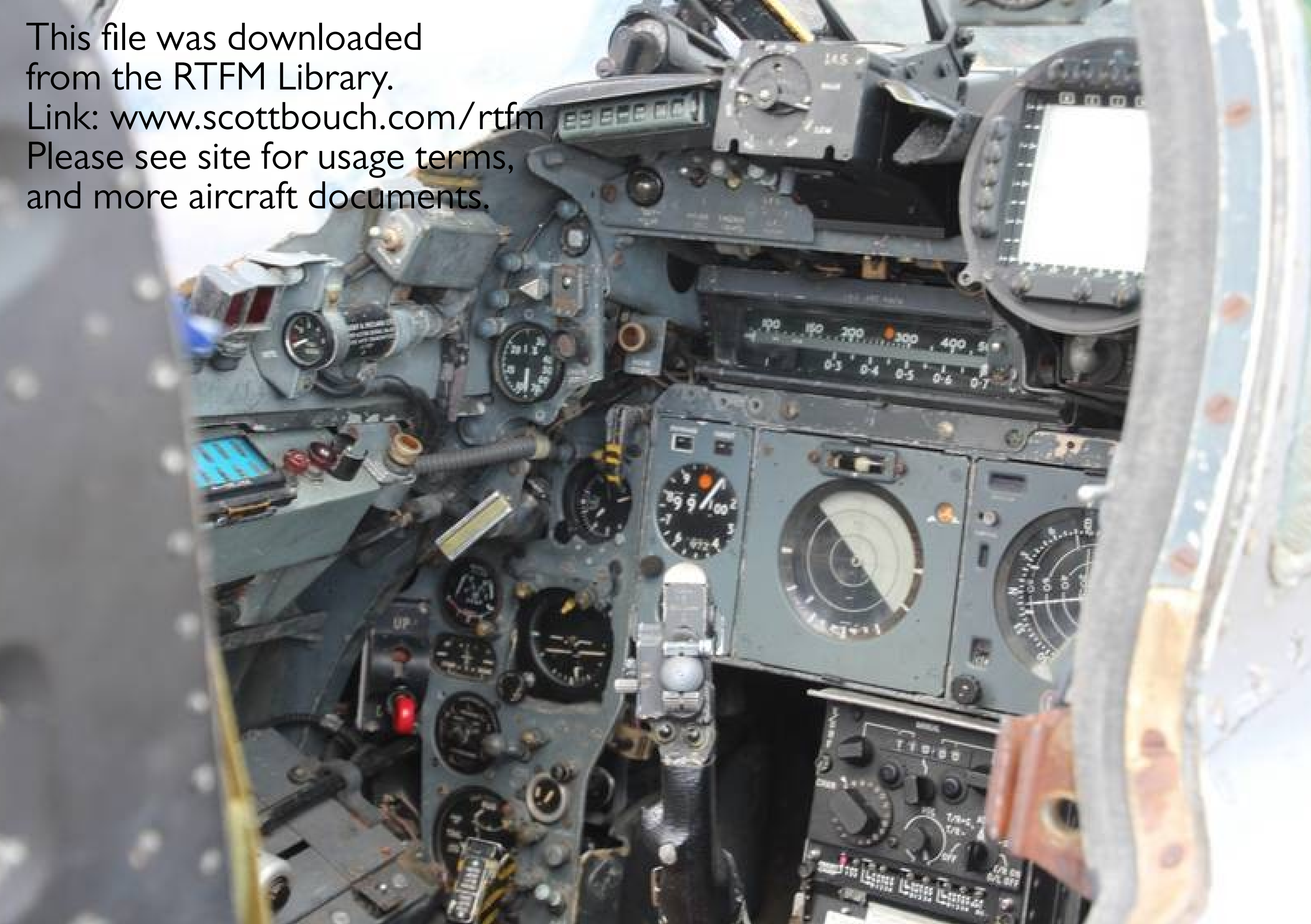


Fig. 7. Cooling a Multi-Stage Turbine.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