TURBO MACHINES

BME IV/I

Chapter Three: Gas Turbine Engine

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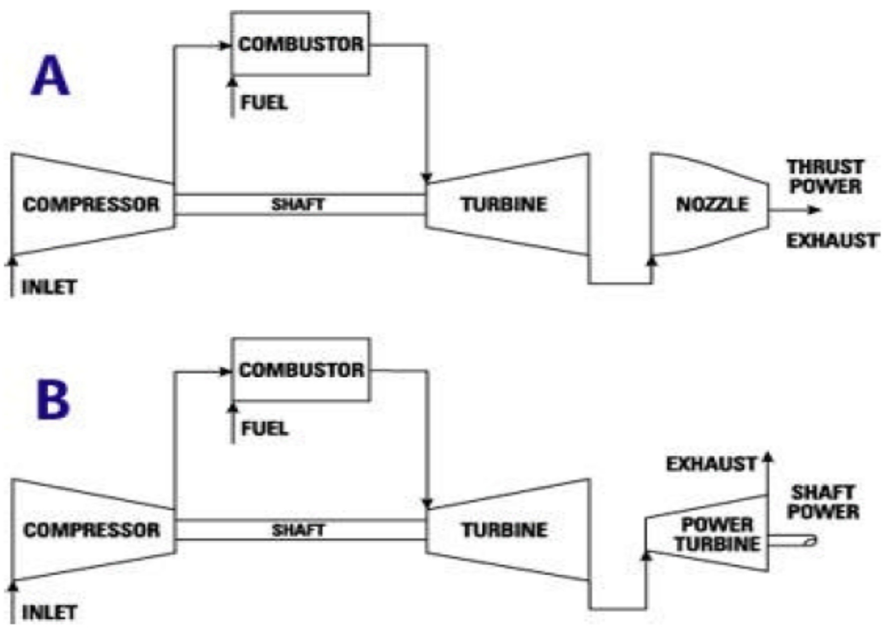
February, 2016

Chapter overview

- Introduction to Gas Turbine Engine
- Theoretical Cycle for gas turbine: Brayton Cycle
- Different sections in gas turbine
- Inlet
- Compressor
- Combustion Chamber
- Turbine
- Exhaust system

Gas Turbine Engine

- A **gas turbine**, also called a **combustion turbine**, is a type of IC engine. It has an upstream rotating compressor coupled to a downstream turbine, and a combustion chamber in between.
- The purpose of the gas turbine determines the design so that the most desirable energy form is maximized.



Schematic for a) an aircraft jet engine; and b) a land-based gas turbine

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Examples of gas turbine configurations:

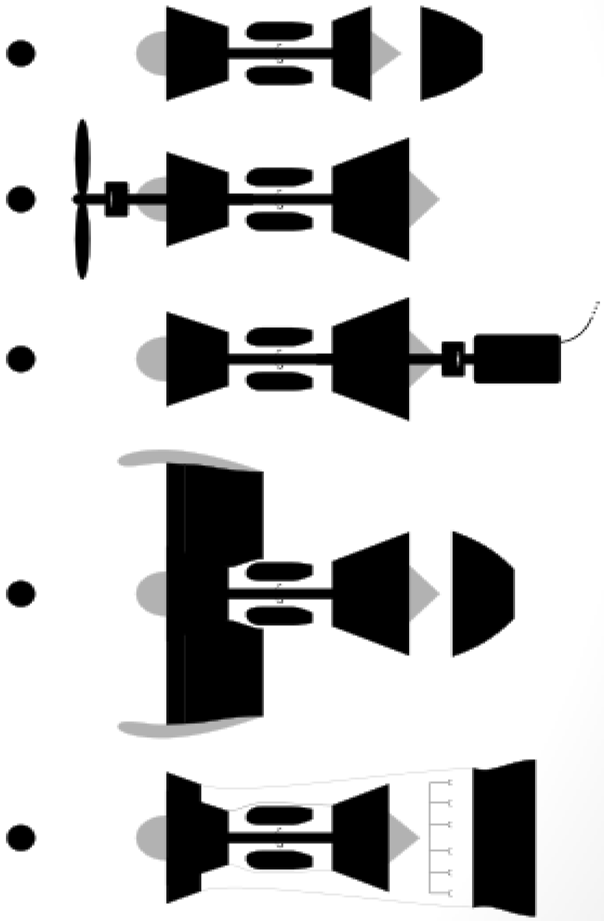
(1) Turbojet

(2) Turboprop

(3) Turbo shaft (electric generator)

(4) High-bypass turbofan

(5) Low-bypass afterburning turbofan.



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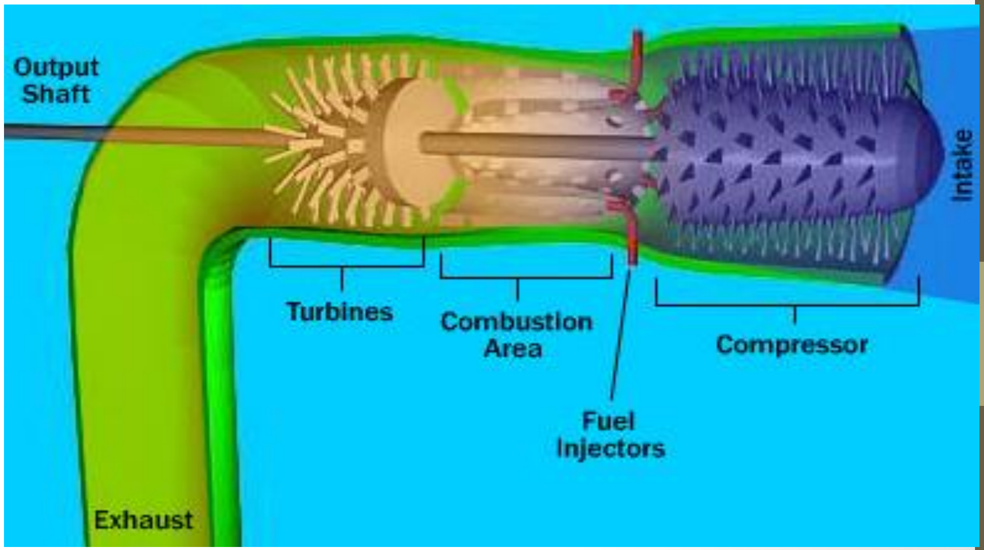
Fields of application

- Gas turbines are used when high power and lightweight are required.
- Contrary to piston engines, turbo machines operate at high flow rates with compact dimensions for
  - driving aircraft with propeller or jet engine
  - driving fast ships, locomotives or heavy motor vehicles
  - driving generators in power plants
  - driving compressors and pumps in the petroleum and natural gas industries

CONTD…

- Components and operation of Gas turbine
  - *compressor* to draw in and compress gas (most usually air);
  - *combustor* (or burner) to add fuel to heat the compressed air;
  - *turbine* to extract power from the hot air flow.
- The gas turbine is an internal combustion (IC) engine employing a *continuous combustion* process.
- This differs from the intermittent combustion occurring in automotive IC engines.



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Advantages of gas turbine engine

- It is capable of producing large amounts of useful power for a relatively small size and weight.
- Since motion of all its major components involve pure rotation (i.e. no reciprocating motion as in a piston engine), its mechanical life is long and the corresponding maintenance cost is relatively low.
- Although the gas turbine must be started by some external means (a small external motor or other source, such as another gas turbine), it can be brought up to full-load (peak output) conditions in minutes as contrasted to a steam turbine plant whose start up time is measured in hours.
- The usual working fluid is atmospheric air. As a basic power supply, the gas turbine requires no coolant (e.g. water).

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- Waste heat is dissipated almost entirely in the exhaust. This results in a high temperature exhaust stream that is very usable for boiling water in a combined cycle or for cogeneration.
- Low lubricating oil cost and consumption.
- Very low toxic emissions of CO and HC due to excess air, complete combustion and no "quench" of the flame on cold surfaces.
- A wide variety of fuels can be utilized. Natural gas is commonly used in land-based gas turbines while light distillate (kerosene-like) oils power aircraft gas turbines. Diesel oil or specially treated residual oils can also be used, as well as combustible gases derived from blast furnaces, refineries and the gasification of solid fuels such as coal, wood chips and bagasse.

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Disadvantage of gas turbines

- Compared to a reciprocating engine of the same size, they are **expensive**. Because they rotate at such high speeds and because of the high operating temperatures, designing and manufacturing gas turbines is a tough problem from both the engineering and materials standpoint.
- Gas turbines also tend to use more fuel when they are idling, and they prefer a constant rather than a fluctuating load.
- Longer startup than reciprocating engines.
- Less responsive to changes in power demand compared with reciprocating engines.

Theoretical cycle for gas turbine

- A cycle describes what happens to air as it passes into, through, and out of the gas turbine.
- The cycle usually describes the relationship between P-V and T-S.
- The Brayton cycle is the air-standard ideal cycle approximation for the gas-turbine engine.
- An open system, steady-flow analysis is used to determine the heat transfer and work for the cycle.
- Comparing to piston engines, following are replaced
  - combustion process by a constant-pressure heat-addition process from an external source,
  - exhaust process by a constant-pressure heat-rejection process to the ambient air.

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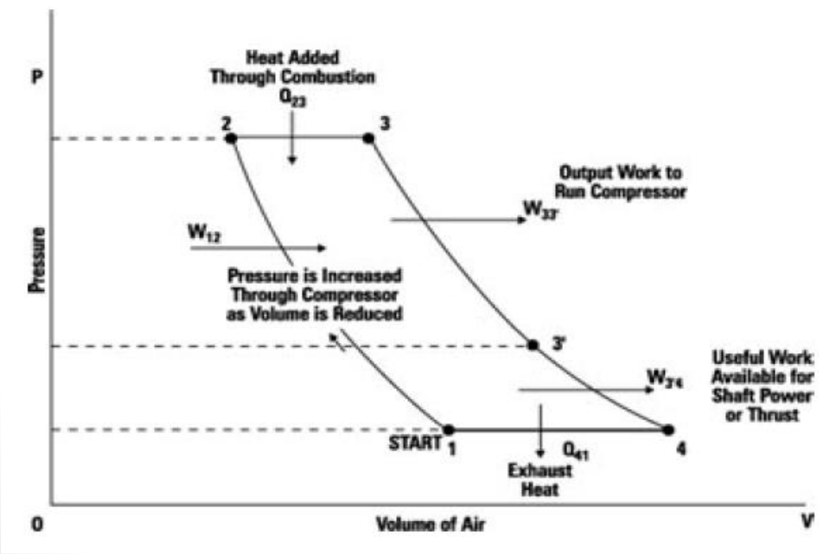
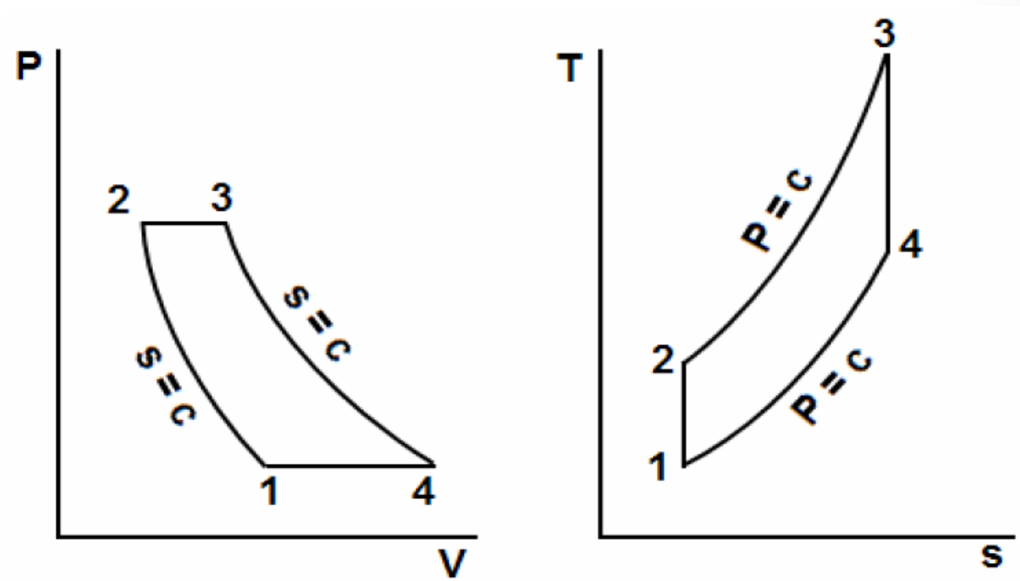
- 1-2 Isentropic compression (in a compressor)
- 2-3 Constant-pressure heat addition
- 3-4 Isentropic expansion (in a turbine)
- 4-1 Constant-pressure heat rejection





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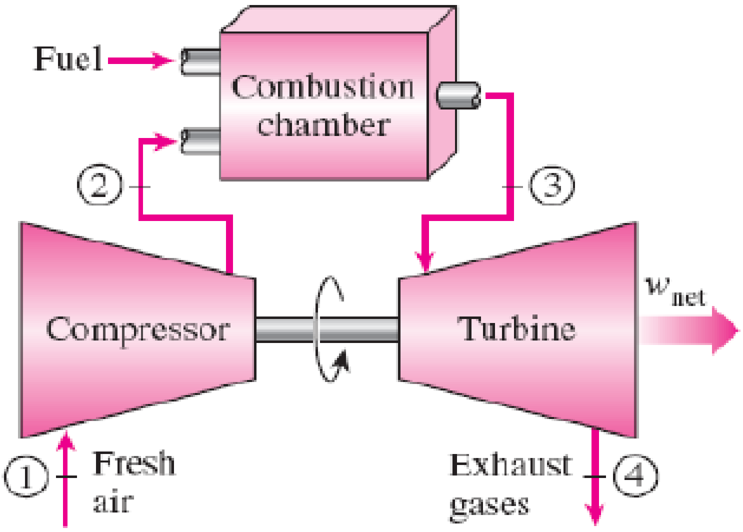
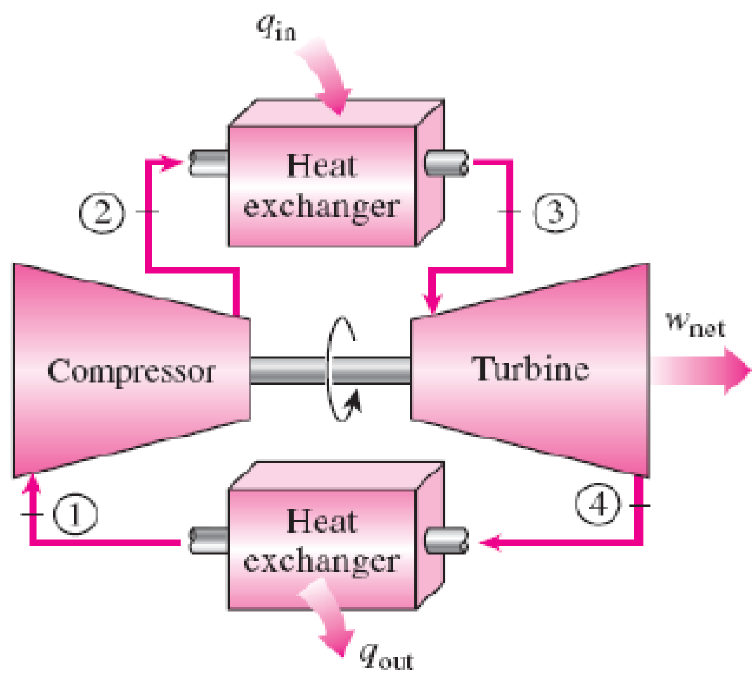


An open-cycle gas-turbine engine.



A closed-cycle gas-turbine engine.

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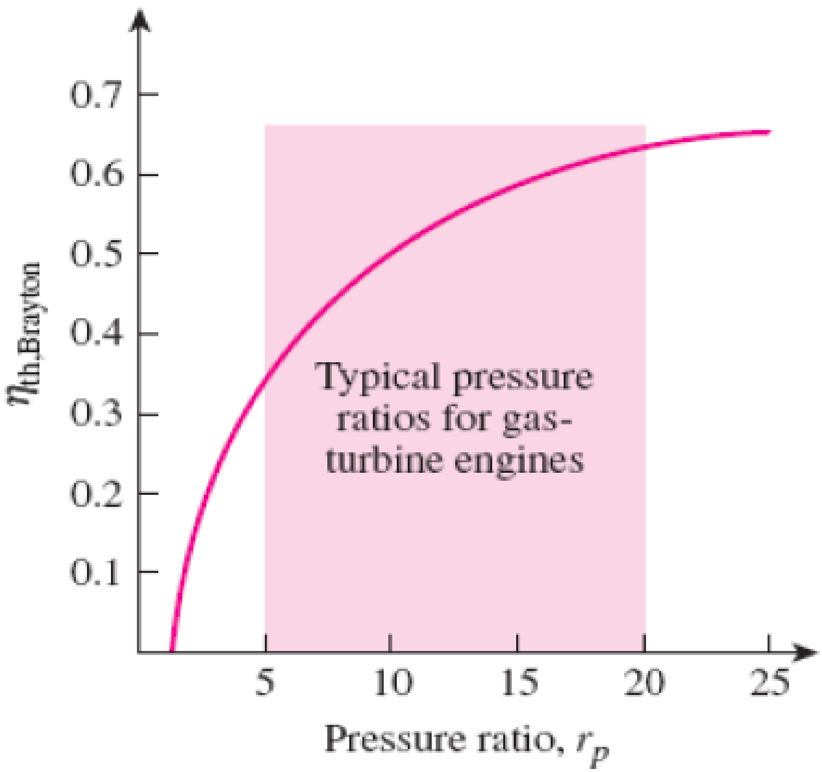
- Efficiency for ideal cycle

$$\eta = 1 - \frac{T_1}{T_2} = 1 - \left(\frac{P_1}{P_2}\right)^{\frac{k-1}{k}}$$

$$\eta_{\text{th,Brayton}} = 1 - \frac{1}{r_p^{(k-1)/k}}$$

$$r_p = \frac{P_2}{P_1}$$ (Pressure ratio)



Thermal efficiency of the ideal Brayton cycle as a function of the pressure ratio.

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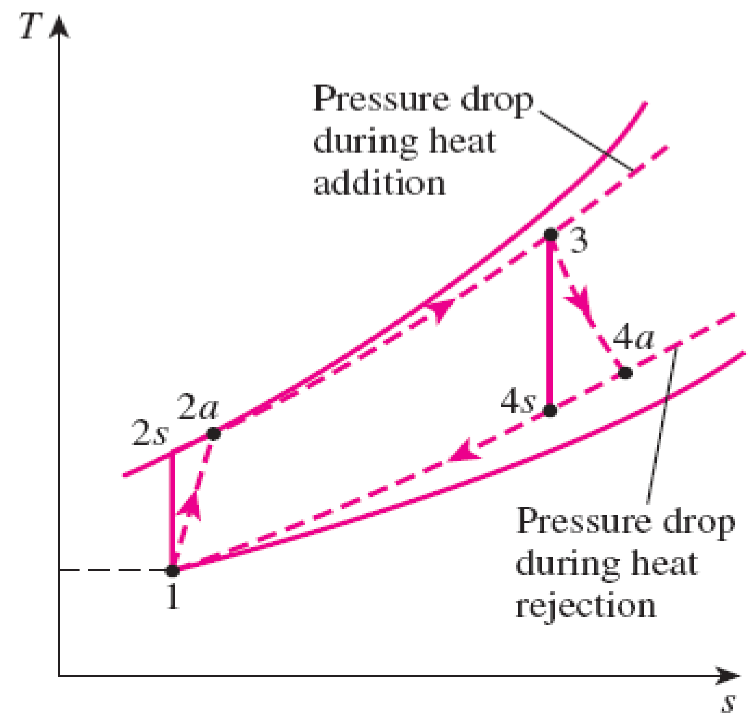
Deviation of Actual Gas-Turbine Cycles from Idealized

- Some pressure drop in an actual gas turbine cycle during heat addition and heat rejection processes is unavoidable.
- Owing to irreversibility, such as friction and non-quasi-equilibrium operation conditions of actual devices, the actual work input of the compressor will be more, and the actual work output from the turbine will be less.
- Ir-reversibilities in turbine and compressors, pre



$$\eta_C = \frac{w_s}{w_a} \cong \frac{h_{2s}}{h_{2a}} \quad \eta_T = \frac{w_a}{w_s} \cong \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

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Efficiency Improvement of Gas Turbines

1. Increasing the turbine inlet (or firing) temperatures
2. Increasing the efficiencies of turbo-machinery components (turbines, compressors)
3. Adding modifications to the basic cycle
   - Regeneration or Recuperation
   - Reheating
   - Intercooling

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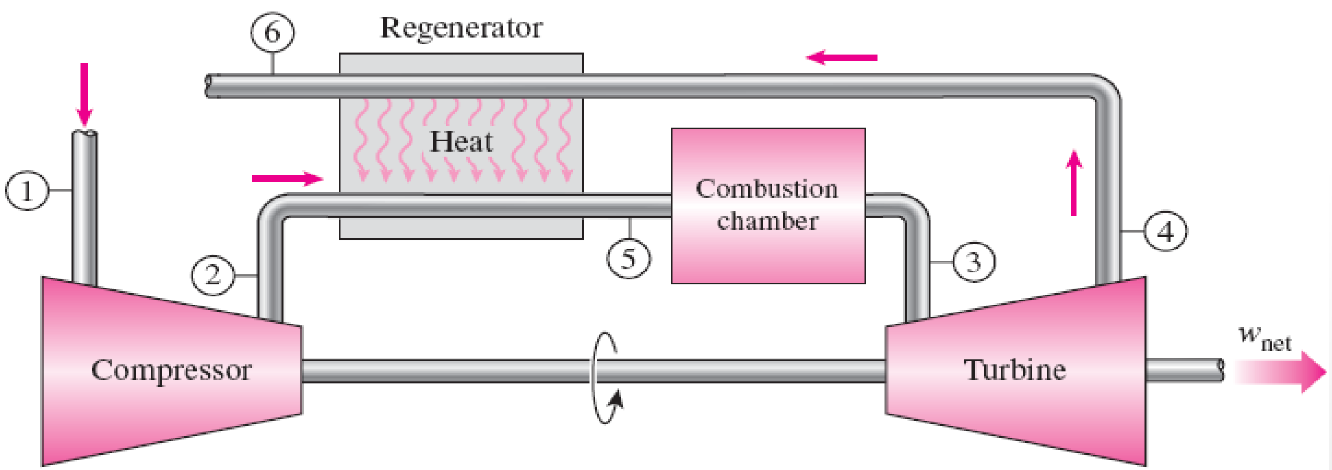
BRAYTON CYCLE WITH REGENERATION

- In gas-turbine engines, the temperature of the exhaust gas leaving the turbine is often considerably higher than the temperature of the air leaving the compressor.
- Therefore, the high-pressure air leaving the compressor can be heated by the hot exhaust gases in a counter-flow heat exchanger (a *regenerator*).
- The thermal efficiency of the Brayton cycle increases as a result of regenera



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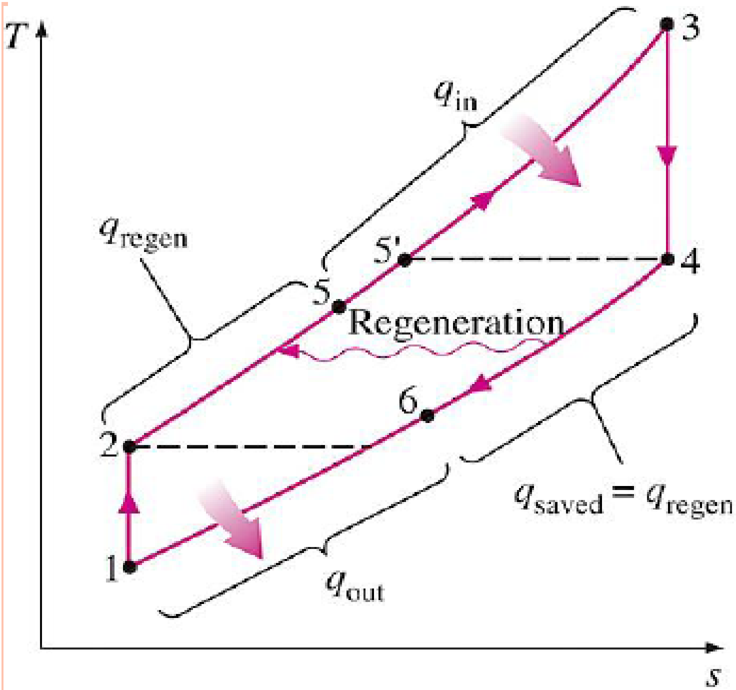


T-s diagram of a Brayton cycle with regeneration.

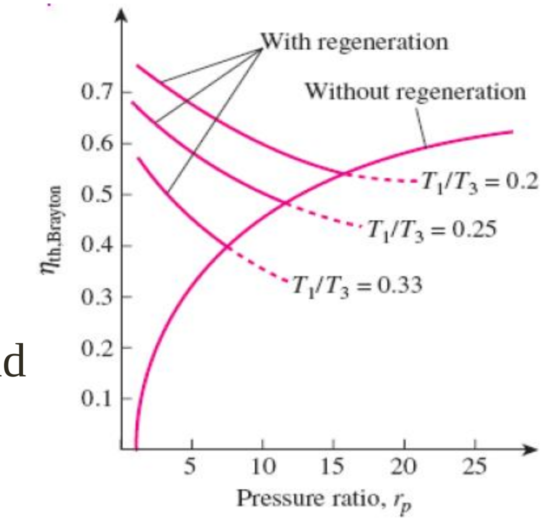
$$q_{\text{regen,act}} = h_5 - h_2$$

$$q_{\text{regen,max}} = h_{5'} - h_2 = h_4 - h_2$$

$$\epsilon = \frac{q_{\text{regen,act}}}{q_{\text{regen,max}}} = \frac{h_5 - h_2}{h_4 - h_2}$$ Effectiveness of regenerator

$$\epsilon \cong \frac{T_5 - T_2}{T_4 - T_2}$$ Effectiveness under cold-air standard assumptions

$$\eta_{th,\,regen} = 1 - \left(\frac{T_1}{T_3}\right)(r_p)^{(k-1)/k}$$



- Regeneration is most effective at lower pressure ratios and low minimum-to-maximum temperature ratios.

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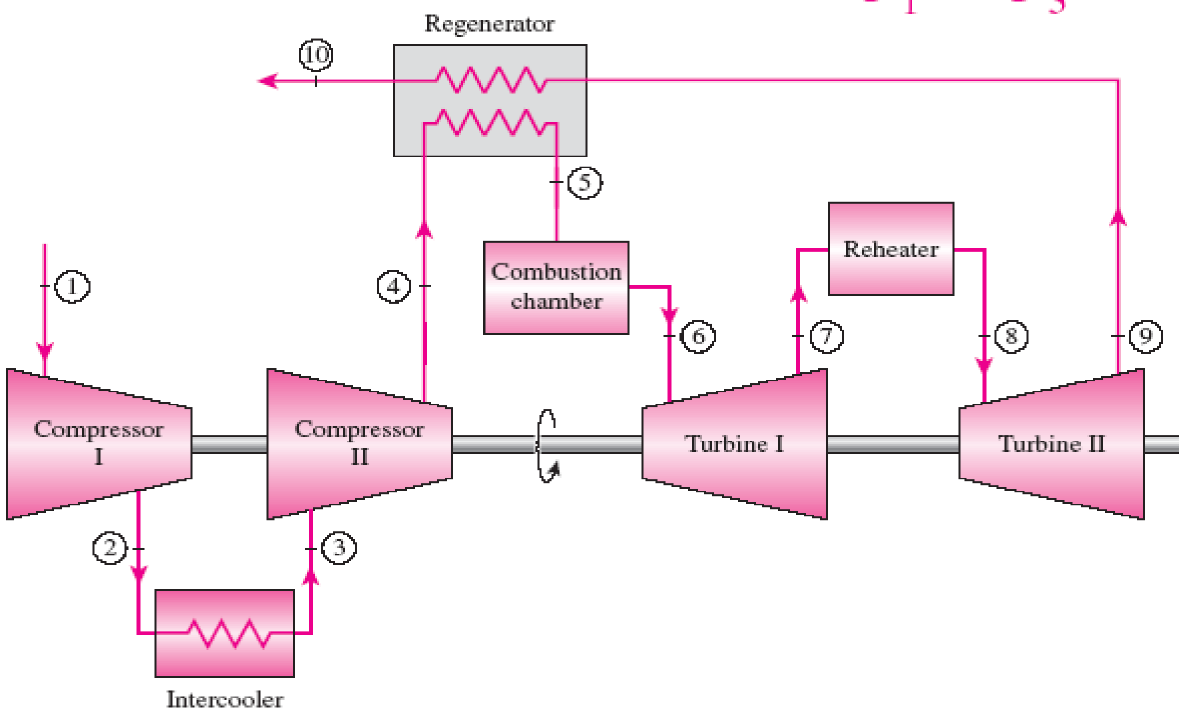
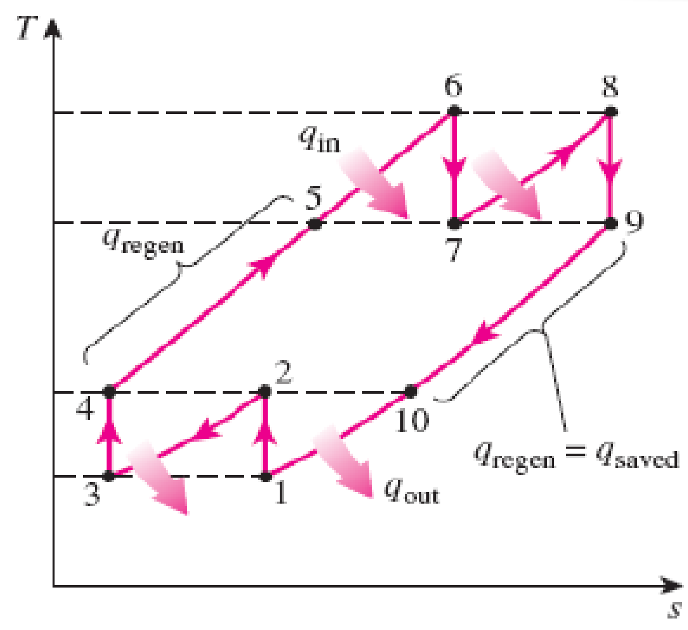
BRAYTON CYCLE WITH INTERCOOLING, REHEATING, AND REGENERATION

- For minimizing work input to compressor and maximizing work output from turbine: $$\frac{P_2}{P_1} = \frac{P_4}{P_3} \quad \text{and} \quad \frac{P_6}{P_7} = \frac{P_8}{P_9}$$





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Multistage compression with inter-cooling:

- The work required to compress a gas between two specified pressures can be decreased by carrying out the compression process in stages and cooling the gas in between.
- This keeps the specific volume as low as possible.

Multistage expansion with reheating:

- keeps the specific volume of the working fluid as high as possible during an expansion process, thus maximizing work output.

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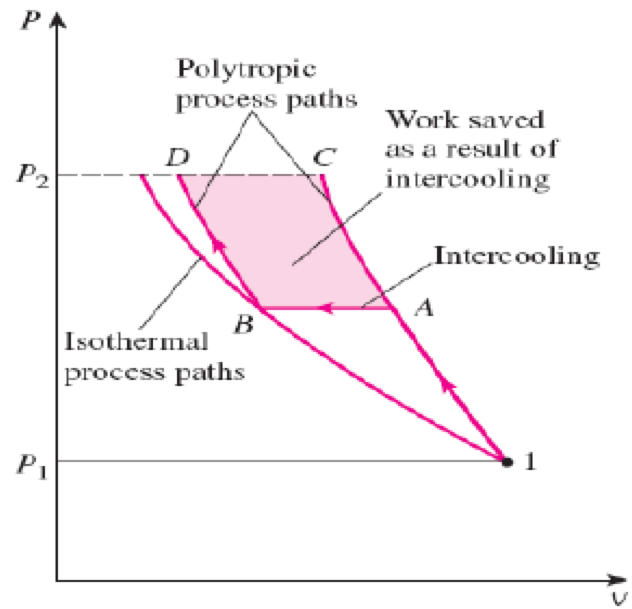
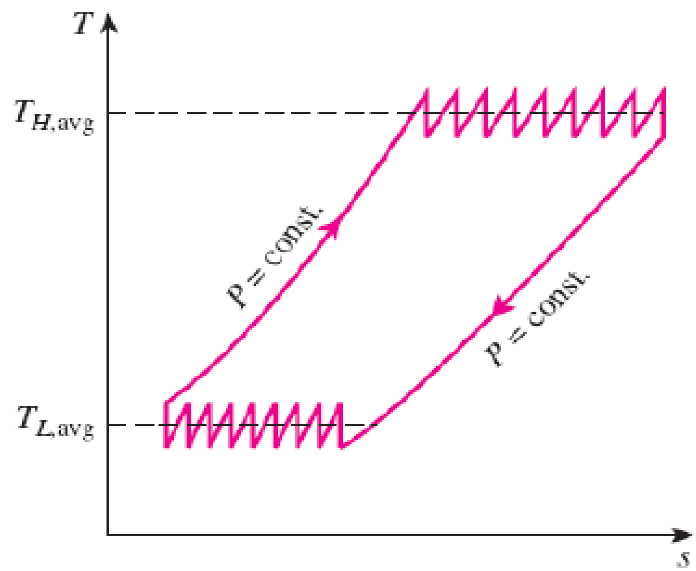
- Comparison of work inputs to a single-stage compressor (1*AC*) and a two-stage compressor with intercooling (1*ABD*).

- As the number of compression and expansion stages increases, the gas-turbine cycle with intercooling, reheating, and regeneration approaches the Ericsson cycle.

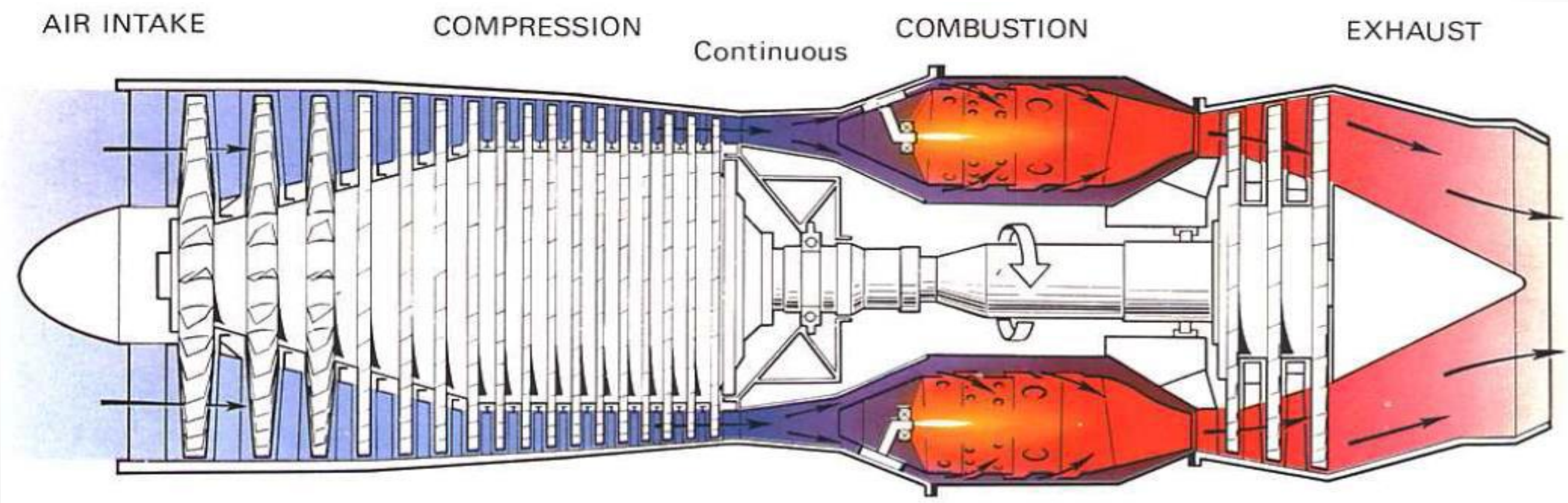




Sections in gas turbine

The primary sections in a gas turbine are:

- Inlet section
- Compressor section
- Combustion section
- Turbine section
- Exhaust section



Inlet section

- Delivers air to the engine with minimum loss of energy in the duct.
- Engine requires intake axial speed less than $M = 0.7$; however, suitably designed inlets can enable the airplane to fly at $M > 1$ in design condition.
- In off-design condition, engine intake Mach number and flight Mach number are different. Therefore, an intake is needed to reduce speed and increase pressure to adapt to the engine.
- At higher supersonic speeds the air flow velocities met are much higher than the compressor can efficiently use, therefore the intake air velocity must be decreased.
- Engine factory does not manufacture inlets. It's a separately designed and optimized component of the airframe, installed into the engine.

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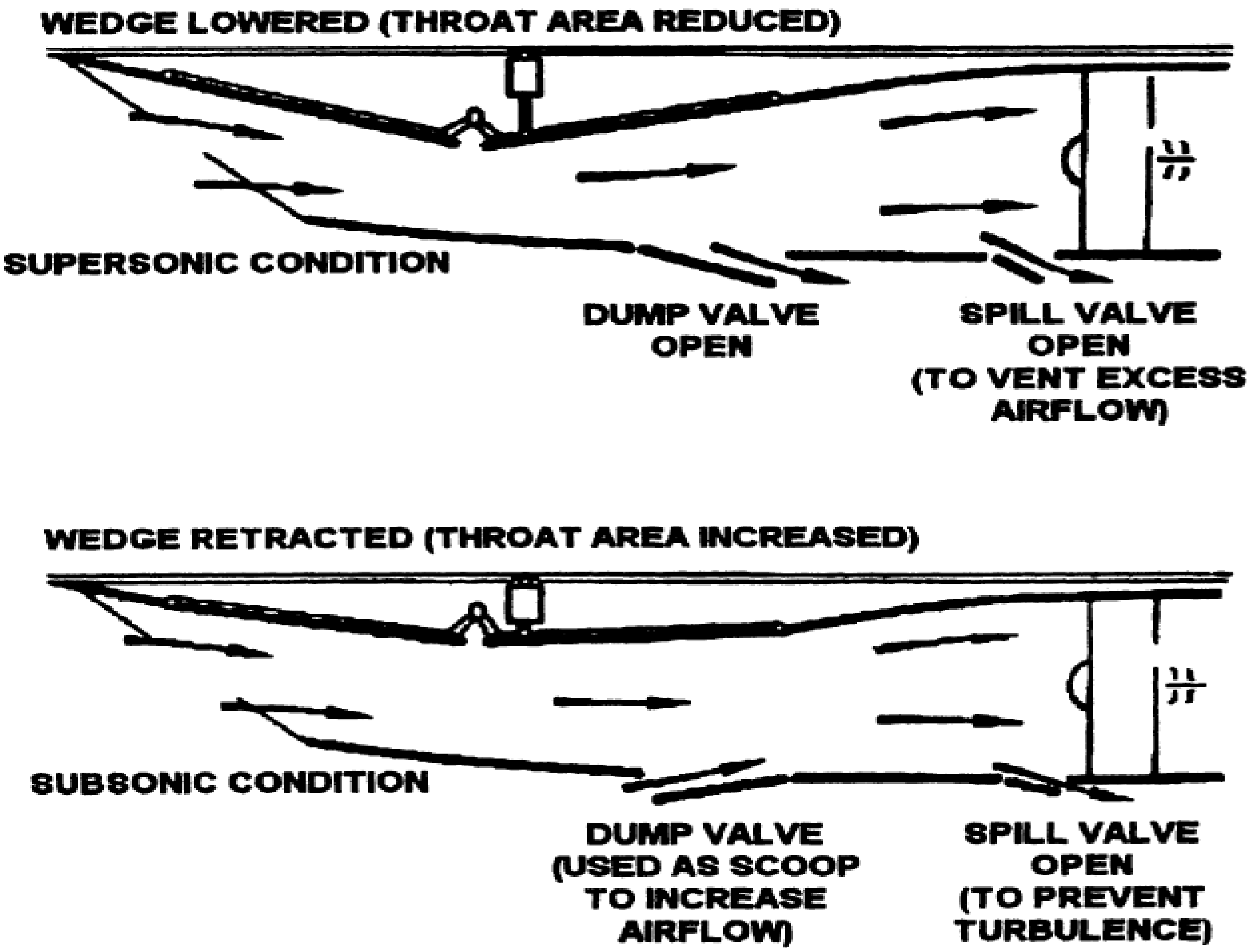
The variable area inlet :



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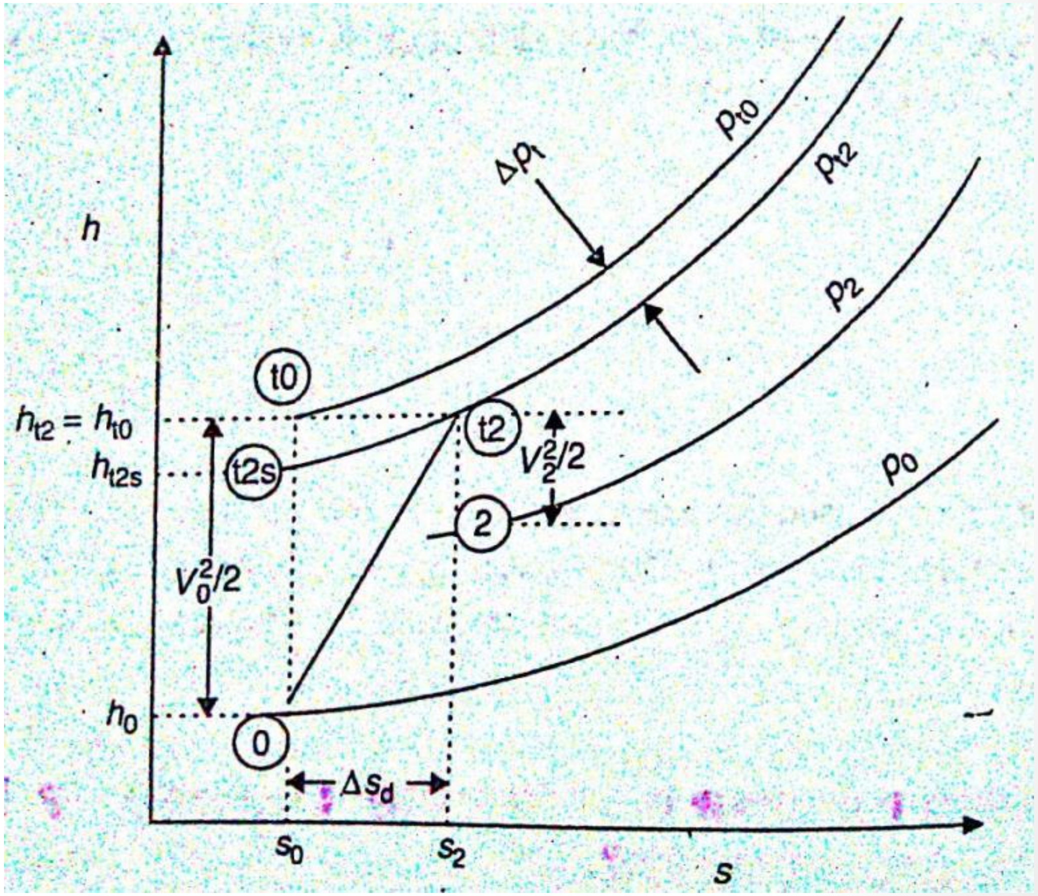
- An ideal inlet is considered to provide isentropic compression of the captured flow to the engine.
- In an actual inlet the adiabatic condition is actually met, but the reversible aspect of an ideal inlet flow assumption is not.
- Actual inlets suffer from the realities of wall friction, and any shocks invariably present in the supersonic flows.



Compressor section

- According to thermal cycle analysis, compressor is a important component which increases gas pressure so that the cycle can output mechanical work.
- Most of the increase is in the form of velocity, with a small increase in static pressure due to the divergence of the blade flow paths.
- The compressor is responsible for providing the turbine with all the air it needs in an efficient manner.
- In addition, it must supply this air at high static pressures.

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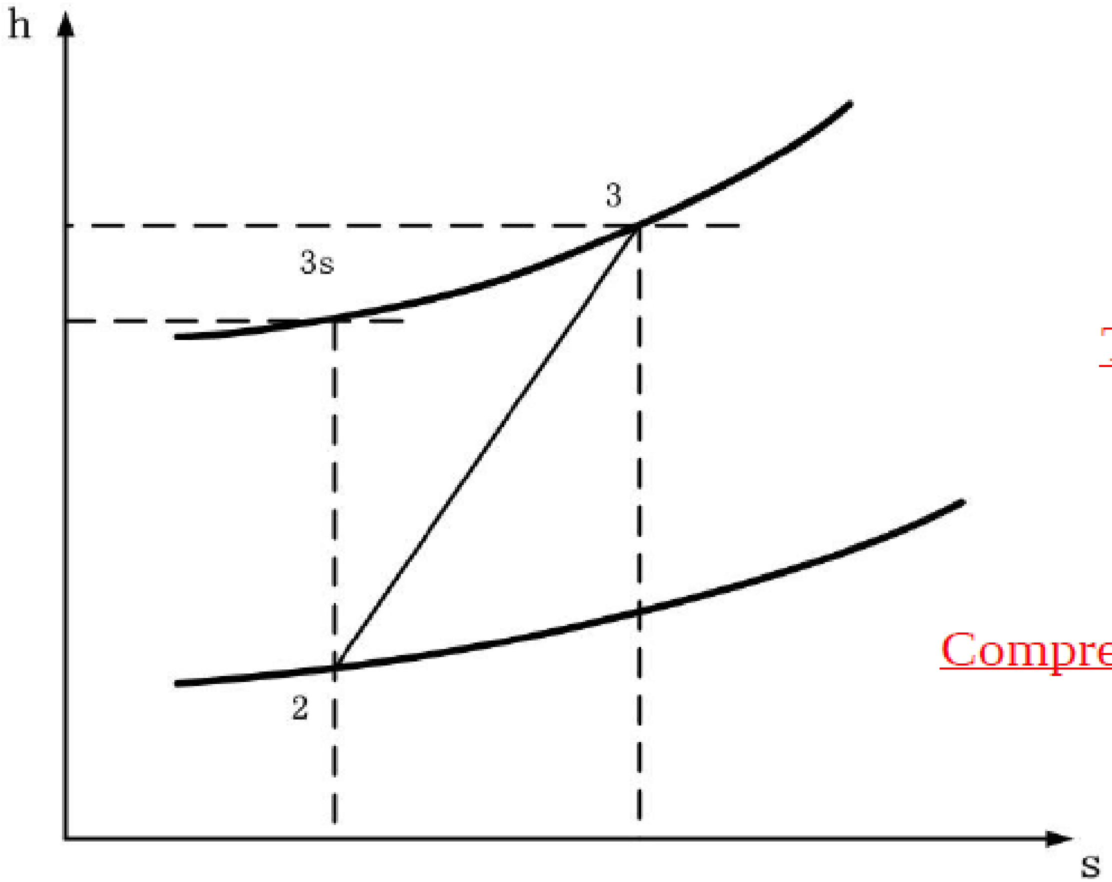
Performance of compressor



Total Pressure Ratio

$$\pi_c = \frac{p_{t3}}{p_{t2}}$$

Total Temperature Ratio

$$\tau_c = \frac{T_{t3}}{T_{t2}}$$

Compressor Adiabatic Efficiency

$$n_c = \frac{h_{t3s} - h_{t2}}{h_{t3} - h_{t2}}$$

CONTD…

- Compressor adiabatic efficiency

$$n_c = \frac{\frac{T_{t3s}}{T_{t2}} - 1}{\frac{T_{t3}}{T_{t2}} - 1}$$

$$\frac{T_{t3s}}{T_{t2}} = \left(\frac{p_{t3s}}{p_{t2}}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{p_{t3}}{p_{t2}}\right)^{\frac{\gamma-1}{\gamma}} = \pi^{\frac{\gamma-1}{\gamma}}$$

Compressor Adiabatic Efficiency

$$n_c = \frac{\frac{T_{t3s}}{T_{t2}} - 1}{\frac{T_{t3}}{T_{t2}} - 1} = \frac{\pi_c^{\frac{\gamma-1}{\gamma}} - 1}{\tau_c - 1}$$

Power Generated

$$\wp_c = \dot{m}_o \left(h_{t3} - h_{t2}\right)$$

CONTD…

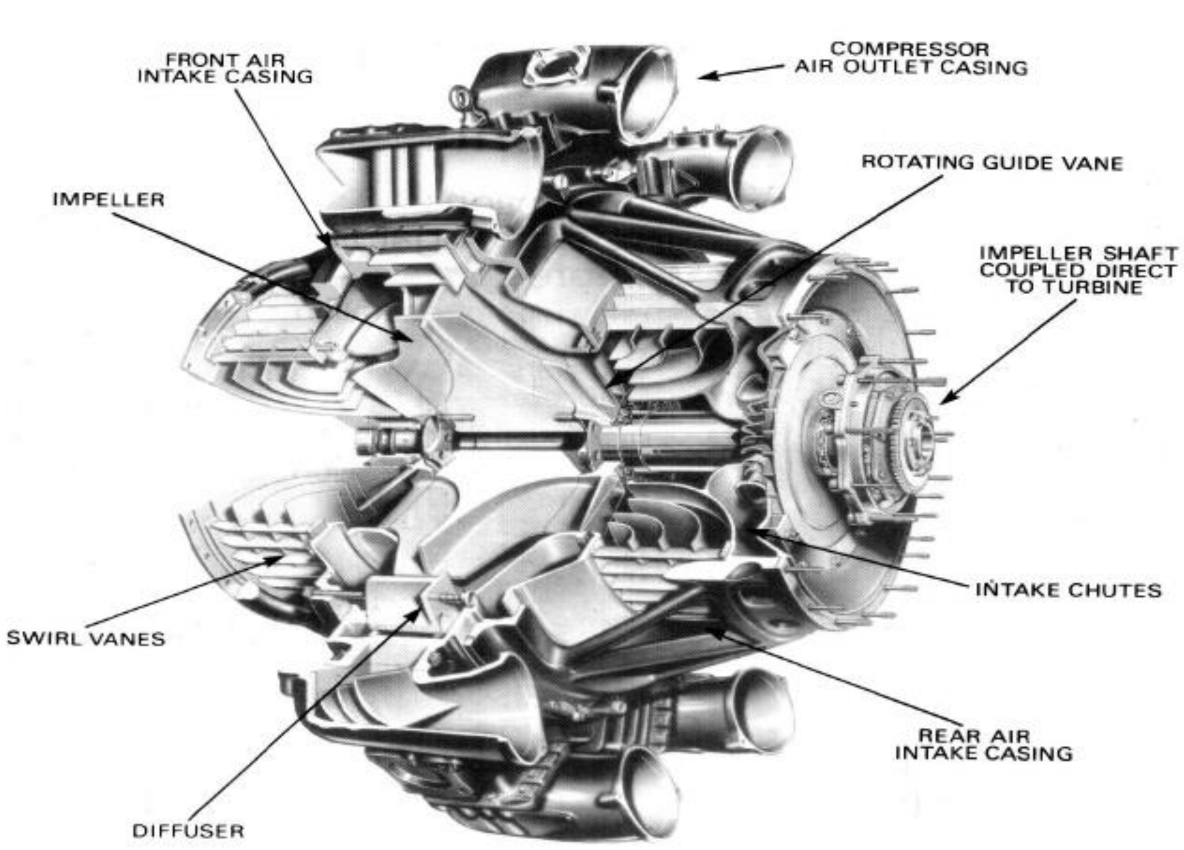
Two basic types of compressor used in Gas- Turbine

- Centrifugal flow: It employs an impeller to accelerate the air and a diffuser to produce the required pressure rise.
- Axial flow: It employs alternate rows of rotating (rotor) blades and stationary (stator) vanes, to accelerate and diffuse the air until the required pressure rise is obtained.

- The power delivered to the medium in a compressor is achieved by one or more rows of rotating blades (rotors) attached to one or more spinning shafts (typically referred to as spools).

CONTD…

Centrifugal air compressor



DOUBLE ENTRY CENTRIFUGAL COMPRESSOR

CONTD…

- Compressor shaft is coupled directly to turbine.
- Impeller can be single or double sided.
- **Rotating guide vane:** Air goes in axially. It can be made in one piece with impeller.
- **Impeller:** Radial blades that increase air speed and pressure.
- **Diffuser:** Reduces speed and gets pressure rise.
- **Air outlet casing:** Turns air to adapt combustion chamber.

CONTD…

- Impeller and diffuser arrangement

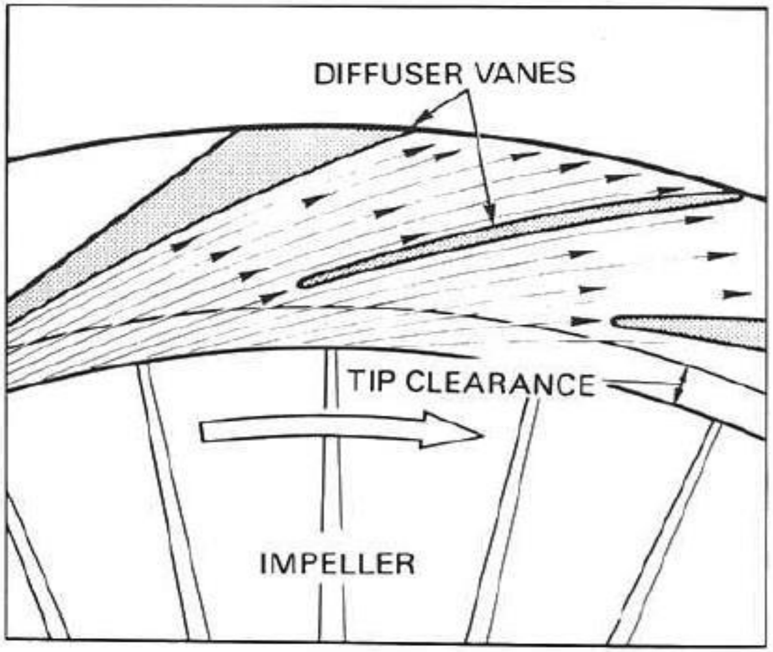
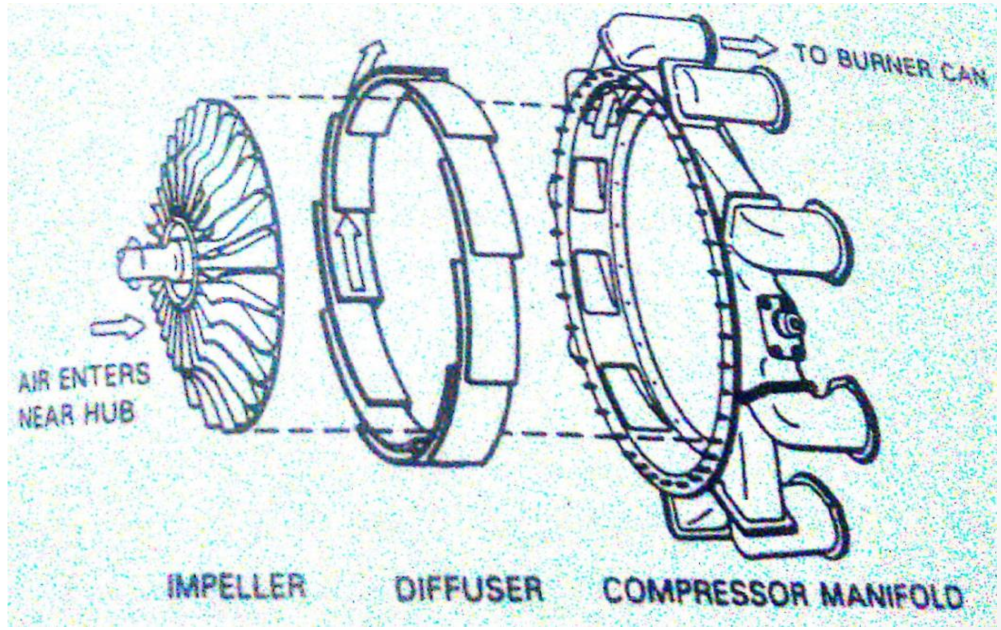


Fig. 3-6 Airflow at entry to diffuser.



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- At high speed, air at the disc center is forced radially outwards along the vanes of the disc.
- The rotational energy of the disc imparts velocity energy to the air, but, because the disc vanes have a divergent passage, some of the energy is converted into pressure and temperature.
- Leaving the impeller tip at high speed, the air enters the *'diffuser'* ring and passes through its divergent passages that cause most of the remaining velocity energy to be converted into pressure and temperature.

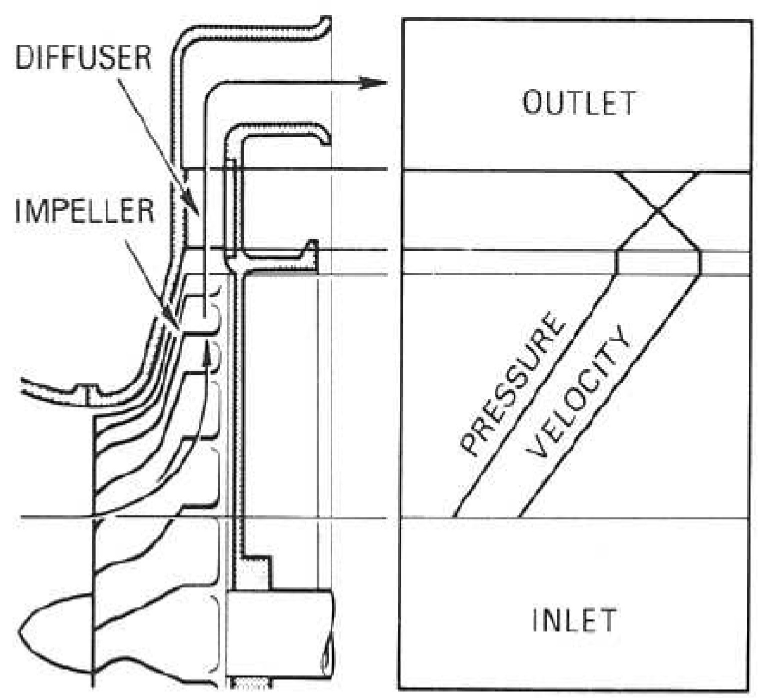

Fig. 3-3 Pressure and velocity changes through a centrifugal compressor.

CONTD…

Benefits of centrifugal compressor

- Simple and reliable structure
- Single stage pressure ratio is high （typically 2-4)
- Stable performance
- Centrifugal compressors have higher single-stage pressure ratios than axial compressors. As a result, centrifugal compressors have lower cross-sectional flow areas per mass flow rate than do axial compressors.
- They also have a larger diameter but shorter length per unit mass flow rate.
- They are physically small units with low flow rates, which makes them ideal for helicopter and small aircraft application.
- They cost less in manufacturing.

CONTD…

Limitation

- Larger frontal area
- Lower efficiency
- The rotating element (impeller) of the compressor is an integral unit of blades and a disk, and thus if one blade is damaged the entire unit is replaced.

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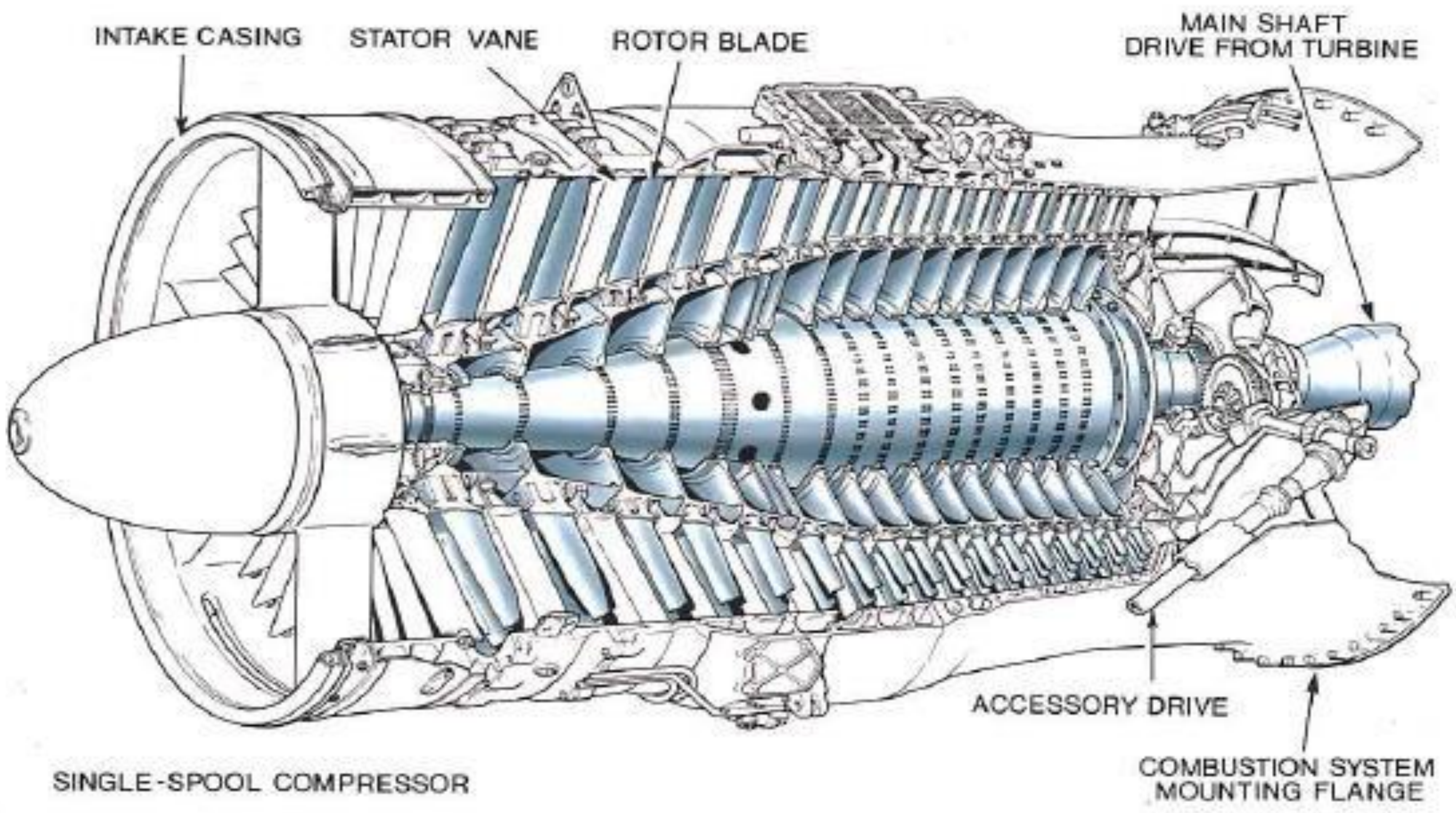
Axial compressor

- Single spool and double spool



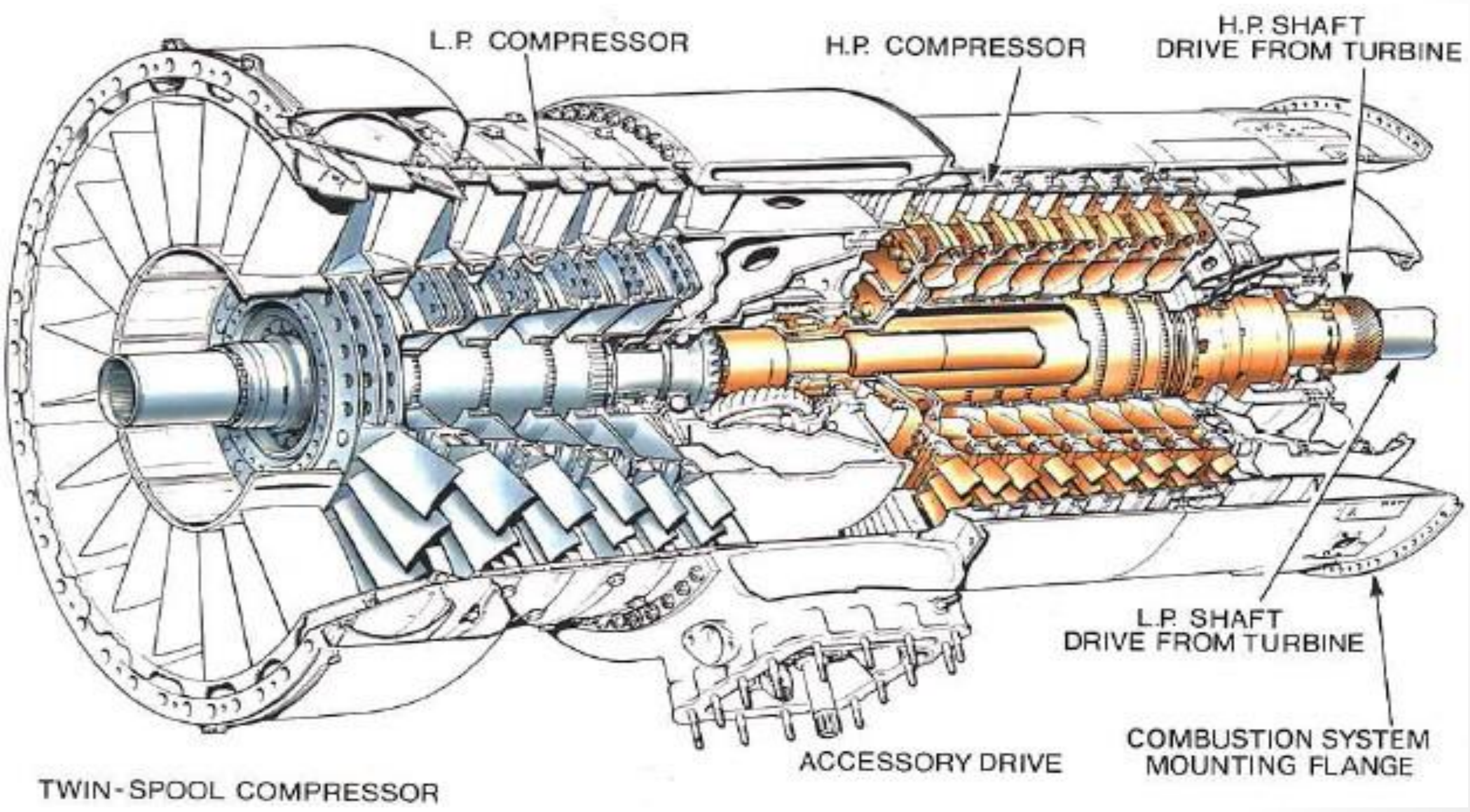
CONTD…

Single spool axial compressor

- It consists of one rotor and one stator.
- The rotor includes blades, disks drum and shaft. They are assembled together and sit on 2 bearings.
- Stator has guide vanes and casing.
- Axial compressor has pressure ratio lower than centrifugal compressor, normally 1.15~1.35. That why multiple stage axial compressor is often used.

CONTD…

- Double spool axial compressor



CONTD…

Double spool compressors

- They are at same axis, but on different shafts.
- Front row is low pressure (LP) compressor, and it rotates with LP Turbine;
- Rear one is high pressure (HP) compressor coupled with HP turbine.
- *Two rotors have no mechanical connection, and they have their own rotational speed.*

- Components: rotor, disc, shaft, drum, blade, stator, casing

CONTD…

Compressor rotors

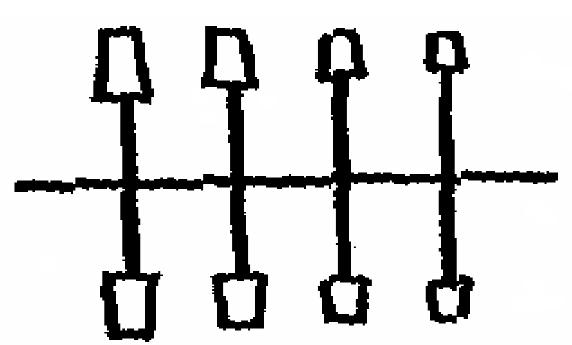
- Have a high thermal resistances and suffer from less fatigue.
- Work under very high rotational speeds(thousands ~ hundreds k rpm)
- Are able to withstand bending moment, torque, centrifugal forces, and vibrations.
- Require light weight construction with enough strength and stiffness

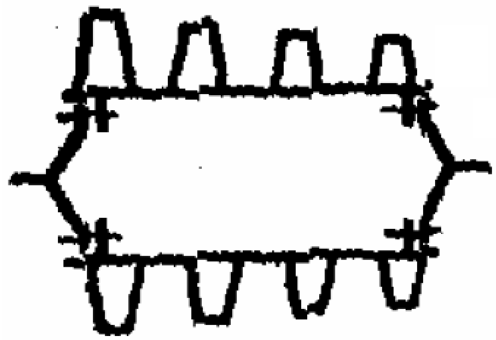
CONTD…

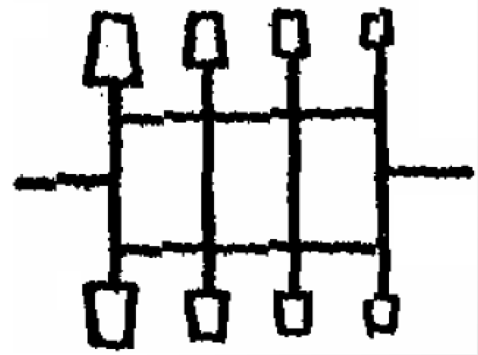
<u>Structure</u>: Disks + shaft:

- Consists of one shaft and many disks where blades are installed.
- Centrifugal forces of blades and disks are borne by the disks and bending stiffness depends on the shaft.
- This type of construction is no more used because of the inherently weak bending stiffness.

- **Drum and drum + disks:**
  - Blades are attached circumferentially or axially in drum or disk. Forces are transferred through the drum and disks.
  - *The drum insures the bending stiffness.*



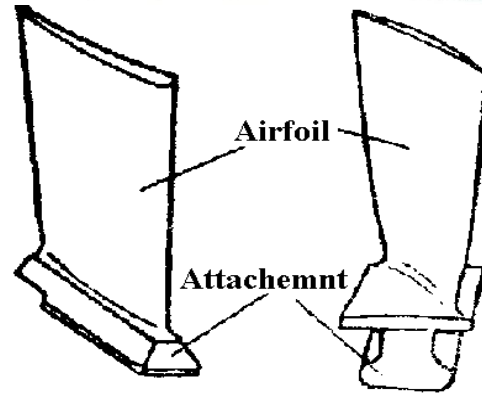


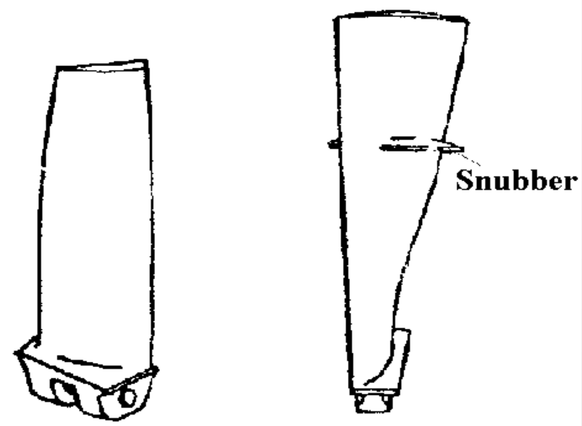


CONTD…

<u>**Blades**</u>

- These are very important parts in axial compressors, composed of airfoil and attachment (fixing) system
- At the end of compressor, temperature can reach up to 500 ~ 600°C, or even higher.
- Blades suffer centrifugal, aerodynamic and vibrating forces.
- Blade attachment
  - **Swallow tail attachment**: easy fabrication.
  - **Pivot attachment**: No bending stress.
- Blades may be broken due to fatigue, especially from fatigue due to vibration .
- To reduce vibration amplitude, long blades are often made with a mid-span support called **snubber or clapper**.
- Increase centrifugal force, Decrease efficiency.
- The materials normally used for the blades are titanium, aluminum alloys, steels and composites.





CONTD…

- **Compressor stator** is the part which does not rotate and consists of vanes and casings.
- It bears axial forces, torques, vibration and rotor's forces transferred by bearings. It is a part of air passage, and hence bears pressure forces as well as thermal stress caused by temperature.
- **Half-half Casing:** Good stiffness; No need disassemble the rotor while assembling; Heavier.
- **Entire Casing:** Must disassemble rotor (blades); Normally used in few stages compressor; Lighter.

CONTD…

- As air leaving each stage is at a higher pressure and occupies smaller space, each stage of compressor is smaller than the preceding one, giving the casing a convergent passage.
- This maintains uniform axial velocity. Both the rotors and stators are of aerofoil section, the cross sectional area is *'divergent'*.
- During rotation the rotors act similarly to a propeller blade and accelerate the air rearwards, velocity energy is converted into pressure and temperature.

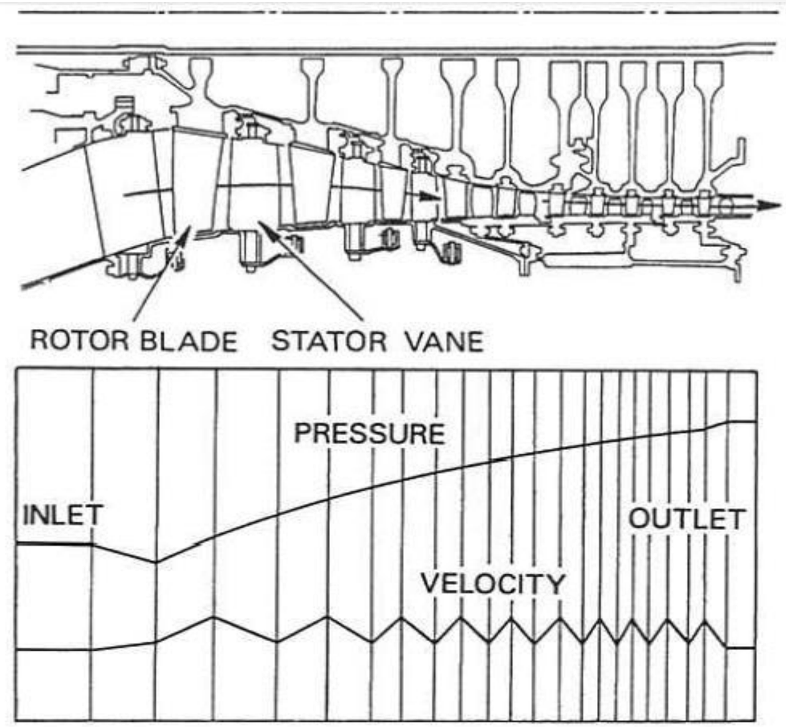


Fig. 3-9 Pressure and velocity changes through an axial compressor.

CONTD…

Anti-icing

- Water droplets may become ice.
- They may reduce air passage and break blades when detached.
- Anti-icing methods
    - Heating (electricity or hot air).
    - Hydrophobic coating.

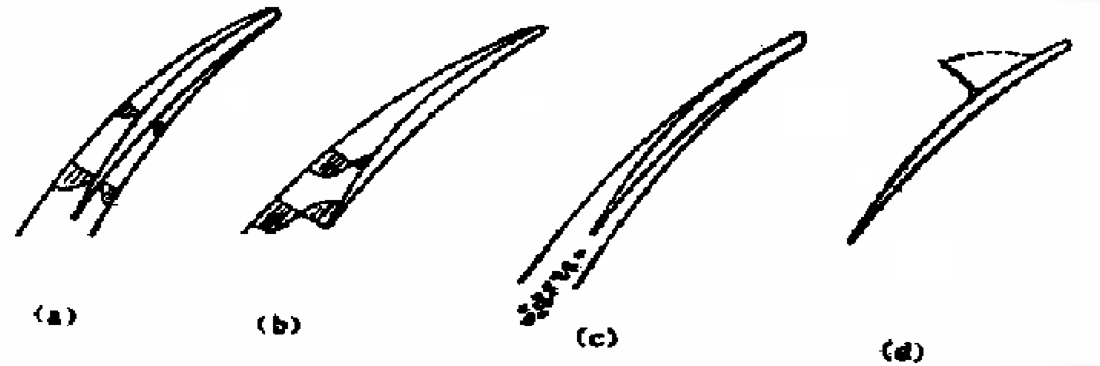
CONTD…

Axial Compressor losses

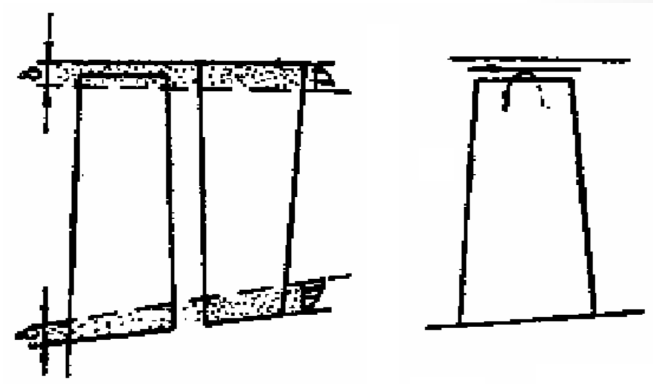
- Due to viscosity, gas flowing in turbo machines will produce many kinds of losses, major types:
  - Airfoil Losses
  - Circumferential Losses

- Airfoil Losses

a. B. layer loss- Fricn
b. Separation loss
c. Tail trace vortexes
d. Shockwave losses



- Circumferential losses (secondary flow)
  - Tip and hub circumferential boundary layers
  - Tip clearance leaking and passage vortices



CONTD…

Compressor Stall and Surge

- For a given axial compressor, the rpm and mass flow rate are the design parameters that must match in order to produce a designed pressure ratio.
- If combustion pressure also increases due to excessive temperature, above compressor outlet pressure, the airflow will reverse in direction and surge forward through the compressor, with possible risk of damage to the engine called compressor stall and compressor surge.
- At compressor stalling, the mass flow leaving the compressor is greatly reduced and as approximately 60% of this air is used to keep combustion chamber temperature within limits, the temperature rises and can cause serious damage to the engine.

CONTD…

- A compressor stall can be recognized by the following:
  - Vibration
  - Rumbling noise
  - Inability of the engine to accelerate
  - Rapid rise in exhaust gas temp

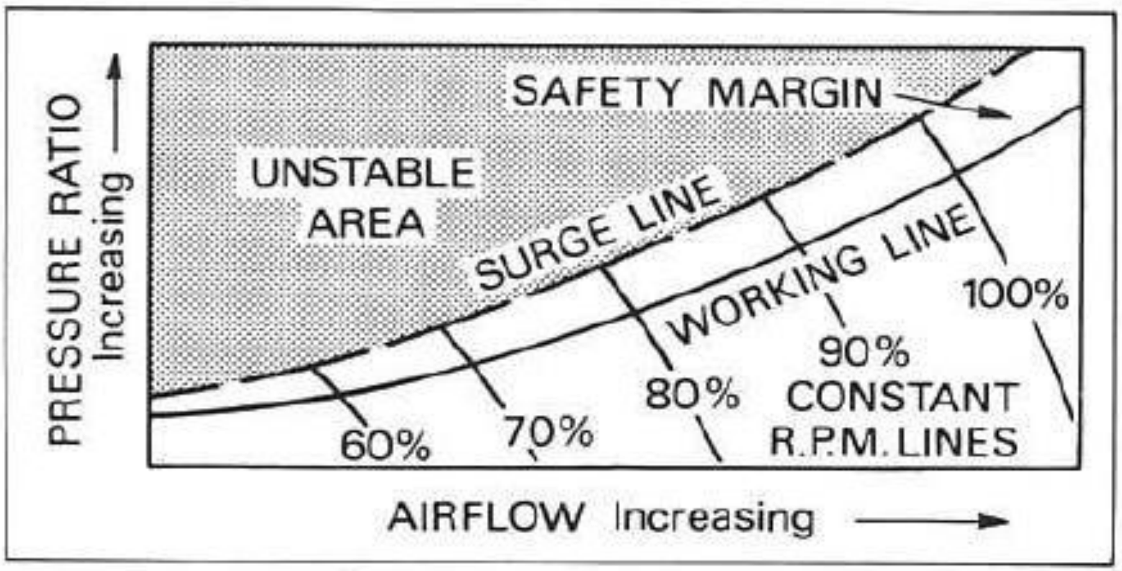


Fig. 3-14 Limits of stable airflow.

Combustion Chamber

- It is needed to burn fuel efficiently without increase in pressure, all energy released by the fuel is converted into heat and velocity energy.
- Very high temperatures (2,000°C) exists in the combustion system.
- For material protection, about 60% of the air flow is used for cooling.
- Combustion chamber changes chemical energy to heat energy by burning fuel-air mixture.
- Cold air comes from compressor and hot gas goes to turbine.
- Compressor exit-diffuser reduces Mach number of the air to a suitable combustor inlet value before it reaches the combustor.
- Combustion requires slow flow velocity for a sufficiently long residence time so that a necessary level of combustion can take place before the gases leave the combustor.

CONTD…

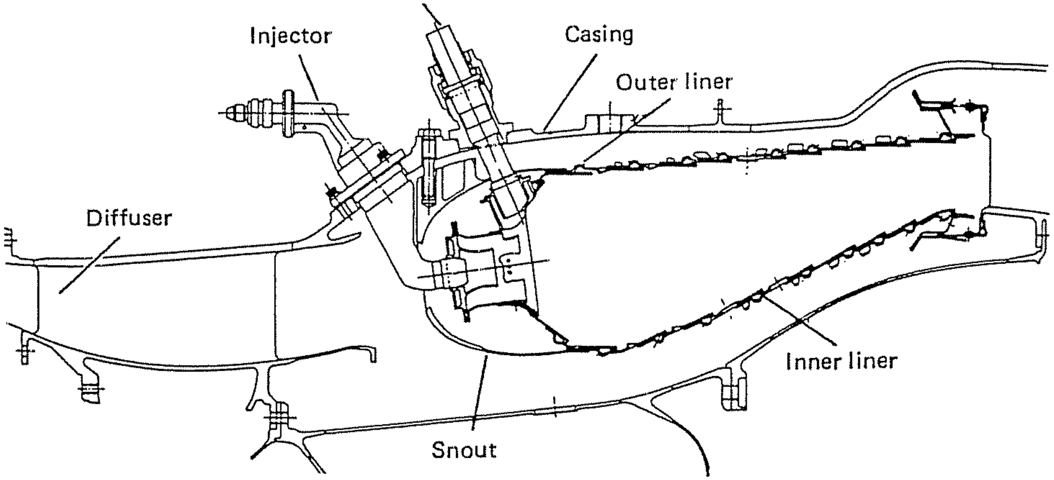
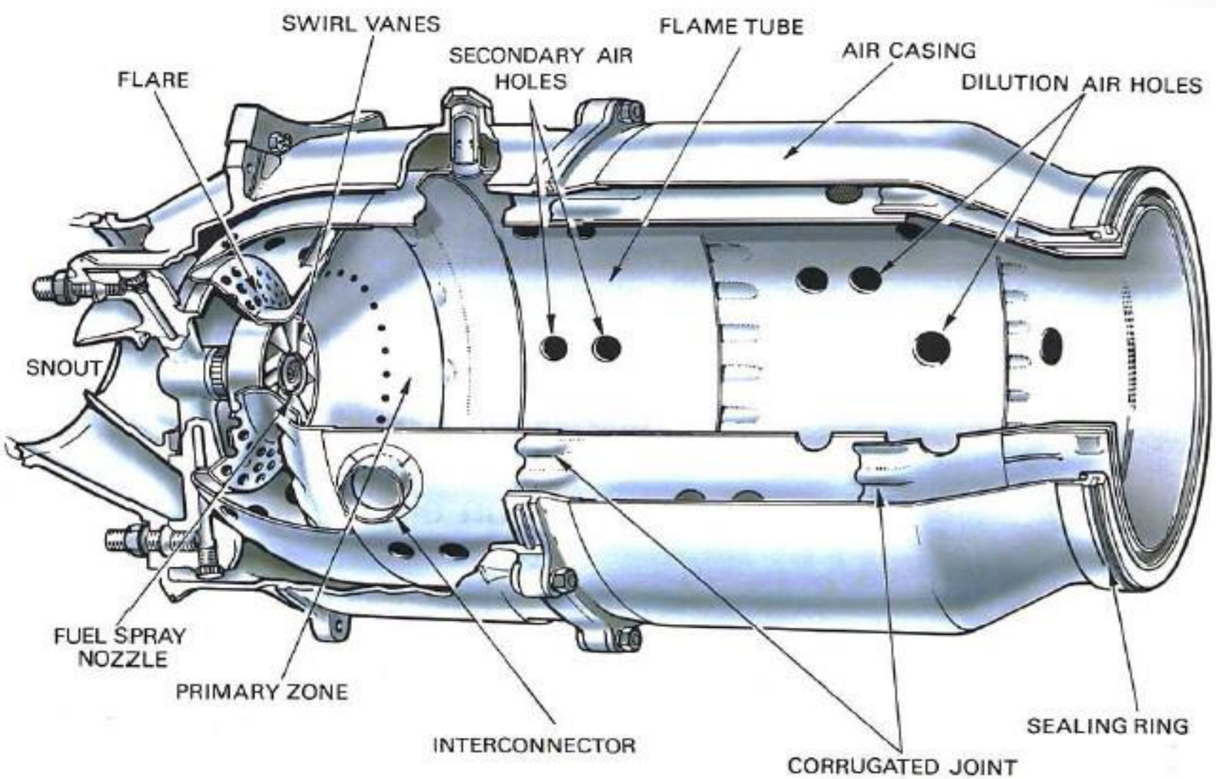


FIG. 1.13 CF6-50 annular combustor (*courtesy General Electric Company*).

<u>Components of combustor</u>

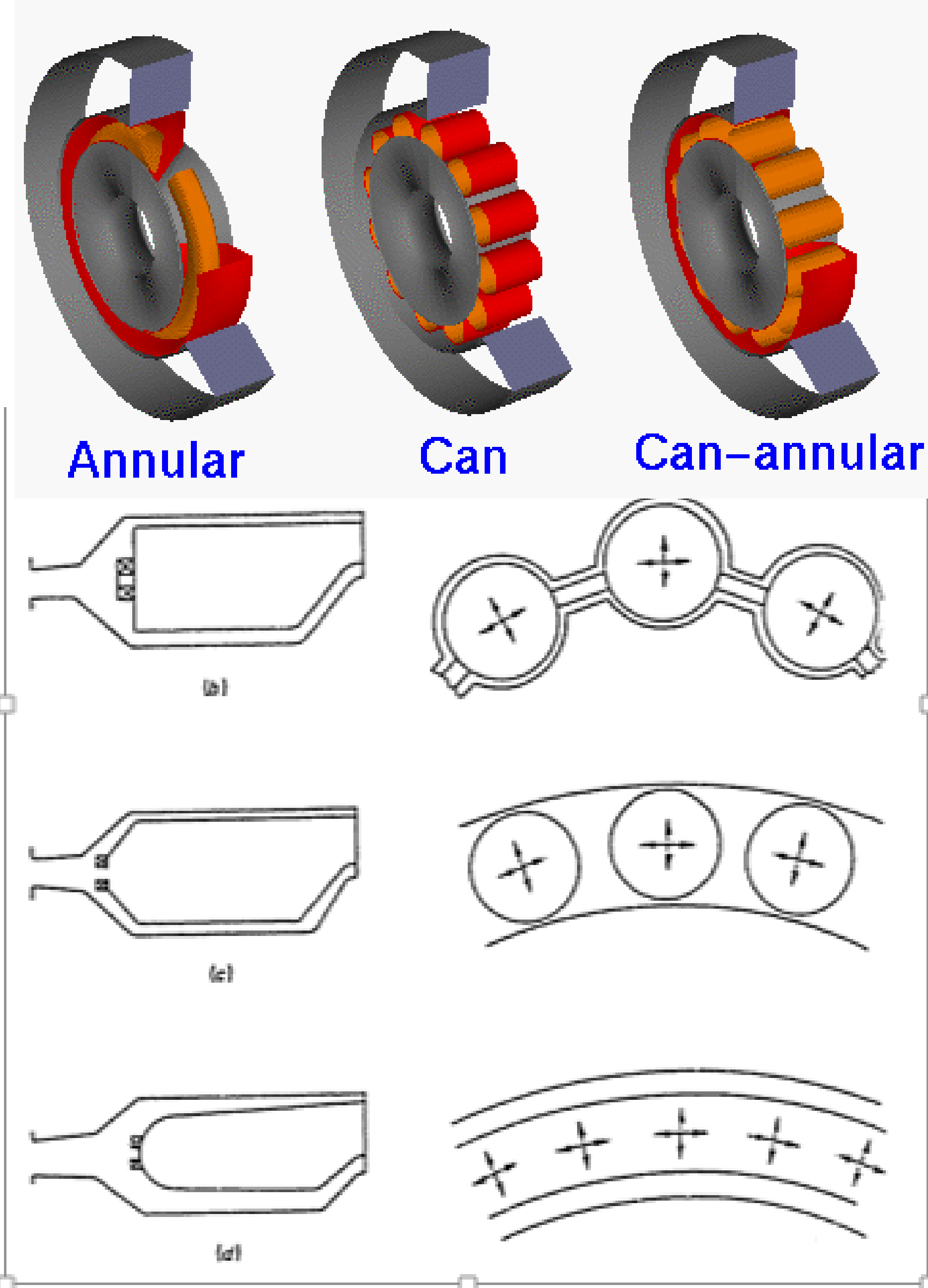
- Casings,
- Flame tubes,
- Casing,
- Can Interconnectors
- Snout,
- Spray nozzles,
- Swirl vanes,
- Dilution Air Holes

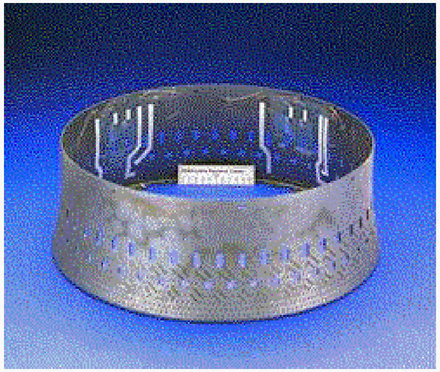


CONTD…

Types of combustion chamber

a. Single pipe (Can)
b. Cannular (Can Annular)
c. Annular





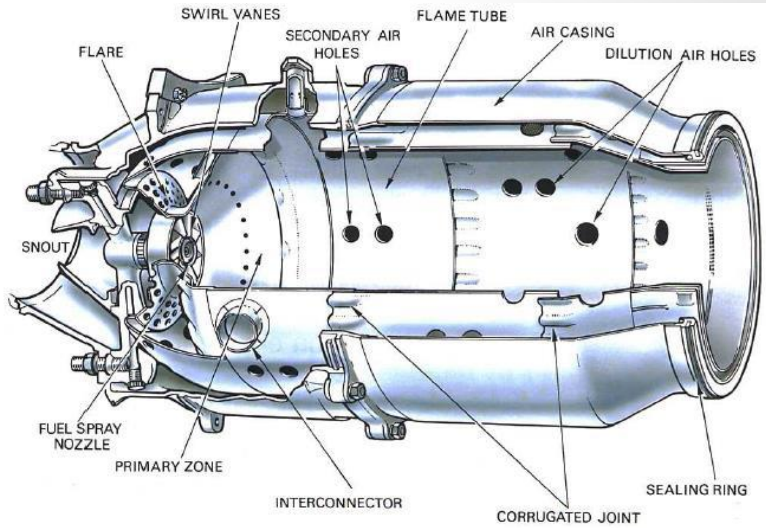
Annular Burner Liner

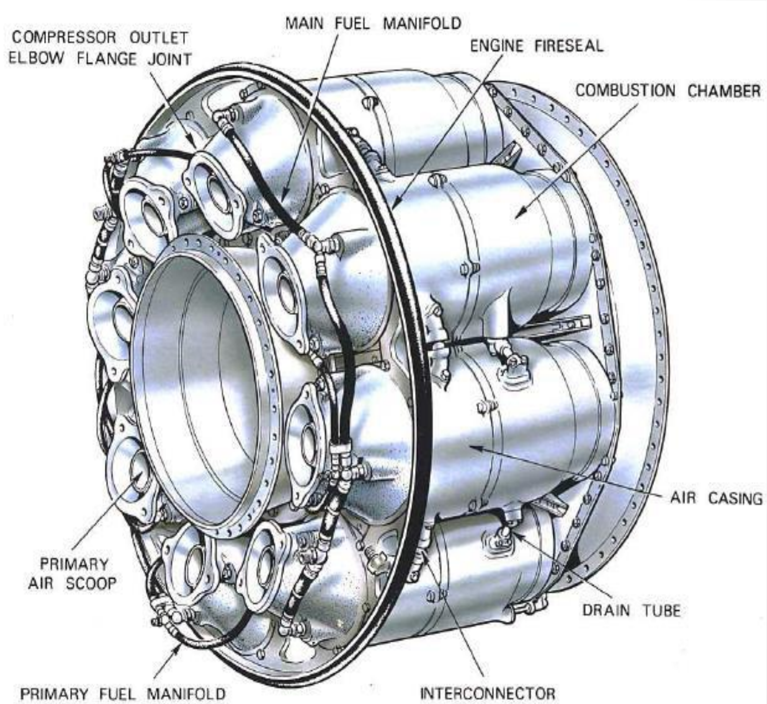
Burner "cans"

CONTD…

Single pipe (Can)

- It consists of many combustion chambers (8~16).
- Interconnectors connect them to pass flame and make pressure equal.
- Each chamber has a casing so that it is easy to test in lab.
- Require less air.
- It was widely used in early engines, especially in combination with centrifugal compressor.
- Simple structure and easy to maintain.
- *Heavy and not efficient in terms of the use of space.*
- *Casing cannot transfer mechanical forces.*
- *Its use increases the resulting part weight of other components.*

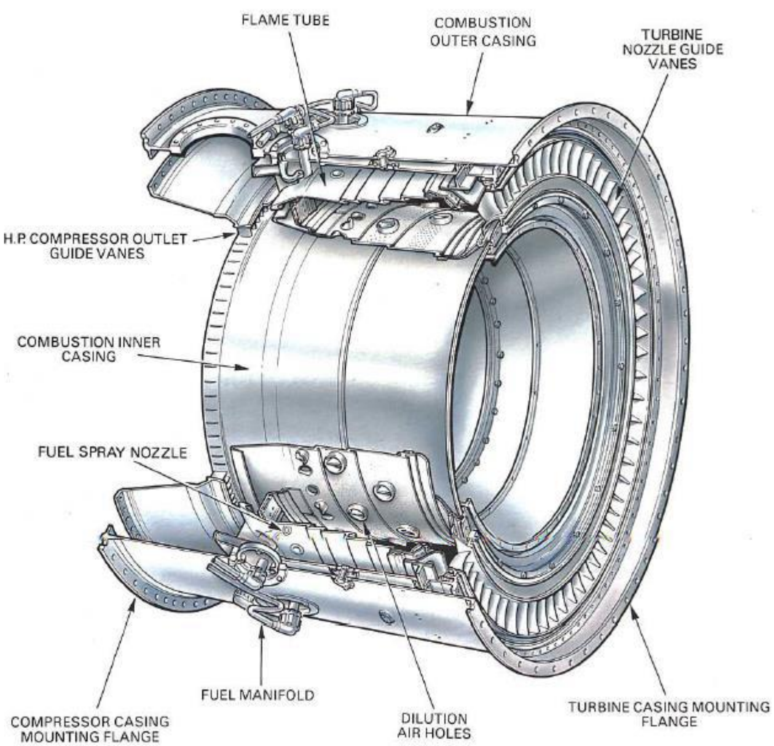




CONTD…

Annular

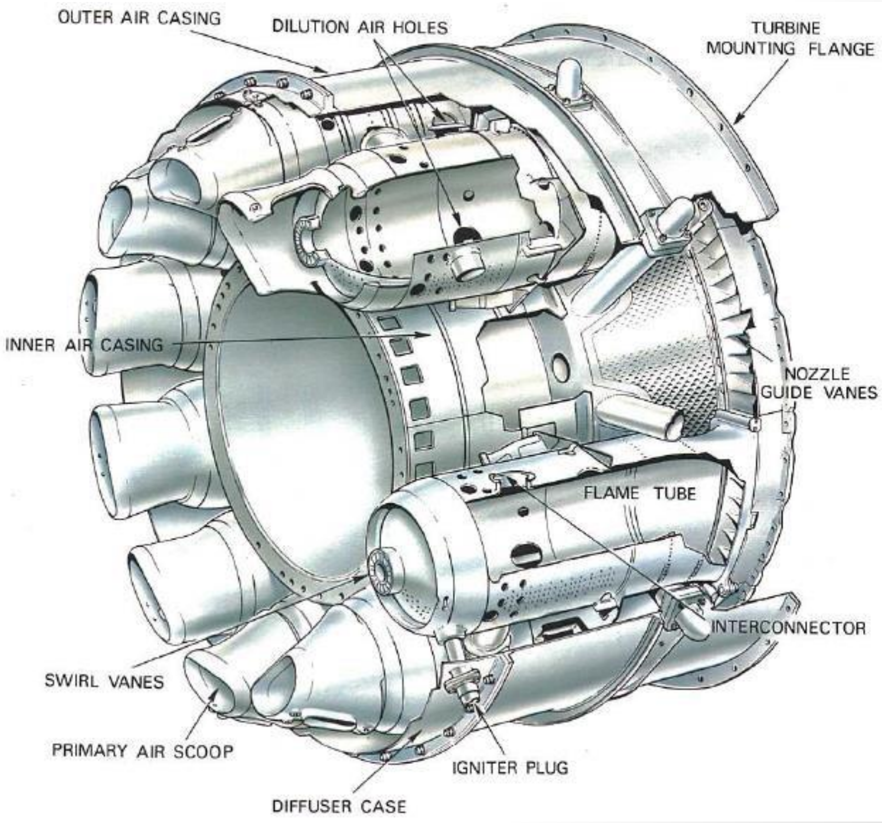
- Typical annular combustors consist of 4 concentric cylinders
- Widely used nowadays.
- Efficient use of space.
- Casing can transfer forces.
- It matches geometrically and aerodynamically with compressor outlet and turbine inlet, so less losses and uniform temperature field.
- It's lighter in weight.
- *Difficult to test in lab, and need large quantity of flow to test.*
- *Difficult to maintain.*



CONTD…

Cannular

- There are several single flame tubes within the same casing.
- Casing can be used to transfer forces.
- Compact structure.
- It is lighter in weight.
- A single-tube is easy to test.



CONTD…

TABLE 1.1 Relative Merits of Various Chamber Types

Chamber type	Advantages	Disadvantages
Tubular	1. Mechanically robust 2. Fuel-flow and airflow patterns are easily matched 3. Rig testing necessitates only small fraction of total engine air mass flow	1. Bulky and heavy 2. High pressure loss 3. Requires interconnectors 4. Incurs problem of light-round
Annular	1. Minimum length and weight 2. Minimum engine frontal area 3. Minimum pressure loss 4. Easy light-round	1. Serious buckling problem on outer liner 2. Rig testing necessitates full engine air mass flow 3. Difficult to match fuel-flow and airflow patterns 4. Difficult to maintain stable outlet temperature traverse
Tuboannular	1. Mechanically robust 2. Fuel-flow and airflow patterns are easily matched 3. Rig testing necessitates only small fraction of total engine air mass flow 4. Low pressure loss 5. Shorter and lighter than tubular chambers	1. Less compact than annular 2. Requires connectors 3. Incurs problem of light-round

(FROM LEFEBVRE)

CONTD…

Combustion chemistry

- General hydrocarbon, CnHm (Jet fuel H/C~2)
- Complete oxidation, hydrocarbon goes to CO2 and water

$$C_nH_m + \left(n + \frac{m}{4}\right)O_2 \rightarrow nCO_2 + \frac{m}{2}H_2O$$

- For air-breathing applications, hydrocarbon is burned in air.
- Air modeled as 20.9 % O2 and 79.1 % N2 (neglect trace species)
- Complete combustion for hydrocarbons means all C → CO2 and all H → H2O

$$C_nH_m + \left(n + \frac{m}{4}\right)(O_2 + 3.78N_2) \rightarrow nCO_2 + \frac{m}{2}H_2O + 3.78\left(n + \frac{m}{4}\right)N_2$$

- Stoichiometric = exactly correct ratio for complete combustion

Stoichiometric Molar fuel/air ratio

$$\overline{\psi}_s = \frac{1}{4.78\left(n + \frac{m}{4}\right)}$$

Stoichiometric Mass fuel/air ratio

$$\psi_s = \frac{(12n + m)}{\left(n + \frac{m}{4}\right)(32 + 3.78(28))}$$

CONTD…

Combustion efficiency

- ηb = Actual Enthalpy (Q or h) Rise / Ideal Enthalpy Rise,

$$\eta_b = \frac{Q_{R,actual}}{Q_{R,Ideal}} \qquad \eta_b = \frac{\bar{c}_P\left[\left(\dot{m}_a + \dot{m}_f\right)T_{t4} - \dot{m}_a T_{t3}\right]}{\dot{m}_f h}$$

- ma, mf= mass flow rate of air, fuel
- Tt3,Tt4 = combustor inlet, outlet temperature
- For kerosene, h = 42.9 MJ/kg and For JP-10, h = 42.2 MJ/kg
- A portion of fuel may not be burnt in the combustor because the flow residence time is not long enough to allow a complete combustion.
- This reduces the overall efficiency.

CONTD…

- Combustion efficiency directly affects the *specific fuel consumption (sfc)—mass (kg) of fuel consumed per hour of net thrust.*

General Observations:

- Under design condition, η_b is around 95%~98%. Because of low pressure at high altitude, η_b goes down
- $\eta_b \downarrow$ as p $\downarrow$ and T $\downarrow$ (because of dependency of reaction rate)
- $\eta_b \downarrow$ as Mach number $\uparrow$ (decrease in residence time)
- $\eta_b \downarrow$ as fuel/air ratio $\downarrow$

CONTD…

COMBUSTOR REQUIREMENTS

- Complete combustion ($\eta_b \rightarrow 1$)
- Low pressure loss ($\sigma_b \rightarrow 1$)
- Reliable and stable ignition
- Wide stability limits
  - Flame stays lit over wide range of pressure, velocity , f/a ratio
- Freedom from combustion instabilities
- Temperature distribution into turbine with no hot spots
- Low emissions
  - Smoke (soot), unburnt hydrocarbons, NOx, SOx, CO
- Effective cooling of surfaces
- Low stressed structures, durability
- Small size and weight
- Design for minimum cost and maintenance

CONTD…

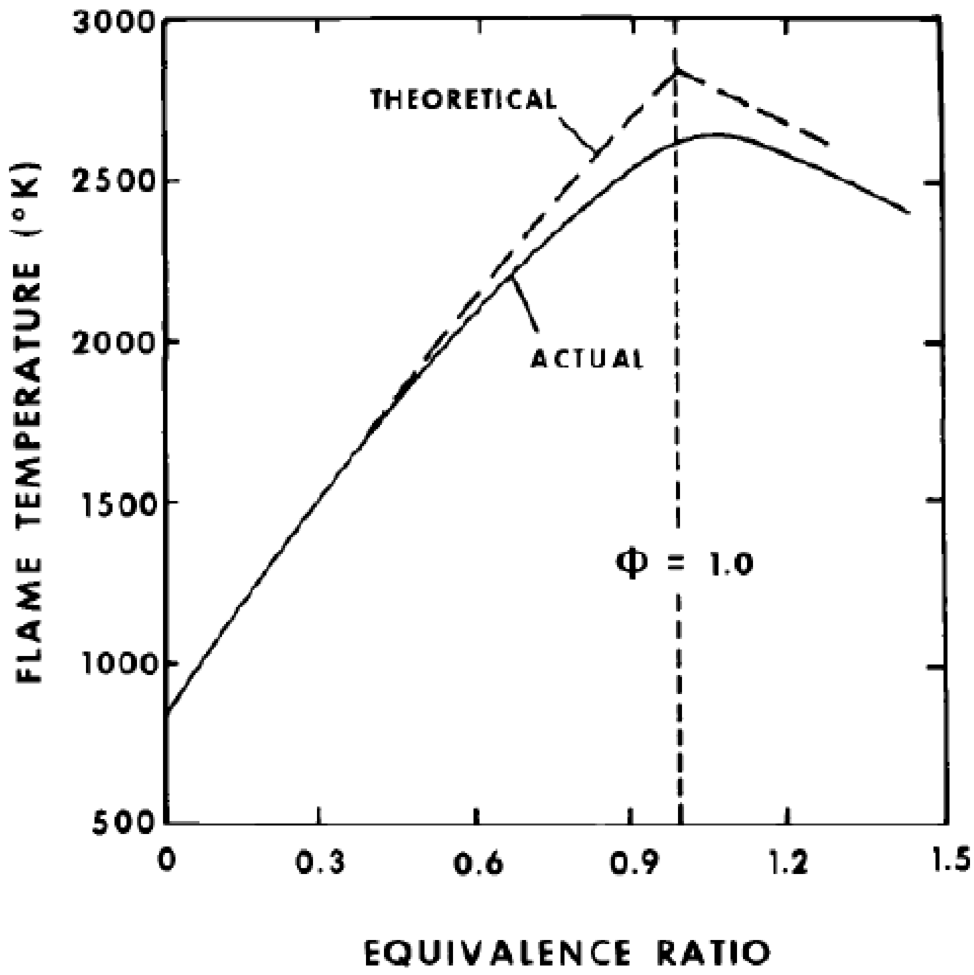
- Based on material limits of turbine (T_{t4}), combustors must operate below stoichiometric values
  - For most relevant hydrocarbon fuels, $\psi_s \sim 0.06$ (based on mass)

- Comparison of actual fuel-to-air and stoichiometric ratio is called equivalence ratio
  - Equivalence ratio = $\phi = \psi/\psi_{stoich}$
  - For most modern aircraft $\phi \sim 0.3$

- Summary
  - If $\phi = 1$: Stoichiometric
  - If $\phi > 1$: Fuel Rich
  - If $\phi < 1$: Fuel Lean

CONTD…

Flame Temperature and Eqv. Ratio (Φ)



CONTD…

Reliable ignition and flame stability

- On ground, it is easy to ignite the combustion because of higher pressure and temperature of the combustor intake flow.
- However, in flight, especially at high altitude, it is difficult to reignite an extinguished combustion because compressor is in **windmill state**, and *p*, *T* are low. The airplane must dive to get high pressure.
- Ignition reliability refers to whether ignition succeeds in certain (bad) conditions (e.g. at high altitudes).

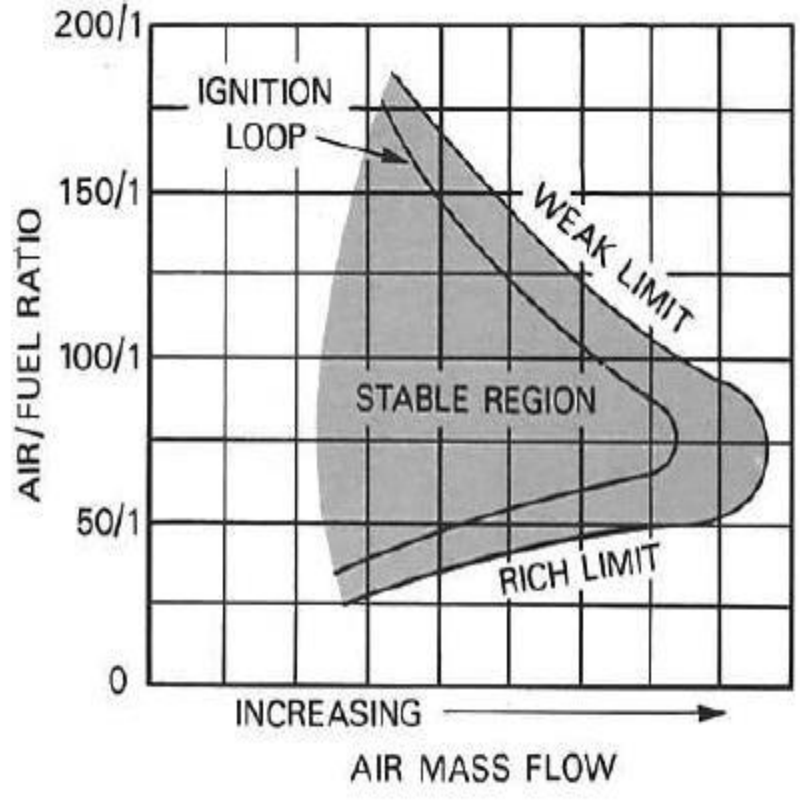


Fig. 4-11 Combustion stability limits.

CONTD…

<u>Eqv. Ratio (Φ) and By- Pass Cooling</u>

- Most mixtures will not burn so far away from stoichiometric mixture which is often called **Flammability Limit.**
- Increase in pressure, increases flammability limit
- Requirements for combustion, roughly $\Phi > 0.8$
- Gas turbines can not operate at (or even near) stoichiometric levels due to turbine inlet temperature considerations
  - Temperatures (adiabatic flame temperatures) associated with stoichiometric combustion are way too hot for turbine
  - Fixed Tt4 implies roughly $\Phi < 0.5$

What do we do?

- Burn (keep combustion going) near $\Phi=1$ with some of compressor exit air
- Then mix very hot gases with remaining air to lower temperature for turbine
- Lower the total pressure loss

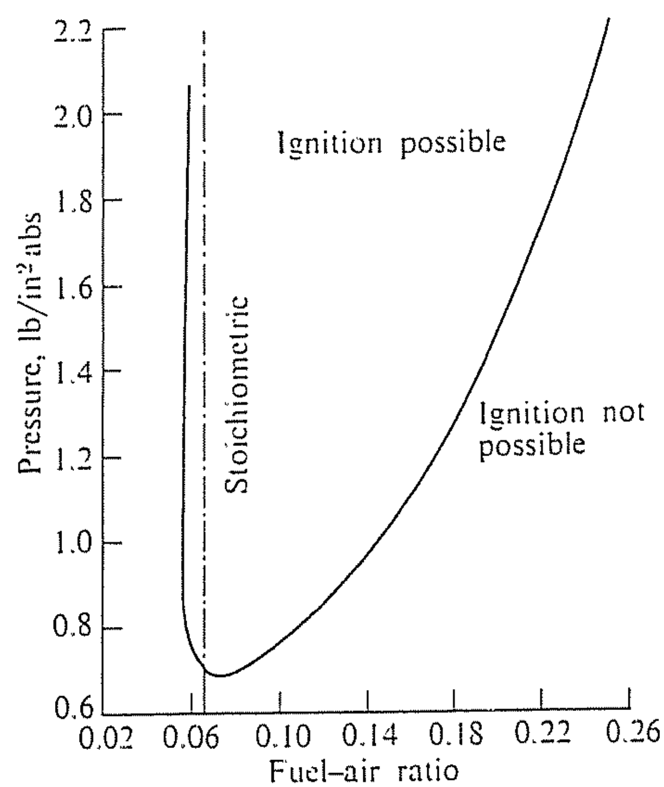


FIG. 7–24. Inflammability limits of gasoline–air mixtures. (Courtesy Olson, *et al.* [18].)

CONTD…

Combustion Zones

1. Primary Zone

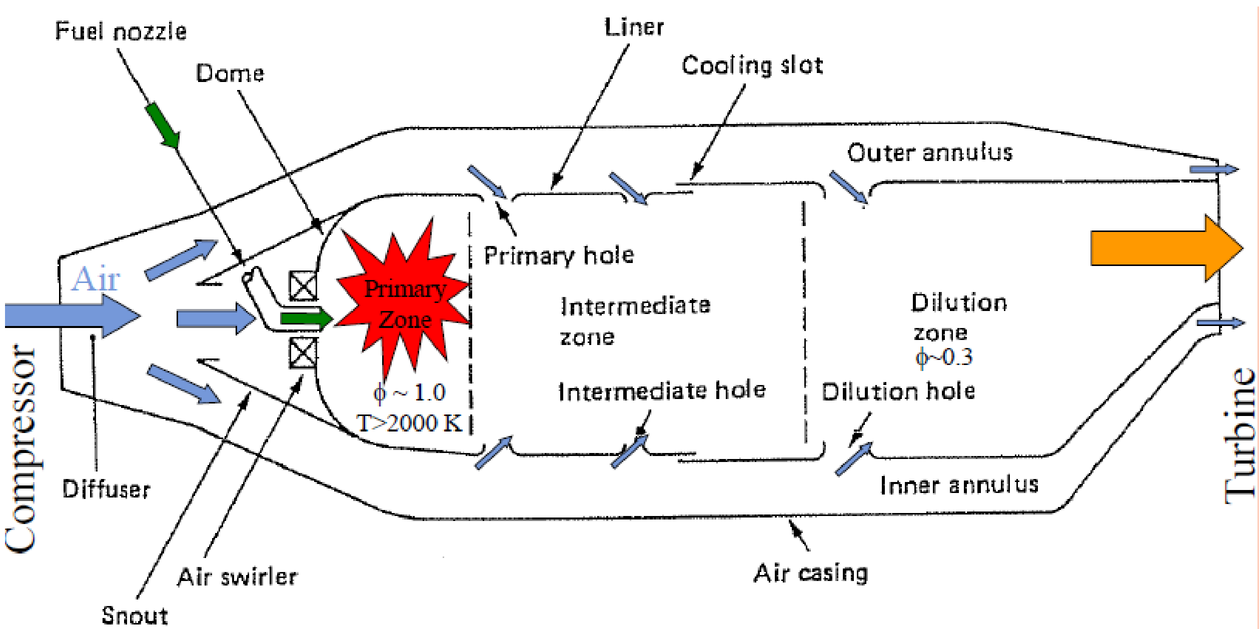
- Anchors Flame
- Provides sufficient time, mixing, temperature for "complete" oxidation of fuel
- Equivalence ratio near Φ =1

2. Intermediate (Secondary Zone)

- **Low altitude** operation (higher pressures in combustor)
  - Recover dissociation losses (primarily CO → CO2) and Soot Oxidation
  - Complete burning of anything left over from primary due to poor mixing
- **High altitude** operation (lower pressures in combustor)
  - Low pressure implies slower rate of reaction in primary zone
  - Serves basically as an extension of primary zone
  - L/D ~ 0.7

3.Dilution Zone (critical to durability of turbine)

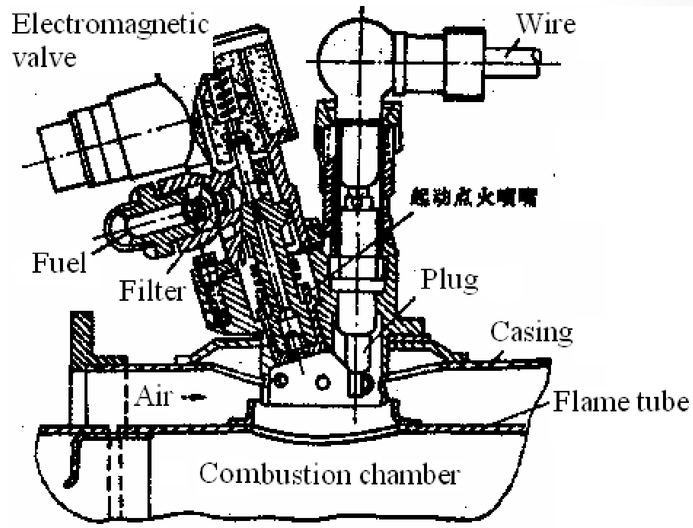
- Mix in air to lower temperature to acceptable value for turbine
- Tailor temperature profile (low at root and tip, high in middle)
- Uses about 20-40% of total ingested core mass flow
- L/D ~ 1.5-1.8



CONTD…

<u>Processes on inside the combustion chamber: Ignition</u>

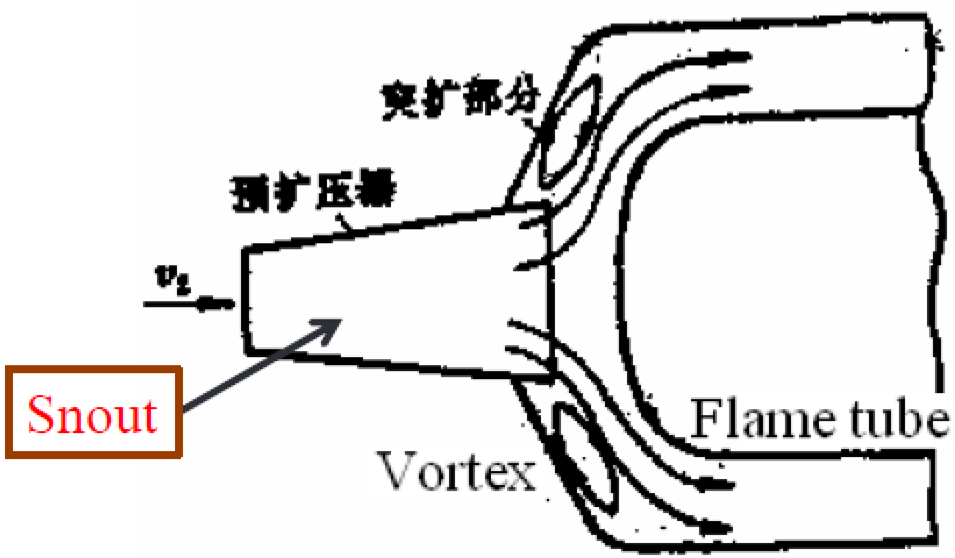
- Ignition process is the same as in an automobile engine, where a high voltage plug is used to ignite fuel-mixture.
- The resulting flame then propagates into the whole premixed combustion zone.
- Igniters stop working once burning zone is flamed.
- In general, one engine has at least 2 igniters to insure ignition success.
- For multiple flame tube structure, interconnectors pass flame from one to others.



CONTD…

Speed Reduction

- Air speed in the last stage of compressor is around 150m/s.
- But combustion chamber flame tube requires flow speed in the range 30~45m/s.
- Divergent geometry at the snout reduce speed quickly.

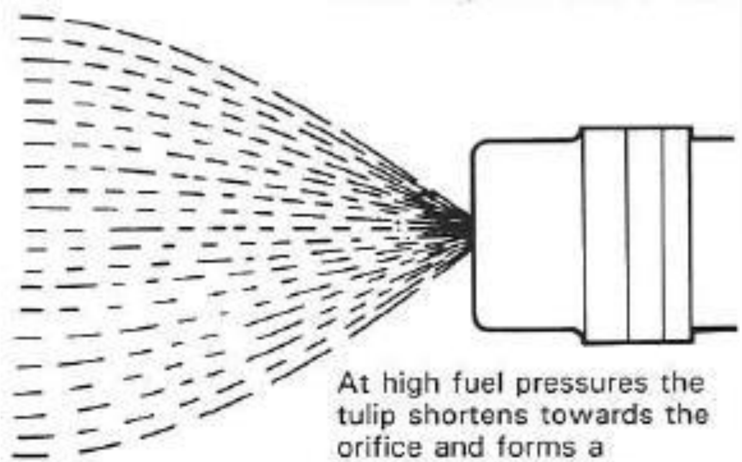


CONTD…

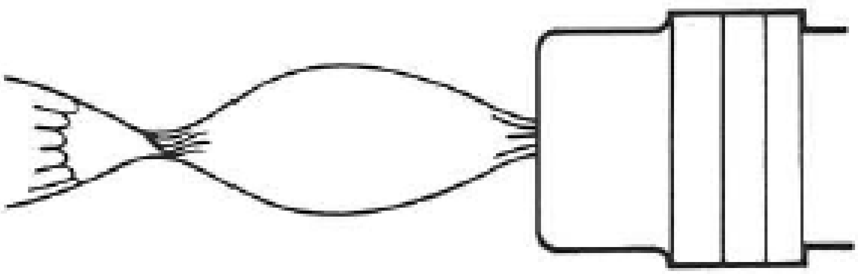
<u>Fuel Vaporization</u>

Atomization

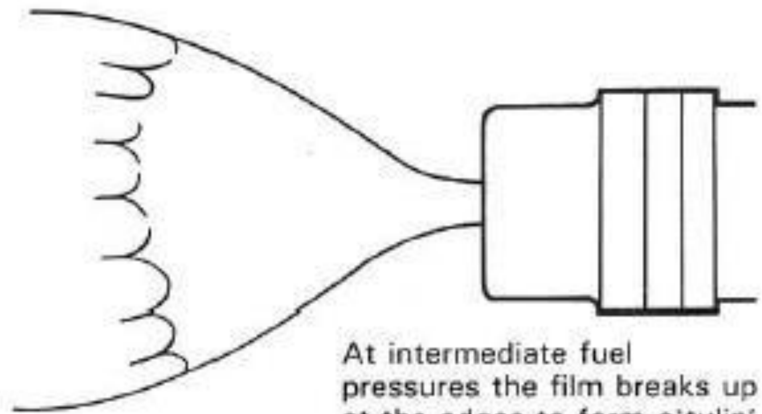
- to get tiny fuel droplets.
- to increase contact surface with air.
- to absorb more heat.
- to vaporize.



At high fuel pressures the tulip shortens towards the orifice and forms a finely atomized spray



At low fuel pressures a continuous film of fuel is formed known as a 'bubble'



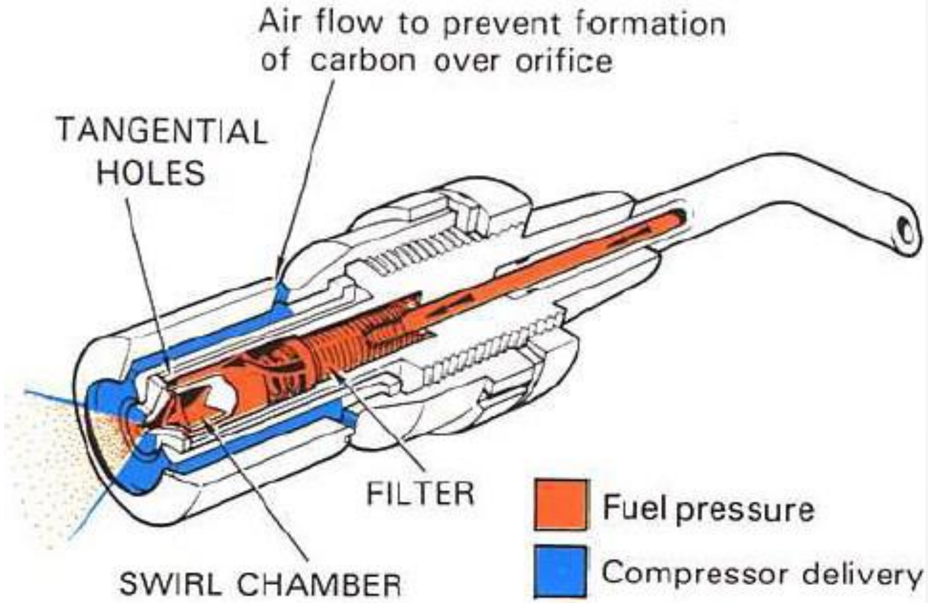
At intermediate fuel pressures the film breaks up at the edges to form a 'tulip'

CONTD…

Injection

Fuel spray nozzle (Swirl Injector)

- For a normal fuel pump, output fuel *flow rate is proportional to the square root of injection pressure*.
- An engine may sometimes require lesser fuel, for example 1/10 (idle) of max-power fuel.
- Under this condition the pump pressure is 1/100 of that at max-power.
- Under low pressure injection conditions, vaporization is bad.

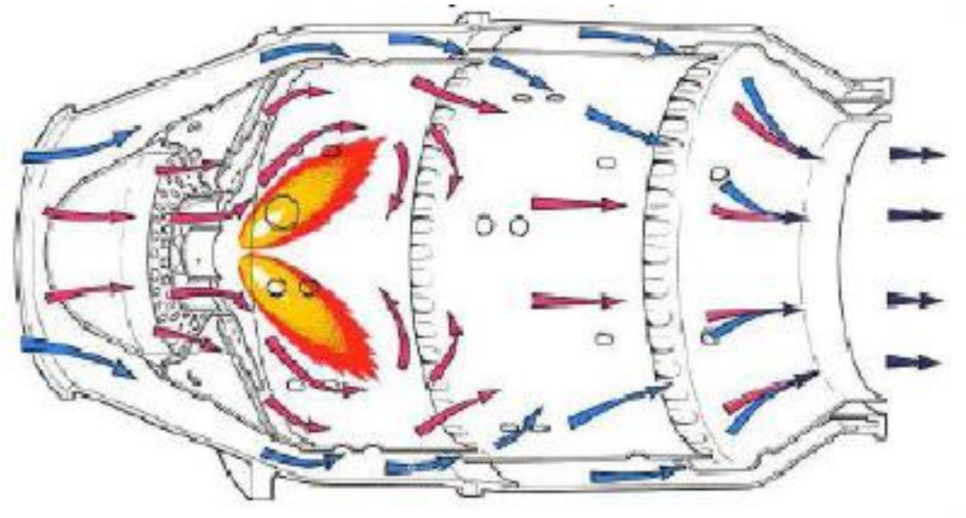


A Simplex fuel spray nozzle

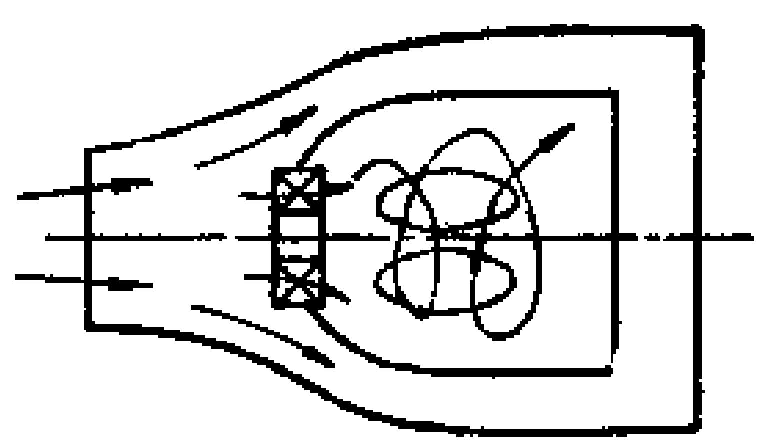
CONTD…

Flame Stabilization

- In the head of flame tube, swirl vanes are installed to provide necessary swirl to the entering air flow.
- Due to viscosity, a low pressure region is formed in the center of the tube which results in the air to flow back from downstream. As a result, a vortex is formed in the flame tube.



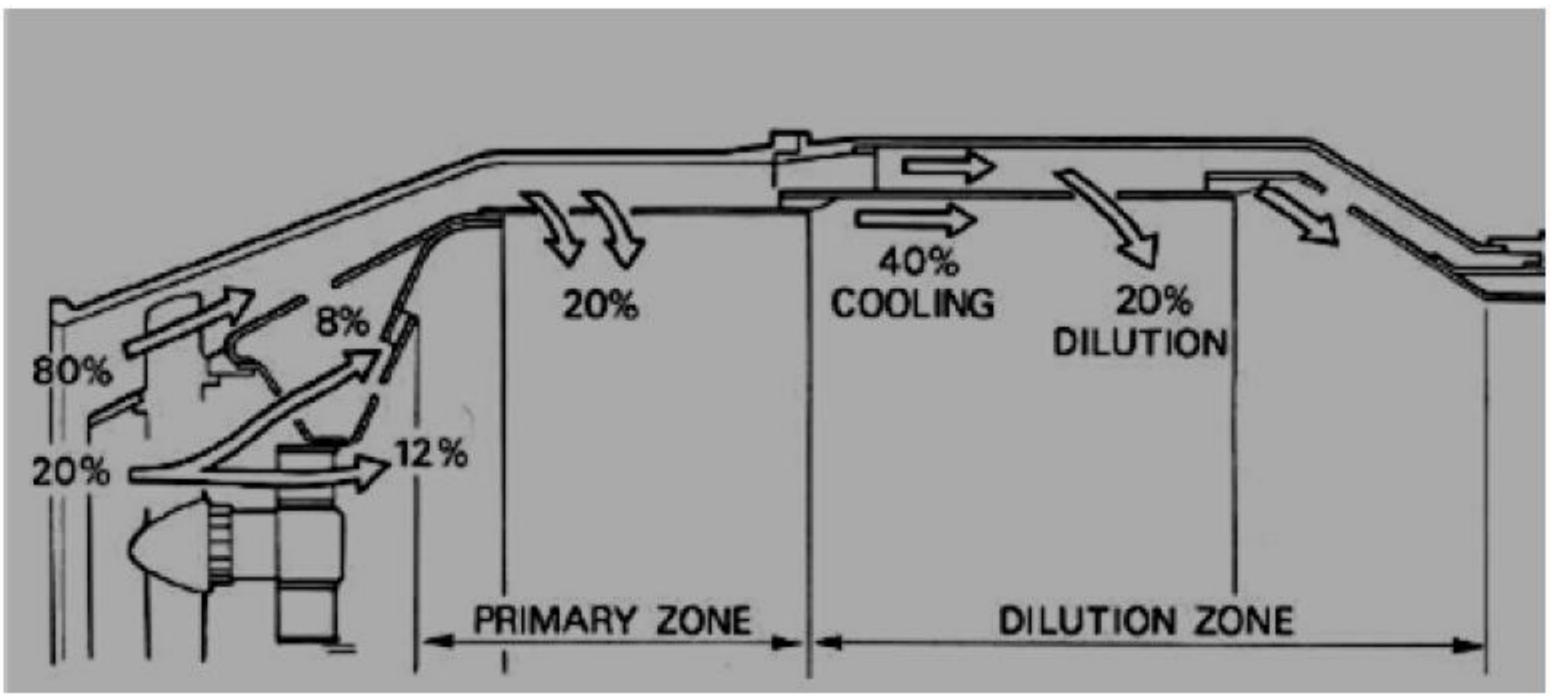
Flame stabilizing and general airflow pattern



CONTD…

Combustion

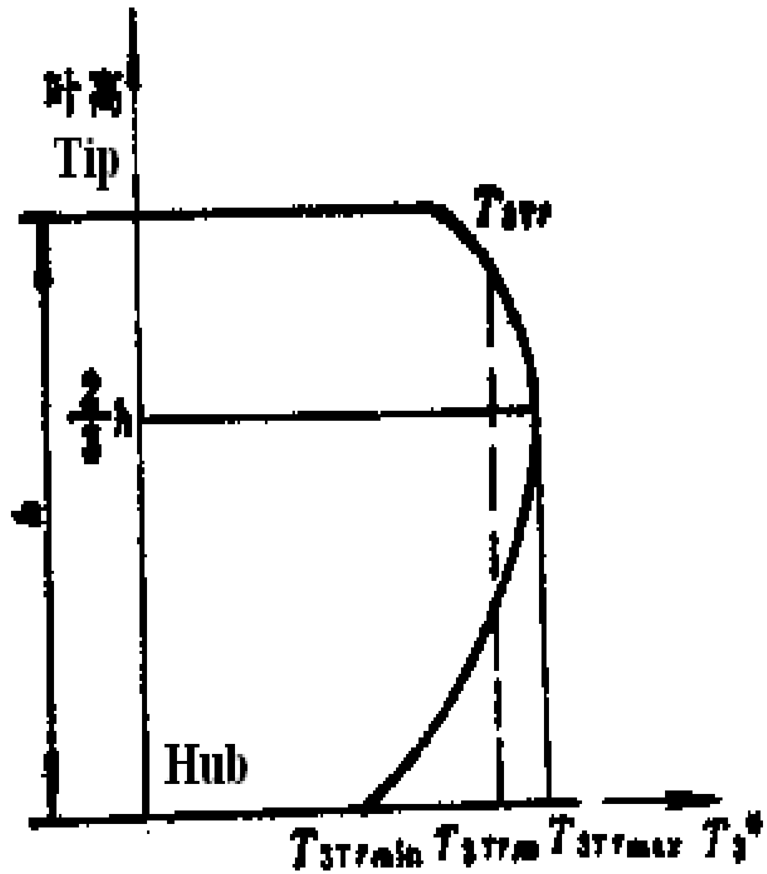
- Fresh air comes from the snout, and fuel is injected from spray nozzle. They are mixed and flamed. When the gas arrives at the outlet of the combustion chamber, it should be burnt completely.



CONTD…

<u>Distribution of temperature at the combustor outlet</u>

- To protect turbine rotating blades, temperature field must follow a distribution as shown in the figure.
- Because of centrifugal force, stress is greater in blade root. So, temperature is lower.
- At the tip, the blade is thin, temperature is also lower.
- Temperature reaches max at 2/3 height so that the blade has a equi-strength.
-



CONTD…

Sizing of combustion chamber

- To increase Thrust/Weight ratio, we need a shorter length of combustion chamber so that the shafts and casings are shorter (and lighter).
- It is difficult to reduce the combustor diameter.
- Shorter combustor size implies that the volume of the chamber is smaller.
- In the other hand, burning more fuel is better and combustion of optimum fuel mass is necessary.

Design Considerations

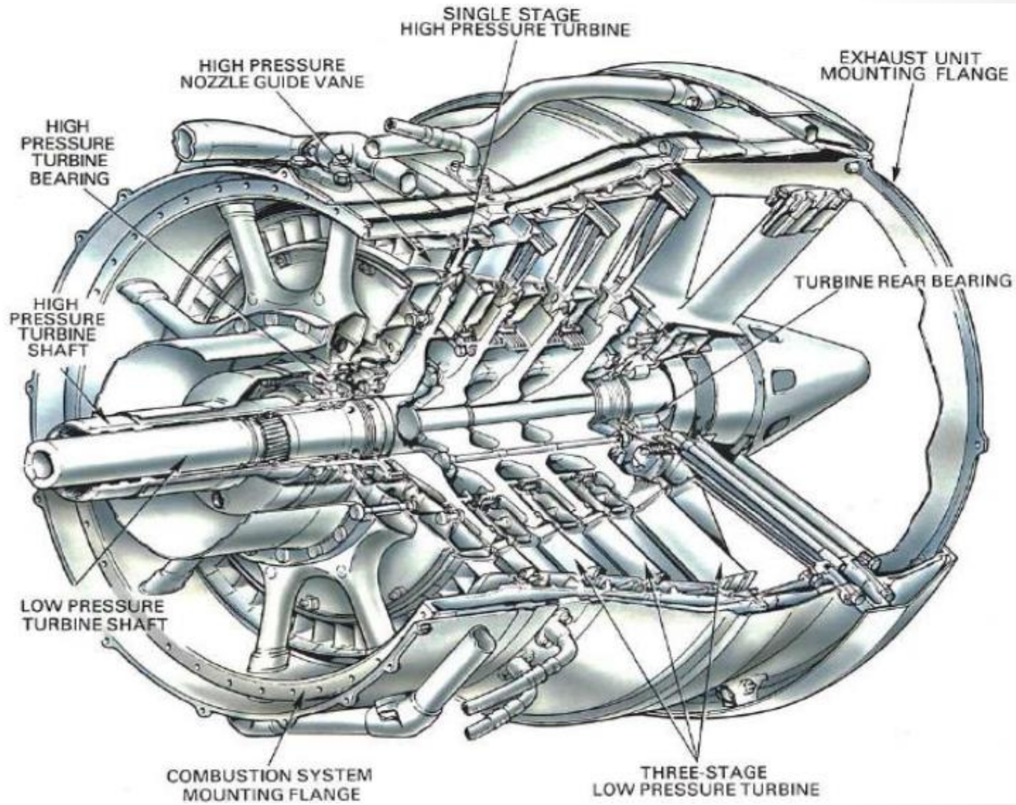
- Design must consider the desirable combustor specifications.
- Pollution problem: limit concentration of CO, NO, NO2 … (NOx) in the emission gases.
- Structural problem: crack in flame tubes and thermal fatigue.

TURBINE

- It provides the power to drive the compressor and accessories and, in the case of engines which do not make use solely of a jet for propulsion, of providing shaft power for a propeller or rotor.
- High stresses are involved in this process, and for efficient operation, the turbine blade tips may rotate at speeds over 500 m/s.
- Gas entry temperature between 850 and 1,700 deg. C. and may reach a velocity of over 750 m/s in parts of the turbine.
- One row of stationary nozzle guide vanes and one row of moving blades.
- The number of stages depends upon the relationship between the power required from the gas flow, the rotational speed at which it must be produced and the diameter of turbine permitted.

CONTD…

- When the gas is expanded by the combustion process, it forces its way into the discharge nozzles of the turbine where, because of their convergent shape, it is accelerated to about the speed of sound which, at the gas temperature, is about 2,500 feet per second.
- At the same time the gas flow is given a ’spin’ or ’whirl’ in the direction of rotation of the turbine blades by the nozzle guide vanes.



CONTD…

- On impact with the blades and during the subsequent reaction through the blades, energy is absorbed, causing the turbine to rotate at high speed and so provide the power for driving the turbine shaft and compressor.
- The whirl will be removed from the gas stream so that the flow at exit from the turbine will be substantially ’straightened out’ to give an axial flow into the exhaust system.
- Excessive residual whirl reduces the efficiency of the exhaust system and also tends to produce jet pipe vibration which has a detrimental effect on the exhaust cone supports and struts.

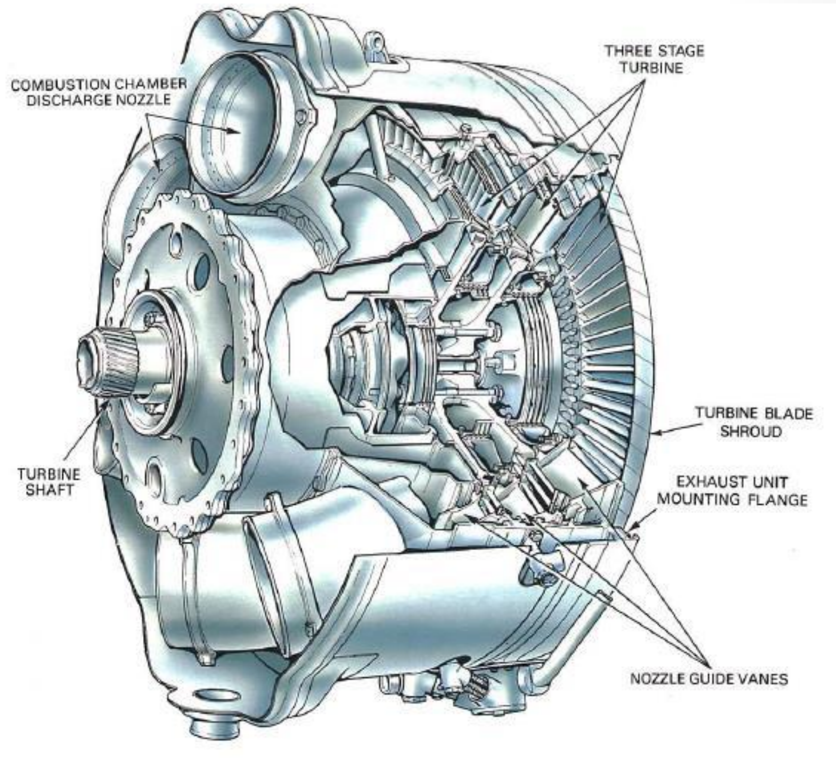
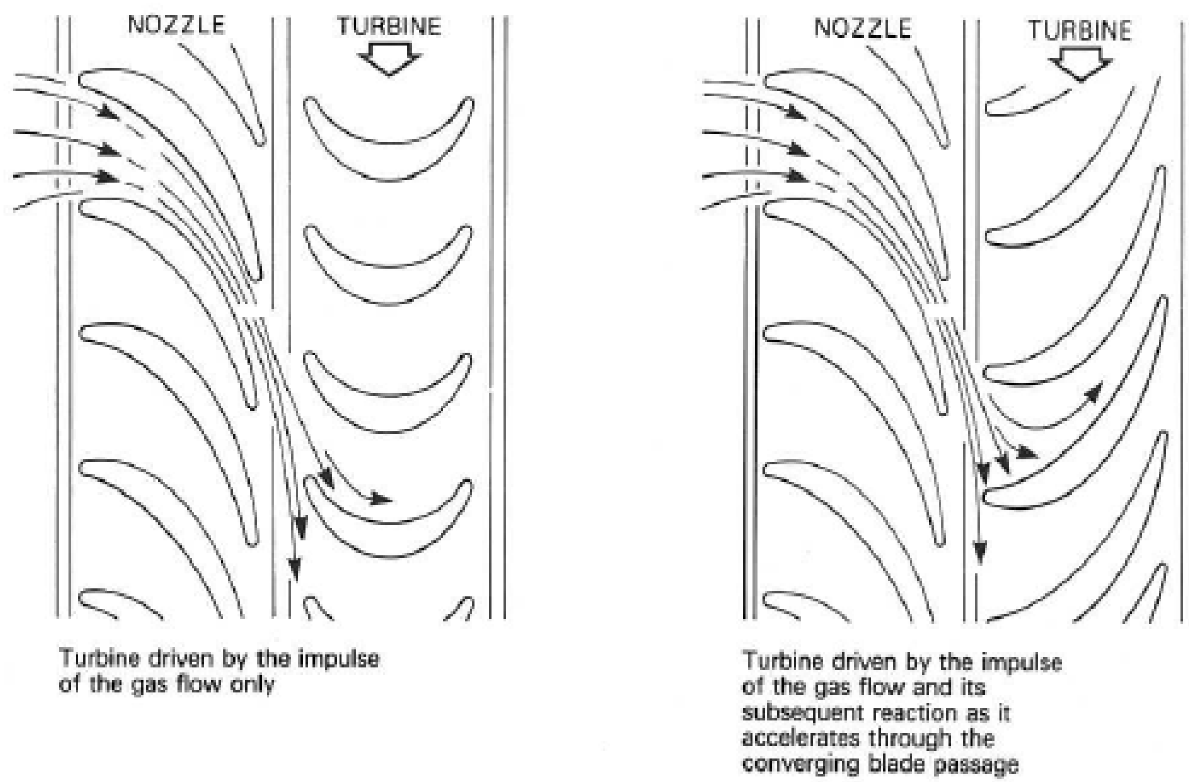


Fig. 5-1 A triple-stage turbine with single shaft system.

CONTD…

Losses in turbine

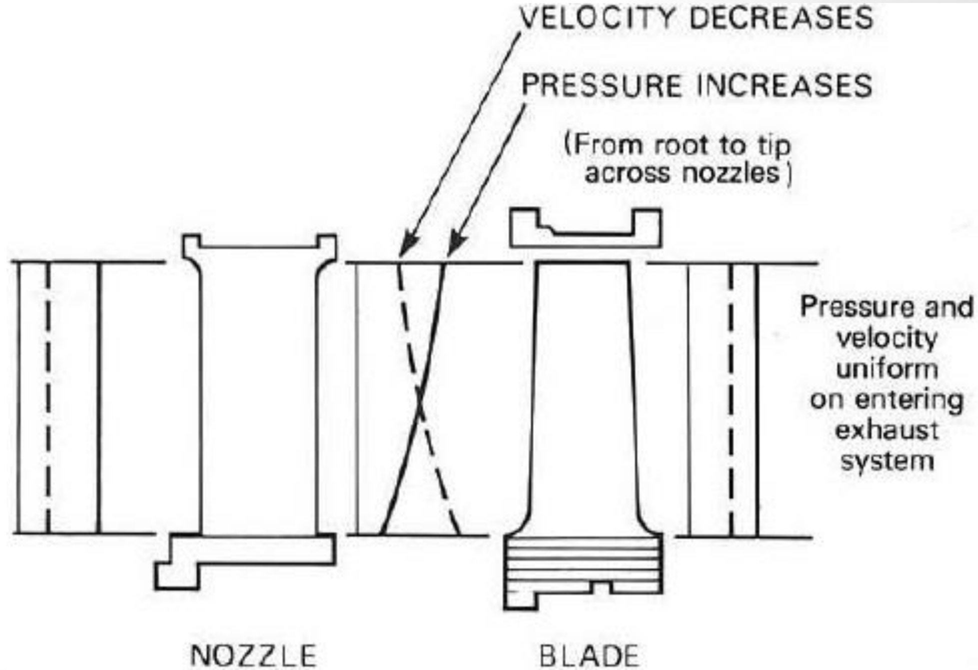
- Aerodynamic losses in turbine blades
- Aerodynamic losses in Nozzle Guide Vane
- Gas Leakage over turbine blade tips
- Exhaust system losses
- Total losses result in an overall efficiency approx. 92%.



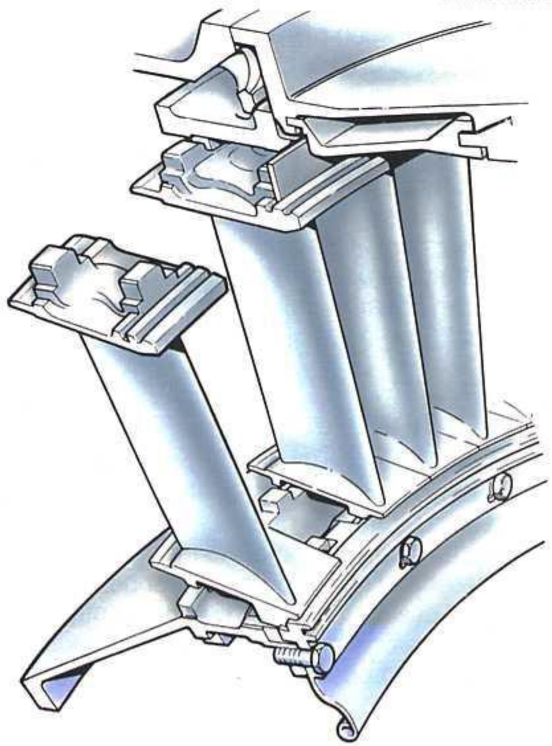
5-5 Comparison between a pure Impulse turbine and an impulse/reaction turbine.

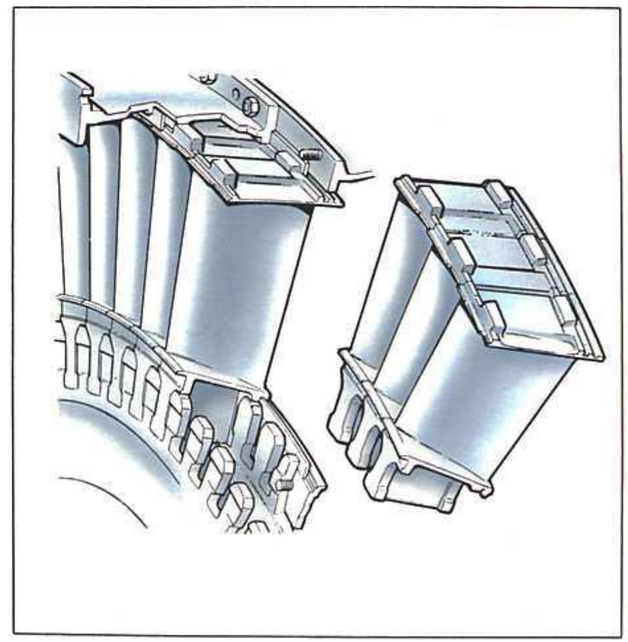
CONTD…

- **Gas flow pattern through Nozzle Guide Vanes and turbine blade**



- **Typical nozzle guide vanes showing their shape and location**





CONTD…

Blade Geometry

- The reason for the twist is to make the gas flow from the combustion system do equal work at all positions along the length of the blade and to ensure that the flow enters the exhaust system with a uniform axial velocity.
- The degree of reaction varies from root to tip, being least at the root and highest at the tip, with the mean section having the chosen value of about 50 per cent.
- The mean blade speed of a turbine has considerable effect on the maximum efficiency possible for a given stage output.

CONTD…

- For a given output the gas velocities, deflections, and hence losses, are reduced in proportion to the square of higher mean blade speeds.
- Stress in the turbine disc increases as the square of the speed, therefore to maintain the same stress level at higher speed the sectional thickness, hence the weight, must be increased proportionately.
- The final design is a compromise between efficiency and weight.

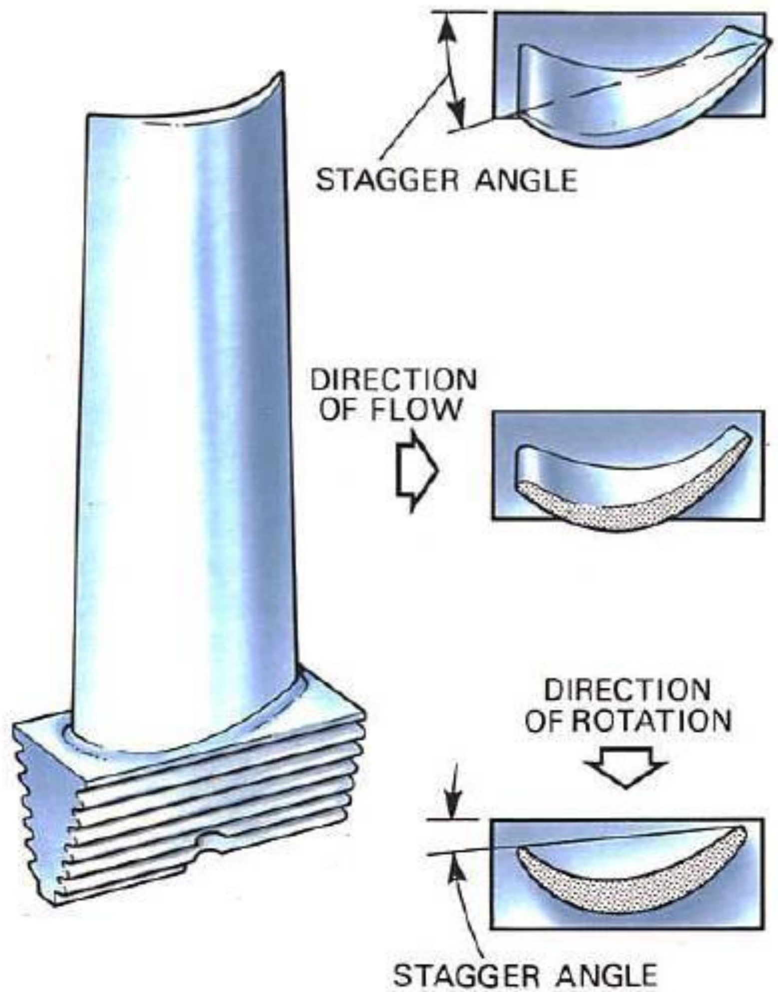


Fig. 5-6 A typical turbine blade showing twisted contour.

CONTD…

Blade Retaining and Fasting

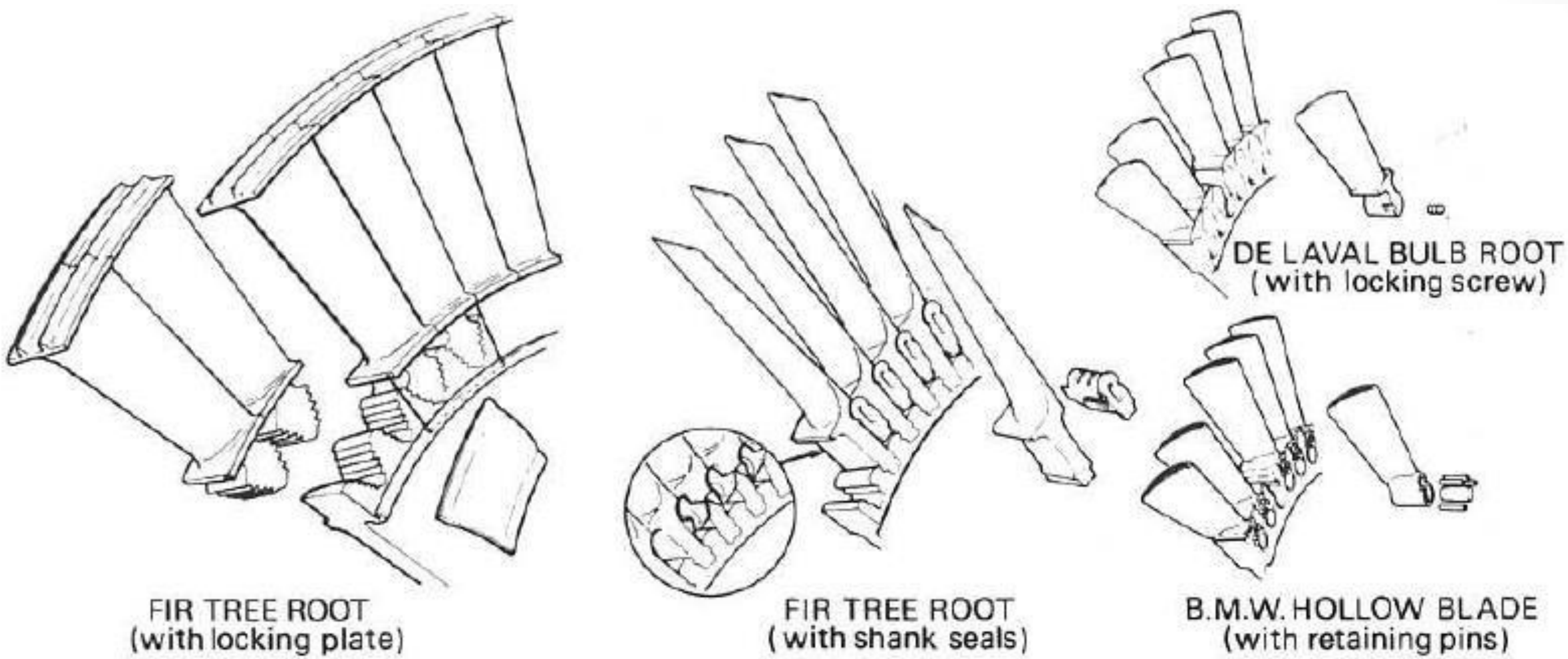
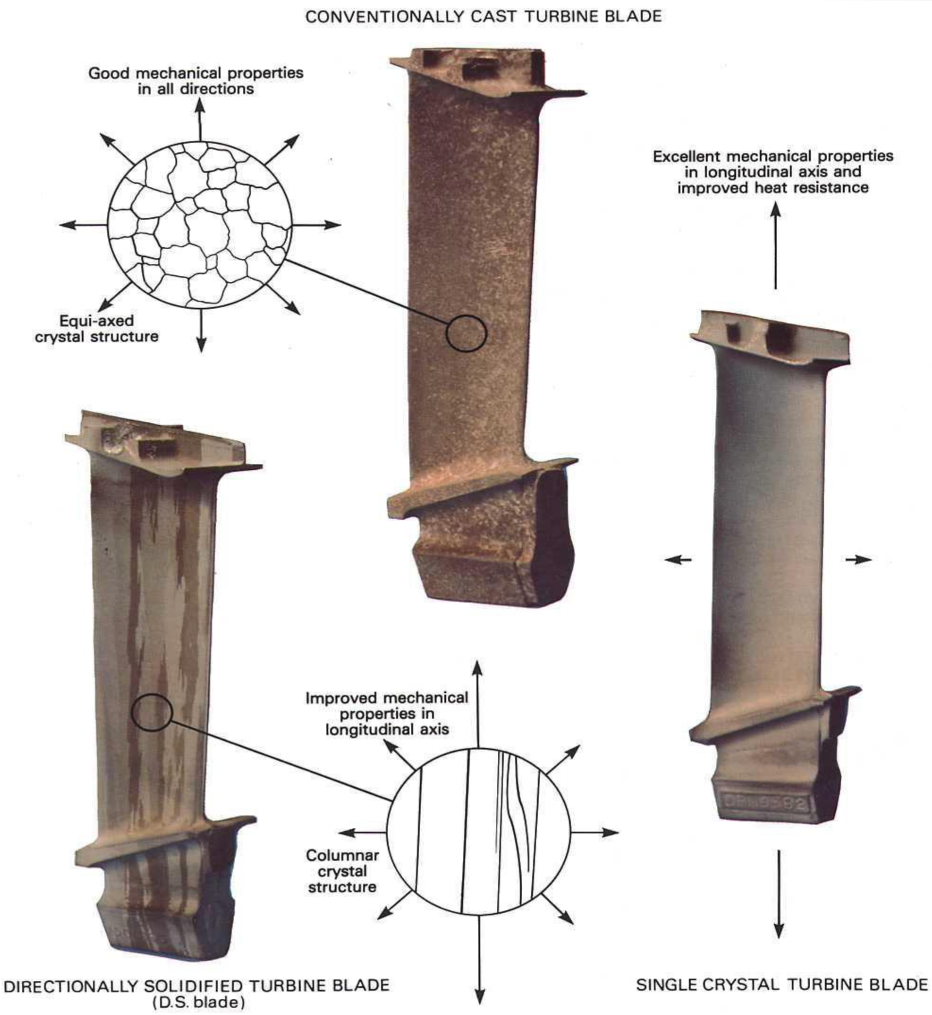


Fig. 5-9 **Various methods of attaching blades to turbine discs.**

CONTD…

Turbine blade material

- For NGV, due to their static condition. do not endure the same rotational stresses as the turbine blades.
- Therefore, heat resistance is the property most required. *Nickel alloys* are used, although cooling is required to prevent melting.
- *Ceramic coatings* can enhance the heat resisting properties and, for the same set of conditions, reduce the amount of cooling air required, thus improving engine efficiency.



CONTD…

- A turbine disc has to rotate at high speed in a relatively cool environment and is subjected to large rotational stresses. The limiting factor which affects the useful disc life is its resistance to fatigue cracking.
- Increasing the alloying elements in nickel extend the life limits of a disc by increasing fatigue resistance. Alternatively, expensive powder metallurgy discs, which offer an additional 10% in strength, allow faster rotational speeds to be achieved.
- A small turbine blade weighing only two ounces may exert a load of over two tons at top speed and it must withstand the high bending loads applied by the gas to produce the many thousands of turbine horsepower necessary to drive the compressor
- Blades experience high frequency fluctuations in the gas conditions, corrosion and oxidization. In spite of all these demands, the blades must be made in a material that can be accurately formed and machined by current manufacturing methods.

CONTD…

Blade life

- Over a period of operational time the turbine blades slowly grow in length. This phenomenon is known as '*creep*' and there is a finite useful life limit before failure occurs.
- The early materials used were high temperature steel forgings, but these were rapidly replaced by cast nickel base alloys which give better creep and fatigue properties.
- Close examination of a conventional turbine blade reveals a countless of crystals that lie in all directions (*equi-axed*).

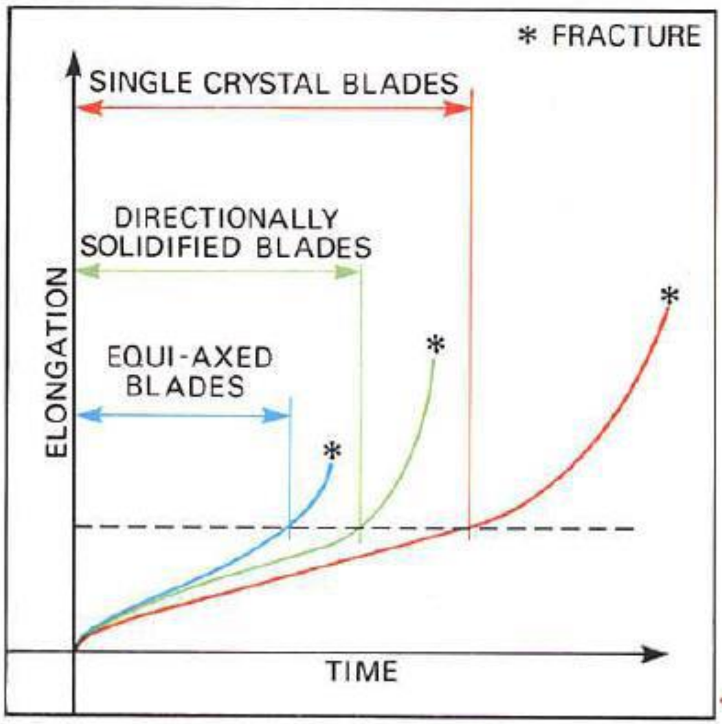


Fig. 5-13 Comparison of turbine blade life properties.

CONTD…

- Improved service life can be obtained by aligning the crystals to form columns along the blade length, produced by a method known as *'Directional Solidification'*.
- A further advance of this technique is to make the blade out of a single crystal.
- Each method extends the useful creep life of the blade and in the case of the single crystal blade, the operating temperature can be substantially increased.

Exhaust system

- Aero gas turbine engines have an exhaust system which passes the turbine discharge gases to atmosphere at a velocity, and in the required direction, to provide the resultant thrust.
- The velocity and pressure of the exhaust gases create the thrust in the turbo-jet engine but in the turbo propeller engine only a small amount of thrust is contributed by the exhaust gases, because most of the energy has been absorbed by the turbine for driving the propeller.
- The design of the exhaust system therefore, exerts a considerable influence on the performance of the engine.

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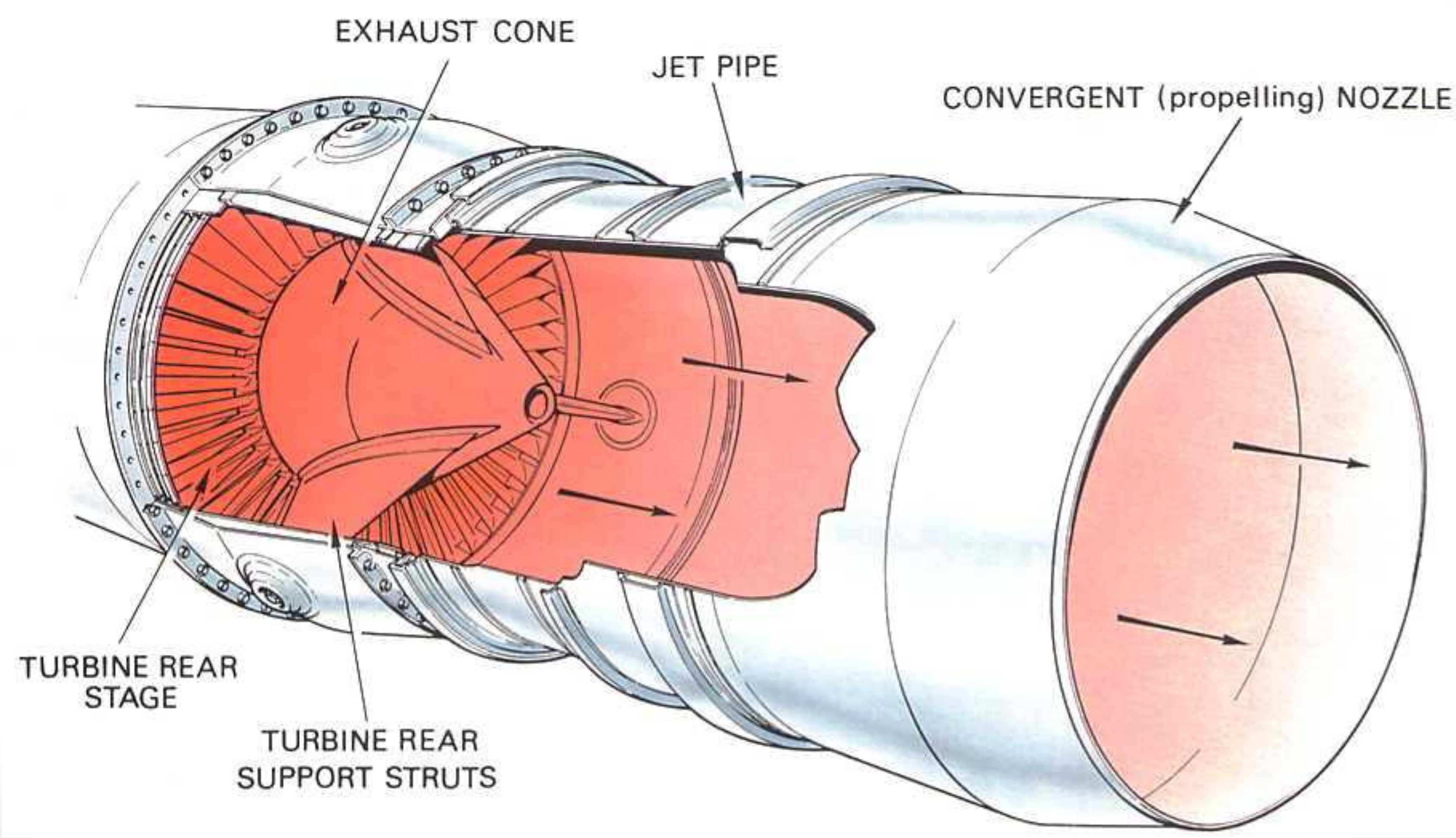
Components of basic exhaust system



CONTD…

- The areas of the jet pipe and propelling or outlet nozzle affect the turbine entry temperature, the mass airflow and the velocity and pressure of the exhaust jet.
- The temperature of the gas entering the exhaust system is between 550 and 850 deg. C. according to the type of engine and with the use of afterburning can be 1,500 deg. C. or higher.
- It is necessary to use materials and a form of construction that will resist distortion and cracking, and prevent heat conduction to the aircraft structure.

CONTD…

<u>Gas flow on exhaust</u>

- Gas from the engine turbine enters the exhaust system at velocities from 200 to 400 m/s because velocities of this order produce high friction losses, the speed of flow is decreased by diffusion.
- This is accomplished by having an increasing passage area between the exhaust cone and the outer wall.
- The cone also prevents the exhaust gases from flowing across the rear face of the turbine disc. It is usual to hold the velocity at the exhaust unit outlet to a Mach number of about 0.5, i.e. approximately 300 m/s.
- Additional losses occur due to the residual whirl velocity in the gas stream from the turbine.
- To reduce these losses, the turbine rear struts in the exhaust unit are designed to straighten out the flow before the gases pass into the jet pipe.

CONTD…

Material on exhaust system

- The exhaust system must be capable of withstanding the high gas temperatures and is therefore manufactured from nickel or titanium.
- It is also necessary to prevent any heat being transferred to the surrounding aircraft structure.
- This is achieved by passing ventilating air around the jet pipe, or by lagging the section of the exhaust system with an insulating blanket.
- Each blanket has an inner layer of fibrous insulating material contained by an outer skin of thin stainless steel, which is dimpled to increase its strength.
- In addition, acoustically absorbent materials are sometimes applied to the exhaust system to reduce engine noise.

THANK YOU !!!