Aircraft Design

Lecture 2:

Aircraft Propulsion

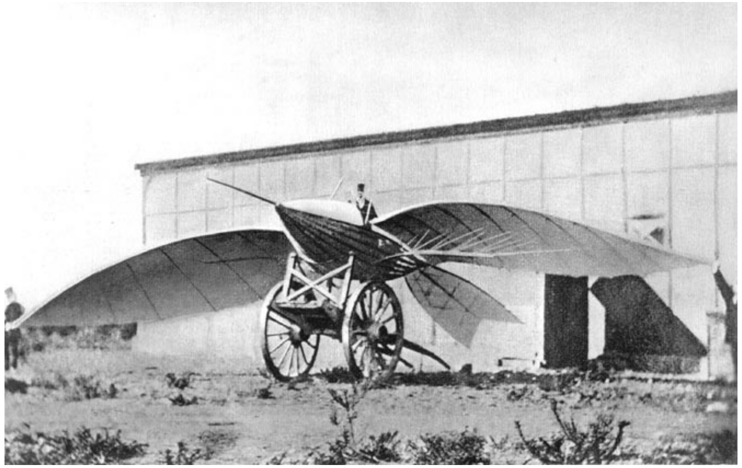
G. Dimitriadis and O. Léonard

Introduction

- A large variety of propulsion methods have been used from the very start of the aerospace era:
  - No propulsion (balloons, gliders)
  - Muscle (mostly failed)
  - Steam power (mostly failed)
  - Piston engines and propellers
  - Rocket engines
  - Jet engines
  - Pulse jet engines
  - Ramjet
  - Scramjet

Gliding flight

- People have been gliding from the mid-18th century.

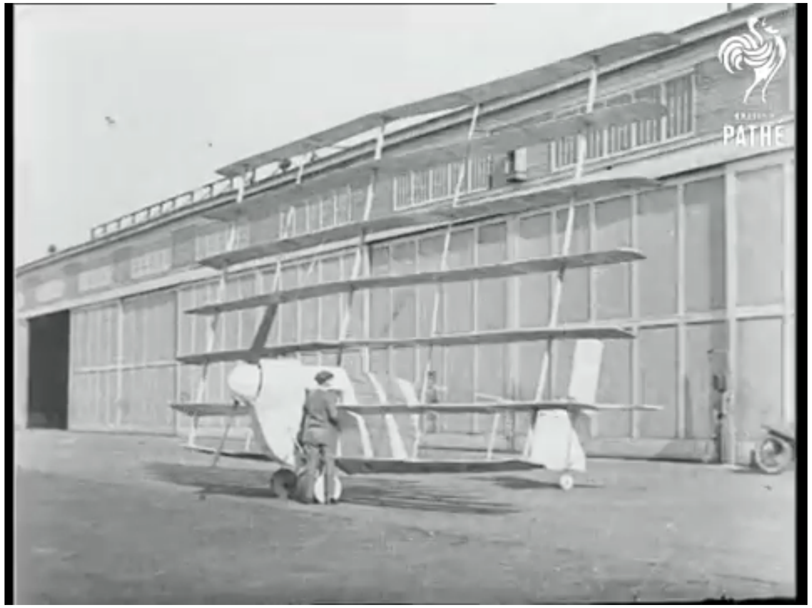


The Albatross II by Jean Marie Le Bris - 1849

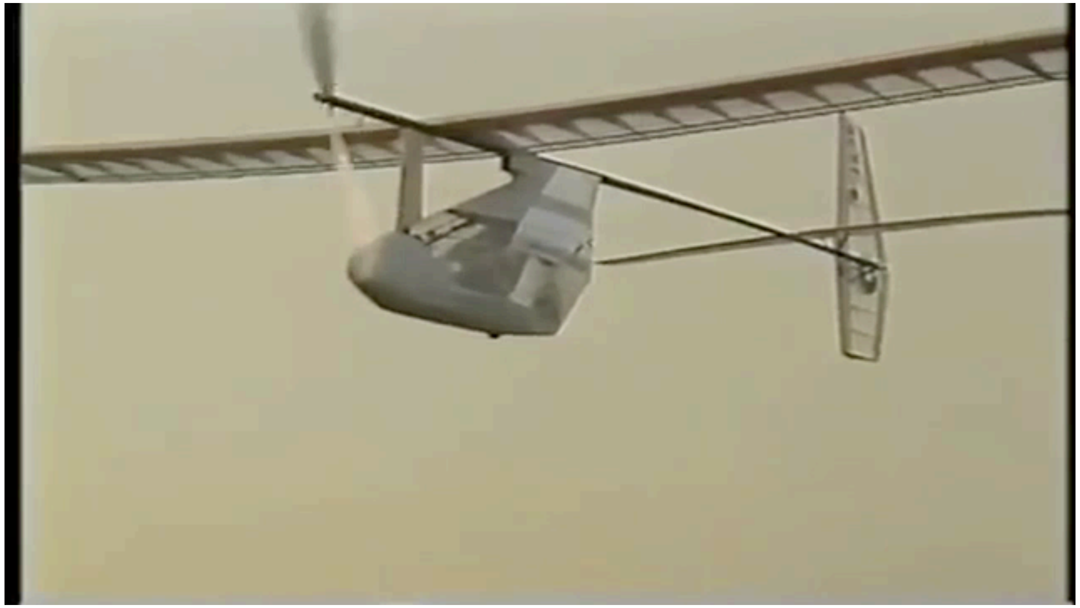
Otto Lillienthal, 1895

Human-powered flight

- Early attempts were less than successful but better results were obtained from the 1960s onwards.



Gerhardt Cycleplane (1923)



MIT Daedalus (1988)

Steam powered aircraft

- Mostly dirigibles, unpiloted flying models and early aircraft

Giffard dirigible (1852)

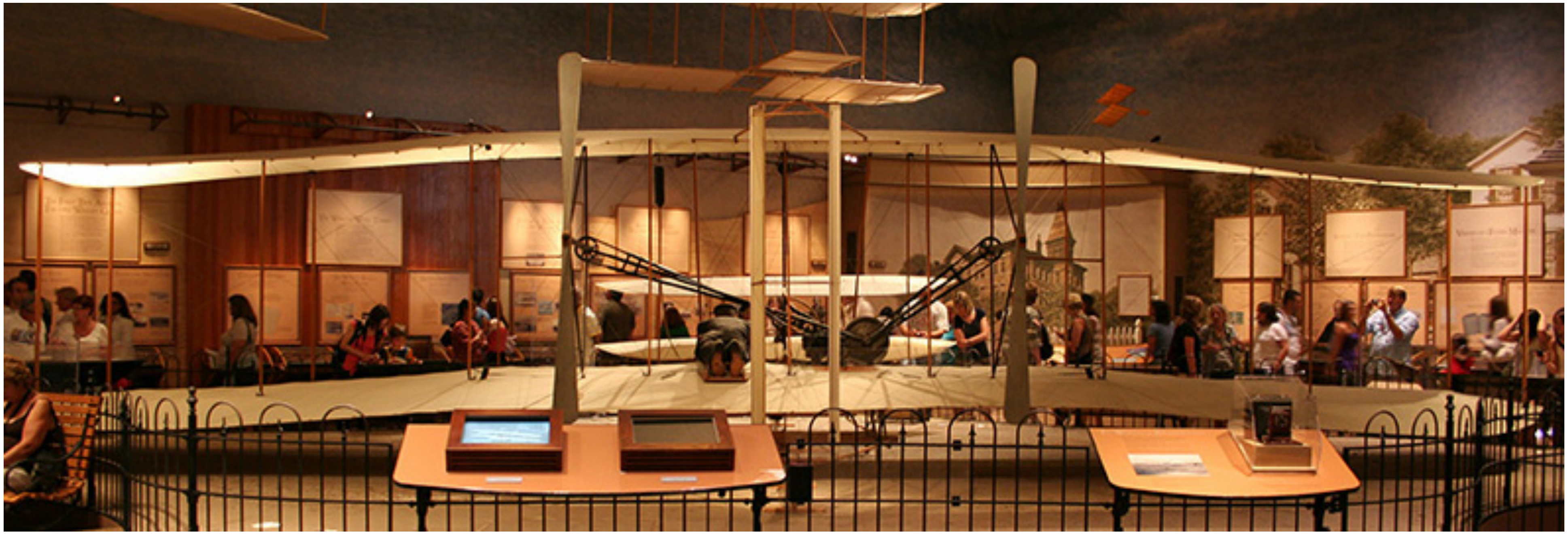
Clément Ader Avion III (two 30hp steam engines, 1897)

Engine requirements

- A good aircraft engine is characterized by:
  - Enough power to fulfill the mission
    - Take-off, climb, cruise etc.
  - Low weight
    - High weight increases the necessary lift and therefore the drag.
  - High efficiency
    - Low efficiency increases the amount fuel required and therefore the weight and therefore the drag.
  - High reliability
  - Ease of maintenance

Piston engines

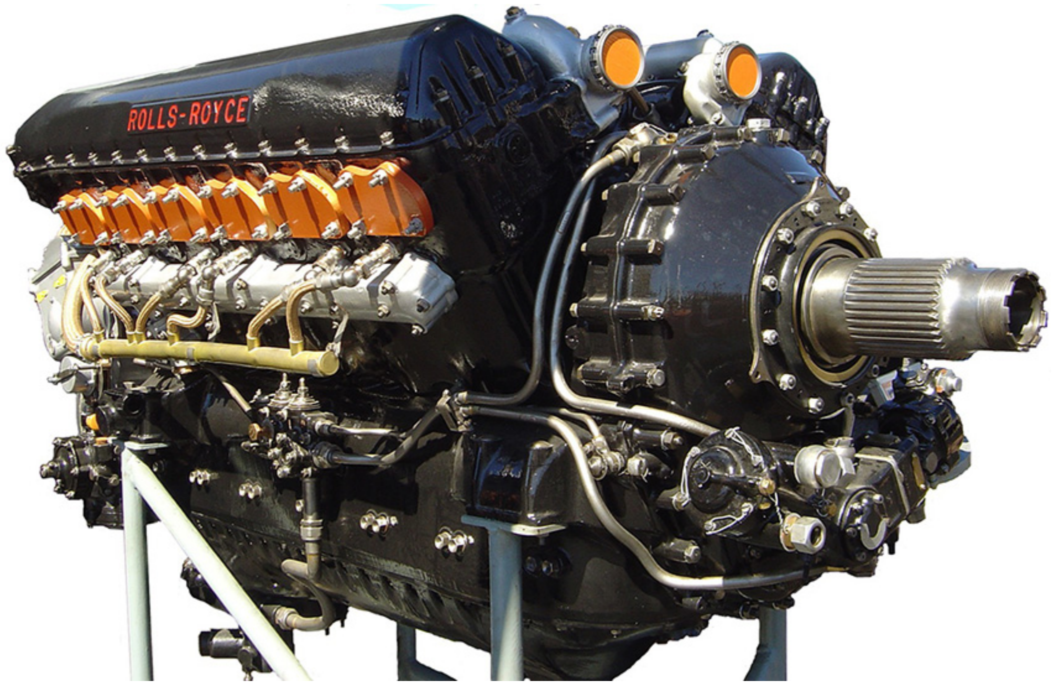
- Wright Flyer: One engine driving two counter-rotating propellers (one port one starboard) via chains.
  - Four in-line cylinders
  - Power: 12 hp
  - Weight: 77 kg



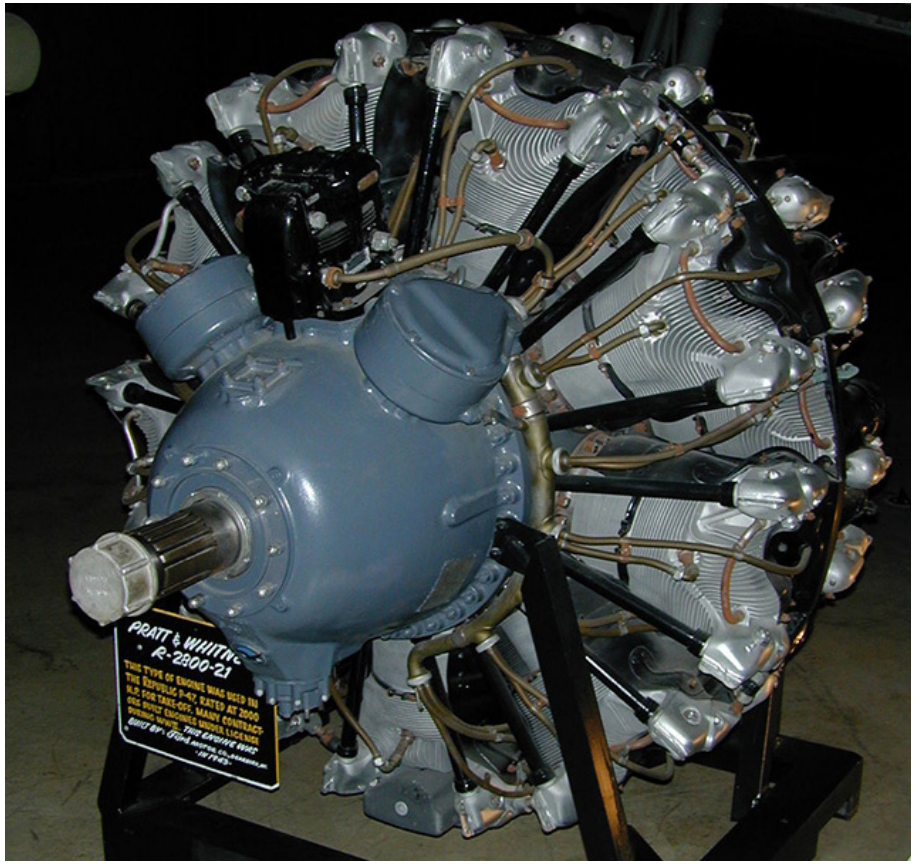
Piston engine development

- During the first half of the 20th century there was considerable development of piston engines.
- Power reached 5000 hp.
- The most popular configurations where:
  - V-shaped engines with in-line cylinders.
    - Low frontal area and drag but needed liquid cooling.
  - Radial engines.
    - High frontal area and drag but air-cooled.
- Fuel was improved, supercharging was introduced etc.

V-shaped vs radial



Rolls-Royce Merlin
Liquid-cooled V-12 with supercharger.
Power: 1030 hp (1937) to 2060 hp (1944)



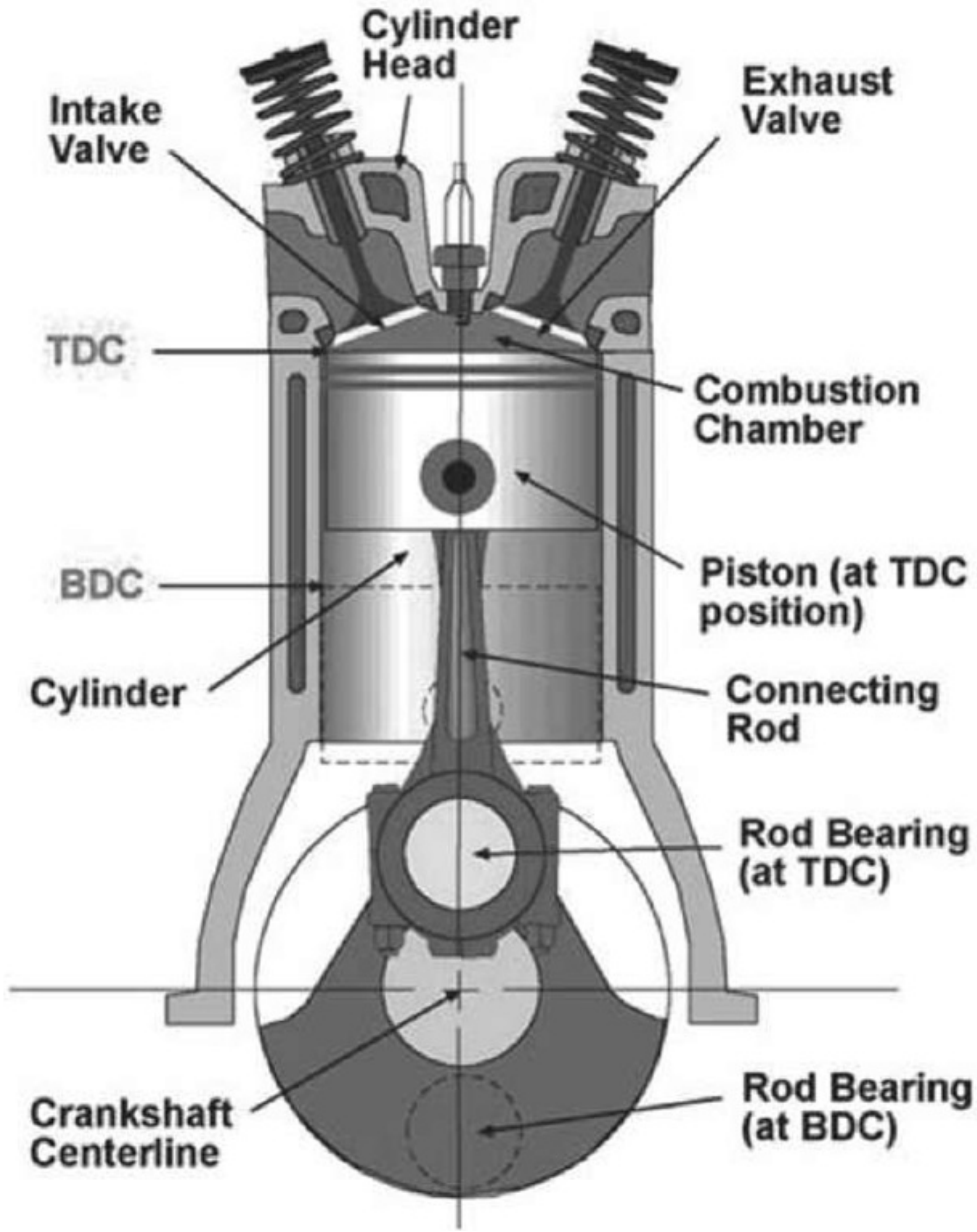
Pratt & Whitney R-2800 Double Wasp. Air-cooled, twin-row radial engine with 18 cylinders.
Power: 1500 hp (1939) to 2800 (with turbocharger, 1945)

Piston engine design

- Cutout of a piston

TDC: Top dead centre
BDC: Bottom dead centre
Compression ratio: ratio volume of cylinder at BDC and TDC.

Crankshaft



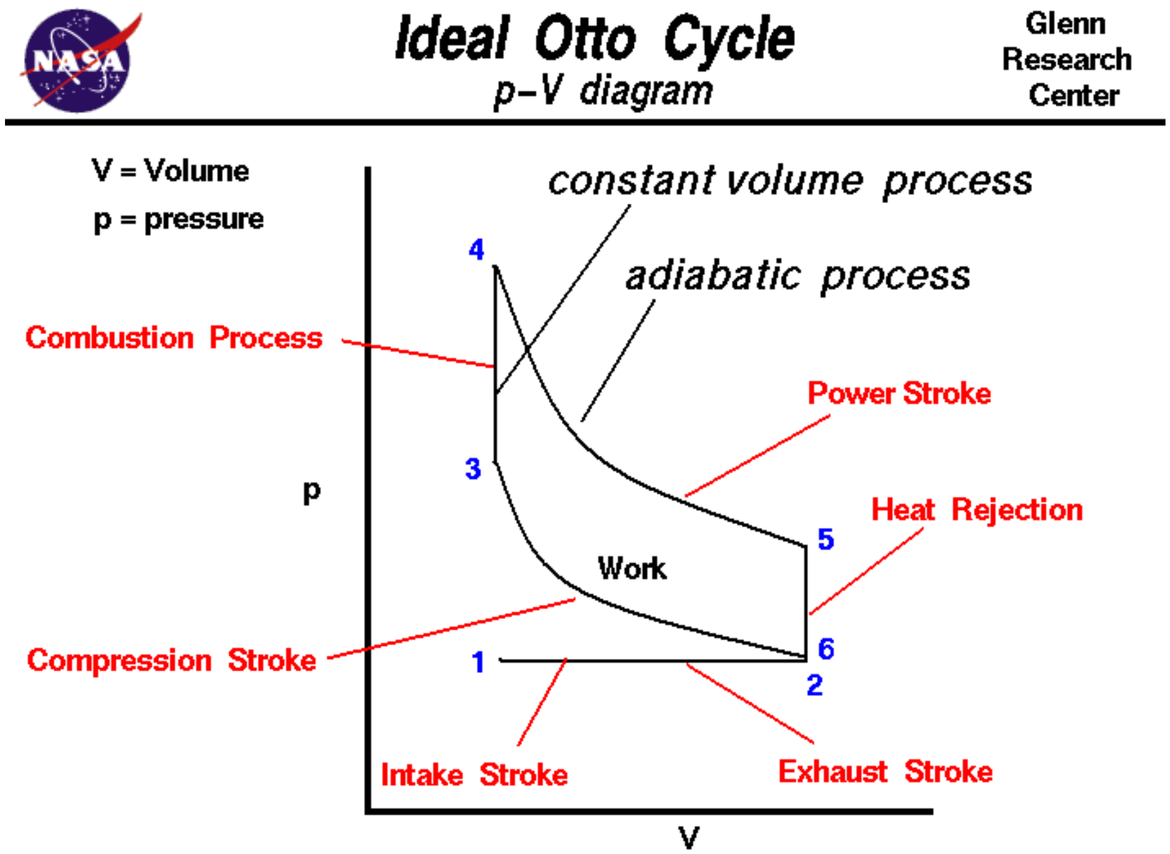
Piston engine operation

- A four-stroke engine cycle has the following stages:
  - Intake: the piston moves from TDC to BDC with the intake valve open and the exhaust value closed. A fresh air-fuel mix is drawn into the cylinder
  - Compression: both valves close and the piston moves from BDC to TDC compressing the air-fuel mix. Combustion is initiated as the piston reaches TDC.
  - Expansion: The high pressure and temperature forces the piston from TDC to BDC, doing work on the crankshaft.
  - Exhaust: The exhaust valve opens and the piston moves from BDC to TDC forcing the spend gases out of the cylinder.

Piston engine cycle

- Pressure-volume diagram

- Heat rejection occurs as the exhaust valve opens while the piston is still at BDC.
- The exhaust stroke then brings the cycle back to the starting conditions.
- The difference between work done on the gas and work done by the gas is the area enclosed by the p-V curve.
- The power is the work done times the number of cycles per second.

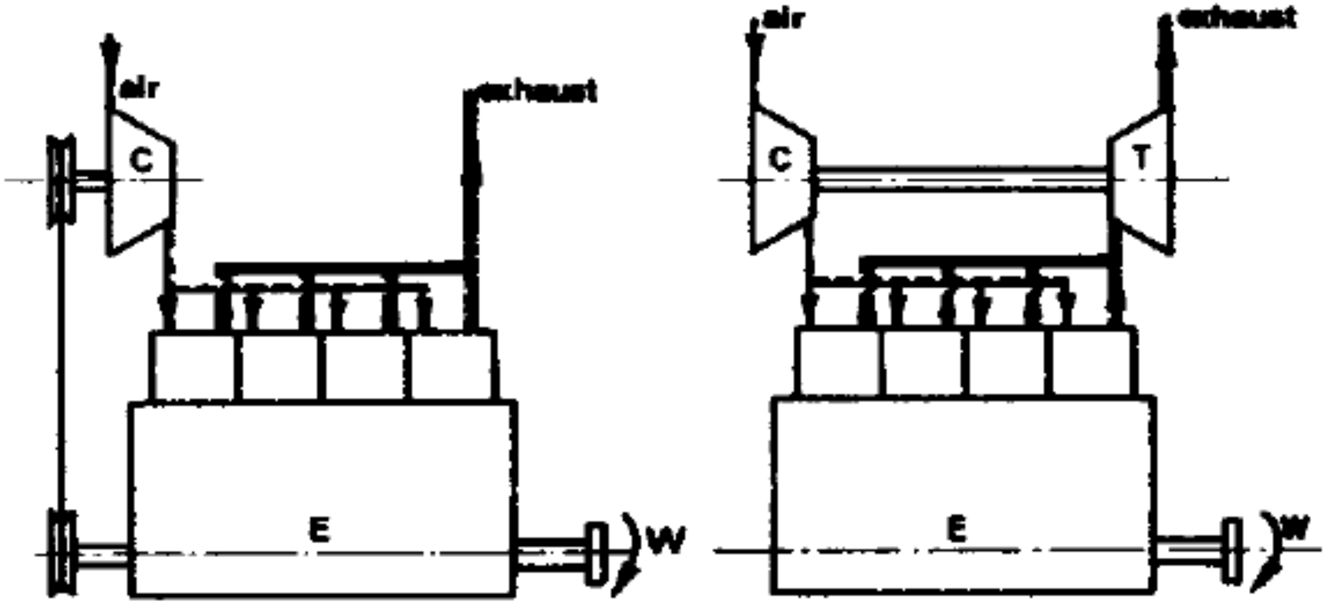


Performance at altitude

- The horsepower of piston engines reduces with altitude, as the atmospheric density decreases.
- An approximate rule is:
- $\frac{\text{BHP at altitude}}{\text{BHP at sea level}} = (1+c)\sigma - c$
- where BHP is break horsepower, $c = 0.132$ and σ is the ratio of the atmospheric density at altitude to sea level density.
- At 20,000 ft the BHP ratio is 47%.
- This loss in power can be regained using supercharging of turbocharging.

Super/turbochargers

- Super and turbocharging increases the engine efficiency by increasing the pressure of the air going into the cylinder.
- A supercharger uses a compressor driven by the engine crankshaft through a belt.
- A turbocharger uses a compressor driven by a turbine, which is in turn driven by the exhaust gas.



MECHANICALLY SUPERCHARGED   TURBOCHARGED ENGINE

Limitations

- As the power of piston engines increases, cooling becomes increasingly difficult.
- By the end of WWII, Pratt & Whitney produced a 3800 hp 28-cylinder engine (four rows of seven cylinders). It would be impossible to increase the number of rows of cylinders and keep effective cooling.
- Liquid-cooled engines reached 5000 hp with H-24 or dual V-12 configurations but required huge radiators and turbochargers.

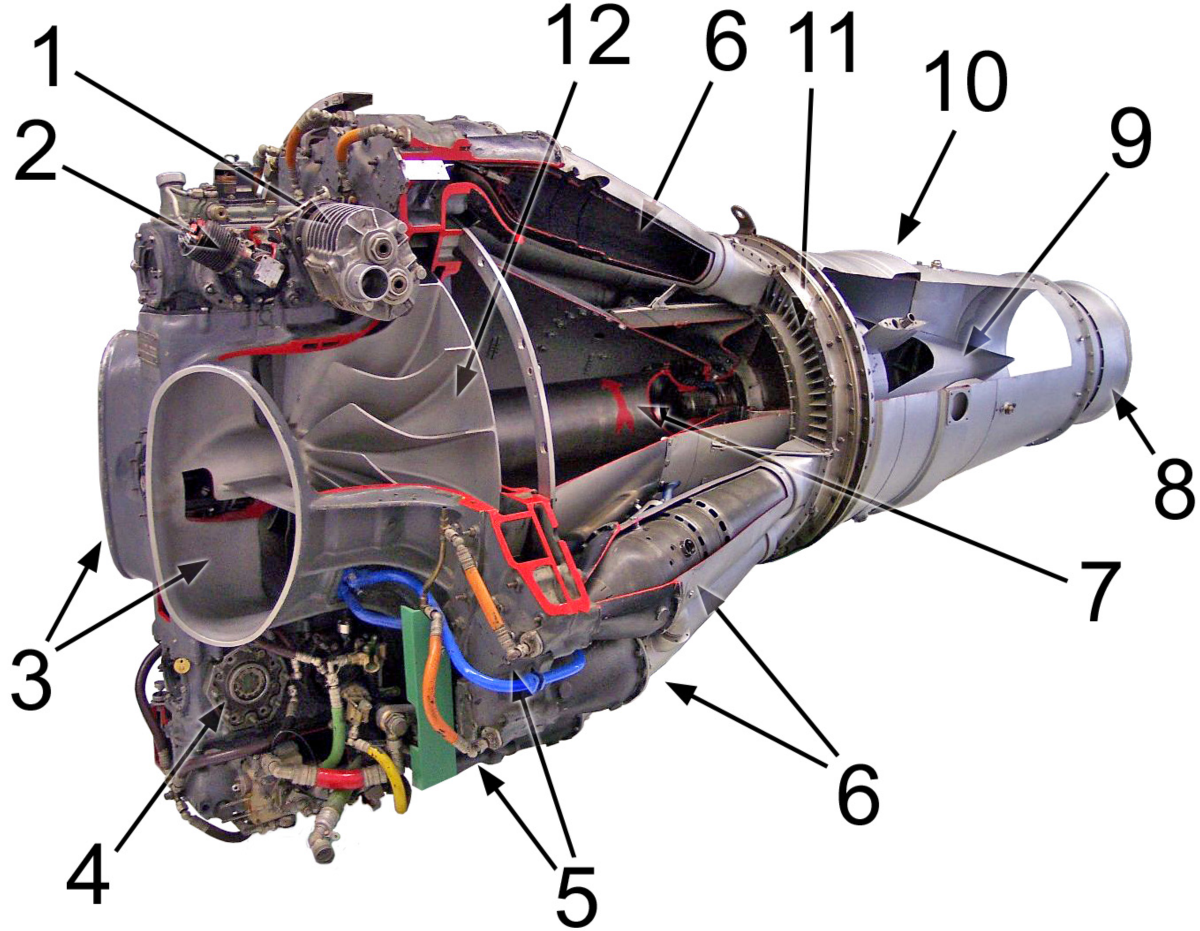
Jet engines

- Steam turbines have existed for many centuries.
- Gas turbines were first proposed in 1791 but not perfected until 1903.
- Maxime Guillaume filed a patent for powering an aircraft with a gas turbine in 1921. It was never built.
- Frank Whittle filed a patent for a turbojet in 1930. His first engine was built in 1937.
- Hans von Ohain also built a functional turbojet in 1937.
- The first ever turbojet aircraft, Heinkel He 178 few in 1937 with one of von Ohain's engines.

Jet engine design

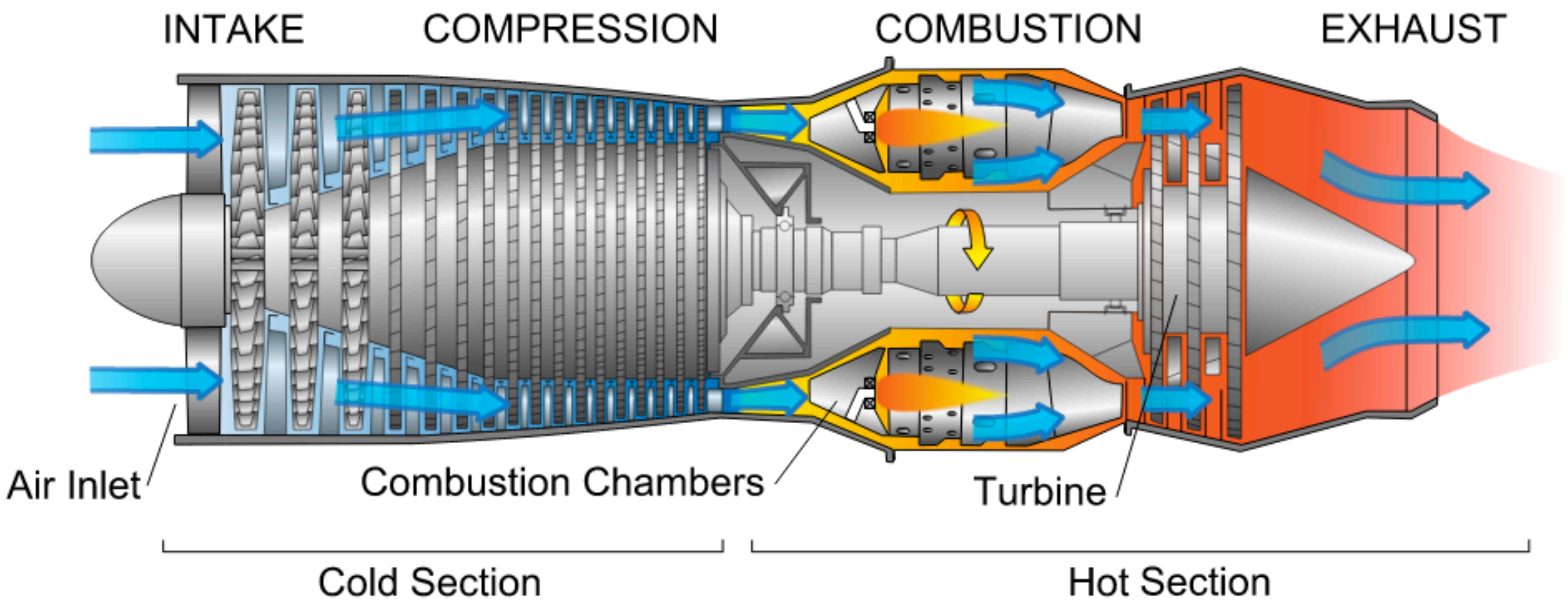
- Cutout of a jet engine with centrifugal compressor

3. Air intakes
6. Combustion chambers
7. Shaft connecting turbine and compressor
8. Nozzle
9. Turbine fairing
11. Turbine
12. Centrifugal compressor



Jet engine design (2)

- Cutout of a turbojet engine with axial compressor



Jet engine operation

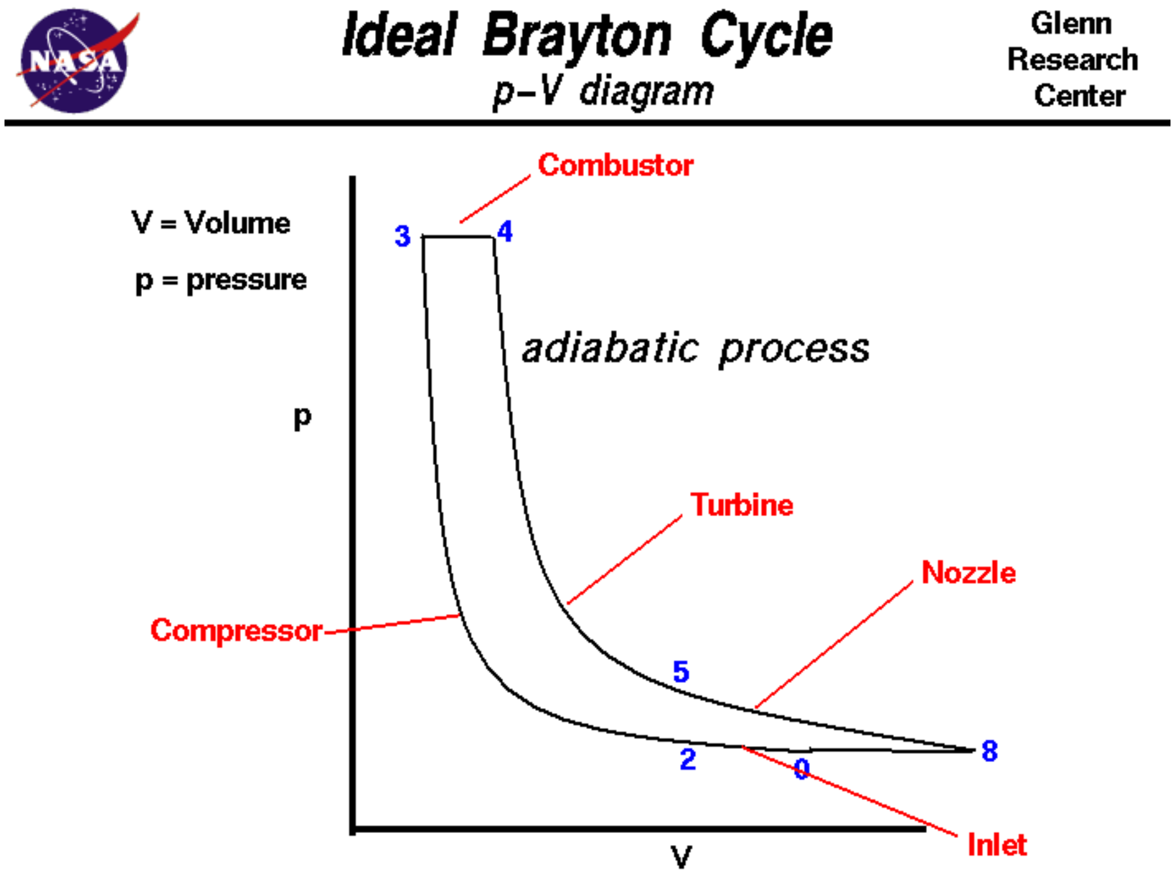
- For both axial and centrifugal compressor designs the operation is the same:
  - A compressor increases the pressure of the air that comes in through the intake.
  - The high-pressure air is fired in the combustion chamber.
  - Some of the energy of the high-pressure, high-temperature air is used to drive a turbine, which in turn drives the compressor.
  - The nozzle converts the energy of the high-pressure, high-temperature air into kinetic energy, which is used to propel the engine forward.

Jet engine cycle

- Pressure-volume diagram

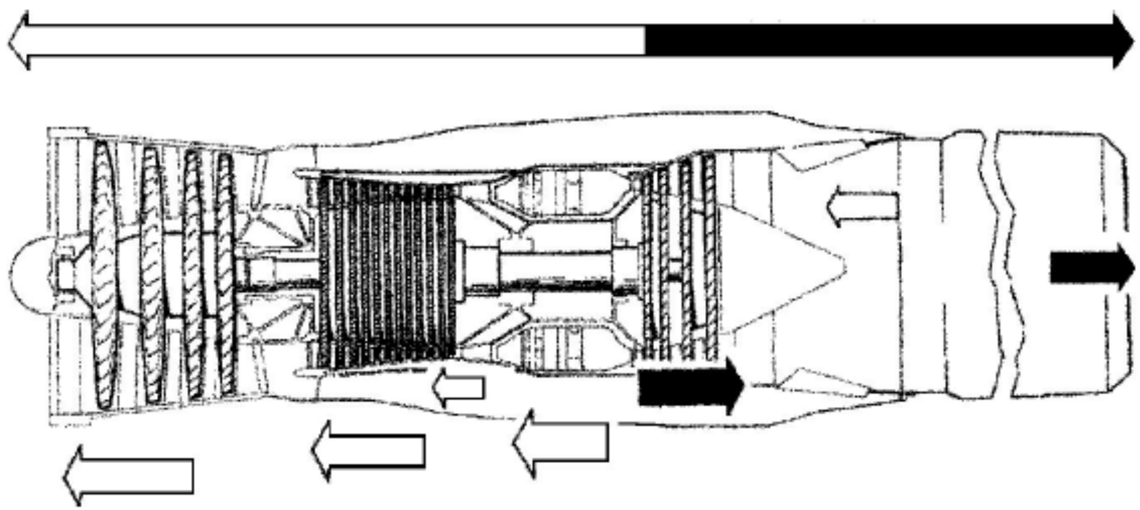
0. Free stream conditions
2. Compressor face
3. Combustion chamber inlet
4. Turbine face
5. Nozzle inlet
8. Nozzle outlet

The air returns to free stream conditions externally (8-0).
The work done by the air on the turbine is equal to the work done by the the compressor on the air.



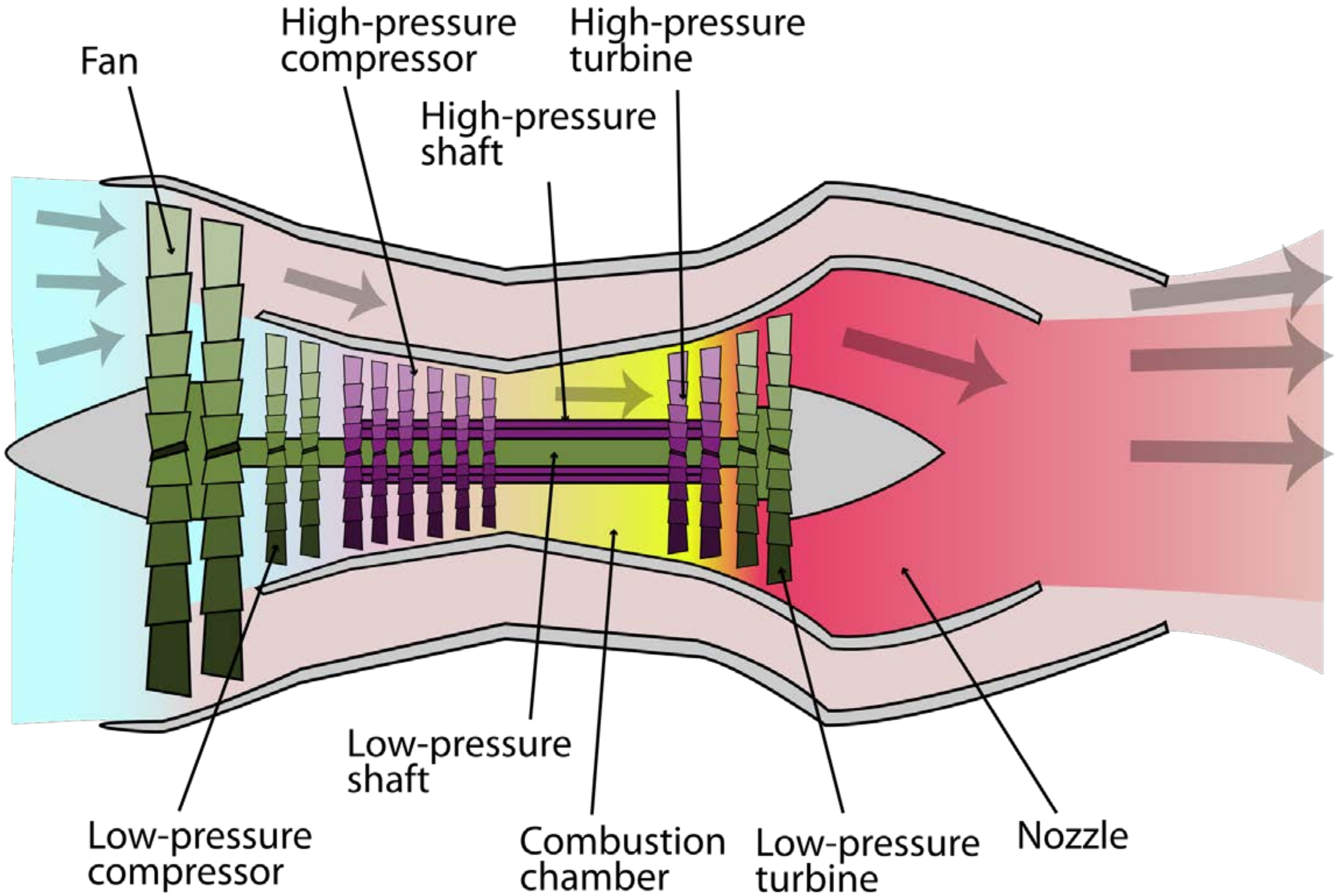
Thrust production

- Thrust is the reaction force exerted by the fluid on the engine.
- Compressor blades and diffusers are the main sources of thrust.
- Combustion induces air expansion and a positive thrust.
- Turbine blades and nozzle induce a negative thrust.



Turbofan

- Cutout of a turbofan engine

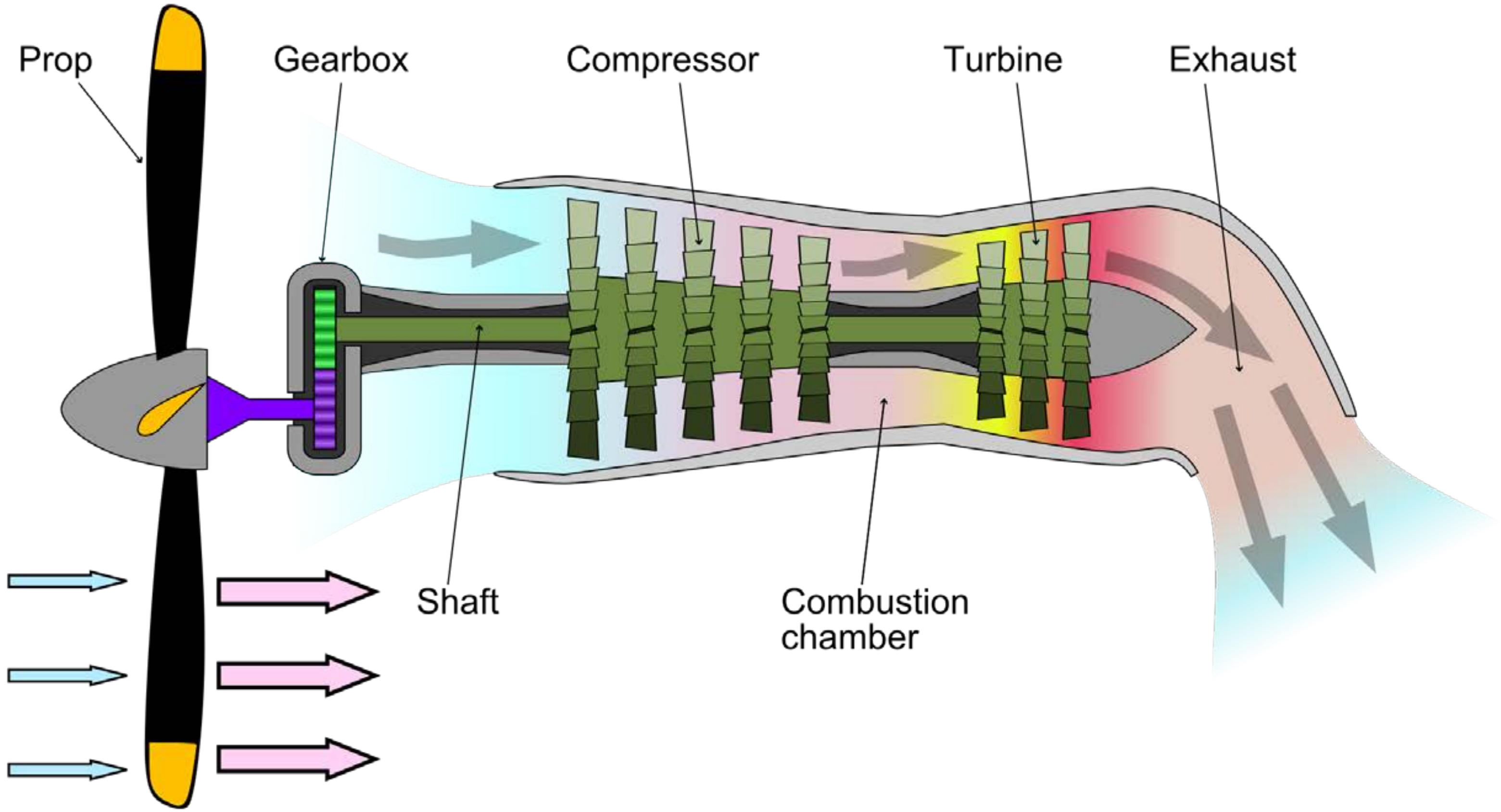


Turbofan vs turbojet

- Turbojet:
  - All of the airflow passes from the combustion chamber.
  - Relatively low mass flow rate with high output velocity.
- Turbofan
  - Part of the flow bypasses the combustion chamber after the low-pressure compressor or a large fan.
  - The fan is also driven by the turbine.
  - Higher mass flow rate with lower output velocity.
  - Noise is reduced and propulsive efficiency increased.
  - Up to 85% of the thrust is generated by the bypass air.

Turboprop

- Cutout of a turboprop engine



Turboprop operation

- In a turboprop engine part of the energy of the high-pressure, high-temperature air is used to drive a propeller.
- The propeller is connected to the shaft through reduction gear:
  - The high RPM and low torque output of the turbine is converted to low RPM and high torque.
- The hot airflow is still accelerated through a nozzle but only a small amount of the thrust is produced in this way.
- The jet velocity of the propeller and nozzle are low so turboprops are efficient at low Mach numbers (M=0.6-0.7).

Jet engine performance

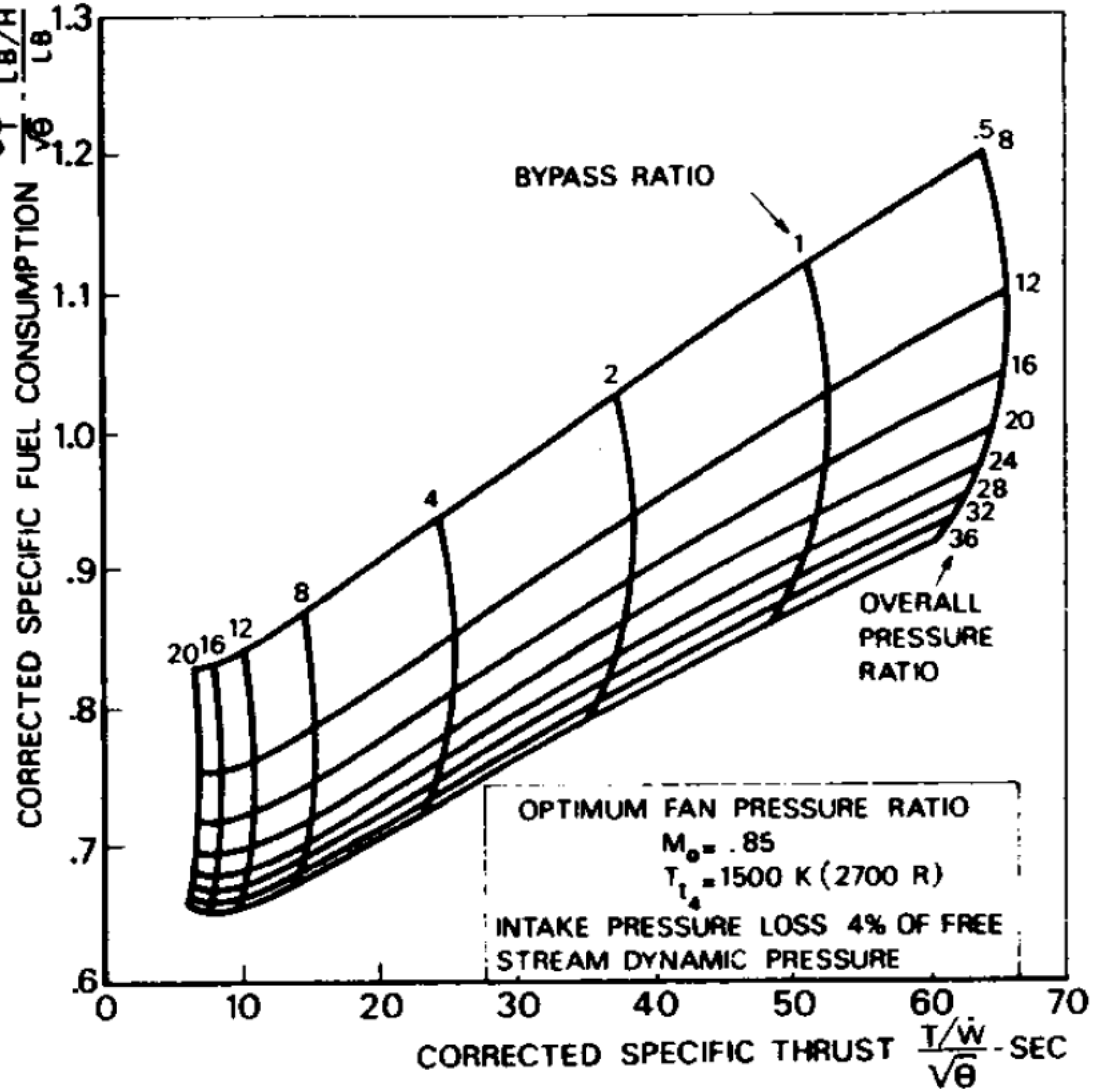
- Thrust is given by $T = q_m(V_{ej} - V_0)$
- where q_m is the mass flow rate through the engine, V_{ej} is the ejection velocity and V_0 is the inlet velocity.
- Specific thrust is the thrust divided by the mass flow rate = $V_{ej} - V_0$.
- Specific fuel consumption = fuel mass flow divided by thrust.

Jet engine performance (2)

- Jet engine performance is governed by the following characteristics:
  - Cycle efficiencies and pressure losses
  - Overall Pressure Ratio (OPR) of the compressor
  - Turbine Entry Temperature (TET)
  - Bypass ratio
  - Fan Pressure Ratio (FPR)

Fuel consumption in cruise

- Specific fuel consumption and specific thrust at cruise conditions
- As the bypass ratio and OPR increase, so does the mass flow rate.
- Specific thrust decreases but so does fuel consumption.



$T_{t_4} = \text{TET}$

Cycle efficiency

- Cycle efficiency is the quality of transformation of fuel heating value into useful power, i.e. the rate of production of kinetic energy:
- $\eta_{th} = \frac{\text{useful power}}{\text{fuel power}} = \frac{q_m\left(\frac{V_{ej}^2}{2} - \frac{V_0^2}{2}\right)}{q_f FHV}$
- where q_f is is the fuel mass flow rate and FHV is the fuel heating value:
  - Part of the FHV goes into kinetic energy in the gas.
  - Part of the FHV is used for propulsion.
  - Part of the FHV is lost in the atmosphere.

Propulsive efficiency

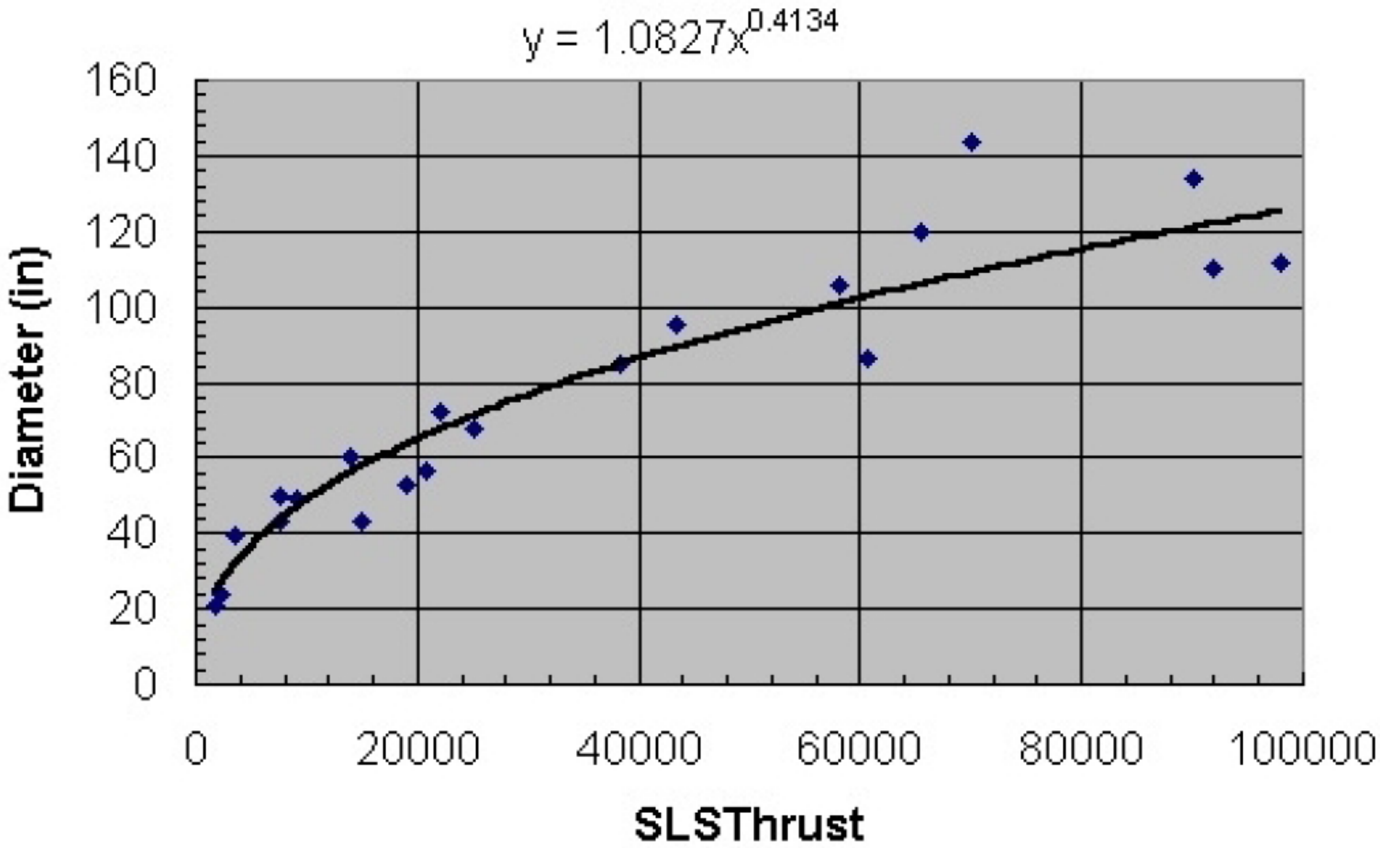
- Propulsive efficiency is the quality of the transformation of the useful power delivered by the cycle into power utilized for propelling the vehicle.
- $\eta_T = \frac{\text{propulsive power}}{\text{useful power}} = \frac{\text{thrust} \times \text{speed}}{\text{useful power}}$
- $\eta_T = \frac{q_m (V_{ej} - V_0) V_0}{q_m \left(\frac{V_{ej}^2}{2} - \frac{V_0^2}{2} \right)} = \frac{2}{1 + V_{ej}/V_0}$

Lowering fuel consumption

- Lowering the specific fuel consumption may be done by increasing the cycle and the propulsive efficiencies.
- Increasing the propulsive efficiency is done by decreasing the specific thrust.
  - the mass flow must be augmented to keep the thrust level.
  - the size of the engine must be increased.
  - the weight, the drag, the cost increase.
- The integration of the engine is more difficult.
  - the optimal engine configuration depends on the mission of the vehicle.

Engine diameter

- Engine diameter (in) variation with thrust (lb).

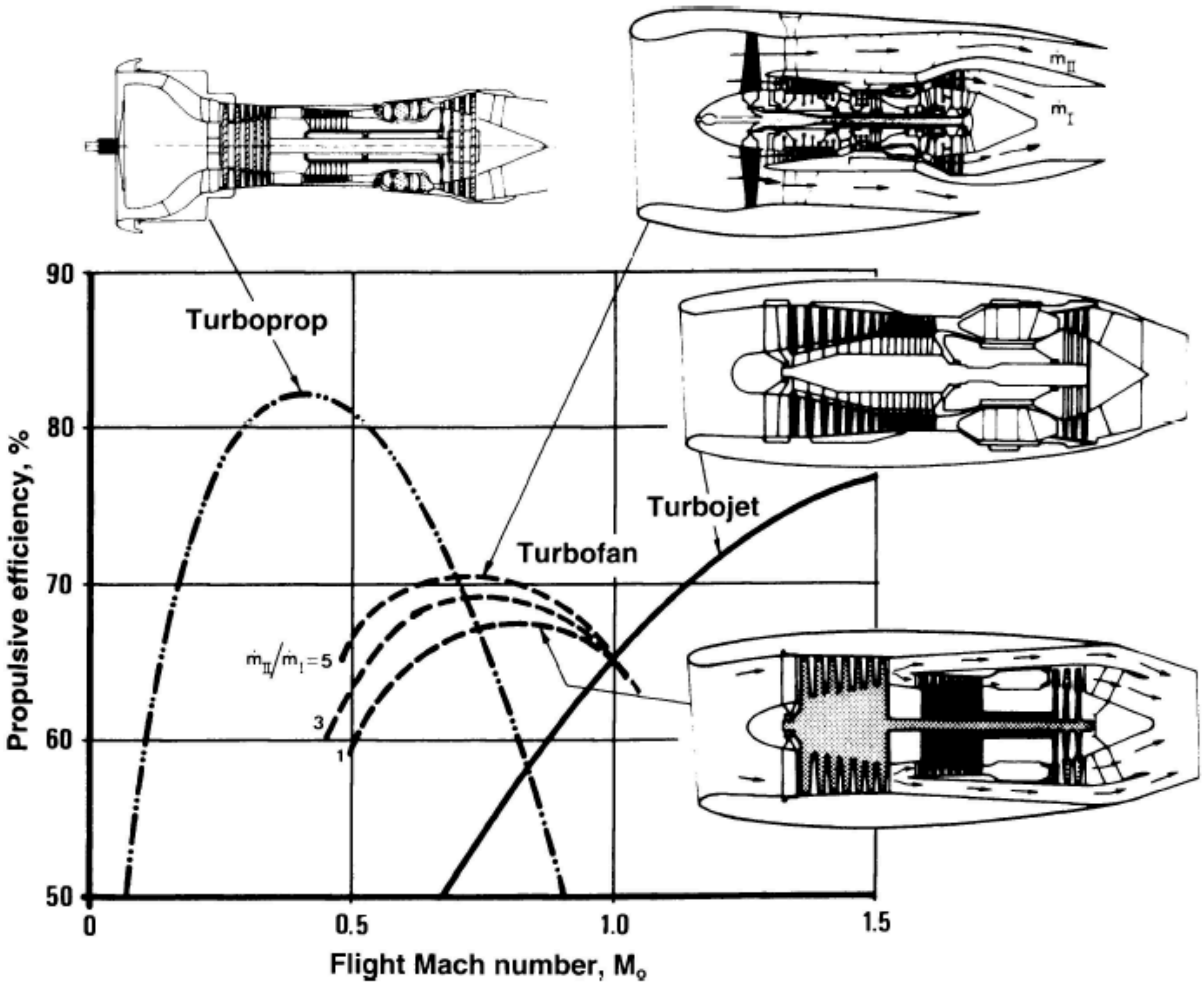


Propulsive efficiency of various engine types

Turboprops are most efficient up to M=0.7

Turbofans are most efficient from M=0.7 to M=1.

Turbojets are most efficient at supersonic conditions.

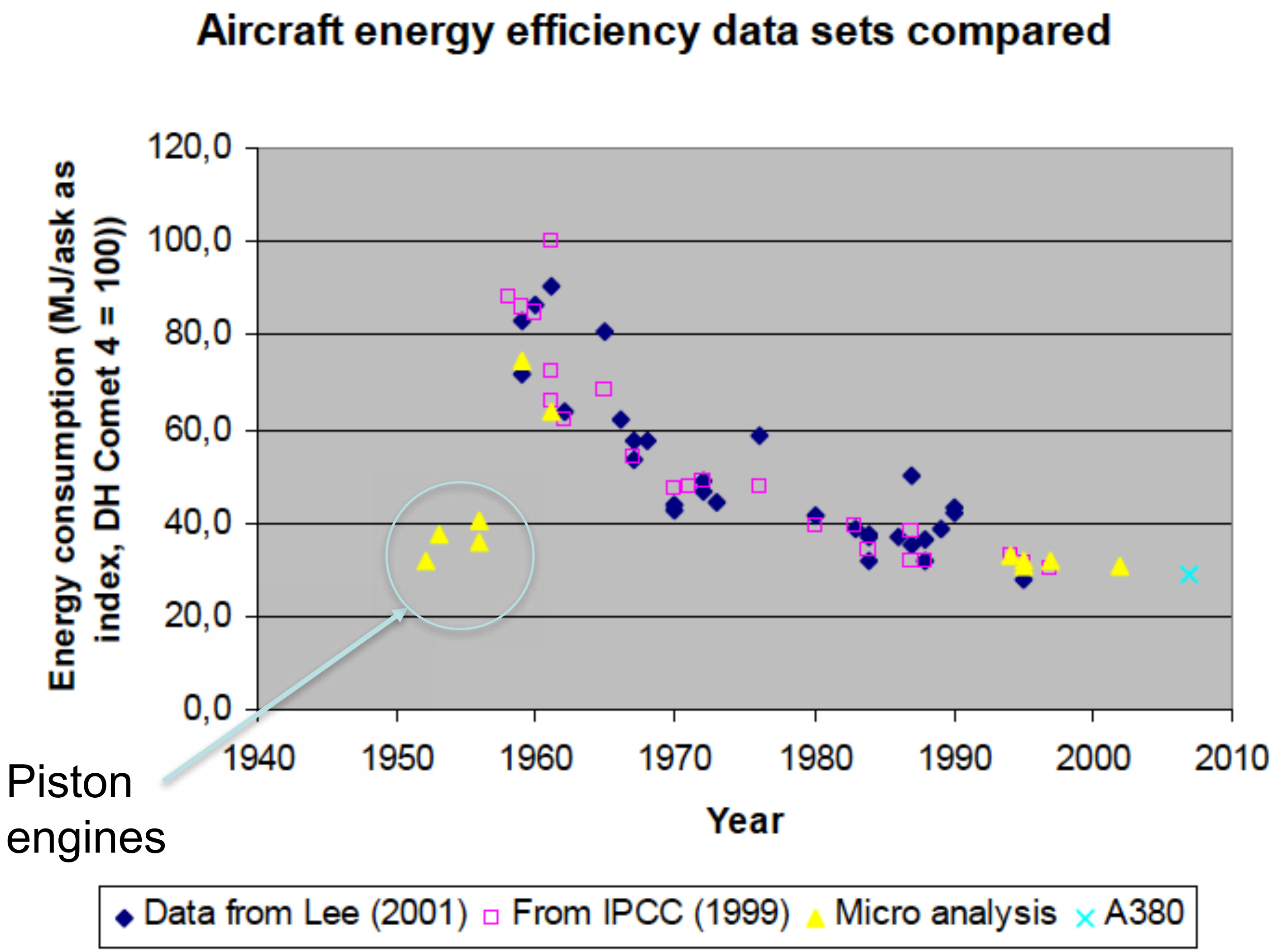


Energy consumption

Energy consumption is measured in mega Joules per Available Seat Kilometer.

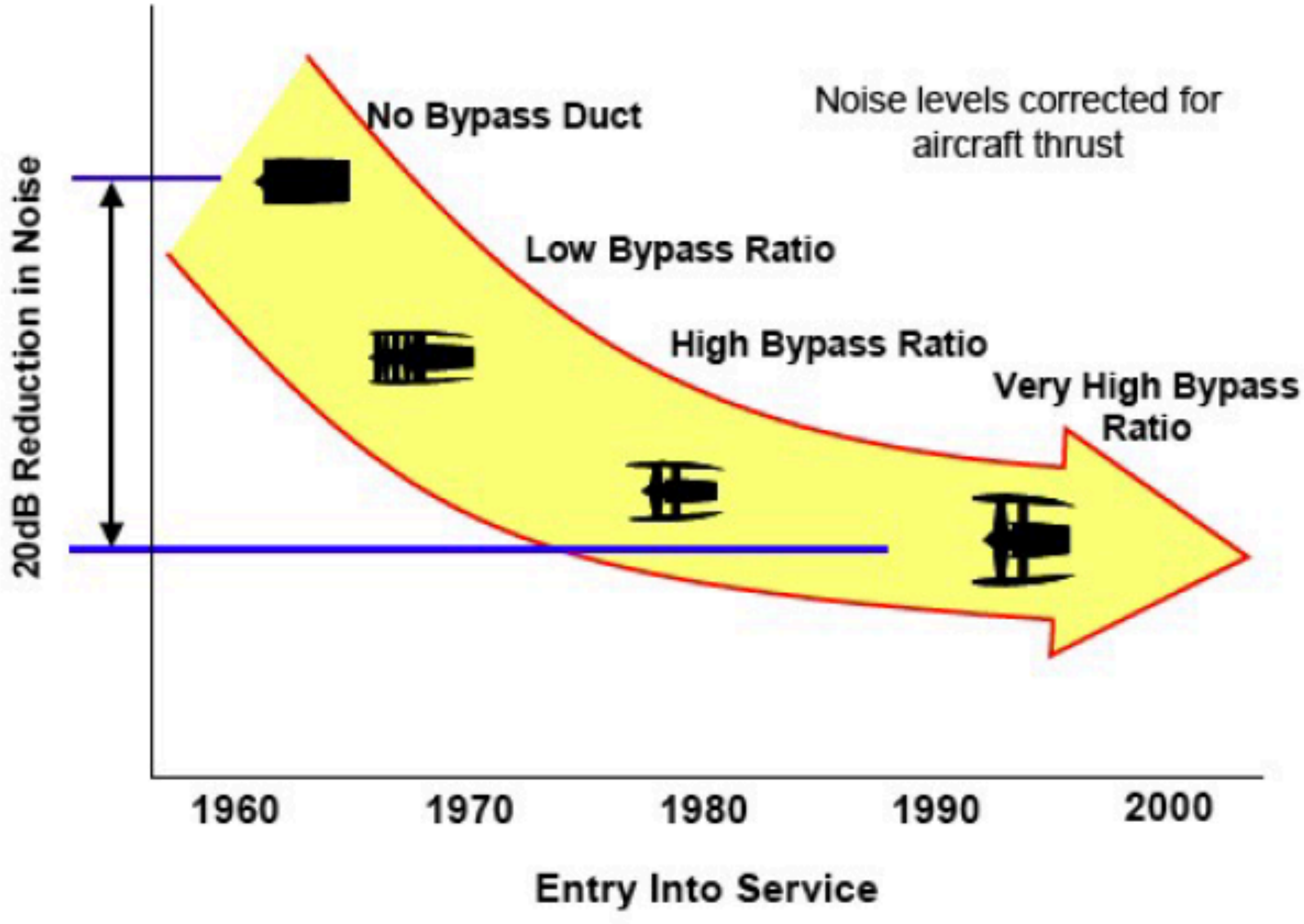
Large gains in efficiency were obtained from the introduction of high bypass engines between 1960 and 1990.

The trend has levelled off over the last 20 years.



Noise reduction

Again, bypass engines led to a significant reduction in noise but the trend has levelled off.



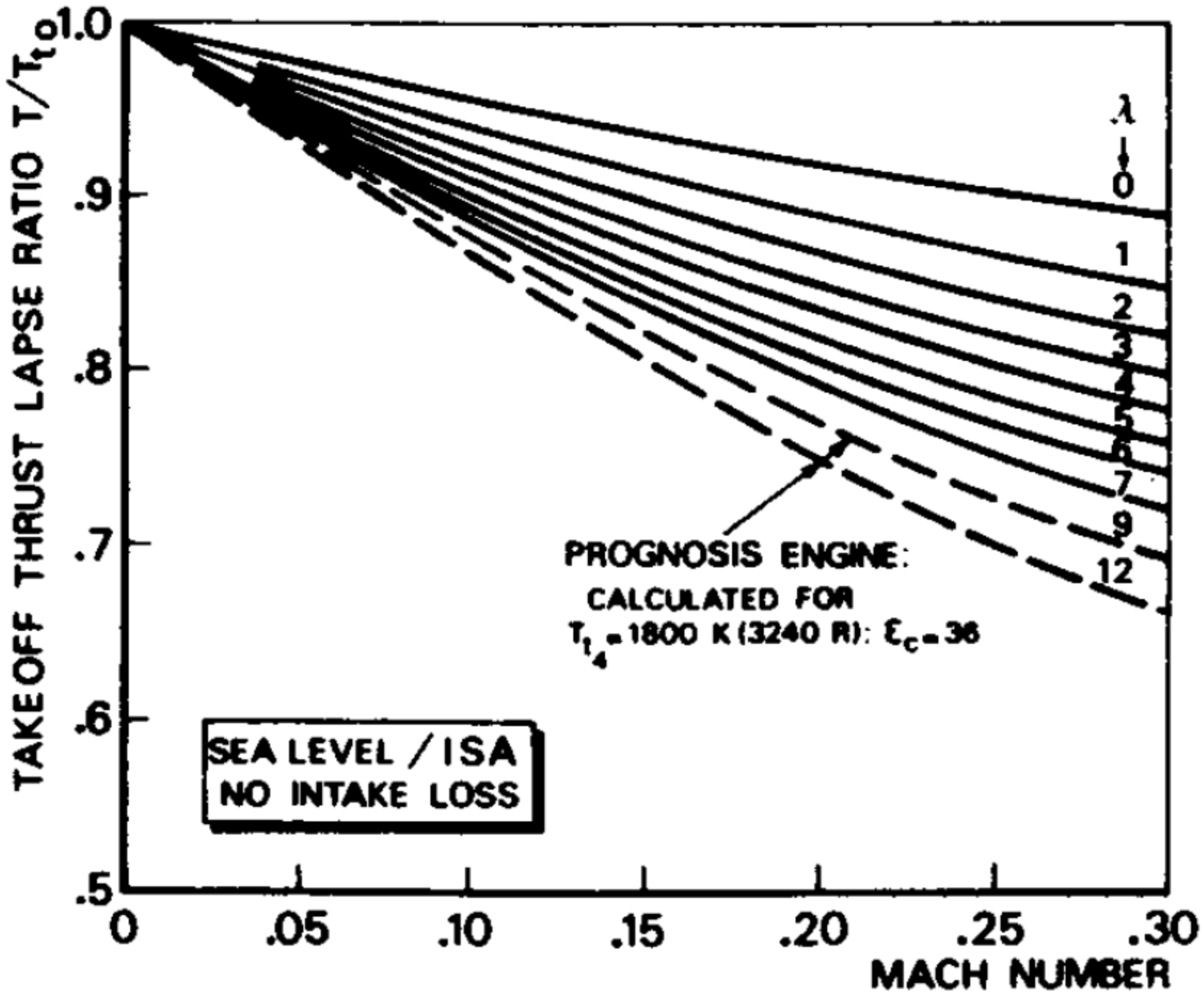
Thrust and Mach number

- The thrust of a jet engine changes with Mach number.
- Maximum thrust is obtained at take-off, T_{to}.
- At any other Mach number the thrust can be approximated from
- $\frac{T}{T_{to}} = 1 - \frac{0.45(1+\lambda)}{\sqrt{(1+0.75\lambda)G}} M + \left(0.6 + \frac{0.11\lambda}{G}\right) M^2$
- where M is the Mach number and G is 0.9 for low bypass, 1.2 for high bypass.

Thrust lapse ratio

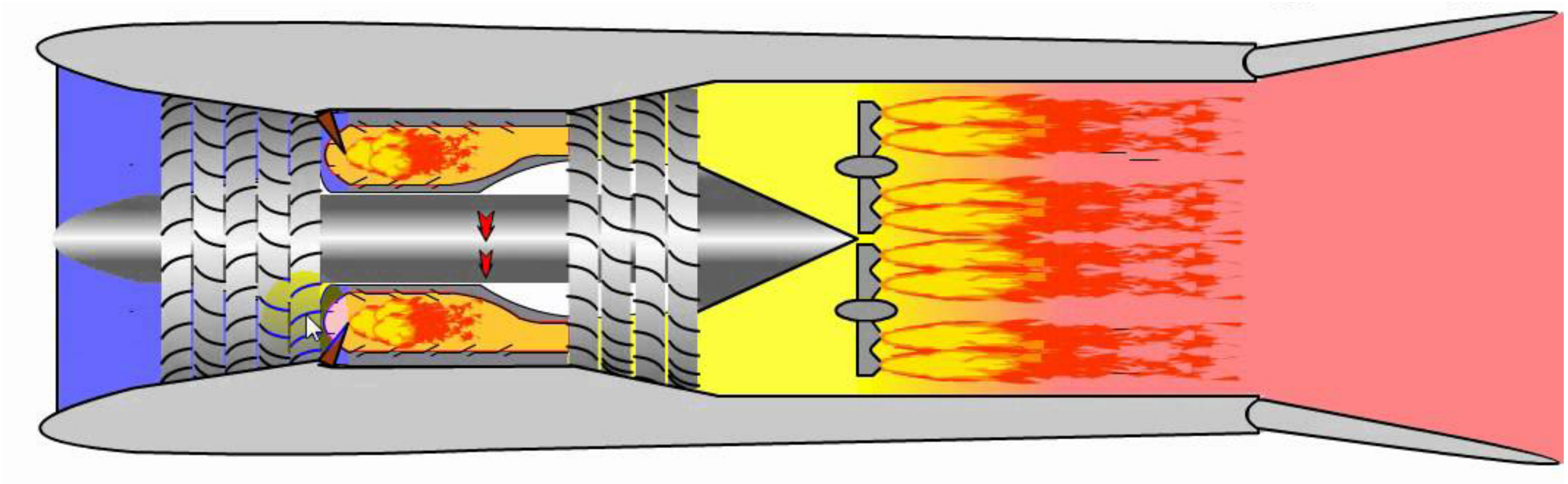
- Thrust ratio against Mach number at take-off.

Low bypass engines loose thrust less quickly.



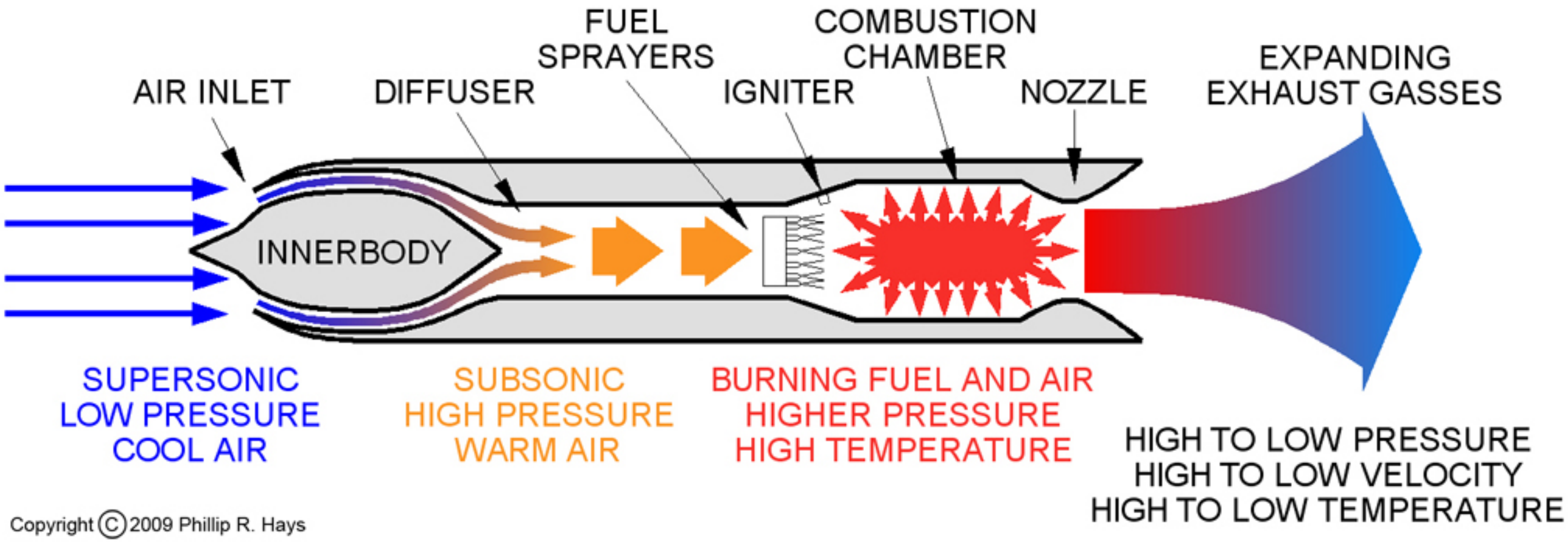
Afterburner

- The thrust of both turbojets and turbofans can be significantly increased using afterburning (or reheat).
- Fuel is injected in the flow downstream of the turbine. The kinetic energy of the gas is increased significantly.
- Reheat is very inefficient and requires high fuel rates so it used mostly in military aircraft for very short times.



Ramjet engine

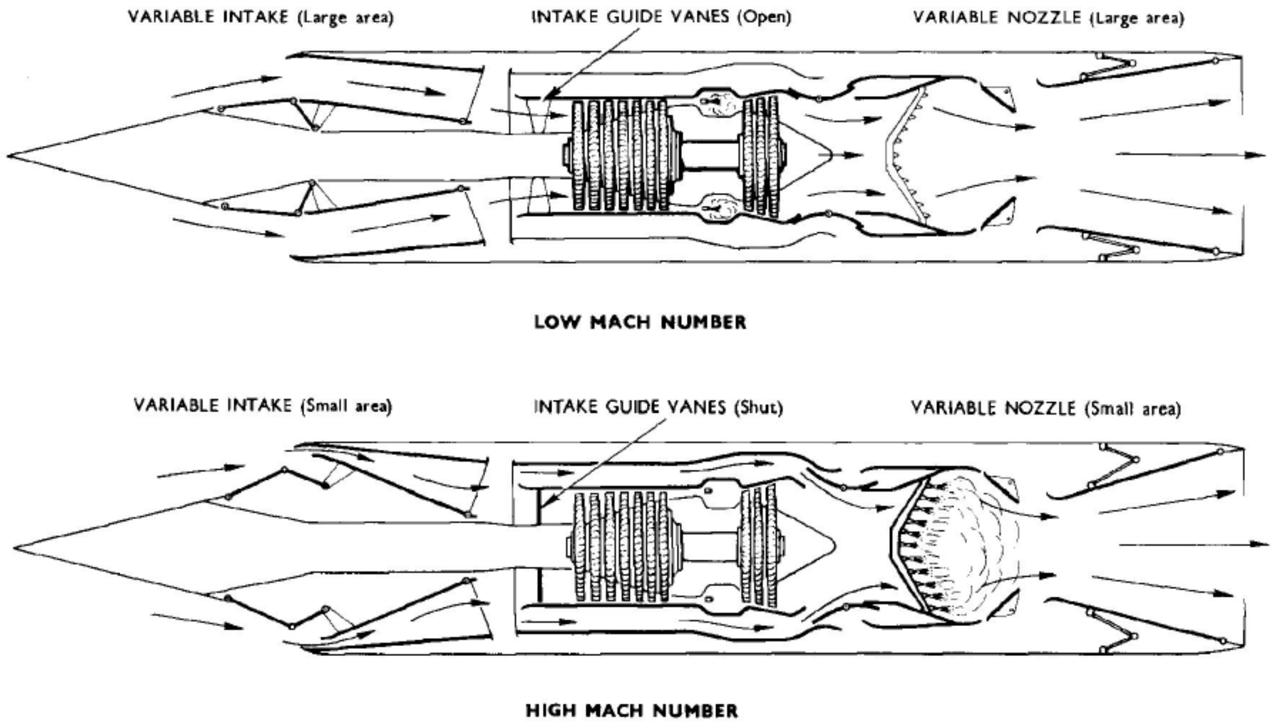
- Cutout of a ramjet



A ramjet has no moving parts. The compression is achieved by decelerating supersonic flow to subsonic.

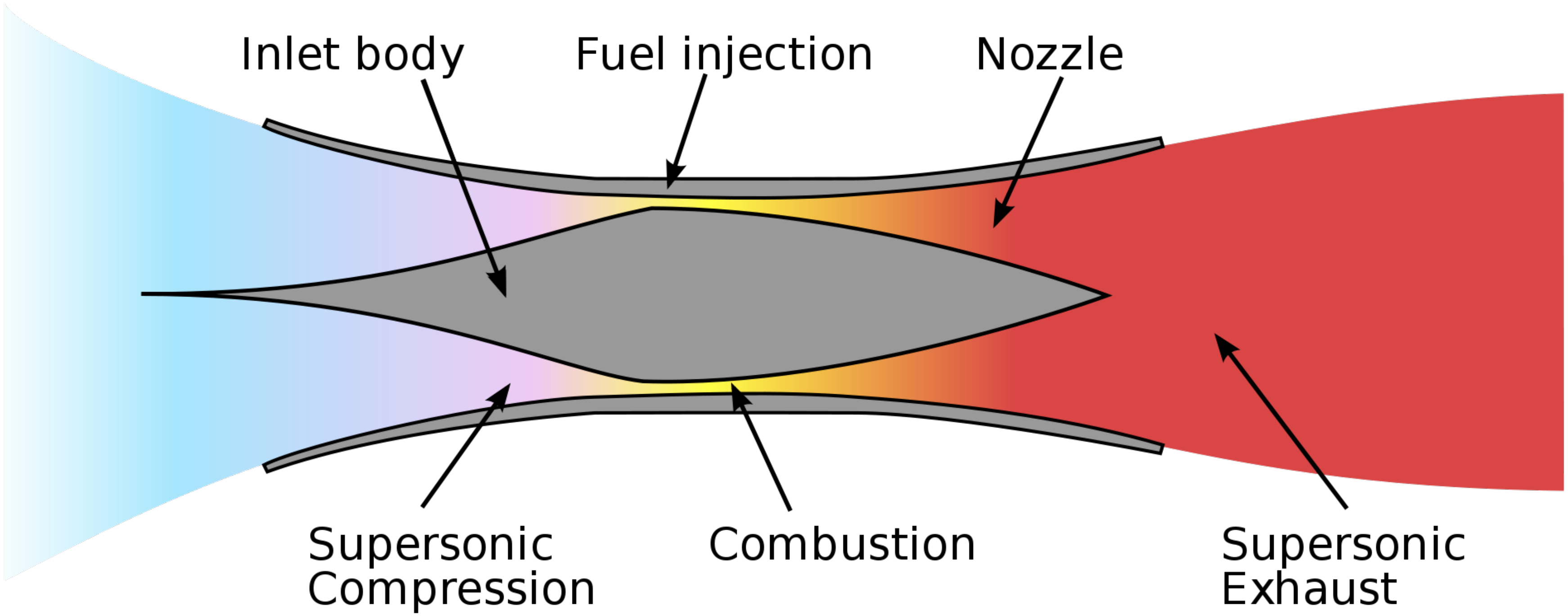
Turbo/ramjet combinations

- A ramjet engine cannot operate at low airspeeds.
- It must be combined with another type of engine.
- Turbojet, ramjet combinations have also been proposed.



Scramjet engine

- Supersonic combusting ramjet.
- The flow is supersonic when it is ignited.



Engine choice

- The following considerations are important:
  - Engine type: piston, turboprop, turbofan, etc.
  - Number of engines: required thrust and probability of failure.
  - Engine installation: underwing, fuselage sides, tail, inside fuselage etc.
  - Choice of propellers: for piston and turboprop engines.

Engine type

- This usually depends on the aircraft specification:
  - Transport aircraft at M < 0.7: Specific Fuel consumption is paramount.
    - Turboprop.
  - Transport aircraft at 0.7< M< 1: Specific Fuel consumption is paramount.
    - Turbofan.
  - Supersonic aircraft M>1: Thrust is paramount.
    - Turbojet.
  - Supersonic aircraft M>3: Thrust is paramount.
    - Ramjet.
  - Hypersonic aircraft M>4: Thrust is paramount.
    - Scramjet.

Various aircraft

ATR 72

Airbus 340

Concorde

Boeing X-51

Number of engines

- Increasing the number of engines increases the maximum thrust.
- It also increases the probability of at least one engine failing.

P is the probability of one engine failing per flying hour. It is a small number.

Doubling the number of engines doubles the probability of failure of 1 engine but multiplies by 6 the probability of failure of 2 engine.

	Probability of engine failure (per flying hour)		
Failure of	1 engine	2 engines	3 engines
twin-engine aircraft	2P	P^2	-
three-engine aircraft	3P	$3P^2$	P^3
four-engine aircraft	4P	$6P^2$	$4P^3$

Engine out case

- If an engine fails at take-off, an airliner must still be able to complete the take-off:
  - At least two engines must be installed.
  - A minimum rate of climb must be achieved with the surviving engines.
- Twin-engined aircraft are oversized for cruise, since they must be able to climb with a single engine:
  - Thrust-to-weight ratio $\frac{T}{W} \approx 0.3$.
- Four-engined aircraft have a lower $\frac{T}{W} \approx 0.2$ but they require more maintenance.
- Three-engined aircraft have $\frac{T}{W} \approx 0.25$. but tail installation is costly and less popular.

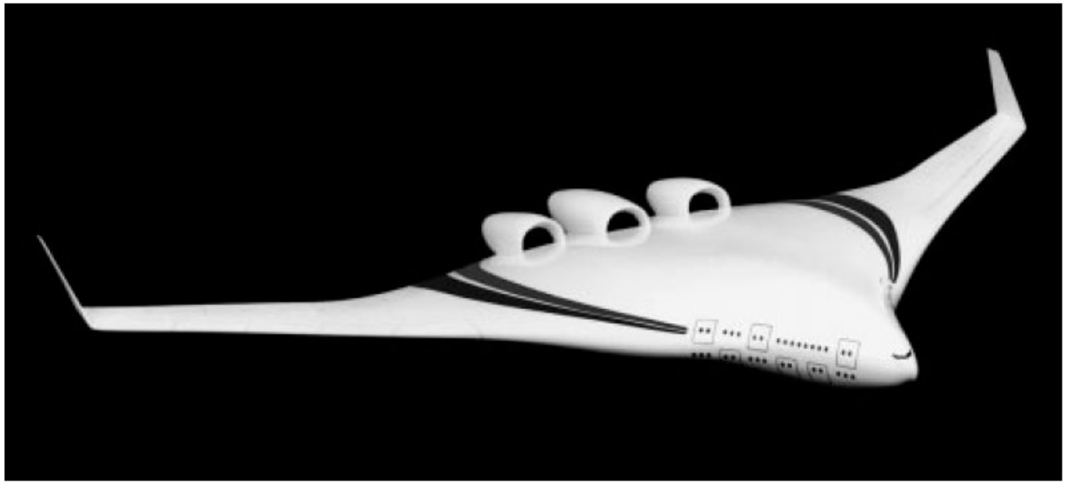
Engine installation

- Underwing:
  - All Boeing except 727, all Airbus, Concorde etc.
  - Heavy military transports C-17, C-5, An-225 etc.
  - Heavy bombers B52, B-58 etc.
- Fuselage side:
  - Regional jets Caravelle, Embraer 145, Fokker 100, CRJ 200
  - Business jets Challenger, Falcon, Phenom, all Learjets, all Gulfstreams etc.

Engine installation (2)

- Tail:
  - Boeing 727, MD-11, DC-10, Tristar etc.
  - Three-engine configurations are no longer popular.
- Fuselage-wing junction:
  - Only De Havilland Comet and some military aircraft.

Engine installation (3)



- Over fuselage:
  - Blended wing bodies, X-48

- Over the tail:
  - Open rotor aircraft, Airbus proposals.

Installed thrust

- The maximum thrust of an engine that is installed on an aircraft is always lower than the maximum uninstalled thrust:
  – Inlet pressure losses, bleed air for de-icing and air conditioning, power for driving aircraft systems etc.
- Typical thrust losses due to installation are 4% for low bypass and 8% for high.
- For propeller aircraft, power also decreases due to installation effects:
  – Propeller installation, drag of aircraft components in the slipstream, intake losses, bleed air etc.
- Typical installed to uninstalled power ratios are 85% for turboprops to 78% for a piston engine in the fuselage nose.

Thrust reversal

- Thrust reversal is used during landing to shorten the landing run.
- The jet is directed forward, applying an additional breaking force.
- Thrust reversal is particularly effective on wet runways.

Auxiliary Power Unit

- An Auxilliary Power Unit (APU) is installed in most modern airliners.
- It is a small gas turbine that has several uses:
  – Supplies pressurized air and power for the air-conditioning system on the ground.
  – Starts the main engines.
  – Supplies power for the electrical systems.
  – Supplies electricity for maintenance work outside the hangar.
- It increases the aircraft weight but makes the aircraft more autonomous and flexible.
- It is usually installed in the tail of the fuselage.

APU examples

Airbus A-380

Boeing 737