UNIT III: Propulsion:

Thrust for Flight- Reciprocating Engines; Jet Engines:

Types of Aerospace Propulsion:

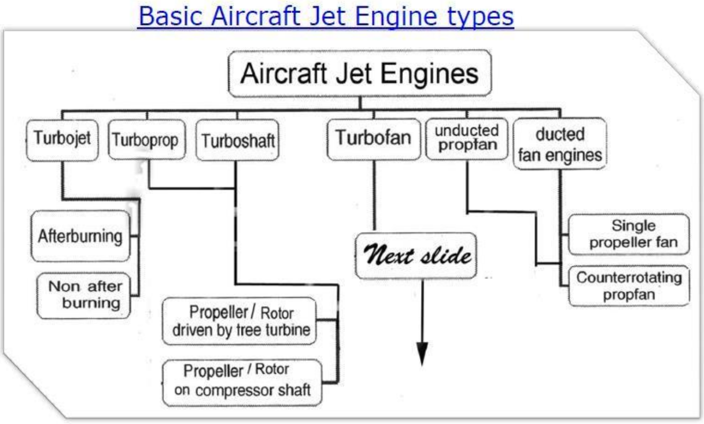
Air Breathing Systems: Broadly grouped as - Reciprocating& Jet Propulsion Engines.

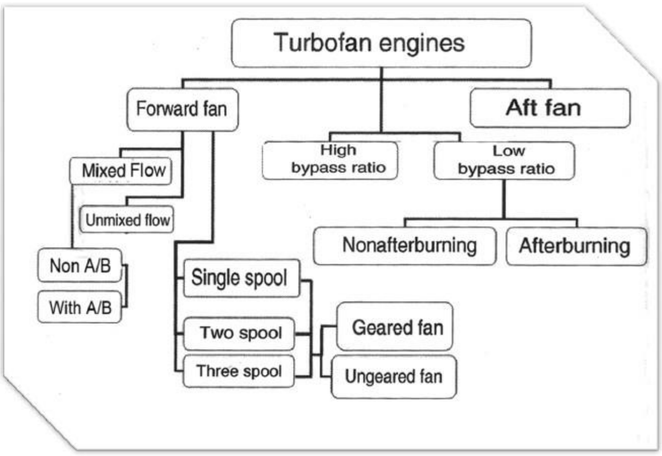
- Reciprocating Engines
- Gas Turbine Engines
- Ram Jets, Pulse Jets & Scram Jets

Non Air Breathing Systems

- Rockets

Basic Aircraft Jet Engine types





Working Principles, Advantages/Disadvantages & Applications:

Reciprocating Engines (I.C Engine): Working Principle: The four strokes of an Internal Combustion (I.C) engine are Intake, Compression, Power and Exhaust strokes.

During intake stroke, the piston moves downwards and the mixture of fuel and air (charge) is admitted in to the cylinder. At the completion of intake stroke, the inlet valve closes.

During the compression stroke, the piston moves up, compressing the charge. At the end of compression stroke, the electric spark ignites the charge.

On ignition, combustion of air fuel mixture releases thermal energy, exerting high force on the piston. This commences the power stroke.

During the power stroke, the piston is driven downwards.

Once the power stroke is completed, the exhaust valve opens. While the piston is moving up, the combustion gases are driven out of the cylinder through the exhaust valve. This creates a suction in the cylinder, that initiates the next cycle of operations.

The reciprocating movement of piston is transmitted to the crankshaft and converted into rotary motion. The crankshaft is connected to the propeller, which produces the forward thrust force for the aircraft.

The rotating output shaft of the I.C engine can be connected to a propeller, ducted fan, or helicopter rotor.

The propeller displaces a large mass of air rearwards, accelerating it in the process.

Reciprocating engines can produce up to 4000 KW power. Power to weight ratio (P/W) of up to 1.4 is produced.

The power produced by an I.C engine is given by

P = $\frac{KNV_c\rho_{air}f Q_f\eta_o}{60}$ where

K = constant; either 1.0 for 2 stroke engine or 0.5 for 4 stroke engine

N = rpm (around 5000-9000 rpm)

V_c = Volume of the cylinder

ρ_{air} = density of air

f = fuel air ratio (usually 13 to 15 ie one part fuel to 15 parts of air to burn the fuel completely)

Q_f = Calorific value of fuel (kerosene- 42 MJ/kg)

η_o = overall efficiency (usually 0.25 to 0.35)

$KNV_c\rho_{air}$ is the mass flow rate ingested in to the engine

- Multiplying mass flow rate with f gives the amount of fuel
- Multiplying with Q_f gives the heat energy released

To increase the power of the I.C engine, we need to

- Increase N –increases P
- As altitude increases ρ decreases, and P reduces. To offset this, turbo superchargers are used.

Advantages of Reciprocating Engines:

- Reciprocating engines provide excellent fuel economy and good take-off characteristics within their range of operations
- Highly suitable for small aircraft flying up to 500 km/hr and operating at low altitudes
- Components of reciprocating engines are subjected less thermal stresses than gas turbine-propeller combination
- Aircraft fitted with reciprocating engines need short runways
- Mainly used for business travel, farming & agriculture, air-taxi/ambulance, pilot training and unmanned aerial vehicles

Disadvantages of Reciprocating Engines:

- Reciprocating engines suffer drop in power at altitudes
- Difficulty in cooling and lubrication
- Low Power/Weight ratios compared to gas turbine engines
- Need high octane fuels to improve power output
- Increase in power output require larger number of cylinders, thereby increasing the frontal area and weight
- Use of reciprocating engines is limited to low speeds and altitudes
- Development reached a saturation stage as far as maximum power is concerned
- Maintenance requirement of piston-prop engines is more than turbojet aircraft
- Exhaust gases have less impurities in turbojet engines

Aircraft gas turbine Engines

All modern aircraft are fitted with gas turbine engines. Gas turbine engines can be classified into the following:-

(a) Turbojet engines

(b) Turbofan engines

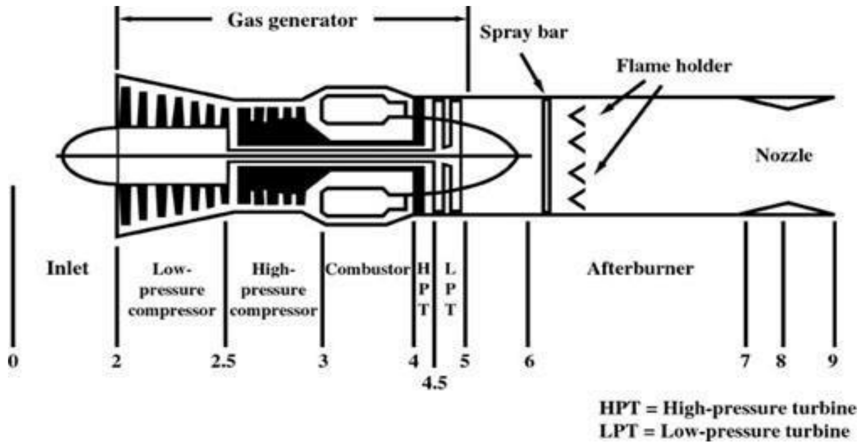
(c) Turbo-shaft engines

(d) Turboprop engines

Taken in the above order they provide propulsive jets of increasing mass flow and decreasing jet velocity. Therefore, in that order, it will be seen that the turbojet engines can be used for highest cruising speed whereas the turboprop engine will be useful for the lower cruising speed at low altitudes.

In practice the choice of power plant will depend on the required cruising speed, desired range of the aircraft and maximum rate of climb.

Turbojet Engine: Schematic diagram of a turbojet engine with station numbering is given below:



Working Principle:

1. The thrust of a turbojet engine is developed by compressing the free stream air in the diffuser or inlet and compressor. The diffuser converts the kinetic energy of the entering air into pressure rise which is achieved by ram effect. Diffusion in the inlet occurs due the geometric shaping of the inlet.
2. The compressor is driven by the turbine. It rotates at high speed, adding energy to the airflow and at the same time squeezing (compressing) it into a smaller space. Compressing the air increases its pressure and temperature
3. Compressor types used in turbojets were typically axial or centrifugal.
4. Use of axial flow compressors enable high pressure ratios. Modern axial compressors are split into low pressure and high pressure spools, driven by corresponding two stage turbine. High compressor ratios of 15:1 or more can be achieved while improving stability of operation at off-design conditions. The high pressure air is then mixed with fuel and burnt in the combustion chamber under constant pressure condition.

5. The combustion gasses at high temperature and pressure are expanded in the turbine and the exhaust nozzle. The expansion of gasses in the turbine provides power to drive the compressor while the exhaust nozzle expands the gasses to atmospheric pressure, thereby producing propulsive force, thrust.
6. The net thrust delivered by the engine is the result of converting internal energy to kinetic energy.
7. The exhaust products downstream of the turbine still contain adequate amount of oxygen. Additional thrust augmentation can be achieved by providing an afterburner in the jet pipe in which additional amounts of fuel can be burnt.
8. Turbojet engines are most suitable for speeds above 800 km/hr and up to 3.0 mach number

Advantages of Turbojet:

1. Power to Weight ratio is about 4 times that of Piston-Prop combination
2. Simple, easy to maintain, requires lower lubricating oil consumption. Complete absence of liquid cooling reduces frontal area
3. Turbojets allow faster supersonic speeds up to 3.0 M
4. There is no limit to power output while piston engines reached their peak power, beyond which any increase will result in high complexity and greater weight/frontal area.
5. Speed of turbojet is not limited by the propeller.
6. Turbojets can attain higher speeds than turboprop aircraft

Disadvantages-Turbojet:

- Fuel economy at low operational speeds is very poor
- It has low take-off thrust and hence poor starting characteristics
- High operating temperatures and engine parts are subjected to thermal stresses

Application: Turbojet engine is highly suited for aircraft at speeds above 800 km/hr.

Advantages of Gas turbines over Reciprocating Engines:

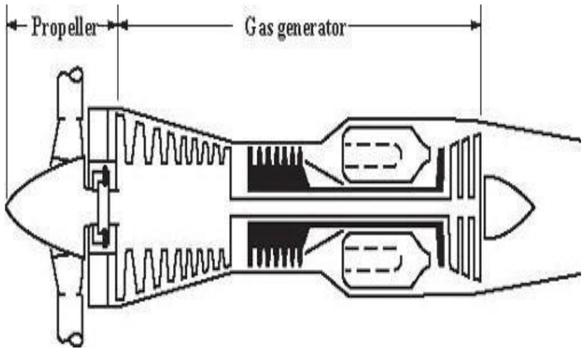
- **Mechanical Efficiency**: Mechanical efficiency of gas turbine engines is higher than reciprocating engines. This is mainly due to high friction losses in reciprocating engines.
- **Balancing**: Due to absence of reciprocating mass in gas turbine engines, balancing can be near perfect. Torsional vibrations are absent because gas turbine is a flow machine.

- **Smooth & Vibration-free operation**: Turboprop engines have fewer moving parts than piston-prop engines, offering greater reliability and time-between-overhaul (TBO).
- **Power**: The higher power of a turbo-prop engine allows it to fly at higher speeds and altitudes.
- **Shape**: Gas turbine engines have streamlined shape suitable from aerodynamic point of view.
- **Fuel**: Aviation turbine fuel is much cheaper than the high octane fuels used by reciprocating engines.
- **Lower Cost**: For a given power, gas turbine engine has lower cost and can be built faster
- **Weight:** Gas turbine engines have higher power-to-weight ratios. This means, for a given weight, gas turbine engines develop more power.
- **Lubrication:** Lubrication in gas turbine engines is much simpler than reciprocating engines. The requirement is chiefly to lubricate the main bearing, compressor shaft and bearing auxiliaries.
- **High operational speed:** Turbine can be run at much higher speed than reciprocating engine. Turbine can also be made lighter than the reciprocating engine of similar output. Therefore, for a given output, and higher speed, the torque can be lower. Gas turbine engines have better torque characteristics.
- **Silent Operation:** Since exhaust from gas turbine engines occurs under practically constant pressure conditions unlike the pulsating nature of the reciprocating engine exhaust, the usual vibrational noises will be absent in gas turbine engines.
- **Maintenance:** Relatively simpler in case of gas turbine engines.

Advantages of Reciprocating Engines over Gas turbine Engines:

- **Efficiency**: The overall efficiency of gas turbine engines is much less than the reciprocating engines.
- **Temperature Limitation**: The turbine blades in gas turbine engine are exposed to high temperature gasses continuously, and hence cannot exceed 1500 K.
- **Cooling**: We can achieve very good results by cooling the cylinder walls effectively. Cooling of turbine blades is complicated.
- **Ease of Starting**: It is more difficult to start a gas turbine than a a reciprocating engine.
- **Complexity**: Reciprocating engines are far less complex than their turbo-prop counter parts, from engineering considerations. This is primarily because of the high temperatures and forces unique to turbo-prop engine operation, which must be accommodated from materials and engine design.

Turboprop Engine: Schematic diagram is given below:



Working Principle: Turboprop engine is an intermediate between a pure jet engine and a propeller engine.

Turboprop engine provides high thrust per unit mass flow of fuel burnt by increasing mass flow of air. It offers better fuel economy. The propeller displaces a large mass of air rearwards, thereby increasing the net thrust.

The turbine extracts more power from the combustion gasses to drive the propeller. A small remaining energy is extracted by expansion in the jet nozzle.

The propeller and the compressor may be mounted on a single shaft or on separate shafts with a free turbine driving the propeller.

Advantages:

Turboprop engines have a higher thrust at take-off and better fuel economy.

The engine can operate economically over a wide range of speeds ranging from low speeds, where turbojet is uneconomical, to high speeds of about 800 km/hr where piston-prop engine cannot operate efficiently

It is easy to maintain and has lower vibration levels than piston-prop engine. The frontal area is much less than corresponding piston-prop engine.

Disadvantages:

The main disadvantage is that the propeller efficiency decreases greatly at high speeds due flow separation and shocks. The maximum speed is thus limited.

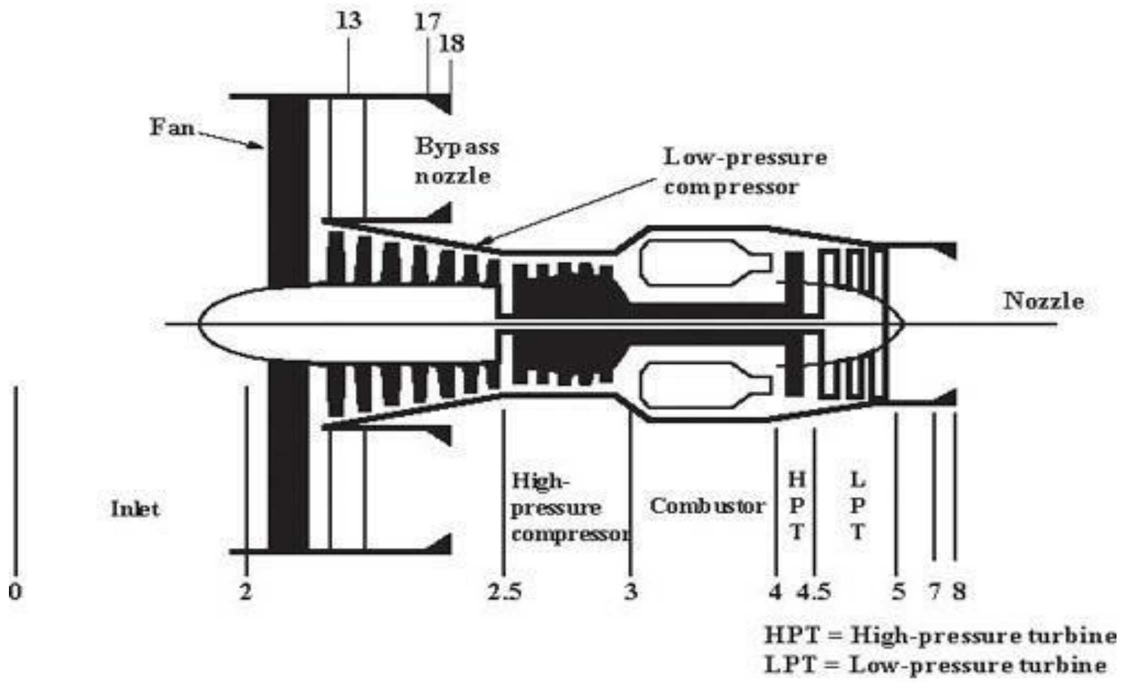
The turbine speeds need to be reduced through a suitable reduction gearing so that propeller runs at lower speeds, which adds to weight.

Applications:

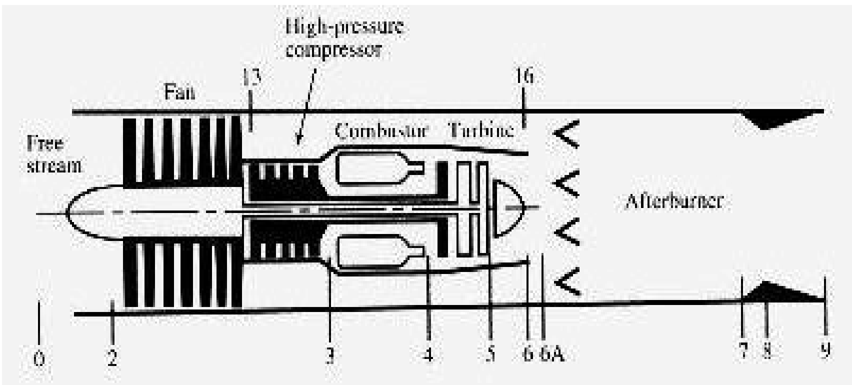
The turboprop engine is widely used in commercial and military aircraft due to its flexibility of operation and good fuel economy.

Turbofan Engine

Schematic Diagram of Turbofan (with station numbering): High by-pass ratio (used for commercial aircraft)



Turbofan with afterburner & Mixed flow: Low by-pass ratio (used for military aircraft)



Turbofan engine is designed as a compromise between turbojet and turboprop engines. The turbofan engine consists of a fan larger in diameter than the compressor, driven by the turbine. The fan displaces/bypasses free stream air around the primary engine. Two streams of air flow through the engine, primary airstream pass through the compressor and is delivered to the combustion chamber at high pressure to mix with fuel, while the other stream bypasses the primary engine to be expanded in the nozzle as a cold stream. The **hot and cold streams may be expanded through separate nozzles or combined together through a single nozzle**. The ratio of mass of cold air to the hot air is the by-pass ratio.

Thus the turbofan accelerates a larger mass of air at lower velocity than turbojet for a higher propulsive efficiency. Turbofan engines can also employ afterburner for higher thrust.

Turbofan engines can be aft-fan or forward fan (position of the fan), mixed or unmixed(hot and cold air streams) and high and low bypass ratio configuration

Advantages:

Fan is not as large as the propeller, therefore higher aircraft speeds can be attained without facing flow separation problems.

Turbofan engines do not encounter vibration problems associated with propellers. The fan could be encased in a duct/cowling to provide better aerodynamic shape.

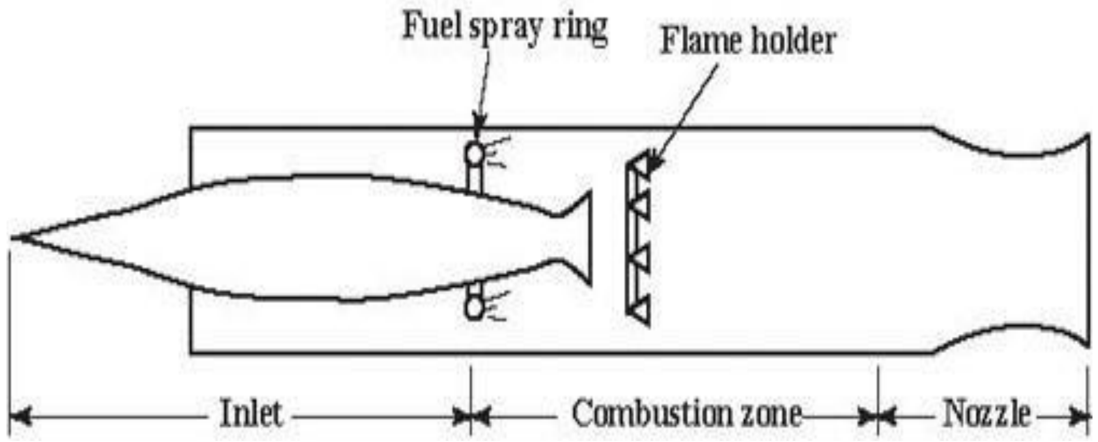
A **geared fan** connected to turbine reduces power consumed by the fan. It also produces low sound.

Turbofan is fuel efficient than turbojet, offers better propulsive efficiencies.

Lowers the sound levels of the exhaust gasses

Ramjet Engine

Schematic Diagram:



Operating Principle:

Ramjet Engine consists of supersonic diffuser, subsonic diffuser, combustion chamber and nozzle section

Air from atmosphere enters the supersonic diffuser at a very high speed. The air velocity gets reduced in the supersonic diffuser through normal and oblique shock waves.

Air velocity is furthur reduced in the subsonic diffuser.

The diffuser converts the kinetic energy of the entering air into static pressure and temperature rise which is achieved by ram effect. Diffusion in the inlet also occurs due the geometric shaping of the diffuser. The diffuser thus slows down the air enabling combustion.

Fuel is injected into the combustor through suitable injectors causing mixing of fuel with the air and the mixture is burnt

Combustion gases attain a temperature of around 1500-2000 k by continuous combustion of fuel air mixture

Fresh air supply continuously will not allow gasses towards the diffuser. Instead, gases are made to expand towards the tail pipe and nozzle, which expands the gases completely.

The gases leave the engine with a speed much higher than the air entering the engine.

The rate of increase of momentum of the working fluid produces thrust F in the direction of flight

Distinguishing Features:

Air enters the engine at supersonic speeds, must be slowed down to subsonic value, to prevent blow out of the flame in the combustor

Velocity must be low enough (approximately around 0.2-0.4 mach number) to allow mixing of fuel and stable combustion

Cycle pressure ratio depends on the diffusion pressure ratio. Very high pressure ratios of about 8 to 10 through ram compression is possible, therefore, a mechanical compressor is not required

Slowing down speeds from mach 3.0 to 0.3 will result in a pressure ratio of more than 30

As the ram pressure increases, a condition is reached where the nozzle gets choked. Thereafter, the nozzle operates at Mach 1 condition at throat

Advantages:

Ramjet is a simple machine and does not have any moving parts

Since turbine is not used, maximum temperature allowed is very high, around 2000 C, as compared to around 900 C in turbojets.

We can burn air/fuel ratios of 13:1which gives greater thrust

Specific fuel consumption is much better than other gas turbine engines, at high speeds and altitudes

Wide range of fuels can be used

It is very cheap to produce; adoptable for mass production

It is not possible to start a ramjet engine without an external launching device

The engine heavily relies on the diffuser and it is very difficult to design a diffuser which gives good pressure recovery over a wide range of speeds

Due to high air speed, the combustion chamber requires flame holders to stabilize the combustion

At very high temperatures of about 2000 C, dissociation of combustion products take place, reducing the efficiency of the plant

High fuel consumption at low speeds

Applications:

Highly suitable for propelling missiles.

Used in high speed military aircraft, in a combined cycle engine (Turbojet-Ramjet combination).

Development is in progress for a hypersonic aircraft system using turbojet-ram-scramjet combined cycle.

Subsonic ramjets are used as target weapons in conjunction with turbojet aircraft.

Pulsejet Engine:

Schematic Diagram:

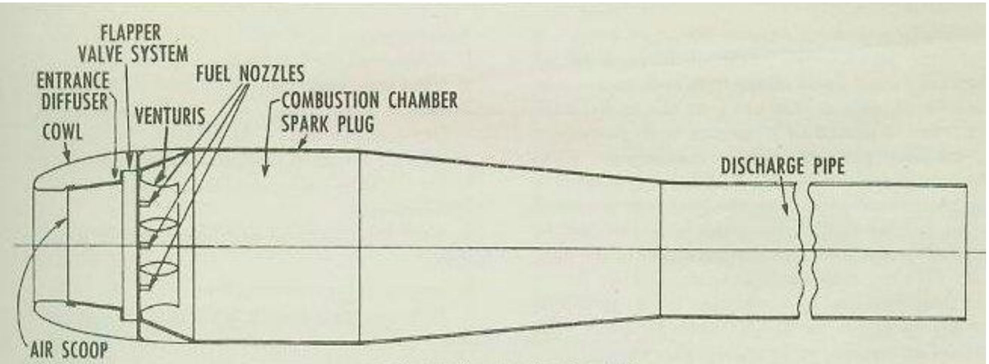


FIGURE 11D3.—A pulse-jet engine.

Basic Components are diffuser, Valve grid with spring loaded flapper valves, Combustion chamber with spark plug, tail pipe and discharge nozzle

Operation:

The diffuser converts the kinetic energy of the entering air into static pressure rise and slows down the air. Ram action also builds pressure in the diffuser.

The pressure differential opens the flapper valves which are spring loaded and the high pressure air enters the combustion chamber.

Fuel is injected and ignited by the spark plug

Combustion proceeds at constant volume with sudden explosion.

There is a sudden pressure rises in the combustion chamber which closes the flapper valves

The combustion gasses expand in the nozzle and escape to the atmosphere at high velocity

As combustion products leave the combustion chamber, a low pressure is created which causes the valves to open and a new charge of air enters the chamber

Distinguishing feature: Since the combustion chamber builds pressure, the engine can operate in static condition also. Proper design makes the duct to fire at a given pulse rate which can be as high as 500 cycles/sec

Advantages:

1. Simple to construct and hence cheap.
2. Can be mass produced in a short time.
3. Since it does not have any moving parts like compressor of turbine, it can be used in high temperatures.
4. Can be used for military applications.

Disadvantages:

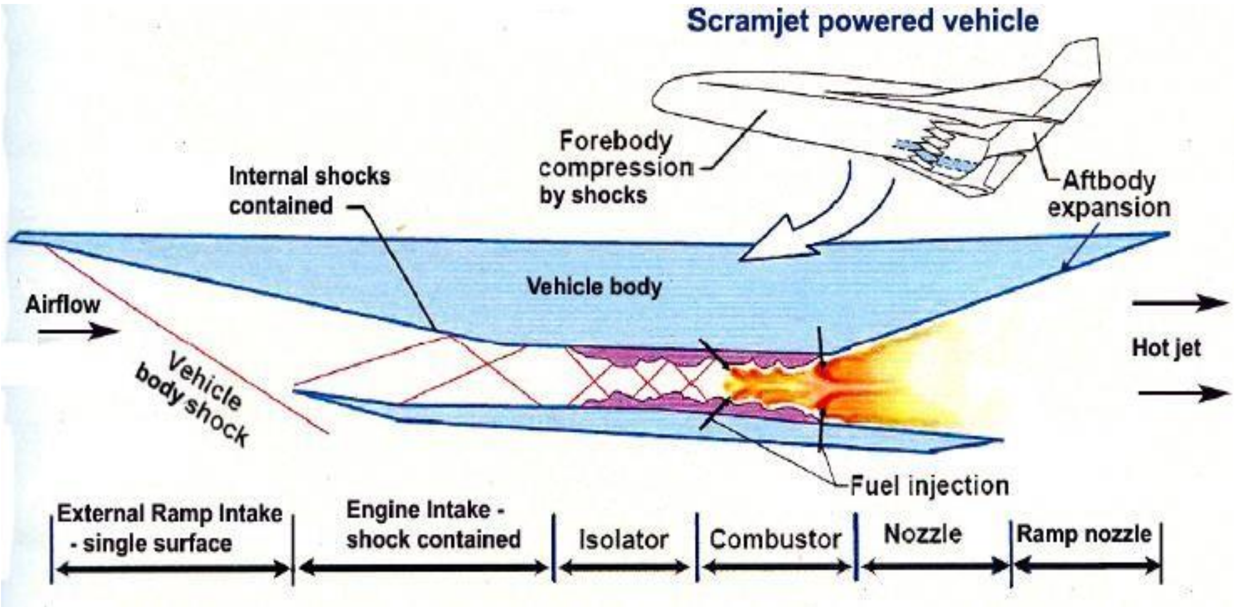
1. It is having limited flight speed only.
2. Limited flying altitude.
3. High vibration and noise due to the pulses of thrust produced

Scramjet Engine:

- Scramjet engine stands for supersonic combustion ramjet engine.
- The flow speed in the combustion chamber is supersonic
- Scramjet engine is characterized by high flow speeds ie low residence times in the engine.
- The engine needs larger combustion volumes; leading to integrated design of airframe and engine.
- In scramjet aircraft, the entire lower body of the aircraft is occupied by the engine. The front portion of the underside operates as external/internal diffuser, with rear portion providing expansion surface.

The scramjet consists of

- Diffuser (compression component) consisting of external ramp intake and engine intake
- Isolator
- Supersonic combustor
- Exhaust nozzle or aft body expansion component



Scramjet Engine- Construction: Scramjet engine is characterized by slow reaction times and high flow speeds ie low residence times in the engine. The engine needs larger combustion volumes; leading to integrated design of airframe and engine. In scramjet aircraft, the entire lower body of the aircraft is occupied by the engine. The front (fore) portion of the underside operates as external/internal diffuser, with rear (aft) portion providing expansion surface.

The scramjet consists of

- Diffuser (compression component) consisting of external ramp intake and engine intake
- Isolator
- Supersonic combustor
- Exhaust nozzle or aft body expansion component

Diffuser

- It consists of fore-body external intake and internal intake
- The fore-body provides the initial external compression and contributes to the drag and moments of the vehicle.
- The internal inlet compression provides the final compression of the propulsion cycle.

Since the flow upstream is supersonic, the geometry of the diffuser is entirely convergent.

Isolator: Isolator is constant area diffuser containing the internal shock structure, swallowed during supercritical operation of the inlet (or during operation after the inlet "started"). The isolator is inserted before the combustor to diffuse the flow further, through a shock train, producing desired flow speeds in the combustors. The function of the isolator is:

- The shock train provides a mechanism for the supersonic flow to adjust to a static back pressure higher than its inlet static pressure
- The isolator cross-sectional area may be constant or slightly divergent to accommodate boundary layer separation.
- When the combustion process begins to separate the boundary layer in the combustor, a pre-combustion shock train forms.
- The shock structure allows the required pressure rise, thus isolating the combustion process from the inlet compression process. Thus the isolator functions to prevent inlet surge or "unstart".

Combustor: Main features include:

- Avoidance of hot pockets near the walls implies that the fuel be injected from centrally located struts.
- The usual circular configuration for combustors can be sacrificed in favor of a rectangular configuration.
- Typical velocities in the combustion chamber are about 1 to 1.5 km/s and the Mach numbers will be 1.4 to 2.3 for a typical combustor entry Mach number of 2.5

Combustion limits: Two limits are very critical for the operation

- First, since when a supersonic flow is compressed, it slows down, the level of compression must be low enough (or the initial speed high enough) not to slow the gas below Mach 1. If the gas within a scramjet goes below Mach 1 the engine will "choke", transitioning to subsonic flow in the combustion chamber. Additionally, the sudden increase in pressure and temperature in the engine can lead to an acceleration of the combustion, leading to the combustion chamber exploding.
- Second, the heating of the gas by combustion causes the speed of sound in the gas to increase (through increase of $\sqrt{t}$ and hence cause Mach number to decrease) even though the gas is still travelling at the same speed. Forcing the speed of air flow in the combustion chamber under Mach 1 in this way is called "**thermal choking**".
- A thermal throat results when the flow is slowed through tailored heat for causing dual-mode operation.
- There are engine designs where a ramjet transforms into a scramjet over the Mach 3-6 range, known as dual-mode scramjets.

Expansion System:

- The expansion system, consists of
  a. Internal nozzle

  b. Vehicle aft body
- It completes the propulsion flow path and controls the expansion of the high pressure and temperature gas mixture to produce net thrust.

Applications of Scramjets:

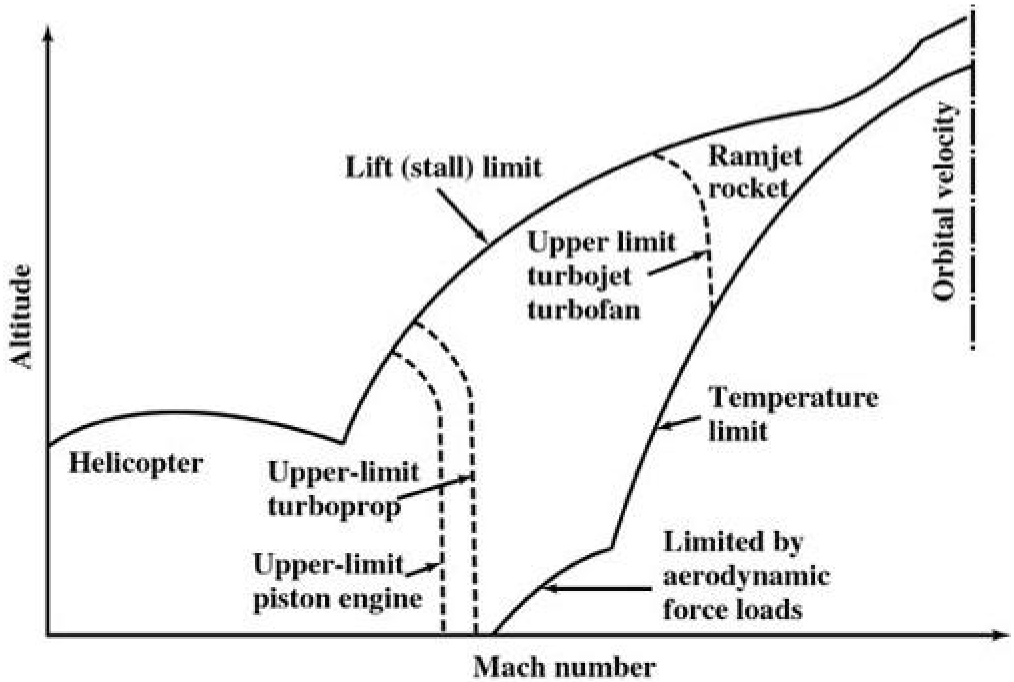
- Weapons systems -hypersonic cruise missiles
- Aircraft systems - global strike / reconnaissance
- Space access systems that will take off and land horizontally like commercial Airplanes
- Using these Scramjet technologies, along with additional ground-and flight-test experiments, will pave the way for affordable and reusable air-breathing hypersonic propulsion systems such as missiles, long range aircraft and space-access vehicles

Advantages:

1. Need not carry oxygen on board
2. No rotating parts makes it easier to manufacture than a turbojet

3. Has a higher specific impulse (change in momentum per unit of propellant) than a rocket engine; could provide between 1000 and 4000 seconds, while a rocket only provides 450 seconds or less
4. Higher speed could mean cheaper access to outer space in the future

Flight Limits/Operating Envelope:



Missiles:

In military parlance, missiles are powered / guided munitions are broadly categorised as follows:

- A powered, guided munition that travels through the air or space is known as a military **missile** (or *guided missile*.)
- A powered, *un*guided munition is known as a **rocket**.

TECHNOLOGY :

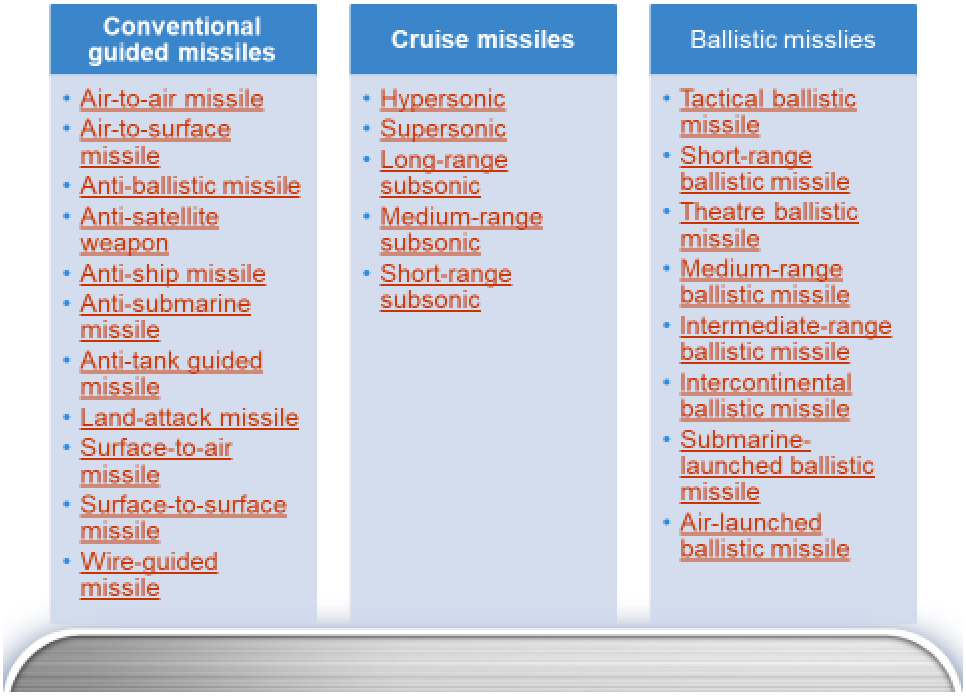
Guided missiles have a number of different system components:

- Targeting and/or guidance
- Flight system
- Engine
- Warhead

Basic categorization

Missiles are generally categorized by their launch platform and intended target. Other kinds of military missiles are Glide- Bombs , Torpedos etc.

Their basic types are



Conventional guided missiles	Cruise missiles	Ballistic misslies
Air-to-air missile	Hypersonic	Tactical ballistic missile
Air-to-surface missile	Supersonic	Short-range ballistic missile
Anti-ballistic missile	Long-range subsonic	Theatre ballistic missile
Anti-satellite weapon	Medium-range subsonic	Medium-range ballistic missile
Anti-ship missile	Short-range subsonic	Intermediate-range ballistic missile
Anti-submarine missile		Intercontinental ballistic missile
Anti-tank guided missile		Submarine-launched ballistic missile
Land-attack missile		Air-launched ballistic missile
Surface-to-air missile		
Surface-to-surface missile		
Wire-guided missile		

Space Launch Vehicle:

A **launch vehicle** is the rocket we see sitting on the launch pad during countdown. In spaceflight a **launch vehicle** or **carrier rocket** is a rocket used to **carry a payload from the Earth's surface into outer space**. A **launch system** includes the launch vehicle, the launch pad and other infrastructure.

ROLE :

- It provides the **necessary velocity change** to get a spacecraft into space.
- At lift-off, the launch vehicle blasts almost straight up to gain altitude rapidly and get out of the dense atmosphere which slows it down due to drag. When it gets high enough, it slowly pitches over to gain horizontal velocity.

A launch vehicle consists of a series of smaller rockets that ignite, provide thrust, and then burn out in succession, each one handing off to the next one like runners in a relay race. These smaller rockets are **stages.** In most cases, a launch vehicle uses at least three stages to reach the mission orbit.