Aerospace Propulsion

Lecture 11

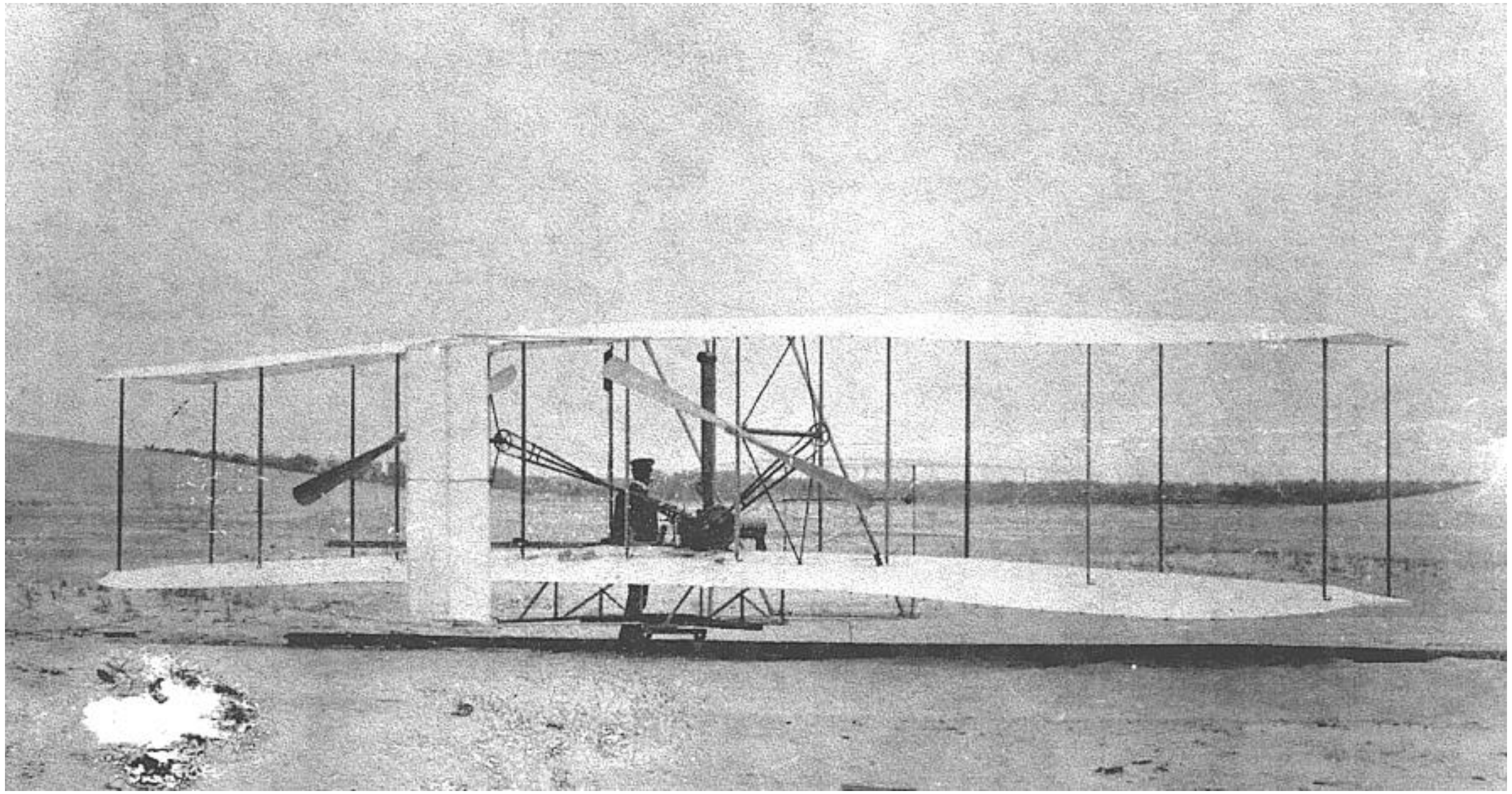
Airbreathing Propulsion I

Airbreathing Propulsion: Part I

- History of Airbreathing Propulsion
- Basics of Gas Turbine (Jet) Engines
- Thrust
- Efficiency
- The Atmosphere

History of Airbreathing Propulsion

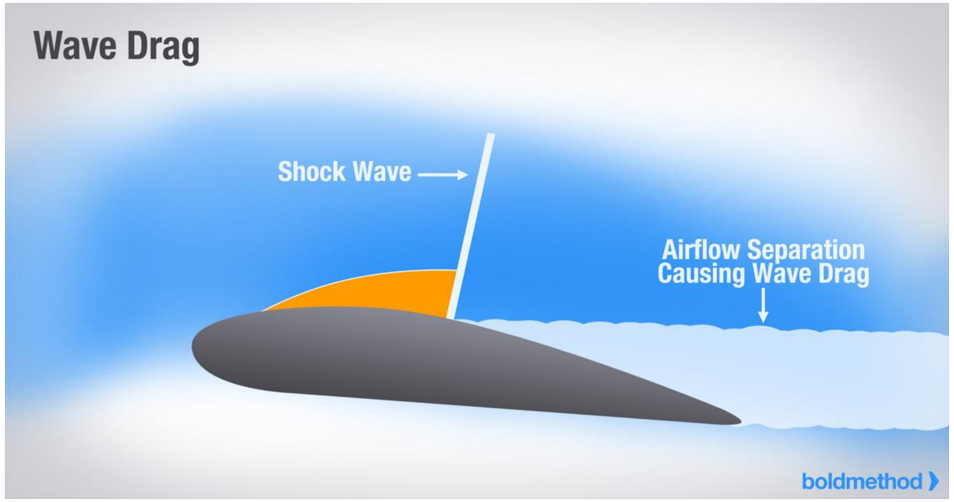
- Wright brothers
  - December 17, 1903
  - Kitty Hawk, North Carolina
  - “The Flyer”
    - Gas powered, 12-hp reciprocating engine
    - Propellers
- Reciprocating engines with propellers until 1930’s



First powered & controlled aircraft

History of Airbreathing Propulsion

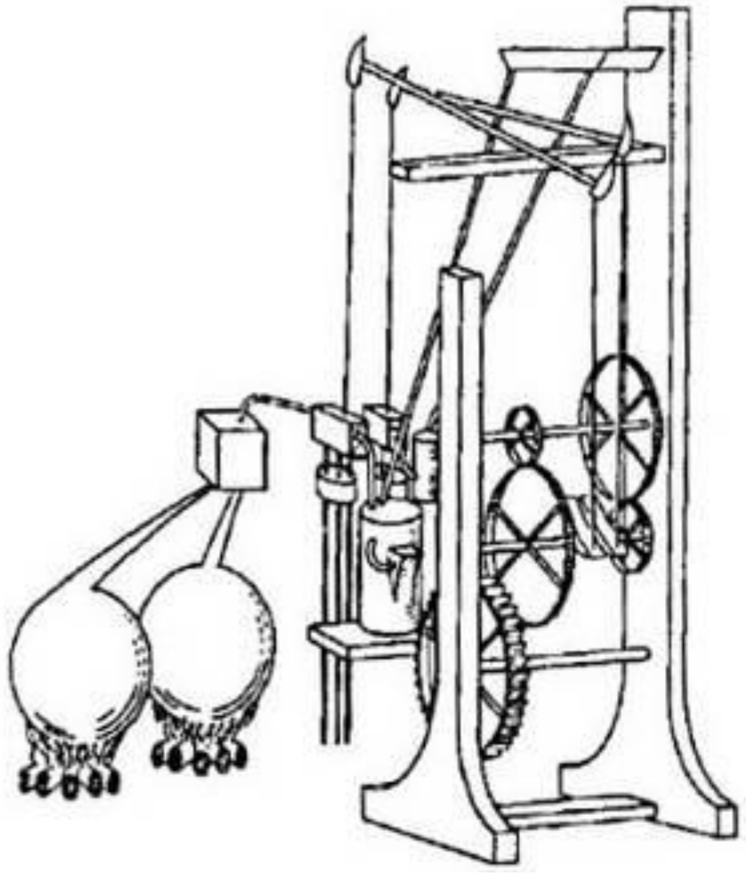
- Why was the gas turbine necessary to advance aviation?
  - Reciprocating engines were mainly used to spin propellers
  - Propeller aircraft limited by velocity of propeller tips
    - Sonic propeller tips exhibit “wave drag” which significantly reduces efficiency
      - Occurs due to shocks
  - Gas turbines do not rely on (fast-spinning) propellers



History of Airbreathing Propulsion

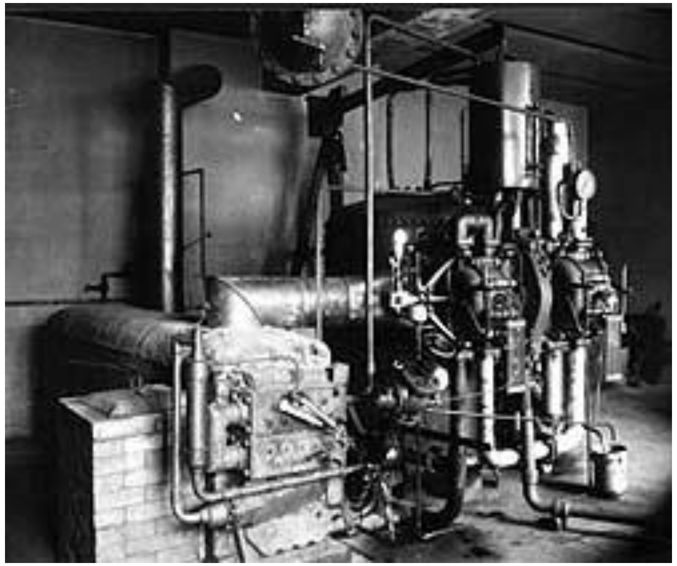
- Next major leap occurred with the introduction of gas turbines to aircraft
- John Barber
  - English inventor
  - First true gas turbine (1791)
  - “Horseless Carriage”
  - Not enough efficiency to power itself so external compression used

Compressor + combustor + turbine



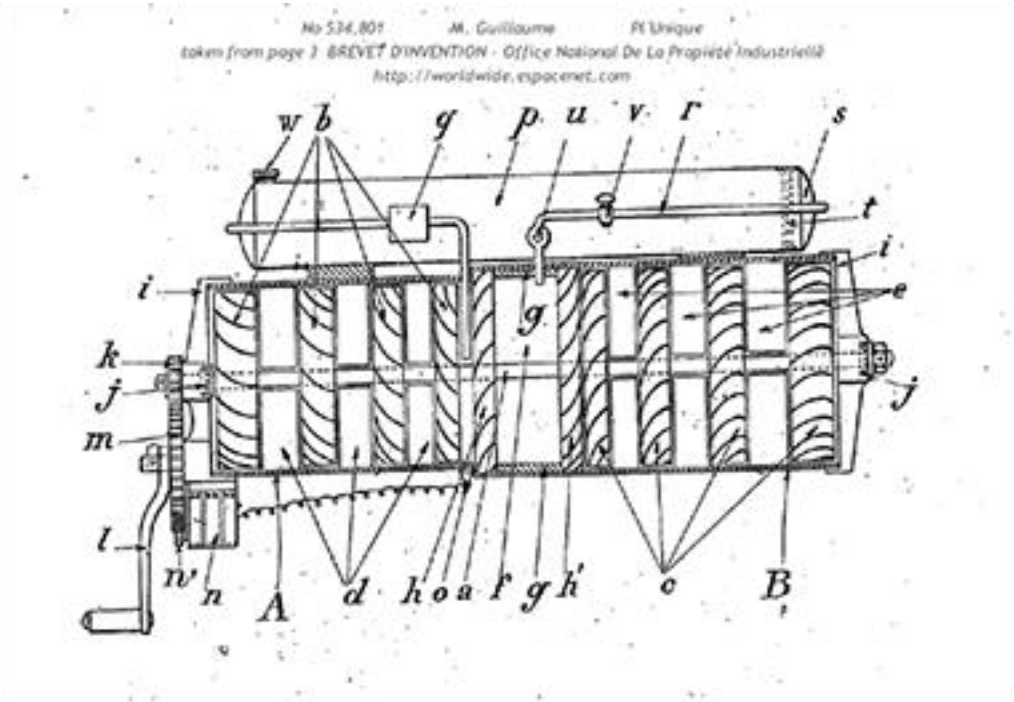
History of Airbreathing Propulsion

- Ægidius Elling
  - Norwegian researcher and inventor
  - First gas turbine producing net power
    - Same year as first flight (1903)
    - Output of 11-hp
    - Engine limited by turbine inlet temperature of 675 K
      - Materials constraint



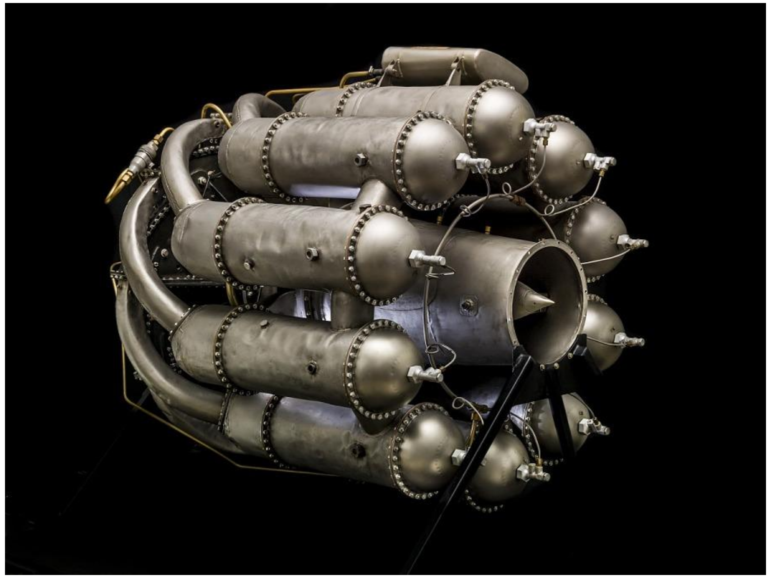
History of Airbreathing Propulsion

- Maxime Guillaume
  - French inventor
  - First patent for turbojet engine (1921)
    - Axial-flow turbojet
    - First time a gas turbine was considered to power an aircraft
    - Never constructed due to insufficient technology to build the compressor



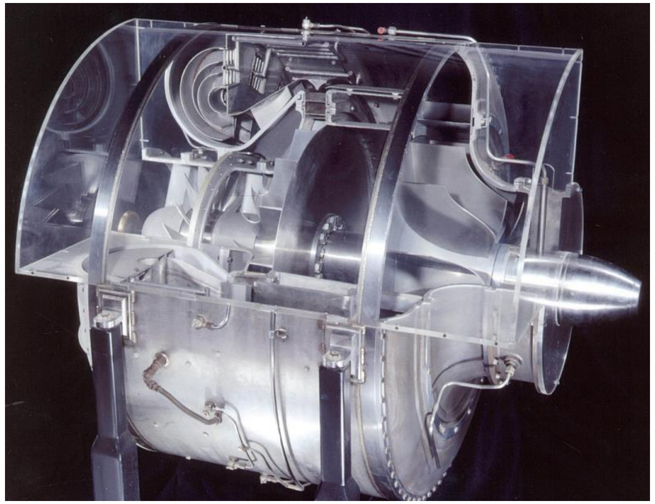
History of Airbreathing Propulsion

- Frank Whittle
  - British engineer (Royal Air Force)
  - Father of turbojet engine (1930 patent)
    - Possible through collaboration with Alan Arnold Griffith in 1926
  - Constructed and tested in 1937
  - Gloster E.28/39 flew using the whittle engine (Whittle W.1) in 1941



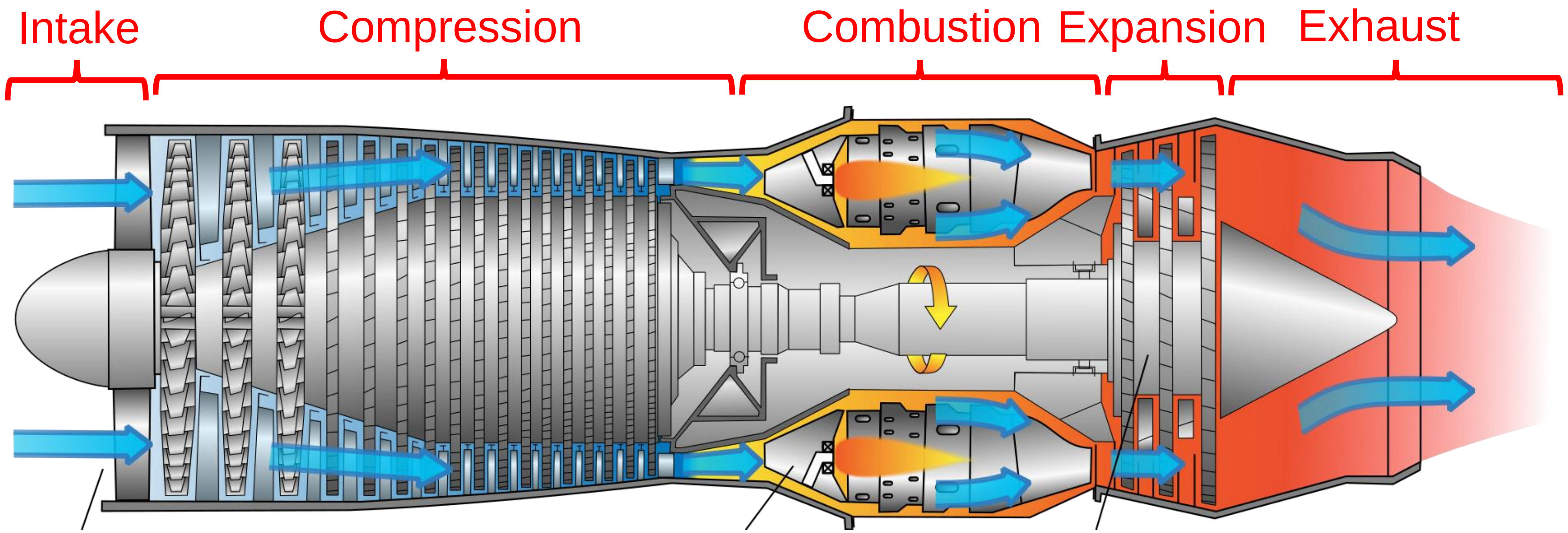
History of Airbreathing Propulsion

- Hans von Ohain
  - German engineer
  - First engine (Heinkel HeS 1) in 1937
    - Fueled by Hydrogen
    - Beat the Whittle engine test by a few weeks
  - First flight in 1939
    - Heinkel He 178 aircraft
    - Heinkel HeS 3 engine
    - Fueled by diesel



Basics of Gas Turbine (Jet) Engines

- Five primary processes in jet engines
  - Intake
  - Compression
  - Combustion
  - Expansion
  - Exhaust

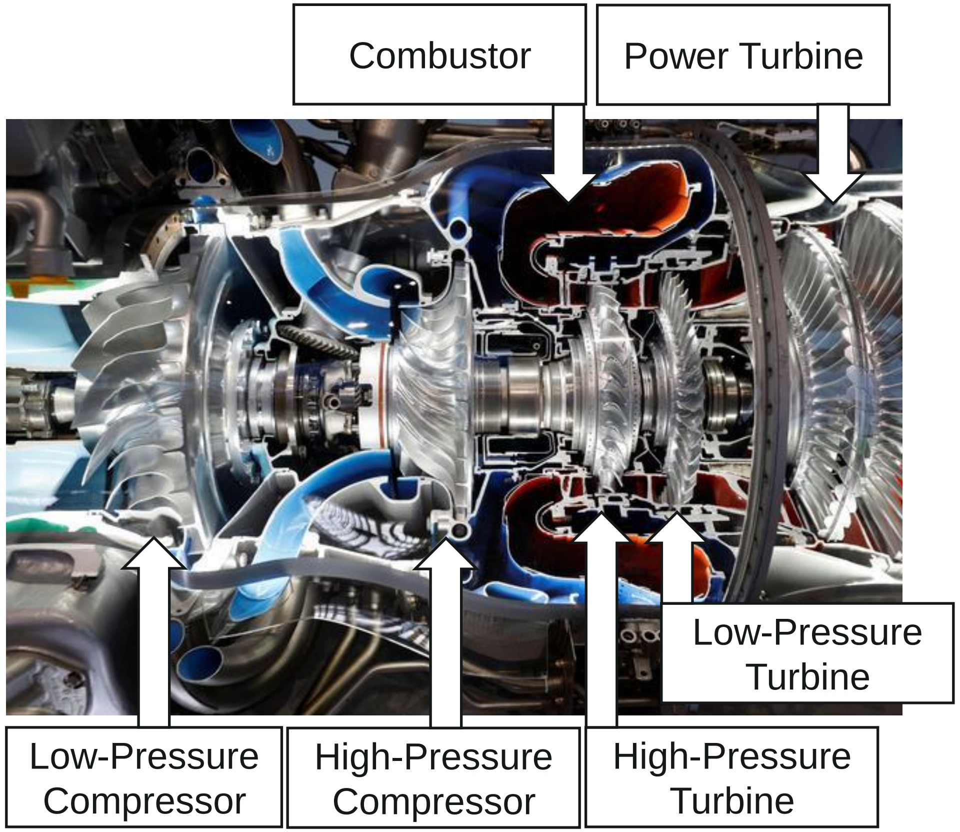


Basics of Gas Turbine (Jet) Engines

- Classification
  - Two sources of power/work in gas turbines
    - Shaft power from turbine(s)
    - Exhaust jet
  - Turboprop Engines
    - All power from shaft used to drive propeller
  - Turbojet Engines
    - All power from exhaust jet
  - Turbofan Engines
    - Some power to exhaust, some power to drive fan

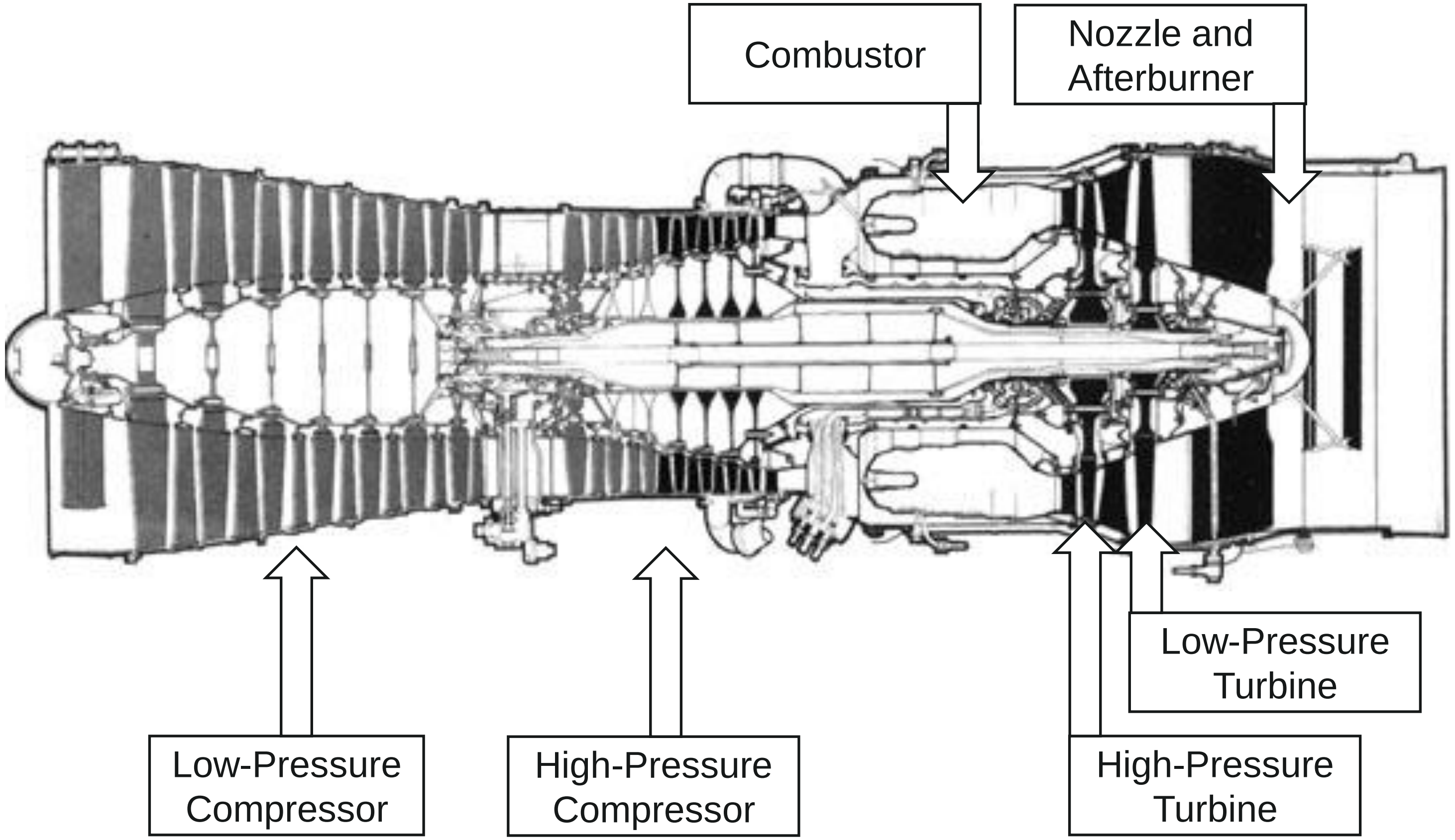
Basics of Gas Turbine (Jet) Engines

- Turboprop Engine
  - Gas turbine used to spin propeller
  - Example: PW123 (Bombardier Q200)
    - Three shafts (2000 hp)
    - Low-pressure compressor connected to low-pressure turbine
    - High-pressure compressor connected to high-pressure turbine
    - Power Turbine connected to Propeller
  - Advantage: Most efficient at low speed
  - Disadvantage: Forward speed limited by propeller tip speed



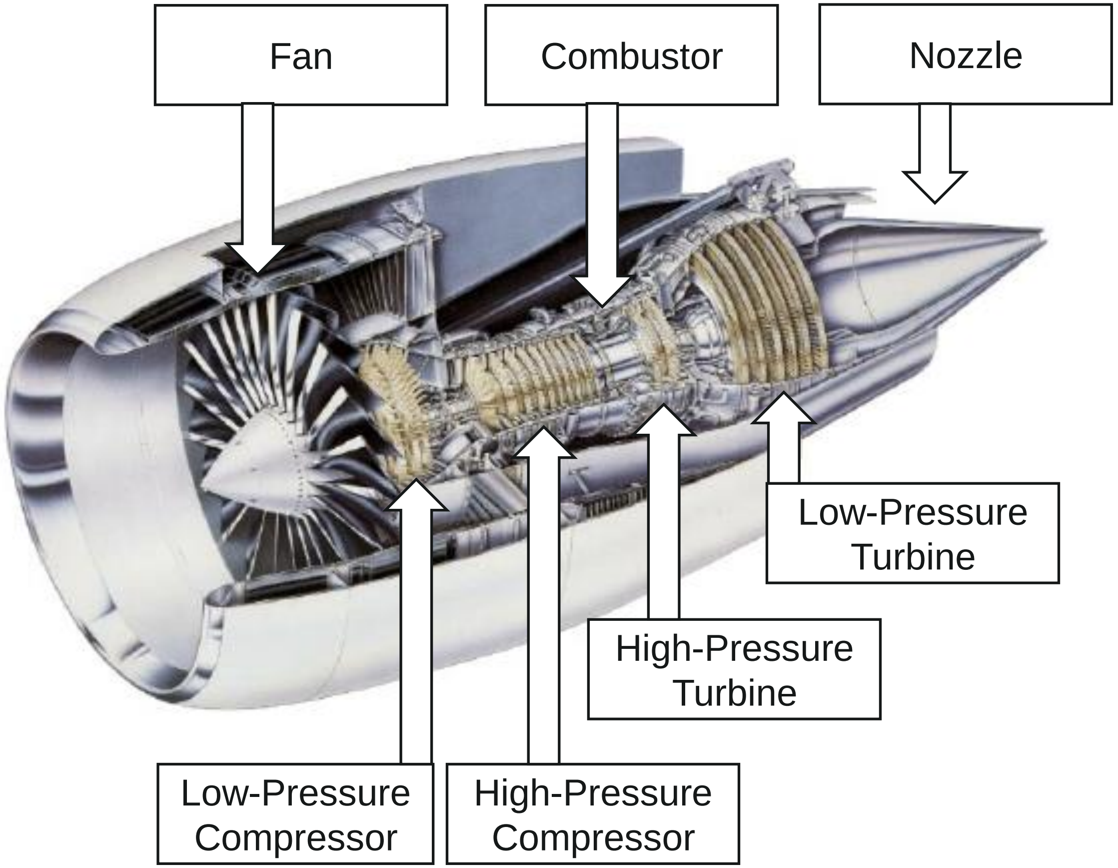
Basics of Gas Turbine (Jet) Engines

- Turbojet Engine
  - Gas turbine exhaust provides propulsion
  - Example: RR Olympus 593 (Concorde)
    - Two shafts (38,000 lb_f)
  - Advantage: Very high thrust enables high speed flight
  - Disadvantage: Very inefficient at low speeds

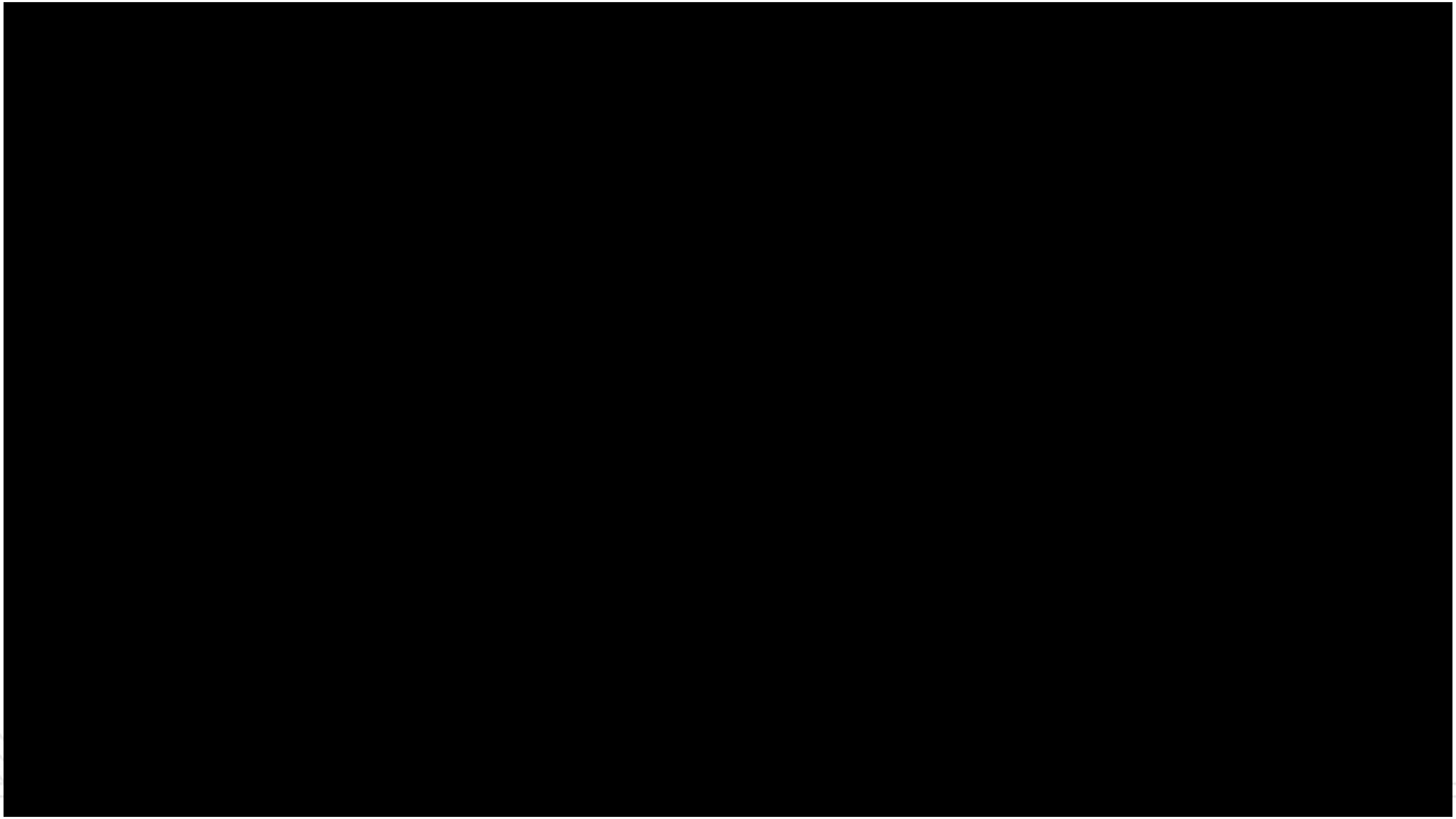


Basics of Gas Turbine (Jet) Engines

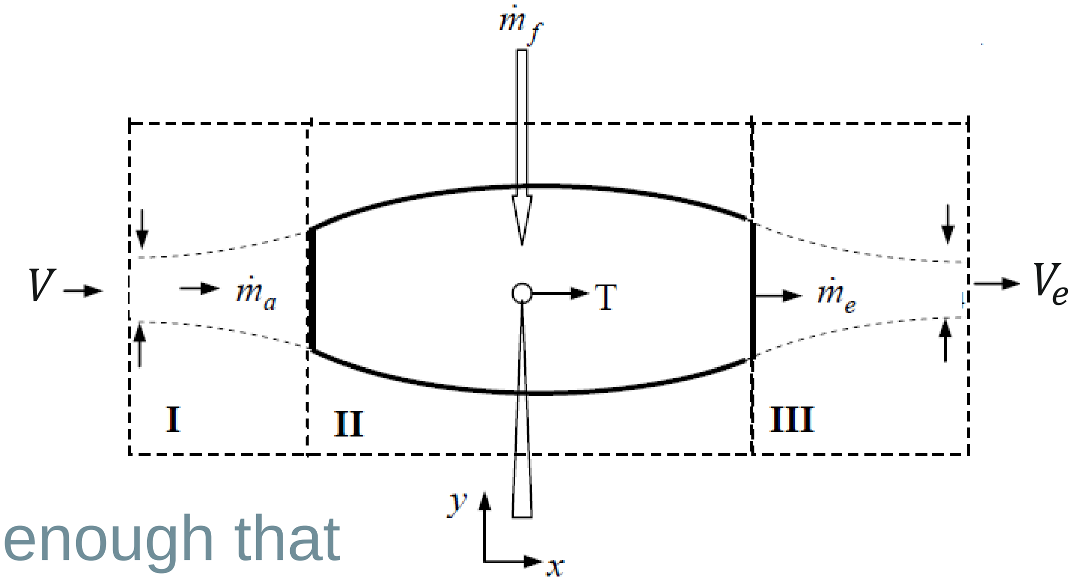
- Turbofan Engine
  - Conceptually, almost a combination of turbojet and turboprop engines
  - Example: GE90 (Boeing 777)
    - Two shafts (115,000 lb_f)
  - Advantage: Good thrust and efficiency at many speeds
  - Disadvantage: For a large enough fan, wave drag



Basics of Gas Turbine (Jet) Engines



Thrust



- Consider an "engine"
- Momentum balance in x-direction
  - Assume control volume borders far enough that pressure doesn't change across them
  - Assume fuel mass flow rate is negligible $(m_a \gg m_f)$

$$\iint \rho \vec{V}(\vec{V}\cdot\hat{n})dA = \sum F_x$$

$$\rho_e V_e^2 A_e - \rho_a V^2 A_a = T$$

$$\dot{m}_e V_e - \dot{m}_a V = T$$

$$\dot{m}_e = \dot{m}_a + \dot{m}_f$$

- $T = (\dot{m}_e V_e - \dot{m}_a V) = \dot{m}_a \left(V_e \frac{\dot{m}_a + \cancel{\dot{m}_f}}{\dot{m}_a} - V\right) \approx \dot{m}_a (V_e - V)$

Thrust

- Net Thrust
  - $T = (\dot{m}_e V_e - \dot{m}_a V) \approx \dot{m}_a (V_e - V)$

- Gross Thrust $(V = 0)$
  - Generally, this is the value quoted for engines
    - Gross thrust at sea level
  - $T_G = \dot{m}_e V_e \approx \dot{m}_a V_e$

- Ram Drag
  - Difference between gross thrust and ne~~x~~t thrust
  - $T_R = T_G - T = \dot{m}_a V$

$$\eta_p = \frac{\dot{W}_{prop}}{\Delta \dot{KE}} = \frac{TV}{\frac{1}{2}\dot{m}_e V_e^2 - \frac{1}{2}\dot{m}_a V^2}$$

$$\approx \frac{2TV}{\dot{m}_a(V_e^2 - V^2)}$$

$$= \frac{2\dot{m}_a(V_e - V)V}{\dot{m}_a(V_e^2 - V^2)}$$

$$= \frac{2(V_e - V)V}{V_e^2 - V^2} = \frac{2(V_e - V)V}{(V_e - V)(V_e + V)}$$

Efficiency

- Propulsive Efficiency
  - $\eta_p = \frac{\dot{w}_{prop}}{\Delta \dot{KE}} = \frac{2V}{V_e + V}$

$$\eta_p = \frac{2V}{V_e + V}$$

- Maximized (with non-negative thrust) when $V_e = V$
  - Zero thrust!
  - More efficient to slightly accelerate more air rather than greatly accelerate less air

Efficiency

Lower Heating Value (LHV) is the amount of energy/heat released from combustion per mass of fuel assuming *gaseous* water as the product

- Thermal Efficiency
  - $\eta_{th} = \frac{\Delta KE}{\dot{Q}_{in}} = \frac{\frac{1}{2}\dot{m}_e V_e^2 - \frac{1}{2}\dot{m}_a V^2}{\dot{m}_f LHV}$
- Overall Efficiency
  - $\eta_o = \frac{\dot{w}_{prop}}{\dot{Q}_{in}} = \eta_p \eta_{th}$
- (Thrust) Specific Fuel Consumption
  - $(t)sfc = \frac{\dot{m}_f}{T}$

The Atmosphere

- Ambient temperature and pressure
  - Aircraft experience a massive variation in ambient pressure, temperature, and density from sea level to cruise altitude (~35,000 ft)
    - At cruise altitude, $T \approx 218.8\ \mathrm{K}\ (-65\ {}^\circ\mathrm{F}), p \approx 0.235\ \mathrm{atm}$
- Rely on "International Standard Atmosphere"
  - Static Quantities
- Why do aircraft cruise between 30,000 and 40,000 ft?

Elevation - z - (m) (ft)	Temperature - T - (K) (°F) (°C)	Pressure - p - (bar) (psi) (kPa)	Relative Density - ρ/ρ_o - Density - ρ (Kg/m3)
10000	223.3	0.2650	0.3376
10500	220.0	0.2454	0.3172
11000	216.8	0.2270	0.2978
11500	216.7	0.2098	0.2755
12000	216.7	0.1940	0.2546