APPLIED THERMAL ENGINEERING (UMT303)

Jet Propulsion

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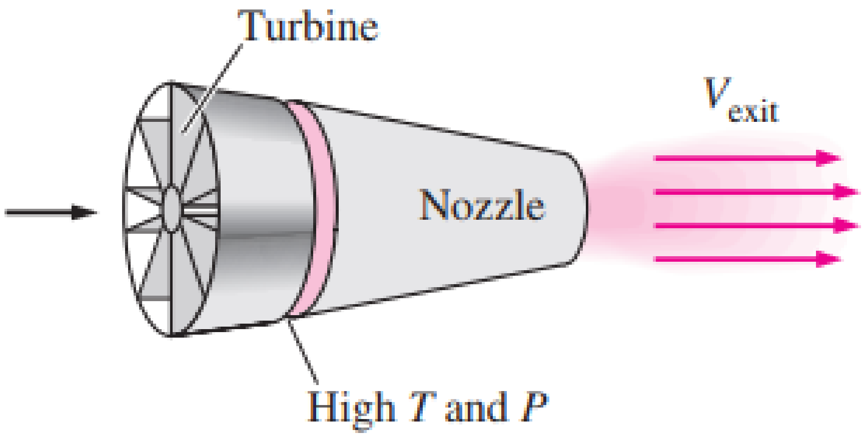
IDEAL JET-PROPULSION CYCLES

Aircraft are propelled by accelerating a fluid in the opposite direction to motion. This is accomplished by either slightly accelerating a large mass of fluid (*propeller-driven engine*) or greatly accelerating a small mass of fluid (*jet* or *turbojet engine*) or both (*turboprop engine*).



In jet engines, the high-temperature and high-pressure gases leaving the turbine are accelerated in a nozzle to provide thrust.

CLASSIFICATION of JET-PROPULSION ENGINE

- Jet propulsion engines
  - Air breathing jet engines or atmospheric jet engines
    - Continuous air flow engine
      - Turbojet engines
      - Turbofan engines
      - Turbojet with afterburner
      - Turboprop or propjet
      - Ram jet or Athodyds and Lorin tube
    - Intermittent air flow engine
  - Non-air breathing jet engines or rocket engines
    - Liquid propellent type rocket engine
    - Solid propellant type rocket engine

PERFORMANCE OF JET PROPULSION ENGINES

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(*i*) **Thrust power (TP):**

$$TP = T \times C_a$$

$$= \left[\left\{\left(1 + \frac{m_f}{m_a}\right) \cdot C_e - C_a\right\} + \frac{A_e}{m_a}(p_e - p_a)\right] \cdot C_a$$

(*ii*) **Propulsive power (PP):**

$$PP = \frac{1}{2}\left\{\left(1 + \frac{m_f}{m_a}\right) \cdot C_e^2 - C_a^2\right\}; \quad \text{W/kg of air}$$

(*iii*) **Propulsive efficiency (ηProp):**

$$\eta_{\text{prop}} = \frac{TP}{PP} = \frac{\left[\left(1 + \frac{m_f}{m_a}\right) C_e - C_a\right] C_a}{\frac{1}{2}\left[\left(1 + \frac{m_f}{m_a}\right) \cdot C_e^2 - C_a^2\right]}$$

$$\eta_{\text{prop}} = \frac{2\,(C_e - C_a) \cdot C_a}{(C_e^2 - C_a^2)}$$

$$= \frac{2C_a}{(C_e + C_a)} = \frac{2}{\left\{1 + \left(\frac{C_e}{C_a}\right)\right\}}$$

PERFORMANCE OF JET PROPULSION ENGINES

(*iv*) Thermal efficiency (ηth):

$$\eta_{th} = \frac{\text{Kinetic energy available}}{\text{Heat supplied}}$$

$$= \frac{\left\{\frac{1}{2}\left((m_a + m_f)\, C_e^2 - m_a\, C_a^2\right)\right\}}{m_f \times \text{Calorific value of fuel}}$$

$$\eta_{th} = \frac{\left(\left(1 + \frac{m_f}{m_a}\right) C_e^2 - C_a^2\right)}{2\left(\frac{m_f}{m_a}\right) \times \text{Calorific value of fuel}},$$

$$= \frac{(1 + FA)\, C_e^2 - C_a^2}{2 \times FA \times \text{Calorific value of fuel}}$$

(*v*) Overall efficiency (ηoverall):

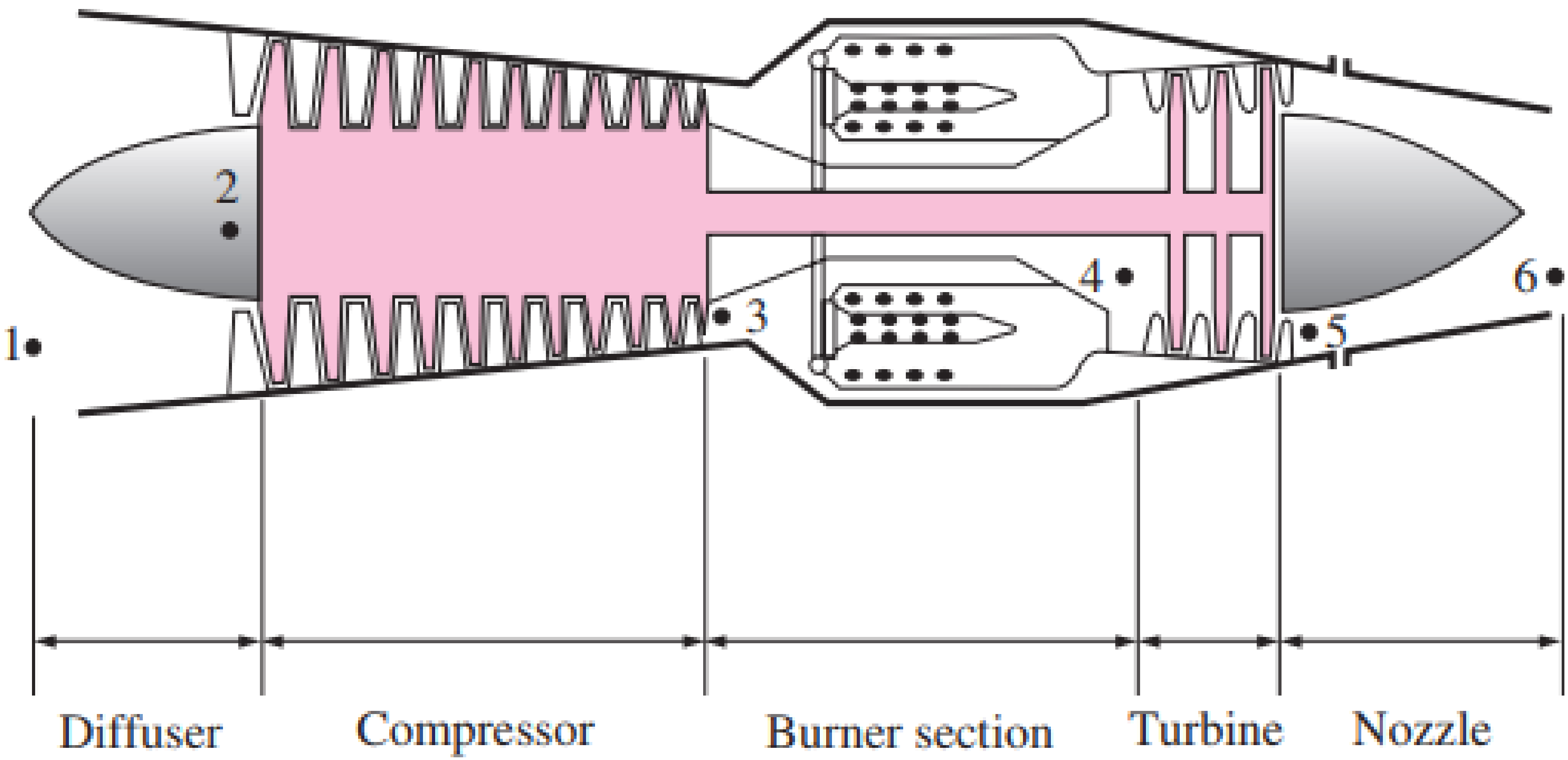
$$\eta_{overall} = \frac{\left[\left(1 + \frac{m_f}{m_a}\right) . C_e - C_a\right] C_a}{\left(\frac{m_f}{m_a}\right) \times \text{Calorific value of fuel}}$$

$$= \eta_{th} \times \eta_{prop}$$

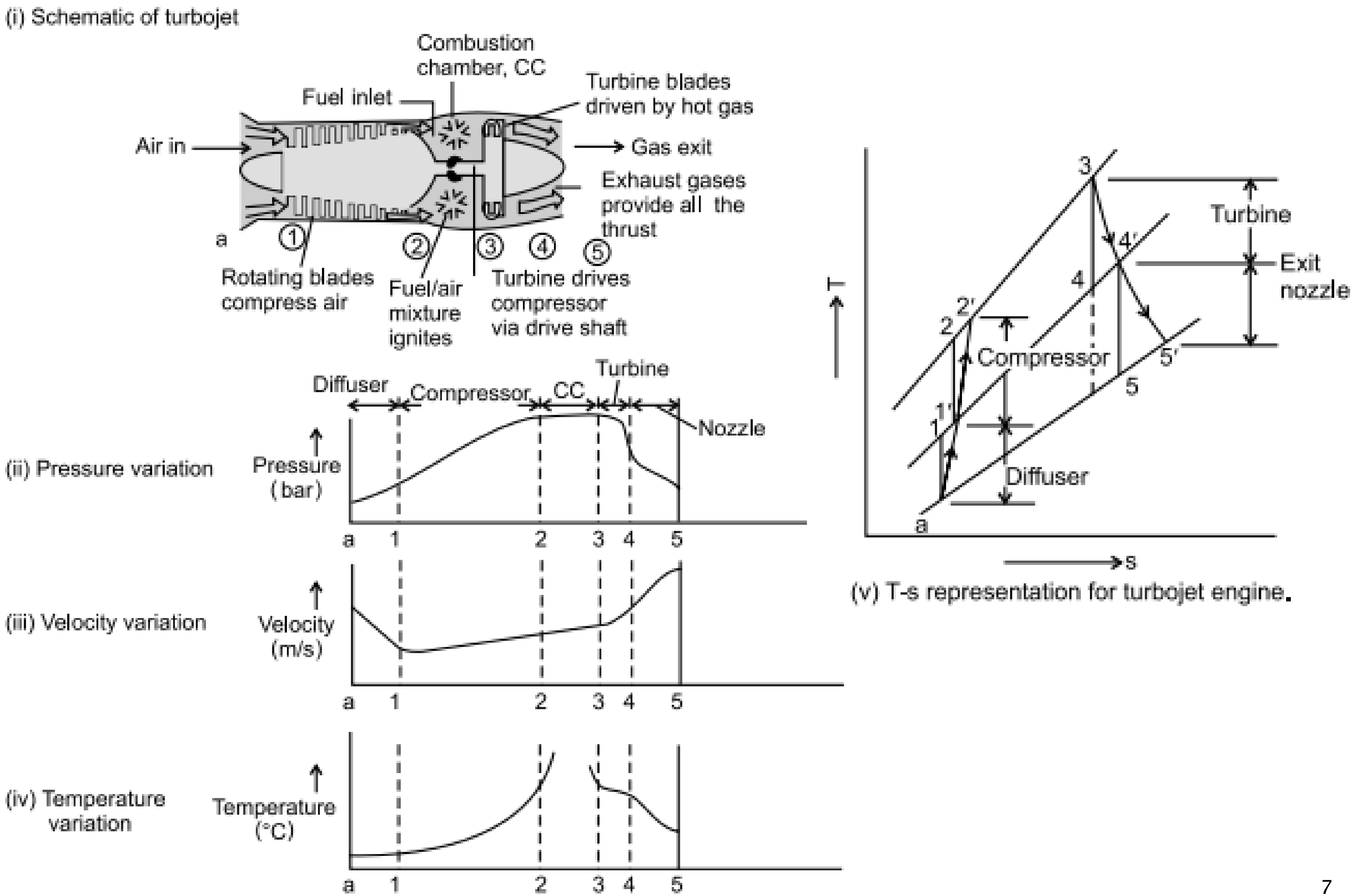
(*vi*) Jet efficiency (ηjet):

Jet efficiency is given by the ratio of final kinetic energy in jet to the total of isentropic heat drop in jet pipe and carry over from turbine.

Basic components of a Turbojet engine



Basic components of a Turbojet engine



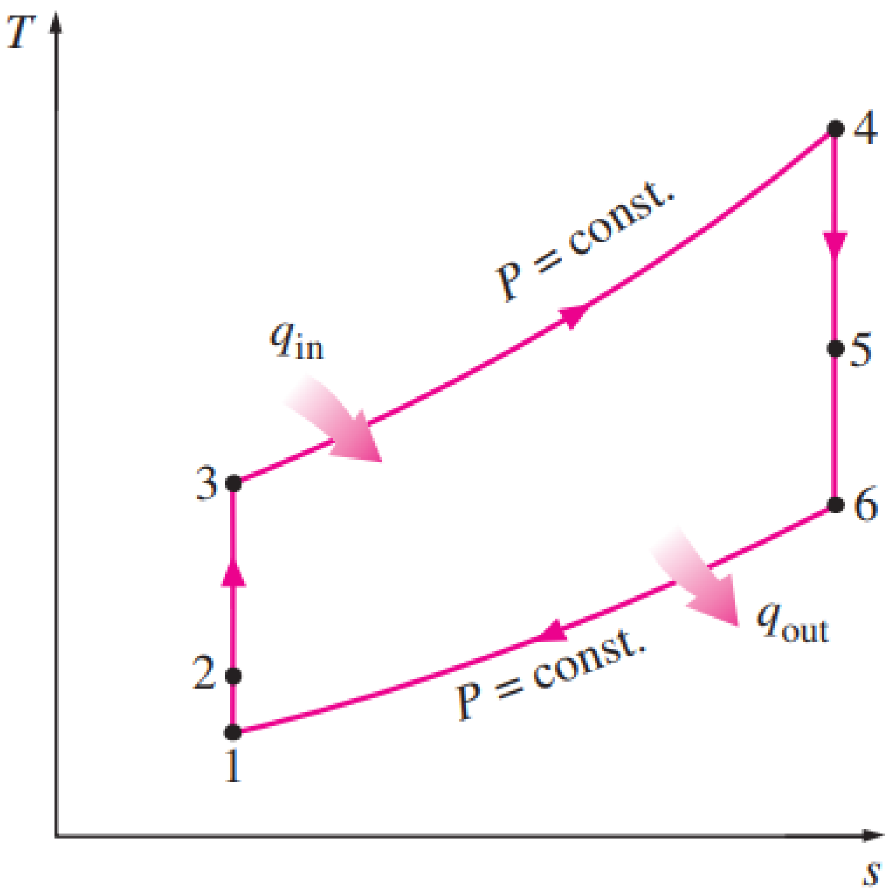
T–s diagram for the ideal turbojet cycle

Net thrust developed by the engine

$$F = (\dot{m}V)_{exit} - (\dot{m}V)_{inlet} = \dot{m}(V_{exit} - V_{inlet}) \qquad \text{(N)}$$

Propulsive power

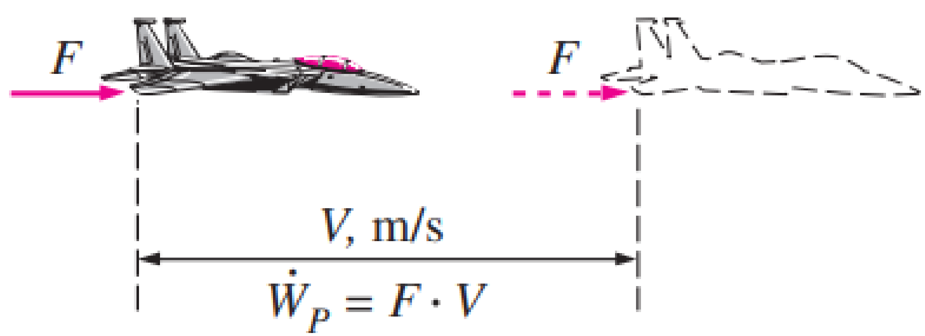
$$\dot{W}_P = FV_{aircraft} = \dot{m}(V_{exit} - V_{inlet})V_{aircraft} \qquad \text{(kW)}$$



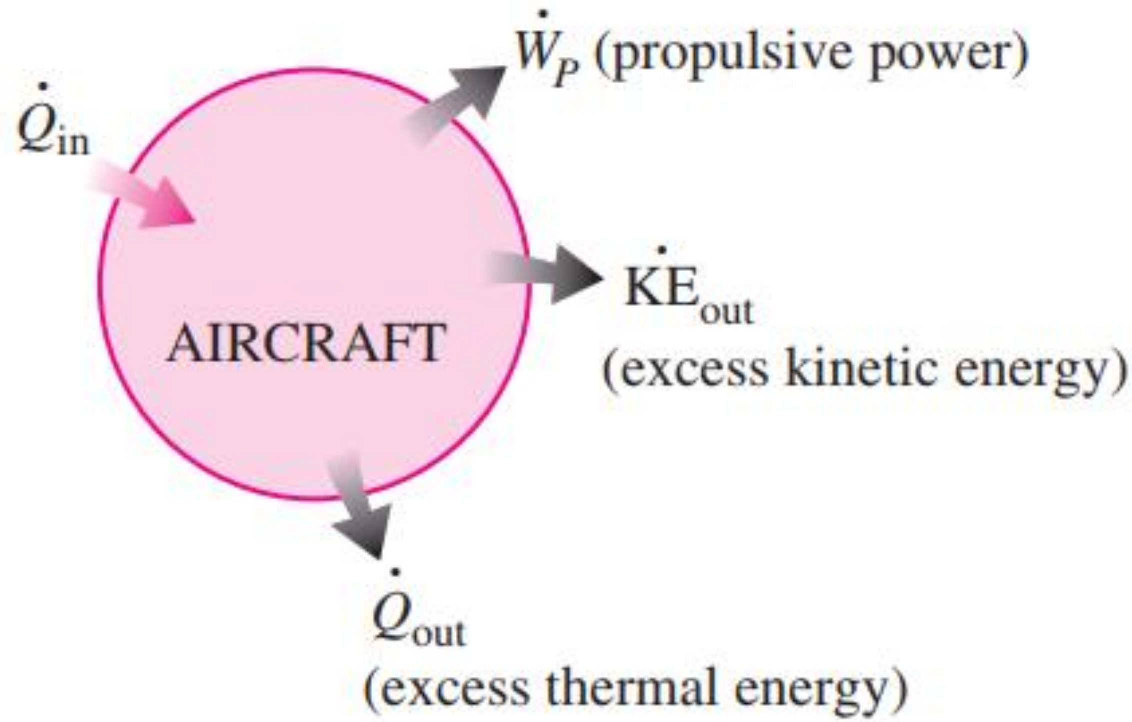
propulsive efficiency

$$\eta_P = \frac{\text{Propulsive power}}{\text{Energy input rate}} = \frac{\dot{W}_P}{\dot{Q}_{in}}$$

Propulsive power is the thrust acting on the aircraft through a distance per unit time.



Energy Balance across an Aircraft

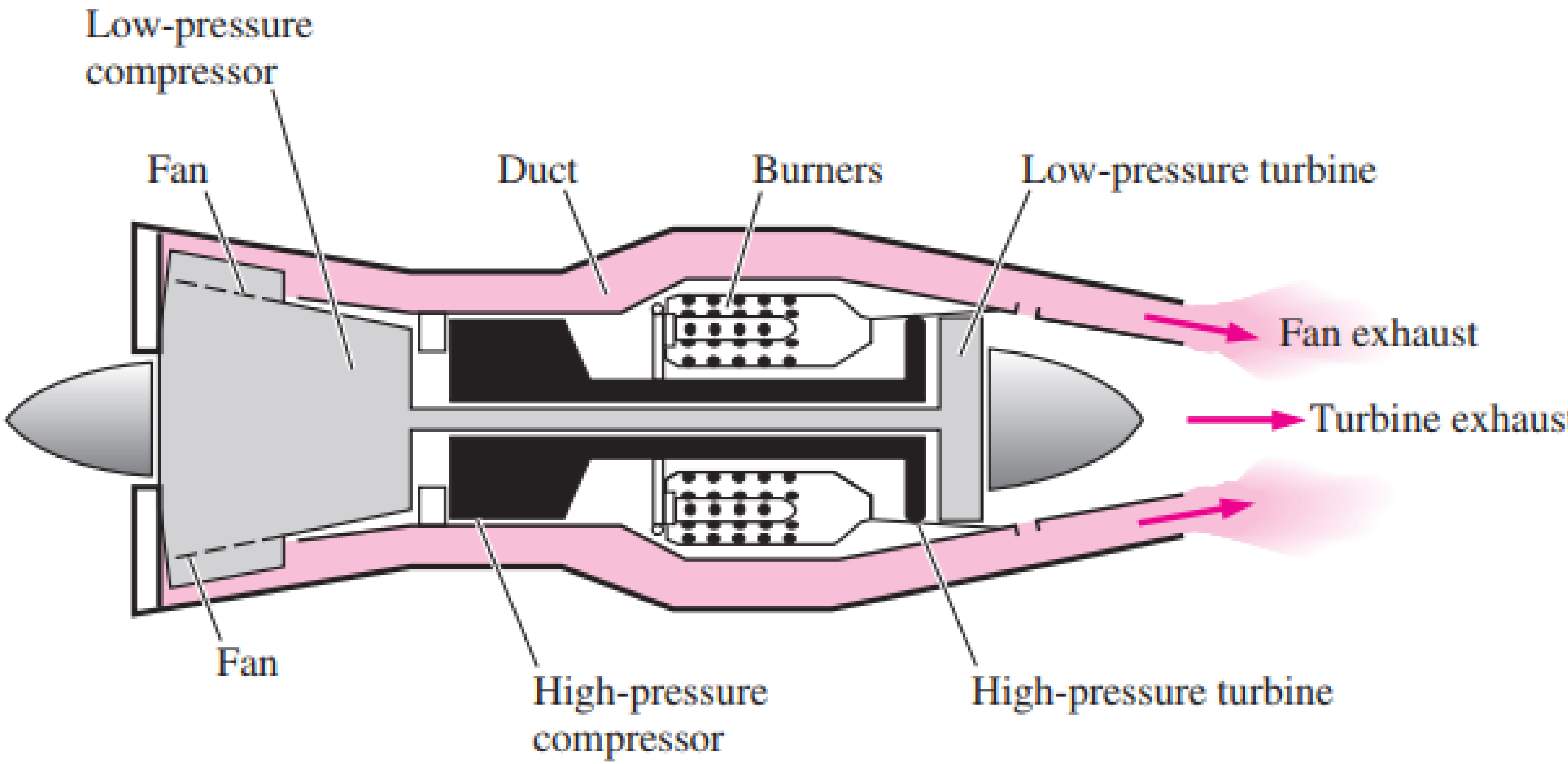


Turbofan Engines

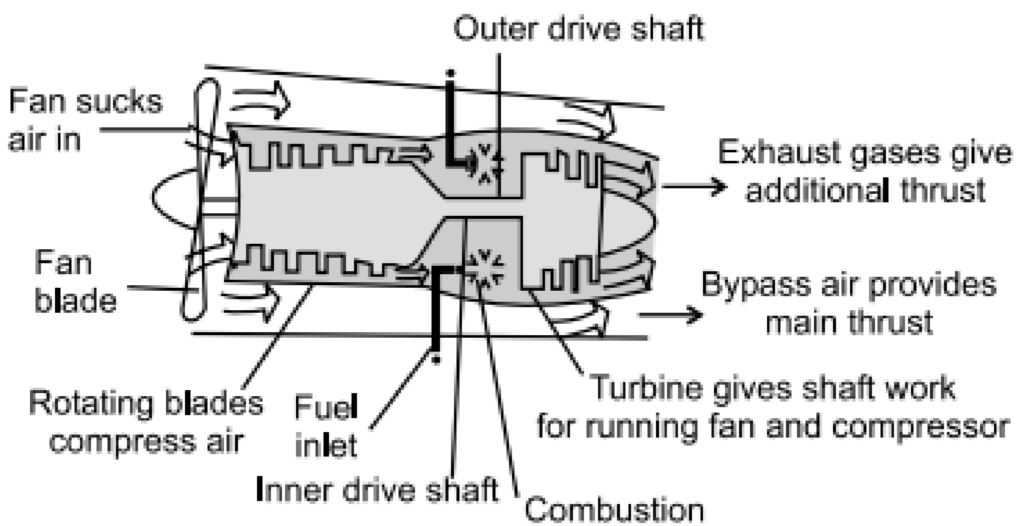
Turbofan engine

Source: The Aircraft Gas Turbine and Its Operation. © United Aircraft Corporation (now United Technologies Corp.), 1951, 1974 .

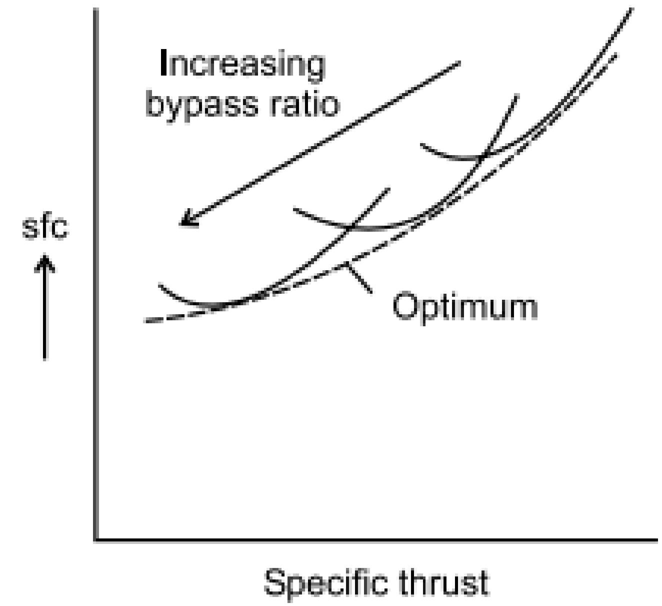
The most widely used engine in aircraft propulsion is the **turbofan** (or *fanjet*) engine wherein a large fan driven by the turbine forces a considerable amount of air through a duct (cowl) surrounding the engine.

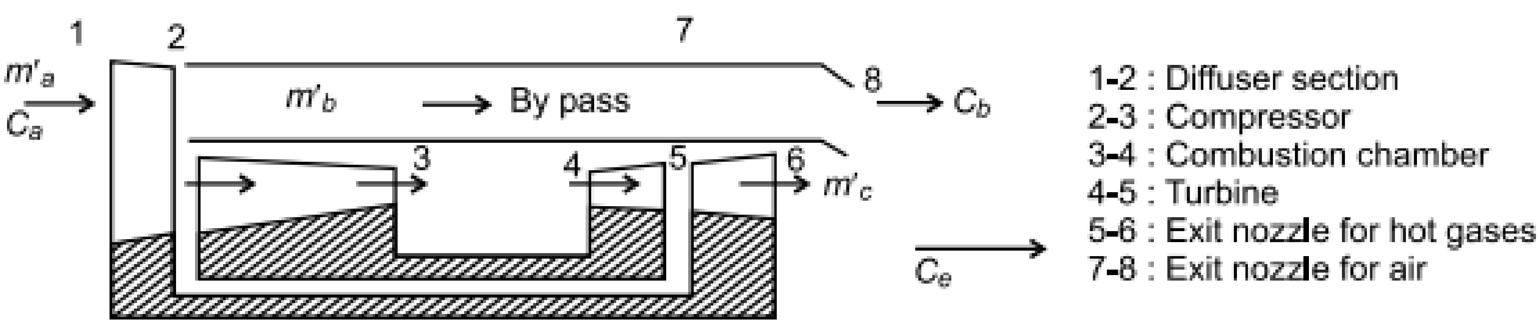


Turbofan Engines



(a) Turbofan engine arrangement



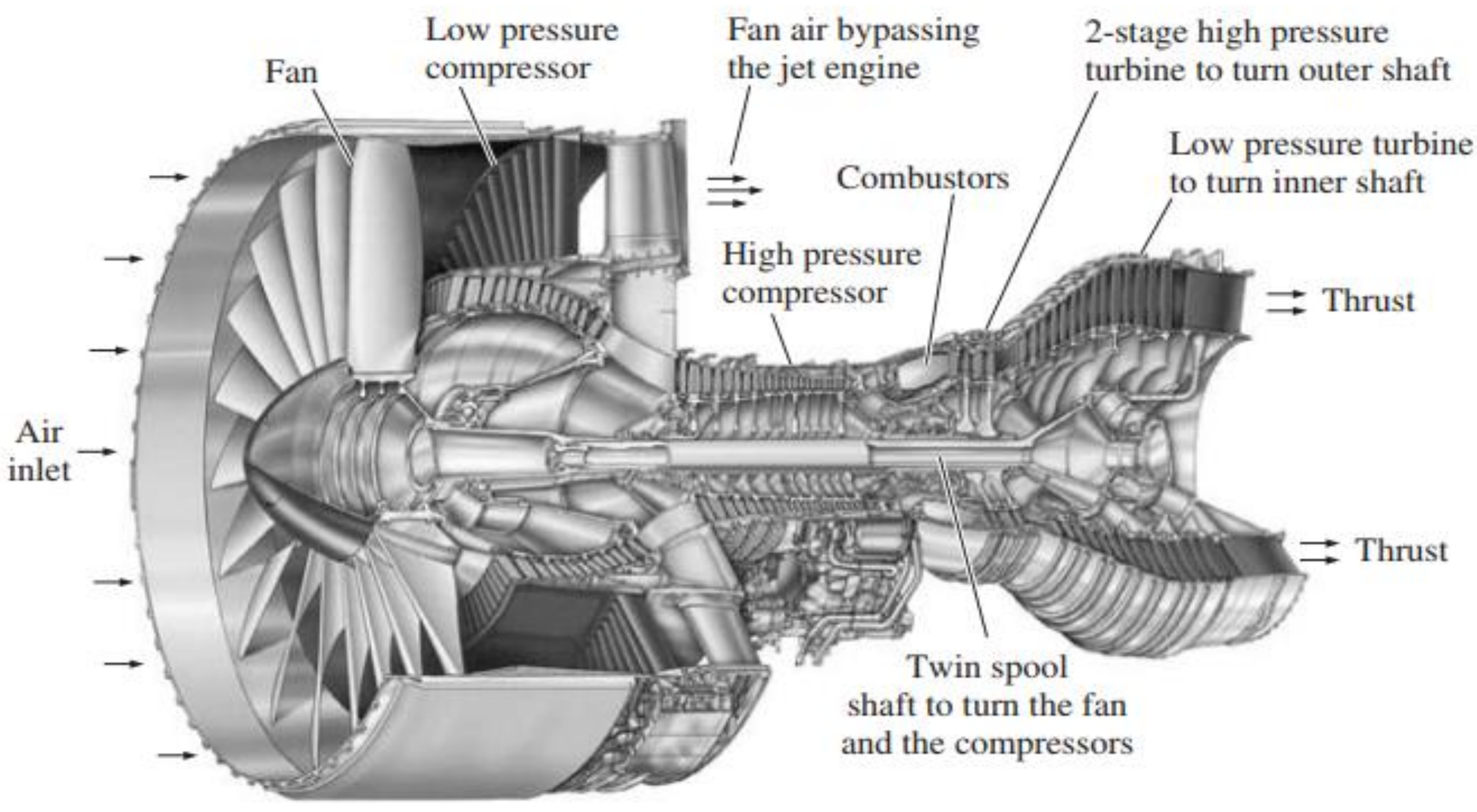


(b) Line diagram showing different sections (not to scale)

Modifications to Turbojet Engines

A modern jet engine used to power Boeing 777 aircraft

Source : Pratt & Whitney PW4084 turbofan capable of producing 84,000 pounds of thrust. It is 4.87 m (192 in.) long, has a 2.84 m (112 in.) diameter fan, and it weighs 6800 kg (15,000 lbm). Turbofan engines deserve most of the credit for the success of jumbo jets that weigh almost 400,000 kg and are capable of carrying over 400 passengers for up to a distance of 10,000 km at speeds over 950 km/h with less fuel per passenger, mile.

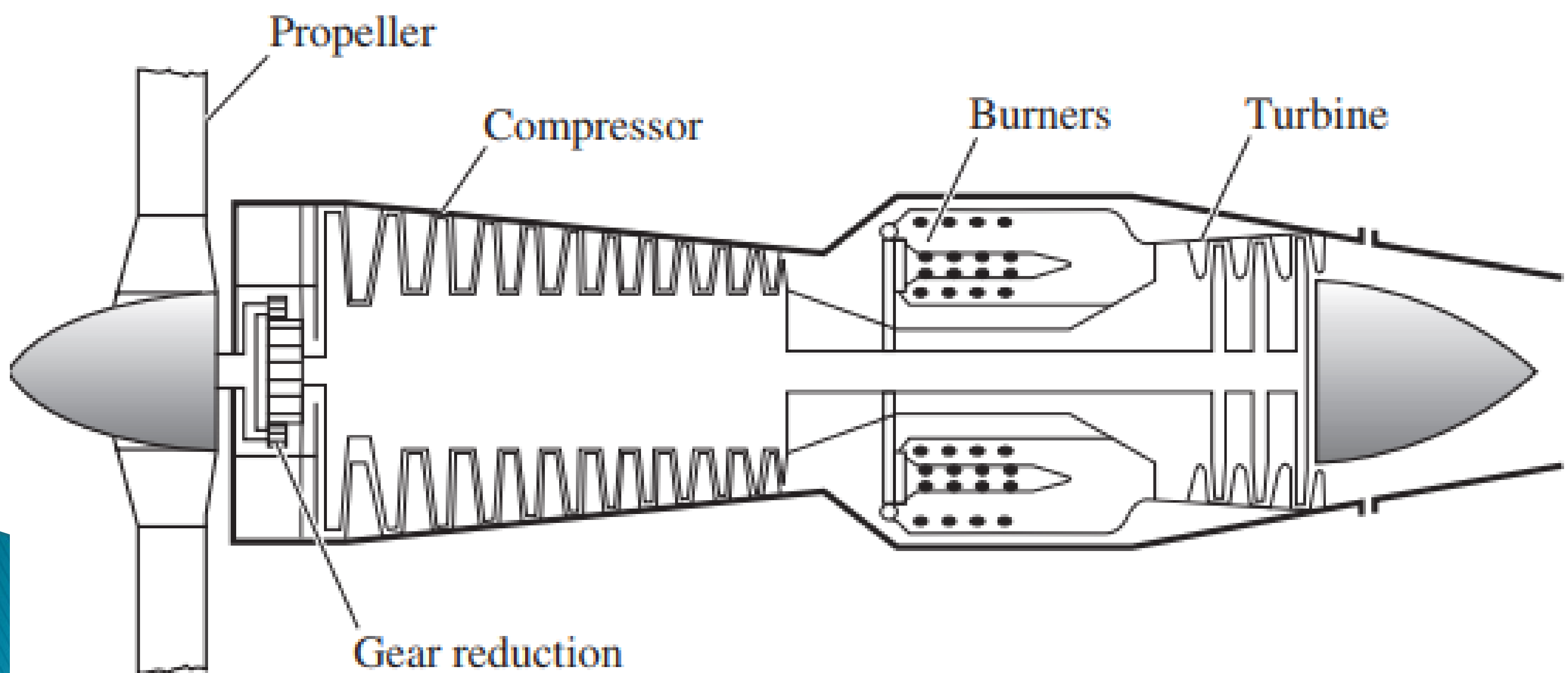


Turboprop Engines

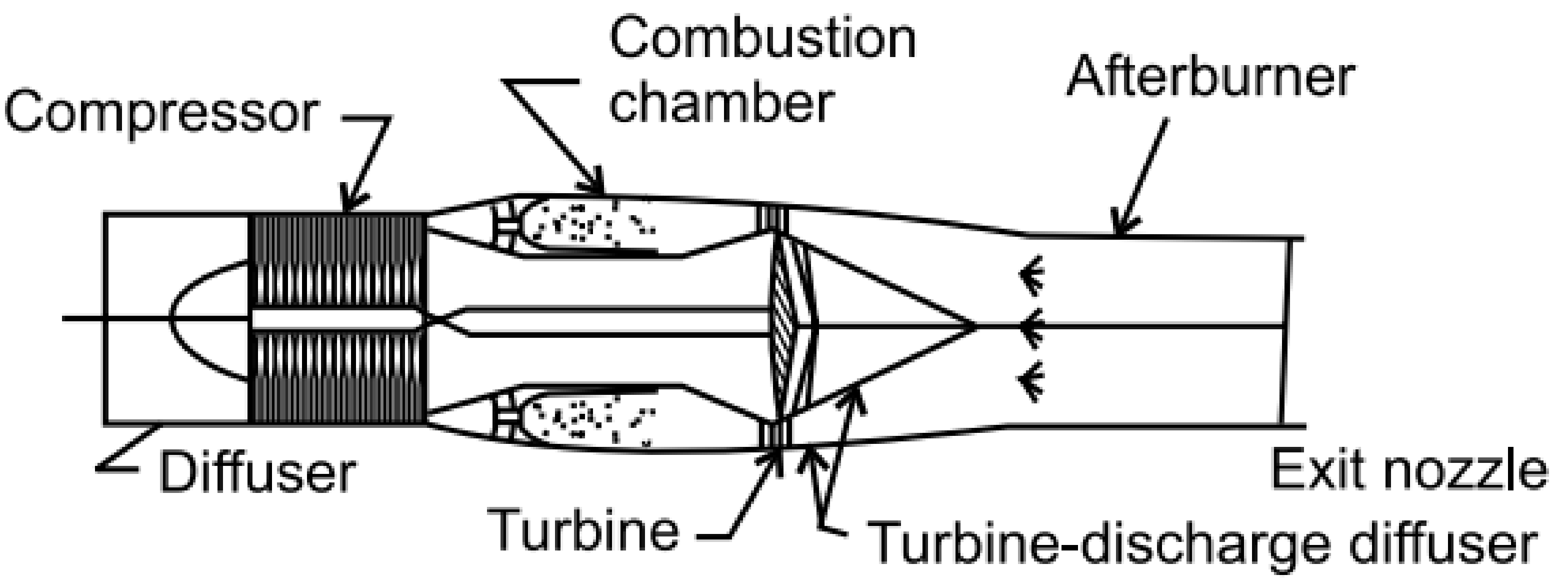
Turboprop engine

Source: The Aircraft Gas Turbine Engine and Its Operation. © United Aircraft Corporation (now United Technologies Corp.), 1951, 1974

Turbofan and propjet engines differ primarily in their bypass ratios: 5 or 6 for turbofans and as high as 100 for propjets. The ratio of the mass flow rate of air bypassing the combustion chamber to that of air flowing through it is called the *bypass ratio.* Thus, it makes sense to remove the cowl from the fan. The result is a **propjet** engine. The new propjet engines (*propfans*) are expected to achieve speeds of about Mach 0.82 and altitudes of about 12,200 m.



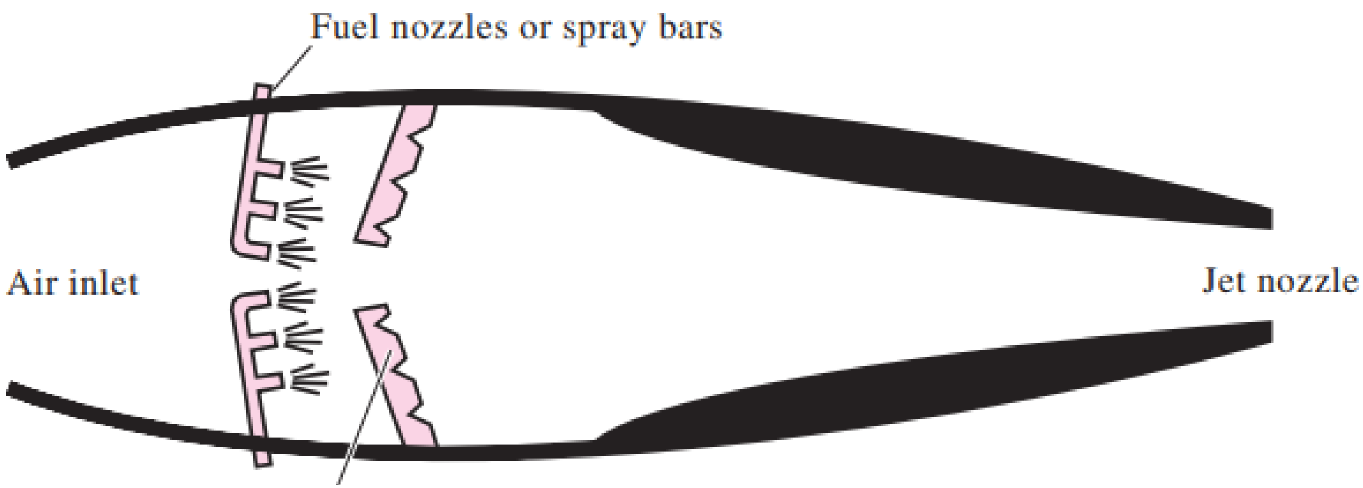
Turbojet Engine with after burner

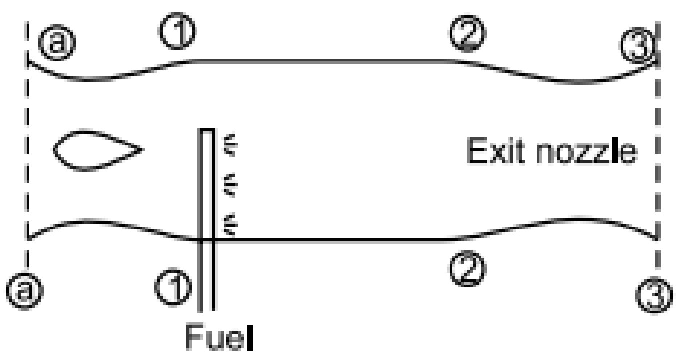


Ramjet Engines

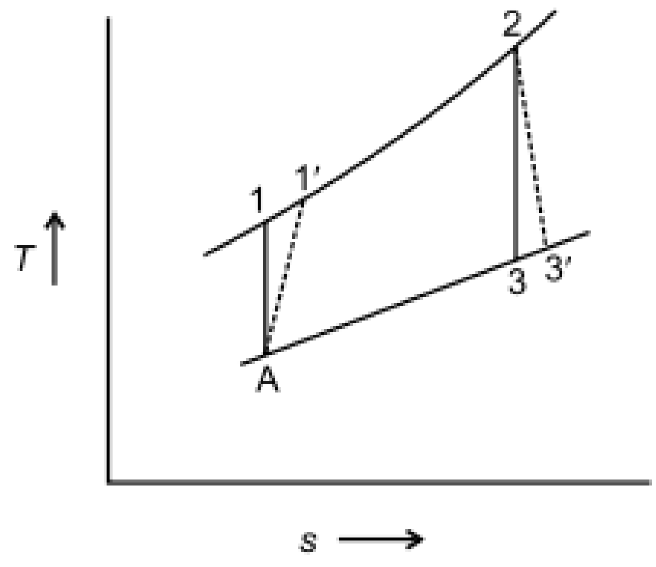
A ramjet engine

Source: The Aircraft Gas Turbine Engine and Its Operation. © United Aircraft Corporation (now United Technologies Corp.), 1951, 1974





(i) Schematic of ram jet



(ii) T-s representation of ram jet

Ramjet Engines

Advantages:

(*i*) It has no moving parts and hence ramjet are better balanced.

(*ii*) It yields greater thrust per unit mass as compared to any other propulsion engine at supersonic speed.

(*iii*) It is much simpler in construction and light in weight.

(*iv*) It yields much greater thrust per unit frontal area at supersonic speeds. Best performance can be had at 1700 km/hr to 2200 km/hr speed range.

(*v*) Variety of fuels can be used in ramjet.

(*vi*) These are ideal propulsion device for aircraft missiles.

Disadvantages:

(*i*) Forward motion is very much necessary to realize ram compression.

(*ii*) Ram pressure ratio increases gradually.

(*iii*) Ramjets are unable to work at low flight speeds.

Ram compression results in decrease in velocity and increase of pressure of air passing through this diffuser section. At the end of diffuser section a pressure barrier is created and after this point fuel is injected through nozzles and ignited using spark plug. Combustion results in expansion of gases which is restrained due to pressure barrier on one side and so move out through exit nozzle with high velocity.

Modifications to Turbojet Engines

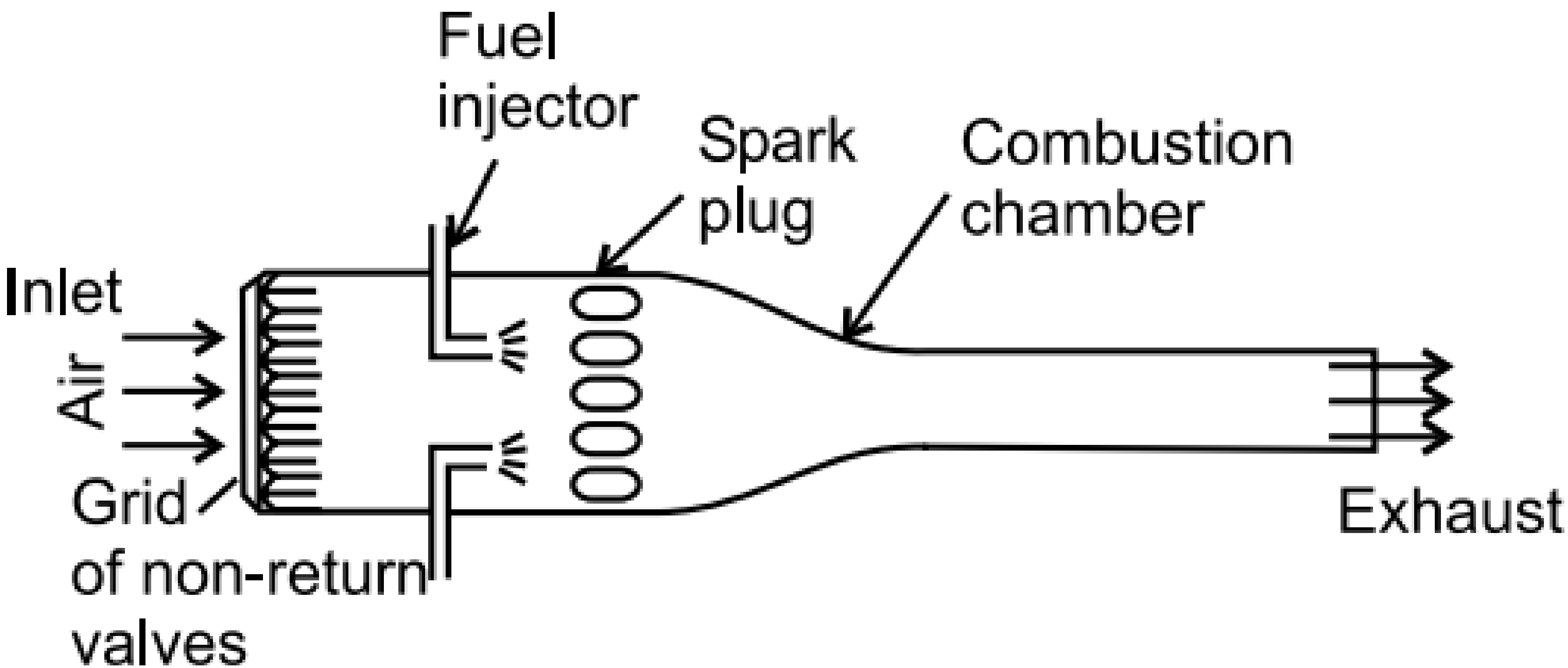
Another modification that is popular in military aircraft is the addition of an **afterburner** section between the turbine and the nozzle. Whenever a need for extra thrust arises, such as for short takeoffs or combat conditions, additional fuel is injected into the oxygen-rich combustion gases leaving the turbine.

A **ramjet** engine is a properly shaped duct with no compressor or turbine, and is sometimes used for high-speed propulsion of missiles and aircraft. The pressure rise in the engine is provided by the ram effect of the incoming high-speed air being rammed against a barrier. A ramjet engine needs to be brought to a sufficiently high speed by an external source before it can be fired.
The ramjet performs best in aircraft flying above Mach 2 or 3. In a ramjet, the air is slowed down to about Mach 0.2, fuel is added to the air and burned at this low velocity, and combustion gases are expended and accelerated in a nozzle.

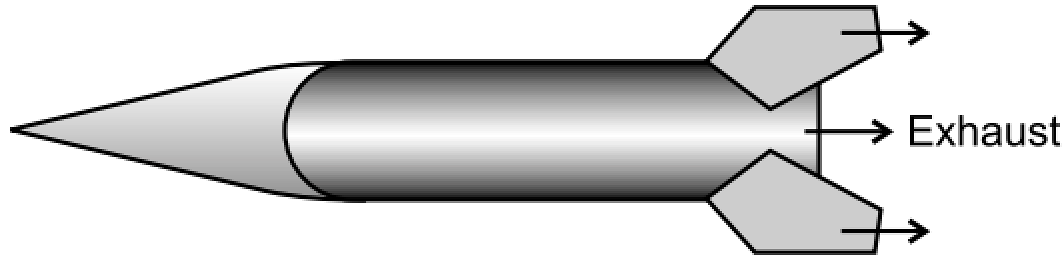
A **scramjet** engine is essentially a ramjet in which air flows through at supersonic speeds. Ramjets that convert to scramjet configurations at speeds above Mach 6 are successfully tested at speeds of about Mach 8.

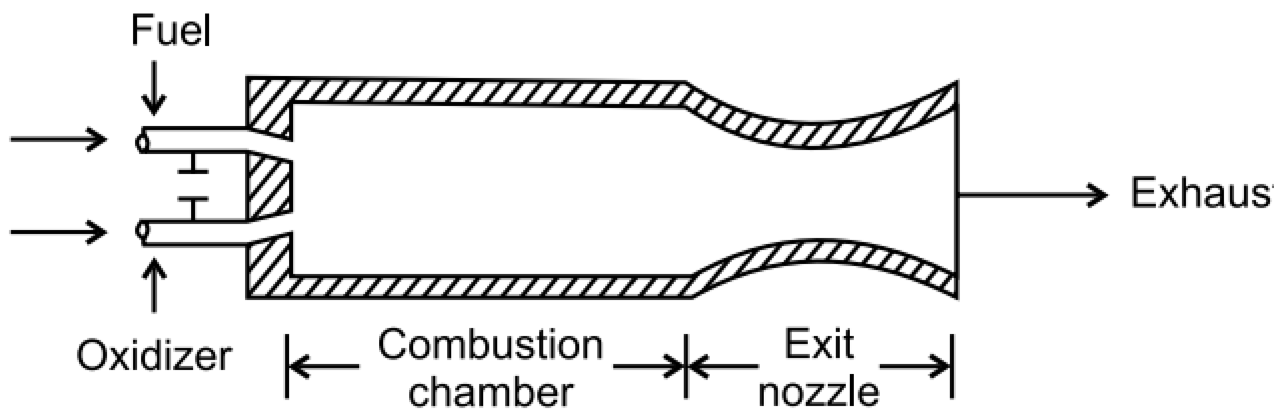
Finally, a **rocket** is a device where a solid or liquid fuel and an oxidizer react in the combustion chamber. The high-pressure combustion gases are then expanded in a nozzle. The gases leave the rocket at very high velocities, producing the thrust to propel the rocket.

PULSE JET ENGINE



PRINCIPLE OF ROCKET PROPULSION





$$T = m'_p C_e + A_e (p_e - p_a) = m'_p \cdot C_{ej}$$

$$TP = T \cdot C_a = m'_p \cdot C_{ej} \cdot C_a$$

$$C_{ej} = C_e + \frac{A_e}{m'_p} (p_e - p_a)$$

$$\eta_{prop} = \frac{TP}{TP + \text{loss of kinetic energy}}$$

$$I_{sp} = \frac{T}{m'_p} = C_{ej}$$

$$\eta_{prop} = \frac{2\,(C_a/C_{ej})}{1 + (C_a/C_{ej})^2}$$

CLASSIFICATION OF ROCKET ENGINE

(*i*) Solid propellant rocket engine
(*ii*) Liquid propellant rocket engine.

Desired properties of propellant for rocket engine are,
(*i*) propellant should have large heating value.
(*ii*) propellant should have high density so that storage space required is small.
(*iii*) propellant should be capable of having smooth ignition.
(*iv*) propellant should have stability and ease of handling and storage.
(*v*) propellant should be non-toxic and non-corrosive.
(*vi*) propellant should be environment friendly.

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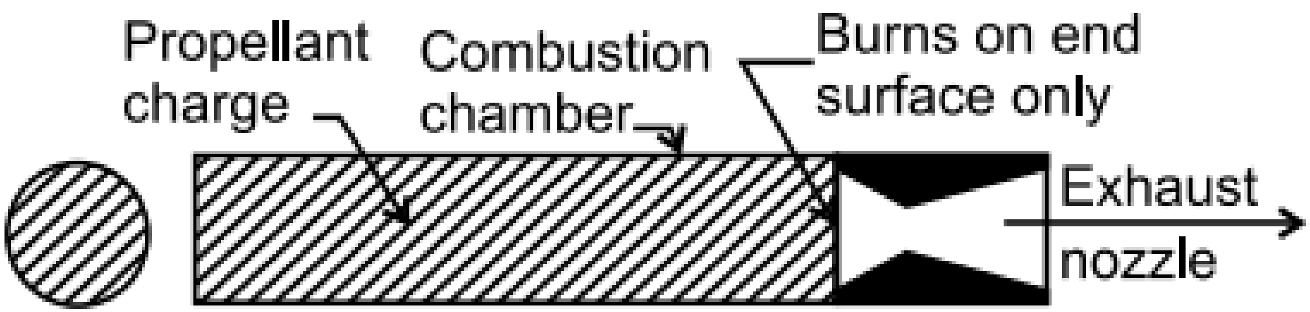
SOLID PROPELLANT ROCKET ENGINES

Specific requirements of solid propellant are,

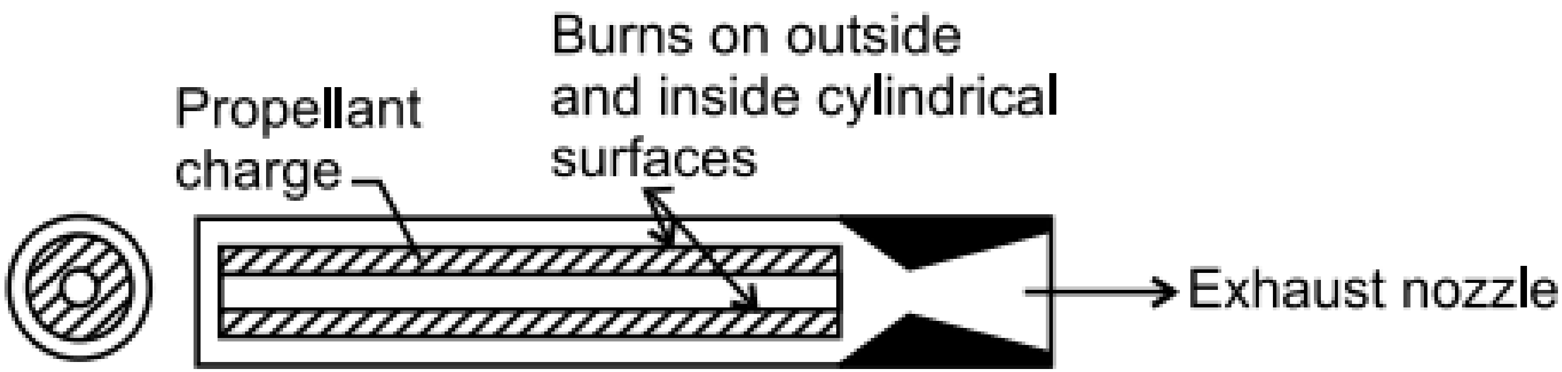
(*i*) Propellant should have sufficient compressive and impact strength at low temperature.

(*ii*) Propellant should give uniform burning.

(*iii*) Propellant should give high specific impulse.

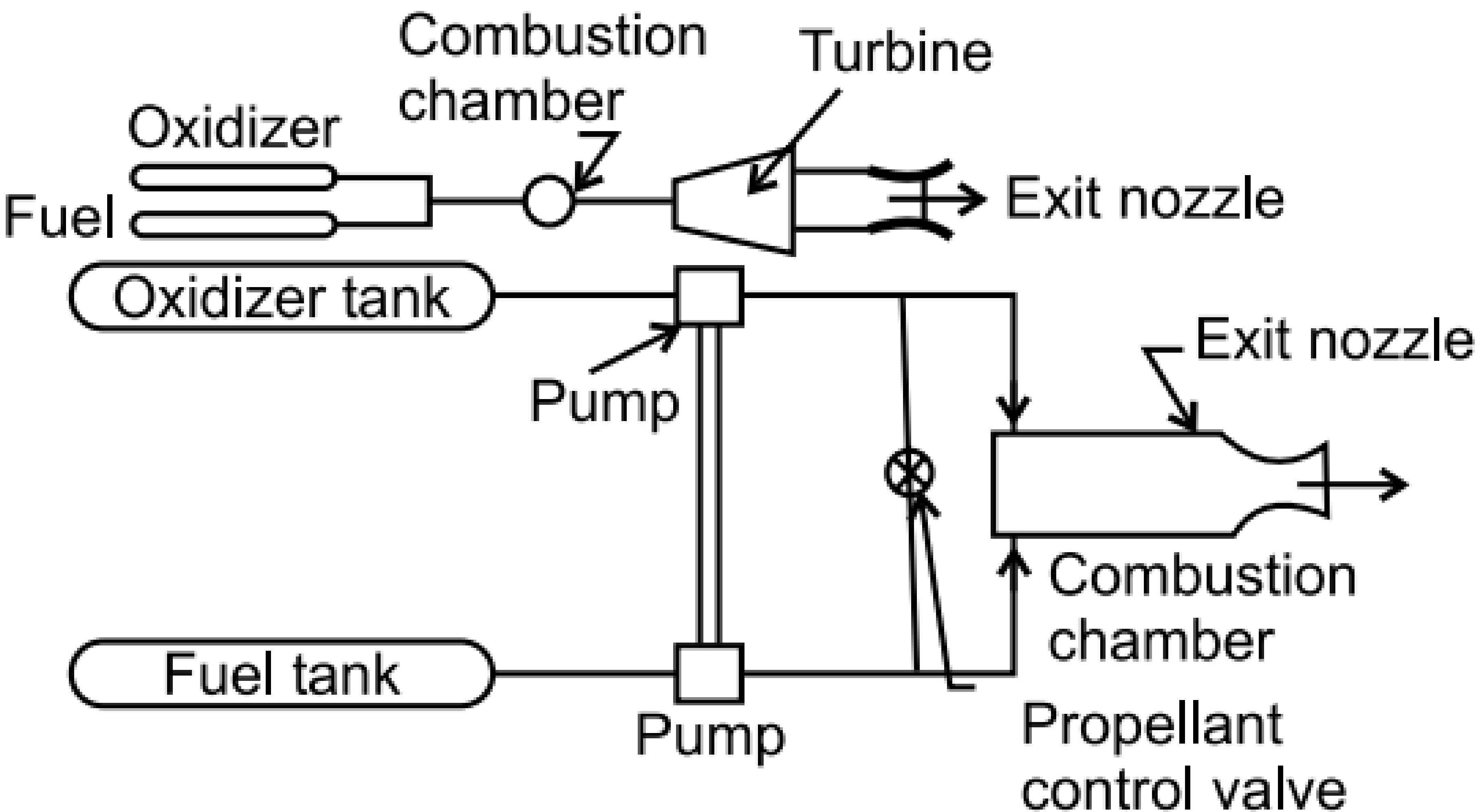


(a) Restricted burning rocket engine

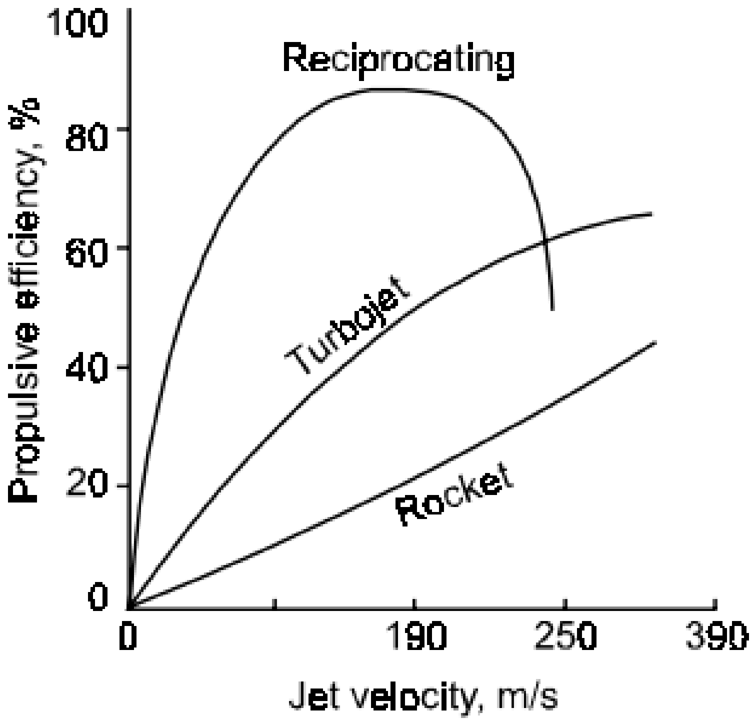


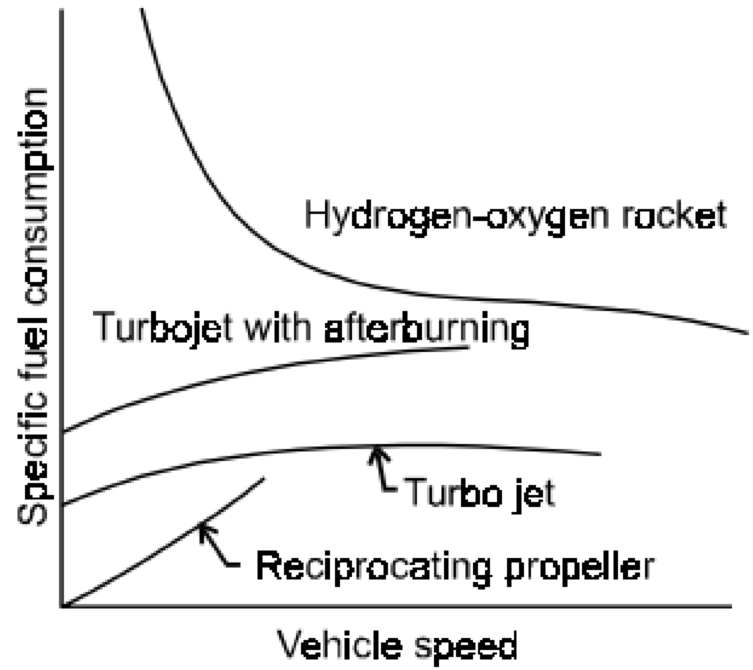
(b) Unrestricted burning rocket engine

LIQUID PROPELLANT ROCKET ENGINES



Comparative Performance





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