SPACE PROPULSION

B. Tech VI semester

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COURSE OBJECTIVES:

The course should enable the students to:	
I	Appraise various space missions, parameters to be considered for designing trajectories and rocket mission profiles.
II	Classify the different chemical rocket propulsion systems, types of igniters and performance considerations of rockets.
III	Discuss the working principle of solid and liquid propellant rockets and gain basic knowledge of hybrid rocket propulsion.
IV	Illustrate electric propulsion techniques, ion and nuclear rocket and the performances of different advanced propulsion systems.

COURSE OUTCOMES (COs):

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CO 1	Evaluate various space missions, parameters to be considered for designing trajectories and rocket mission profiles.
CO 2	Classify the different chemical rocket propulsion systems, types of igniters and performance considerations of rockets.
CO 3	Discuss the working principle of solid propellant rockets, propellant grain designs and combustion.
CO 4	Demonstrate the working principle of liquid propellant rockets, feed systems and gain basic knowledge of hybrid rocket propulsion.
CO 5	Illustrate electric propulsion techniques, ion and nuclear rocket and the performances of different advanced propulsion systems.

UNIT 1

PRINCIPLES OF ROCKET PROPULSION

CLOs	Course Learning Outcome
CLO 1	Demonstrate the basic principles of space propulsion and its applications in different types of orbits.
CLO 2	Describe the concept of orbital elements and basic orbital equations.
CLO 3	Adapt the concepts of vertical takeoff and landing for space applications and launch trajectories.

Brief History of Rockets- Archytas' Wooden Bird

Archytas, (around 400 B.C.), a Greek philosopher and mathematician, showed off a wooden pigeon that was suspended on wires.

The pigeon was pushed around by escaping steam, according to NASA.

The pigeon used the action-reaction principle, which was not stated as a scientific law until the 17th century.

Figure 1.1 Archytas

Archytas’ Wooden Bird

Figure 1.2 Archytas’ Wooden Bird

Hero of Alexandria- Aeolipile

- Around 300 years after the pigeon experiment, Hero of Alexandria is said to have invented the **Aeolipile** (also called Hero's engine), NASA added.
- The sphere-shaped device sat on top of a boiling pool of water. Gas from the steaming water went inside of the sphere and escaped through two L-shaped tubes on opposite sides. The thrust created by the escaping steam made the sphere**....?**

Reliability

Figure 1.3 Hero of Alexandria's Aeolipile

Chinese Fire Arrows

when the first true rockets appeared? - is unclear

Perhaps the first true rockets were accidents.

In the first century A.D., the Chinese reportedly had a simple form of gunpowder made from saltpeter, sulfur, and charcoal dust. To create explosions during religous festivals, they filled bamboo tubes with a mixture and tossed them into fires. Perhaps some of those tubes failed to explode and instead skittered out of the fires, propelled by the gases and sparks produced by the burning gunpowder.

Chinese Fire Arrows

The Chinese began experimenting with the gunpowder-filled tubes. At some point, they attached bamboo tubes to arrows and launched them with bows. Soon they discovered that these gunpowder tubes could launch themselves just by the power produced from the escaping gas. The true rocket was born.

Chinese Fire Arrows

The date reporting the first use of true rockets was in 1232. At this time, the Chinese and the Mongols were at war with each other.

Figure 1.4 Chinese Fire Arrows

Chinese Fire Arrows

During the ***battle of Kai-Keng***, the Chinese repelled the Mongol invaders by a barrage of "arrows of flying fire."

Figure 1.5 Chinese Soldier Launches Fire-Arrow

Rocket Experiments

- Following the battle of Kai-Keng, the ***Mongols*** produced rockets of their own and may have been responsible for the spread of rockets to Europe.

- All through the 13th to the 15th centuries there were reports of many rocket experiments.

- In **England**, a monk named ***Roger Bacon*** worked on improved forms of gunpowder that greatly increased the range of rockets.

Rocket Experiments

- In **France**, ***Jean Froissart*** found that more accurate flights could be achieved by launching rockets through tubes.

  Froissart's idea was the forerunner of the modern bazooka.

Figure 1.6 Bazooka

Rocket Experiments

- ***Joanes de Fontana*** of **Italy** designed a surface-running rocket-powered torpedo for setting enemy ships on fire.

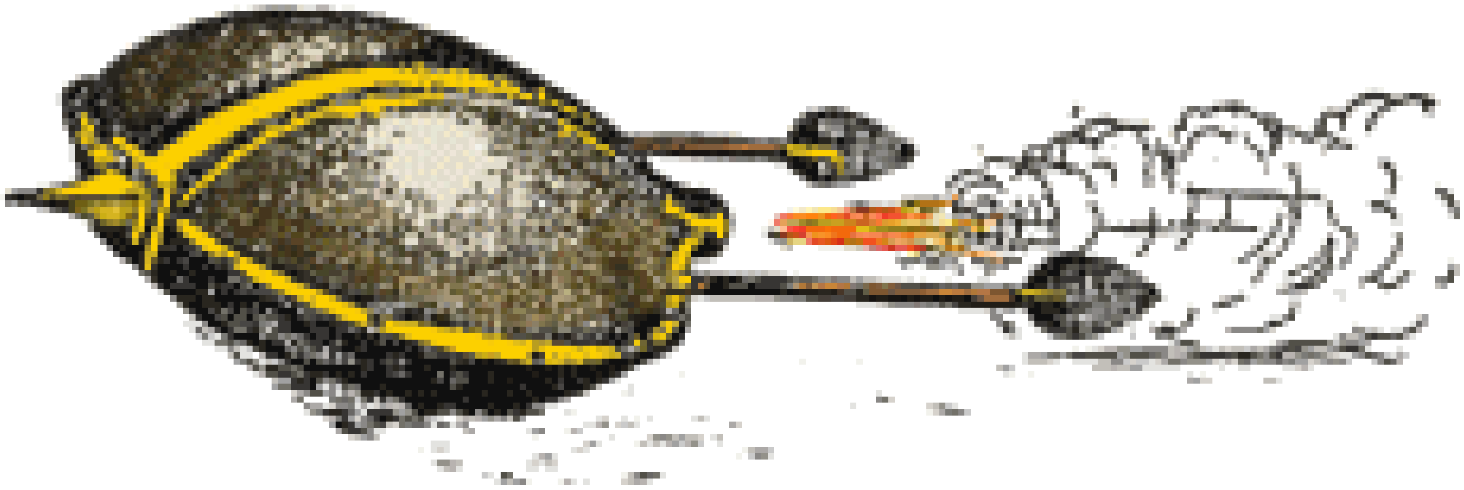


Figure 1.7 Surface Running Torpedo

Rocket Experiments

- By the 16th century rockets fell into a time of ***disuse as weapons of war***, though they were still used for fireworks displays, and a **German** fireworks maker, ***Johann Schmidlap***, invented the "**step rocket**," a multi-staged vehicle for lifting fireworks to higher altitudes. A large sky rocket (first stage) carried a smaller sky rocket (second stage). When the large rocket burned out, the smaller one continued to a higher altitude before showering the sky with glowing cinders.
- Schmidlap's idea is basic to all rockets today that go into outer space.

Rocket Experiments

Nearly all uses of rockets up to this time were for warfare or fireworks, but there is an interesting **old Chinese legend** that reported the use of rockets as a means of transportation.

With the help of many assistants, a lesser-known Chinese official named ***Wan-Hu*** assembled a rocket- powered flying chair. Attached to the chair were two large kites, and fixed to the kites were forty-seven fire-arrow rockets.

Legendary Chinese Wan Hu Rocket Experiment

Figure 1.8 Legendary Chinese official Wan Hu braces himself for “liftoff”

Development of Rocket

- Hero of Alexandria is credited with inventing the rocket principle. He was a mathematician and inventor and devised many machines using water, air pressure.
- The rocket was also used as a weapon of oriental war.
- Konstantin Tsiolkovsky (1857−1935), a mathematics teacher, wrote about space travel, including weightlessness and escape velocity, in 1883, and he wrote about artificial satellites in 1895.

Goddard’s inventions included the use of gyroscopes for guidance, the use of vanes in the jet stream to steer the rocket, the use of valves in the propellant lines to stop and start the engine, the use of turbo-pumps to deliver the propellant to the combustion chamber, and the use of liquid oxygen to cool the exhaust nozzle, all of which were crucial to the development of the modern rocket.

The Russian Space Programme

- The first artificial satellite, the first man in space, the first spacecraft on the Moon, the first docking of two spacecraft, and the first space station.
- In 1961, Yuri Gagarin became the first man in space, and at the same time, several fly-bys of Mars and Venus were accomplished.
- The pre-war Russian attitude to rocketry had found a stimulus in the captured German parts, leading to the development of an indigenous culture which was to produce the best engines.
- It is significant that the Saturn V was the brainchild of Werner von Braun, a German, and the Vostok, Soyuz, and Molniya rockets were the brainchildren of Korolev and Glushko, who were Russian.

THE UNITED STATES SPACE PROGRAMME

- The achievement of the United States in realising humanity’s dream of walking on the Moon cannot be overrated.

- Its origin in the works of Tsiolkovsky and Oberth, its national expression in the dream of Robert Goddard, and its final achievement through the will of an American president and people, is unique in human history.

NEWTON’S THIRD LAW

- In its basic form, a rocket is a device which propels itself by emitting a jet of matter.
- The momentum carried away by the jet results in a force, acting so as to accelerate the rocket in the direction opposite to that of the jet.

Ellipse and Eccentricity

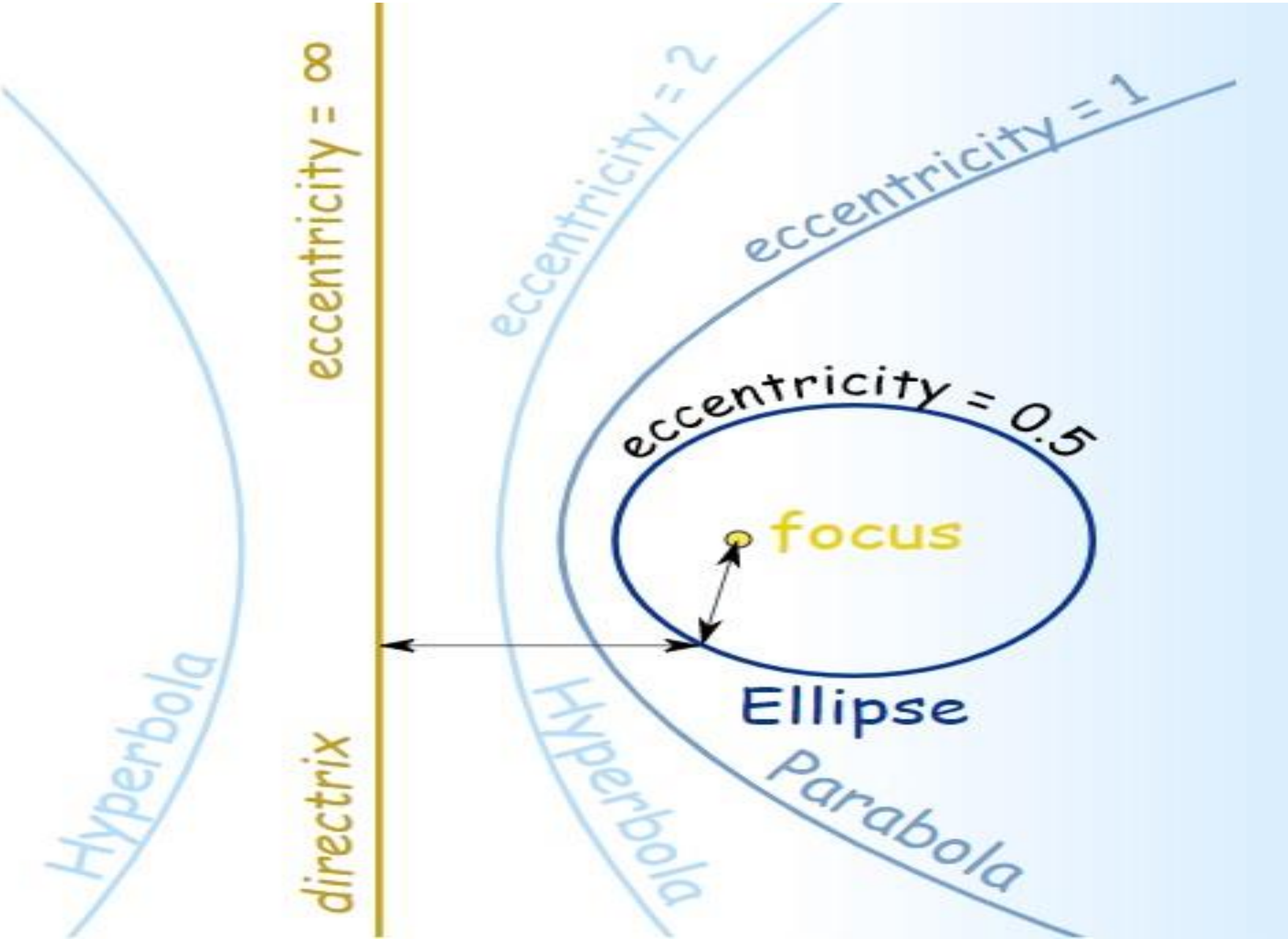
$0 <$ **eccentricity** < 1 we get an ellipse,

eccentricity $= 1$ a parabola, and

eccentricity > 1 a hyperbola.

A circle has an eccentricity of zero, so the eccentricity shows us how "un-circular" the curve is. The bigger the eccentricity, the less curved it is.

Ellipse and Eccentricity



Types of Orbits

Orbit	Altitude
Low Earth Orbit	160 – 2000 km
Medium low Earth orbit	2000 – 35,780 km
High Earth Orbit /Geosynchronous/ Geostationary	≥ 35,780 km
Lunar Orbit	3, 84,000 km
Sun synchronous orbits	**600 to 800 km**

TYPES OF ORBITS

- For a spacecraft to achieve Earth orbit, it must be launched to an elevation above the Earth's atmosphere and accelerated to orbital velocity. The most energy efficient orbit, that is one that requires the least amount of propellant, is a direct low inclination orbit. To achieve such an orbit, a spacecraft is launched in an eastward direction from a site near the Earth's equator. The advantage being that the rotational speed of the Earth contributes to the spacecraft's final orbital speed.

Geosynchronous orbits (GEO) are circular orbits around the Earth having a period of 24 hours. A geosynchronous orbit with an inclination of zero degrees is called a geostationary orbit. A spacecraft in a geostationary orbit appears to hang motionless above one position on the Earth's equator. For this reason, they are ideal for some types of communication and meteorological satellites. A spacecraft in an inclined geosynchronous orbit will appear to follow a regular figure, pattern in the sky once every orbit. To attain geosynchronous orbit, a spacecraft is first launched into an elliptical orbit with an apogee of 35,786 km (22,236 miles) called a geosynchronous transfer orbit (GTO). The orbit is then circularized by firing the spacecraft's engine at apogee.

- **Polar orbits (PO)** are orbits with an inclination of 90 degrees. Polar orbits are useful for satellites that carry out mapping and/or surveillance operations because as the planet rotates the spacecraft has access to virtually every point on the planet's surface.

- **Walking orbits**: An orbiting satellite is subjected to a great many gravitational influences. First, planets are not perfectly spherical and they have slightly uneven mass distribution. These fluctuations have an effect on a spacecraft's trajectory. Also, the sun, moon, and planets contribute a gravitational influence on an orbiting satellite. With proper planning it is possible to design an orbit which takes advantage of these influences to induce a precession in the satellite's orbital plane. The resulting orbit is called a *walking orbit*, or precessing orbit.

- **Sun synchronous orbits** (SSO) are walking orbits whose orbital plane precesses with the same period as the planet's solar orbit period. In such an orbit, a satellite crosses periapsis at about the same local time every orbit. This is useful if a satellite is carrying instruments which depend on a certain angle of solar illumination on the planet's surface. In order to maintain an exact synchronous timing, it may be necessary to conduct occasional propulsive maneuvers to adjust the orbit.

- Molniya orbits are highly eccentric Earth orbits with periods of approximately 12 hours (2 revolutions per day). The orbital inclination is chosen so the rate of change of perigee is zero, thus both apogee and perigee can be maintained over fixed latitudes. This condition occurs at inclinations of 63.4 degrees and 116.6 degrees. For these orbits the argument of perigee is typically placed in the southern hemisphere, so the satellite remains above the northern hemisphere near apogee for approximately 11 hours per orbit. This orientation can provide good ground coverage at high northern latitudes.

- **Hohmann transfer orbits** are interplanetary trajectories whose advantage is that they consume the least possible amount of propellant. A Hohmann transfer orbit to an outer planet, such as Mars, is achieved by launching a spacecraft and accelerating it in the direction of Earth's revolution around the sun until it breaks free of the Earth's gravity and reaches a velocity which places it in a sun orbit with an aphelion equal to the orbit of the outer planet. Upon reaching its destination, the spacecraft must decelerate so that the planet's gravity can capture it into a planetary orbit.

Orbit- Velocity

- In order to understand *how the orbit varies with the initial velocity of the space craft*, the angular momentum and the eccentricity are given by the following formulae:

$$h = MrV$$

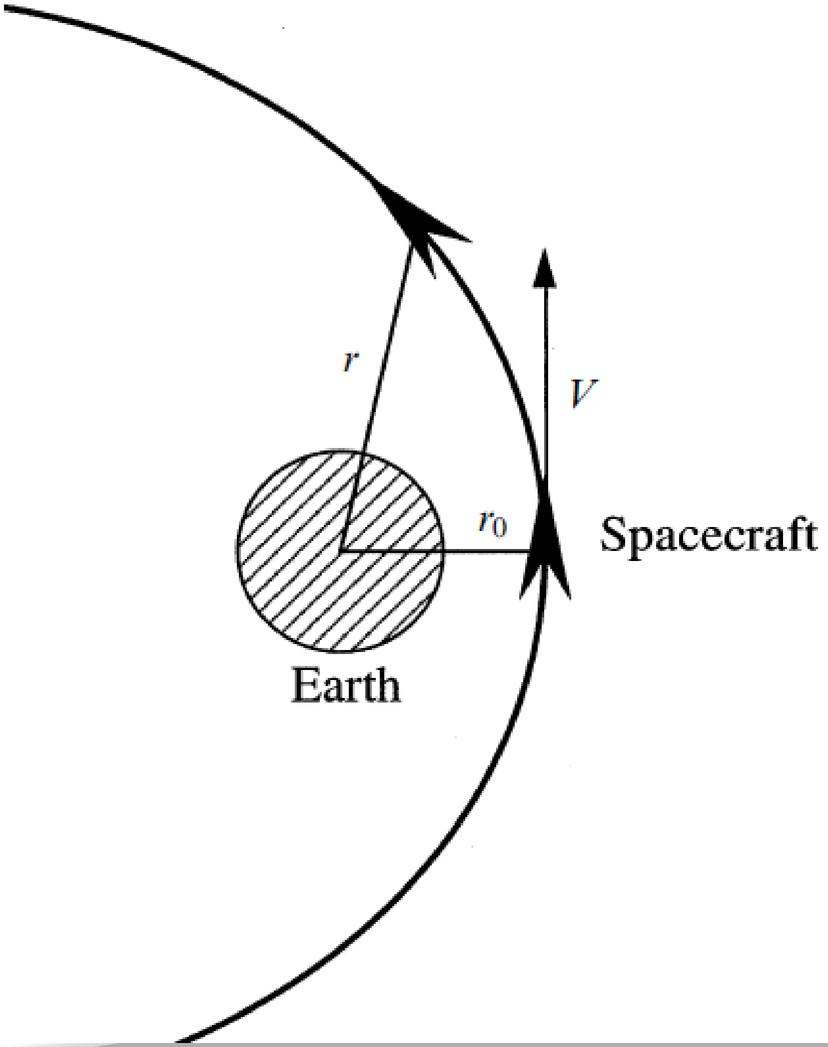
$$\varepsilon = \frac{h^2}{GM_{\oplus}M^2 r_0} - 1$$

Orbit

h is constant through out the orbit, it can be evaluated at the minimum radius point, r_0 and the initial given velocity, V_0

So

$$h = M r_0 V_0$$



- Having fixed values for the initial radius and velocity, we can see that both the angular momentum and eccentricity are fixed.
- Thus, ***the shape of the orbit depends only on the initial velocity and the distance from the center of the Earth.***

If $r_0 V_0^2 = GM_\oplus$

The eccentricity becomes zero, the orbit for this case becomes ‘circular’

Given the distance from the centre of the Earth,
the initial velocity,

$$V_0 = \sqrt{\frac{GM_\oplus}{r_0}}$$

The mass of the Earth is 5.975×10^{24} kg,
The mean radius is 6371 km, and the
G, gravitational constant is 6.670×10^{-11} Nm^2 kg^2

Elliptical Transfer Orbits

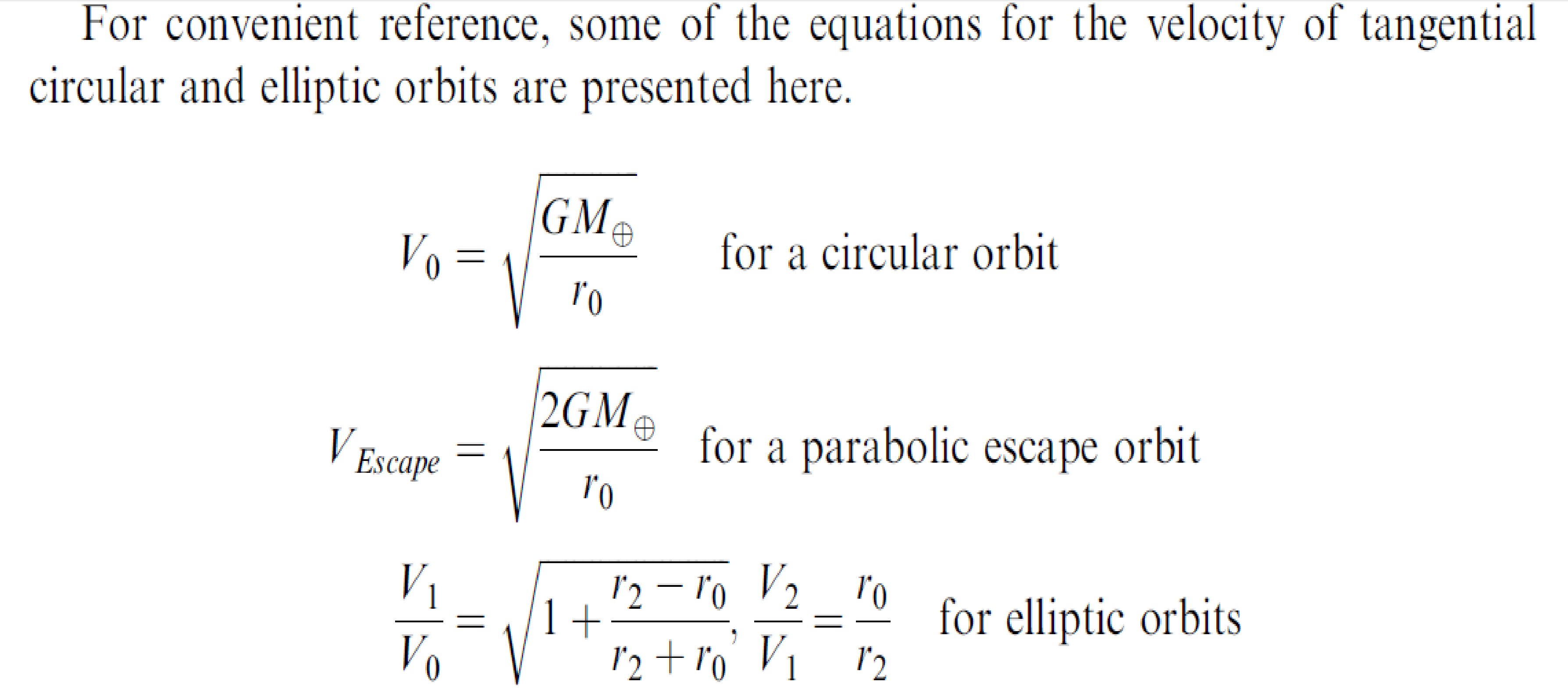
From the expression for eccentricity we see that for $\varepsilon = 1$,

$$\frac{r_0 V_0^2}{GM_\oplus} = 2$$

and

$$V_0 = \sqrt{\frac{2GM_\oplus}{r_0}}$$

Elliptical Transfer Orbits



For convenient reference, some of the equations for the velocity of tangential circular and elliptic orbits are presented here.

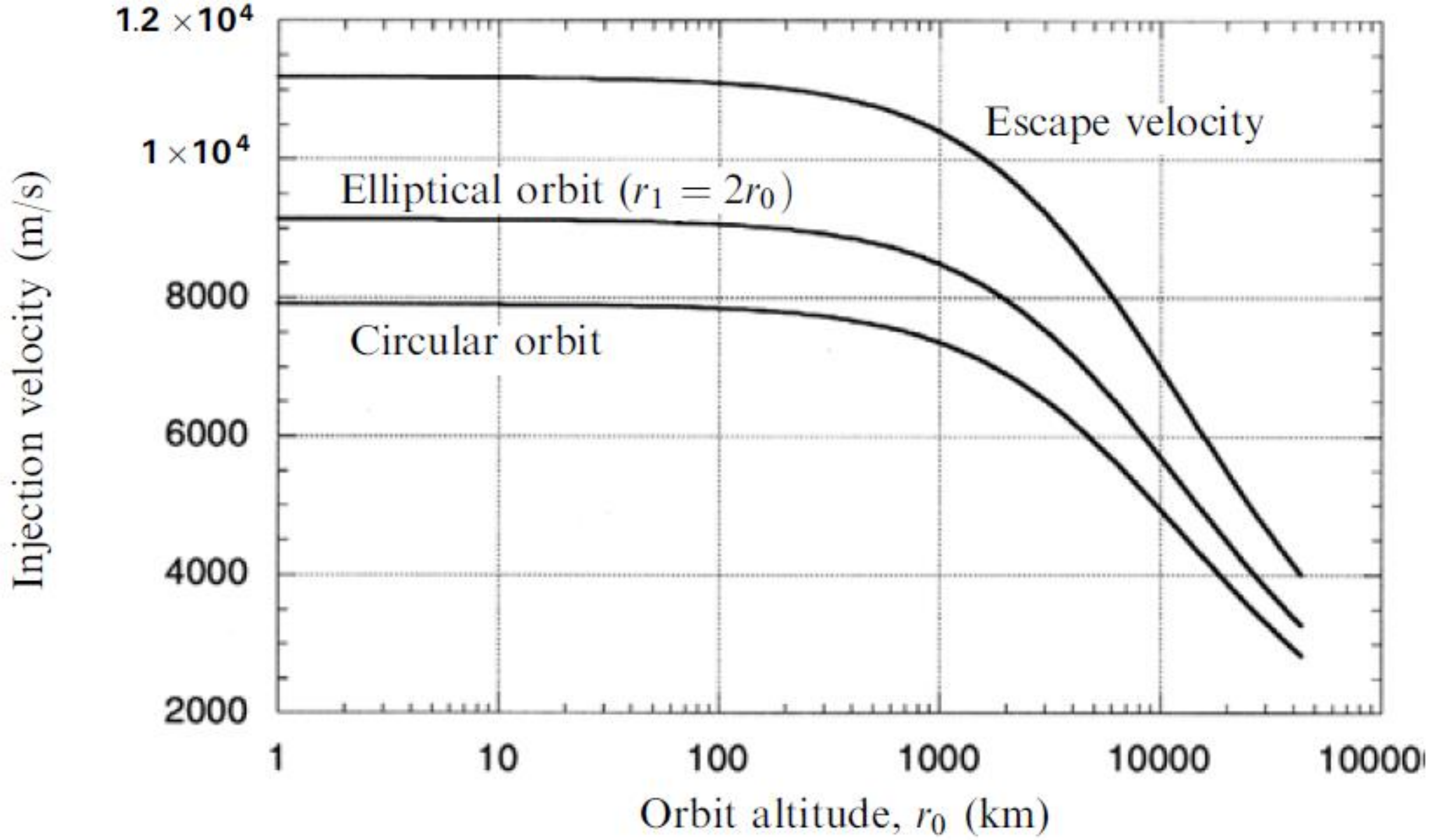
$$V_0 = \sqrt{\frac{GM_{\oplus}}{r_0}} \qquad \text{for a circular orbit}$$

$$V_{Escape} = \sqrt{\frac{2GM_{\oplus}}{r_0}} \qquad \text{for a parabolic escape orbit}$$

$$\frac{V_1}{V_0} = \sqrt{1 + \frac{r_2 - r_0}{r_2 + r_0}}, \; \frac{V_2}{V_1} = \frac{r_0}{r_2} \qquad \text{for elliptic orbits}$$

Where r_0 is the perigee radius, r_2 apogee radius,
V_1 is the elliptic orbit velocity at perigee, and
V_2 is the elliptic orbit velocity at apogee.

Injection Velocity and Altitude



Launch Trajectories- Vertical climb

- The rocket begins by flying straight up, gaining both vertical speed and altitude. During this portion of the launch, gravity acts directly against the thrust of the rocket, lowering its vertical acceleration, called as ‘**gravity loss**’

- For launch from the Earth, the atmosphere is significant problem
- Below 200 km there is significant drag to make an orbit unstable
- An orbit needs to be above 500 km
- For this reason, spacecrafts are launched vertically, after 30 km, more inclined trajectory can be followed.

Launch Trajectories- Vertical climb

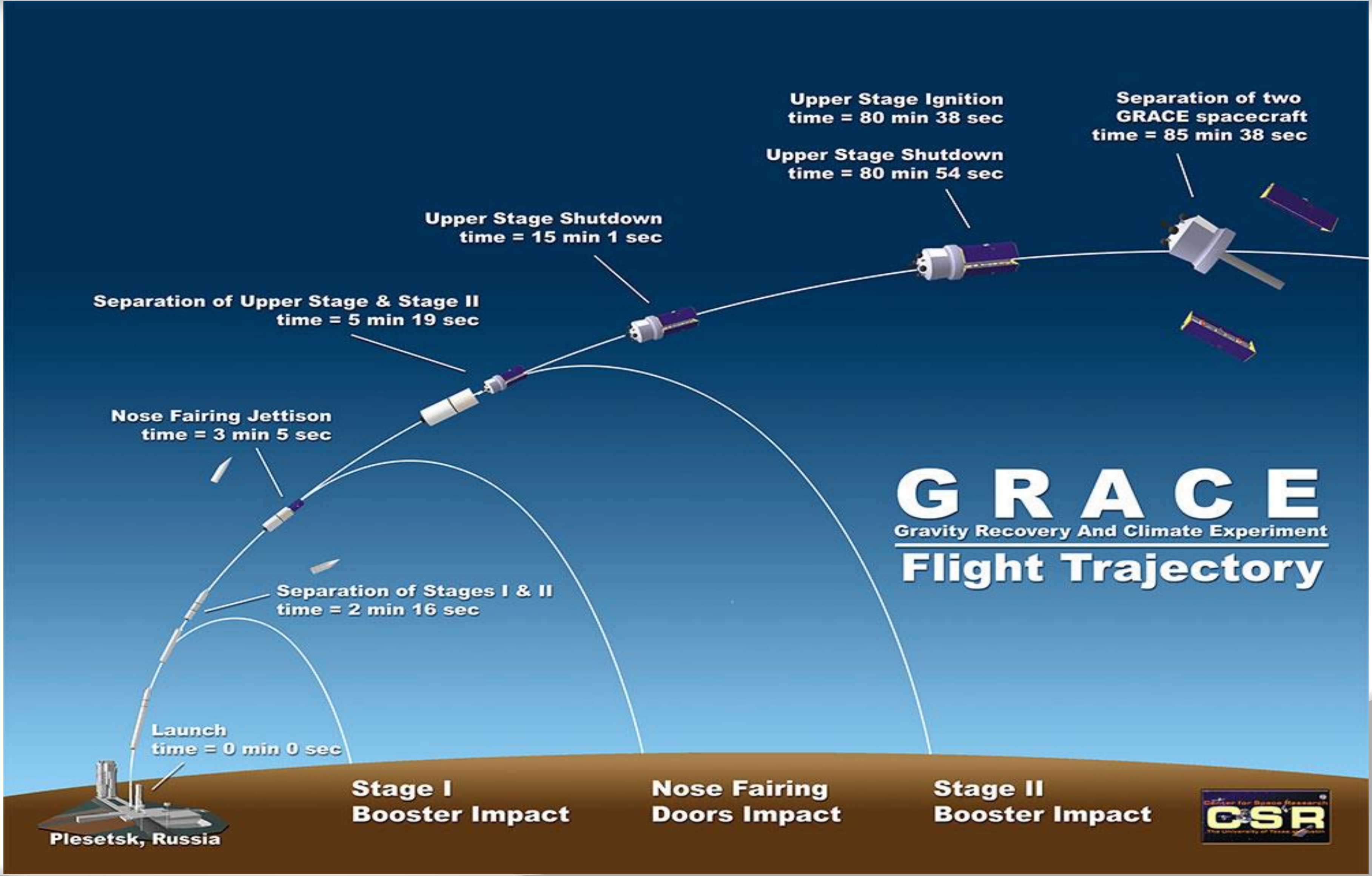
- Losses associated with this slowing are known as gravity drag, and can be minimized by executing the next phase of the launch, the **pitchover maneuver**, as soon as possible.

The pitchover maneuver serves two purposes.

1. It turns the rocket slightly so that its flight path is no longer vertical, and
2. It places the rocket on the correct heading for its ascent to orbit.

After the pitchover, the rocket's angle of attack is adjusted to zero for the remainder of its climb to orbit. This zeroing of the angle of attack reduces lateral aerodynamic loads and produces negligible lift force during the ascent.

Launch Trajectories



Landing

A decrease in velocity when a spacecraft is in circular orbit causes It to enter an elliptical orbit. The apogee is at the same altitude as the circular orbit, and the perigee is determined by the velocity decrease. At perigee, the S/C velocity > the corresponding new circular orbit, Further decrease is needed.

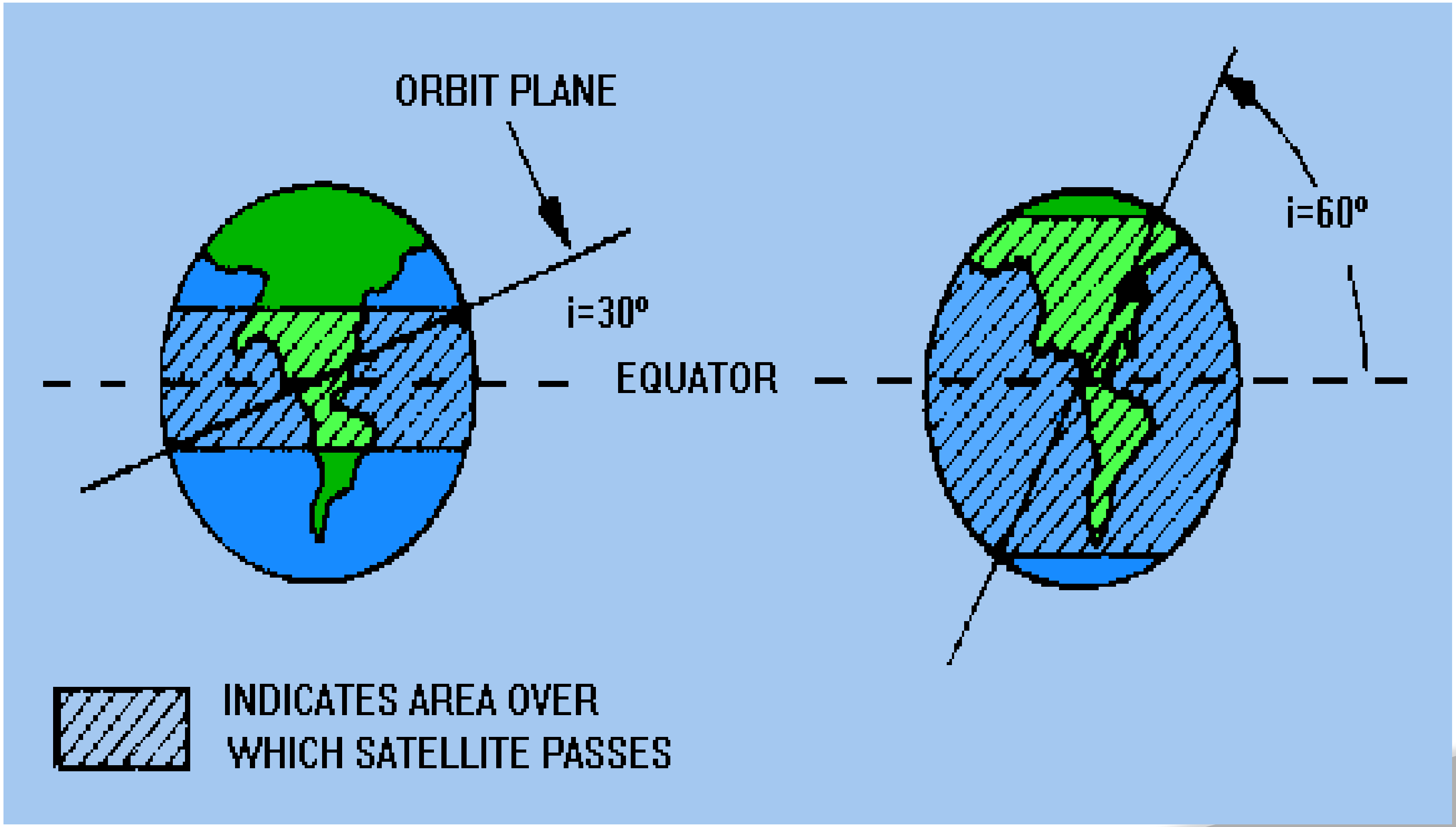
The Apollo 11 descent ellipse did not pass through the correct landing point, (Moon’s gravitational constants were not known). Armstrong had to take over control, by using lateral thrust from the motors.

The Rotation of the Earth

- The Earth rotates once in 24 hours, Small additional component of velocity can be gained from the rotation of the earth

- If the plane of the orbit is parallel to the equator (the planes of all Orbits pass though the centre of the Earth) and satellite travels in a West-East direction, then the speed of the Earth’s rotation is added to the velocity given by the rocket.

Equator and Orbit Plane



The Velocity Increment Needed for Launch

There is a distinction between velocity increment and actual velocity of the vehicle. The velocity increment is the velocity calculated from the rocket equation and is measure energy expended by the rocket. The vehicle velocity is less than this, because of gravity loss, and the energy needed to reach orbital altitude.

Actual velocity of the Vehicle: 7.6 km/s

Velocity increment : 8.7 km/s

The difference represents the energy expended against gravity loss and potential energy.

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BASIC ORBITAL EQUATIONS

- The "centripetal" force required to keep a particle with a mass, *m*, travelling on a circular path of radius, *R* is:

$$F_c = \frac{mv^2}{R}$$

where *v* is the velocity of the particle.

- Equating this force and gravitational force we get:

$$\frac{mv^2}{R} = \frac{GMm}{R^2}$$

- In the equation above [illegible] of the object being orbited (e.g. the Sun) and *m* is the mass of the object in orbit. R is the separation between the two objects (i.e. the length of the string).
- Rearranging this equation you can get:

$$v = \sqrt{\frac{GM}{R}} \qquad M = \frac{v^2 R}{G}$$

$$v = \sqrt{\frac{GM}{R}} \qquad M = \frac{v^2 R}{G}$$

v = the orbital velocity (

G = the universal gravitational constant, G = $6.673 \times 10^{(-11)}$ $N \cdot m^2/kg^2$

m_E = the mass of the Earth (5.98×10^{24} kg)

r = the distance from the object to the center of the Earth

These relations show that you can:

- find the circular orbital velocity needed to launch a satellite into Earth orbit.
- determine the mass of a planet (or star or galaxy...) which has a satellite with a known velocity and separation from the planet.
  - Applying Newton's Laws permits us to determine the mass of just about any structure in the Universe.

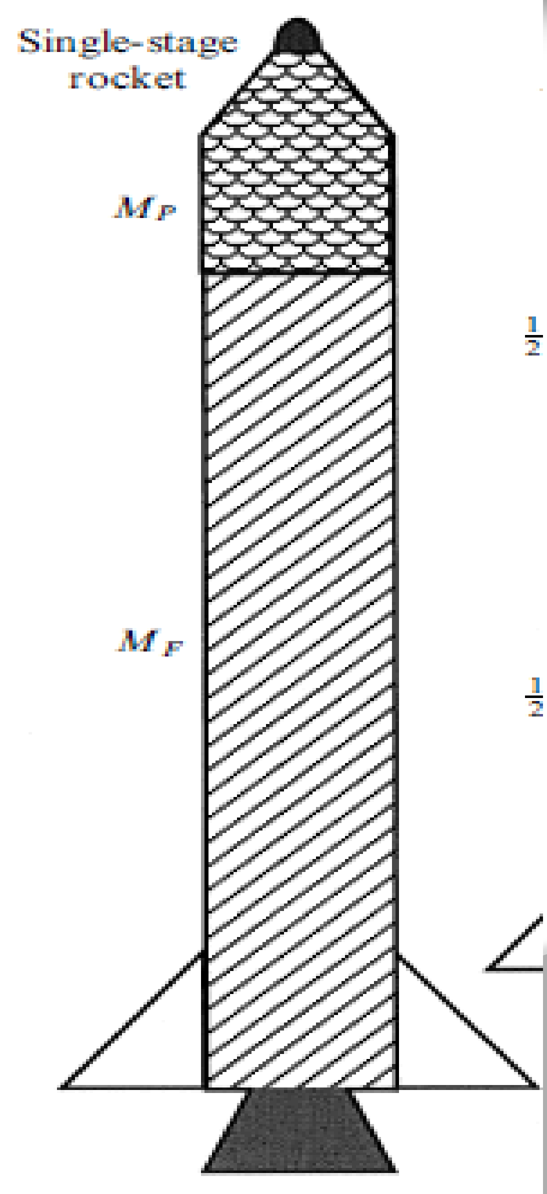
$$v = \sqrt{GM\left(\frac{2}{r} - \frac{1}{a}\right)} \quad (elliptical\ \ orbit)$$

$$v = \sqrt{\frac{GM}{r}} \quad (circular\ \ orbit)$$

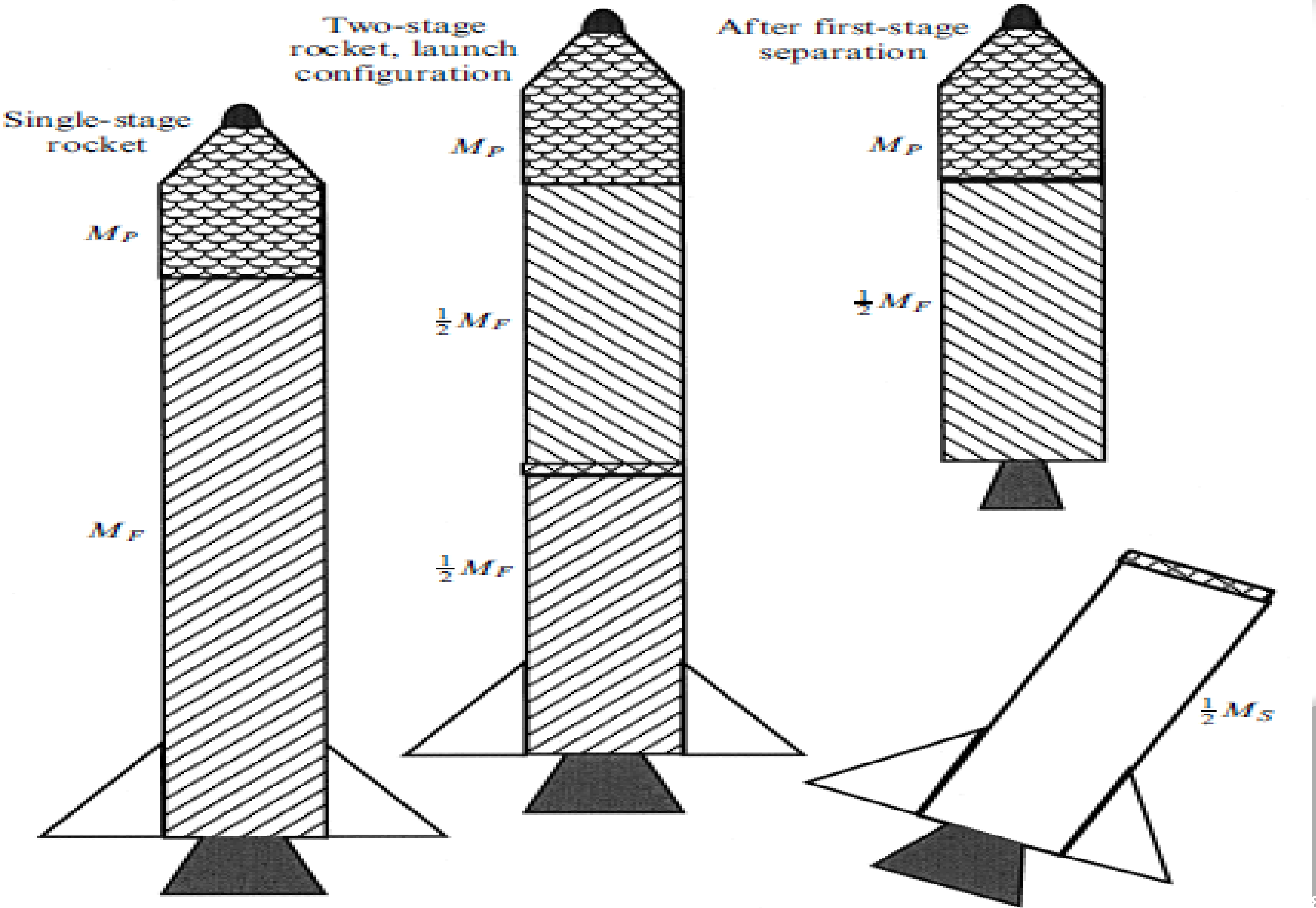
SSTO and TSTO (Multistage Rocket)

Single stage rocket

$$R_0 = \frac{M_S + M_F + M_P}{M_S + M_P}$$



Multistage Rocket



SSTO and TSTO (Multistage Rocket)

$$R_1 = \frac{M_S + M_F + M_P}{M_S + \frac{1}{2} M_F + M_P}$$

$$R_2 = \frac{\frac{1}{2} M_S + \frac{1}{2} M_F + M_P}{\frac{1}{2} M_S + M_P}$$

$$V_0 = v_e \log_e R_0$$

$$V = v_e \log_e R_1 + v_e \log_e R_2$$

SSTO and TSTO (Multistage Rocket)

$$V_0 = 2{,}700 \log_e \frac{10 + 89 + 1}{10 + 1} = 5{,}959\,\mathrm{m\,s^{-1}}$$

$$V_1 = 2{,}700 \log_e \frac{10 + 89 + 1}{10 + 44.5 + 1} = 1{,}590\,\mathrm{m\,s^{-1}}$$

$$V_2 = 2{,}700 \log_e \frac{5 + 44.5 + 1}{5 + 1} = 5{,}752\,\mathrm{m\,s^{-1}}$$

Therefore using the same quantity o fuel and dividing the structural mass between two smaller rockets, an extra 1383 m/s is realised.

Payload Ratio - Structural Efficiency- Mass Ratio

The payload ratio of a single stage is given by $$L = \frac{M_P}{M_S + M_F}$$

Structural efficiency: $$\sigma = \frac{M_S}{M_F + M_S}$$

Mass ratio: $$R = \frac{1 + L}{\sigma + L}$$

The Thermal Rocket Engine

The rocket principle is the basis of all propulsion in space, and all launch vehicles.

The twin properties of ***needing no external medium for the propulsion system to act upon***, and ***no external oxidant for the fuel***, **enable rockets to work in any ambient conditions, including the vacuum of space.**

The thermal rocket is the basis of all launchers, and almost all space propulsion (except the principle of electric propulsion)

The Thermal Rocket Engine

The thermal rocket motor is a heat engine:

It converts the heat, generated by burning the propellants-

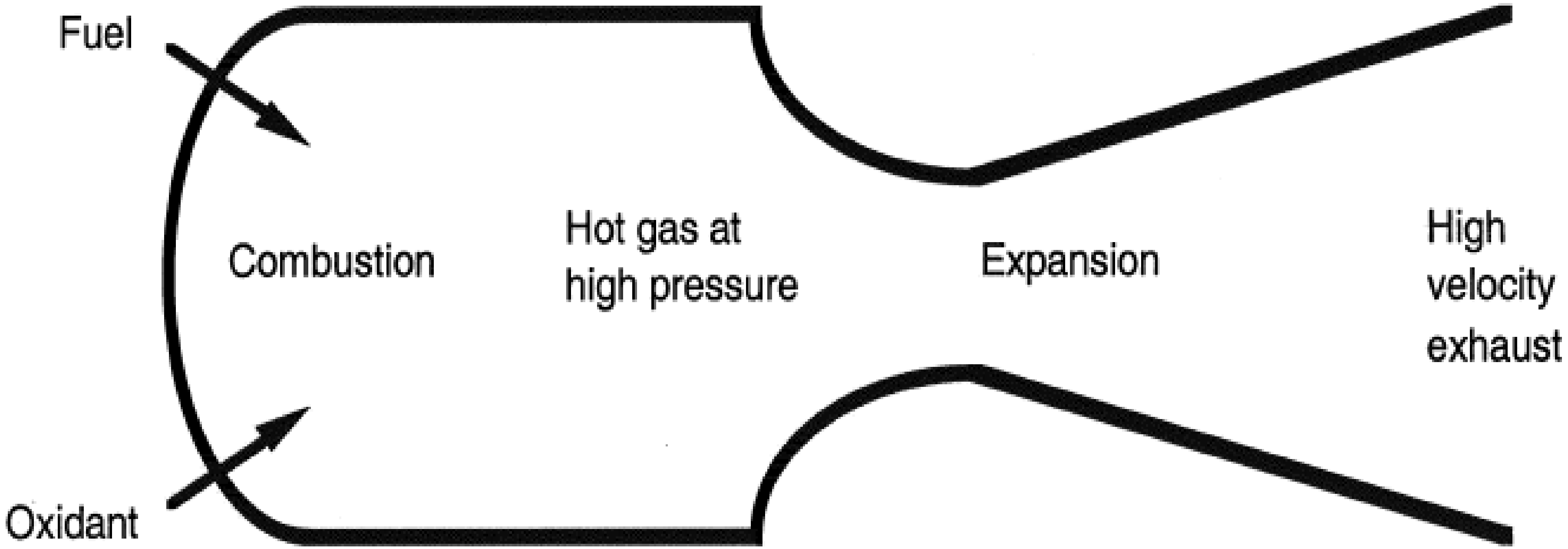
fuel and oxidiser, in the combustion chamber-into kinetic energy of

the emerging exhaust gas.

The momentum carried away by the exhaust gas provides the thrust,

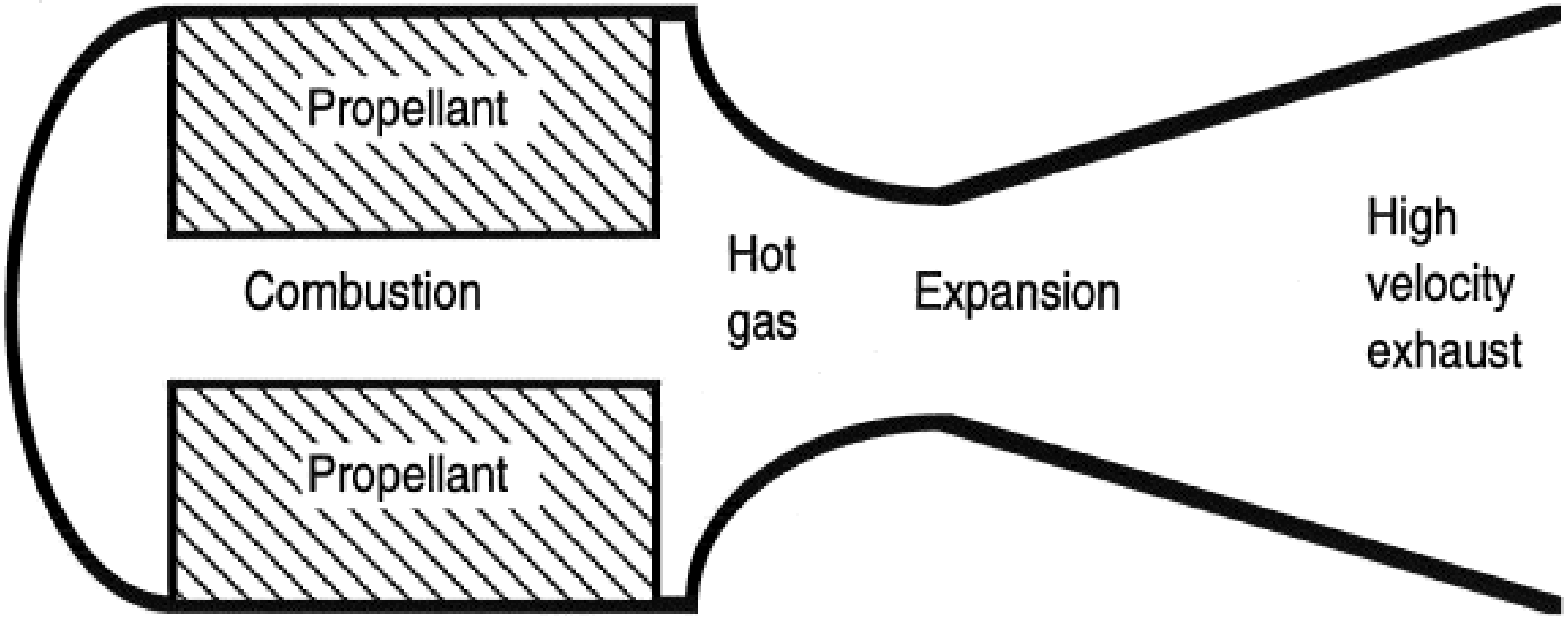
which accelerates the rocket.

The Basic Configuration



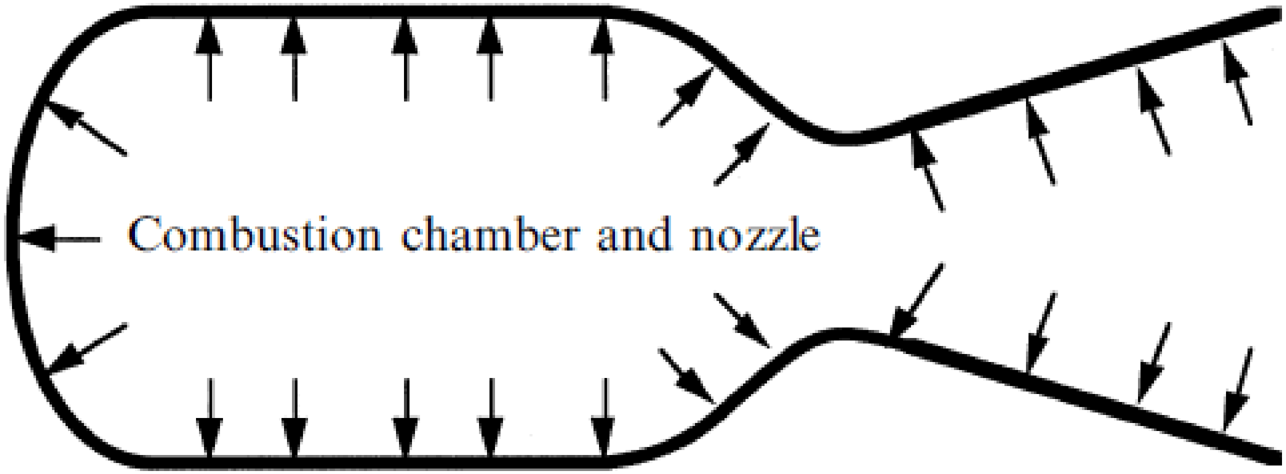
A liquid fuelled rocket engine

The Basic Configuration



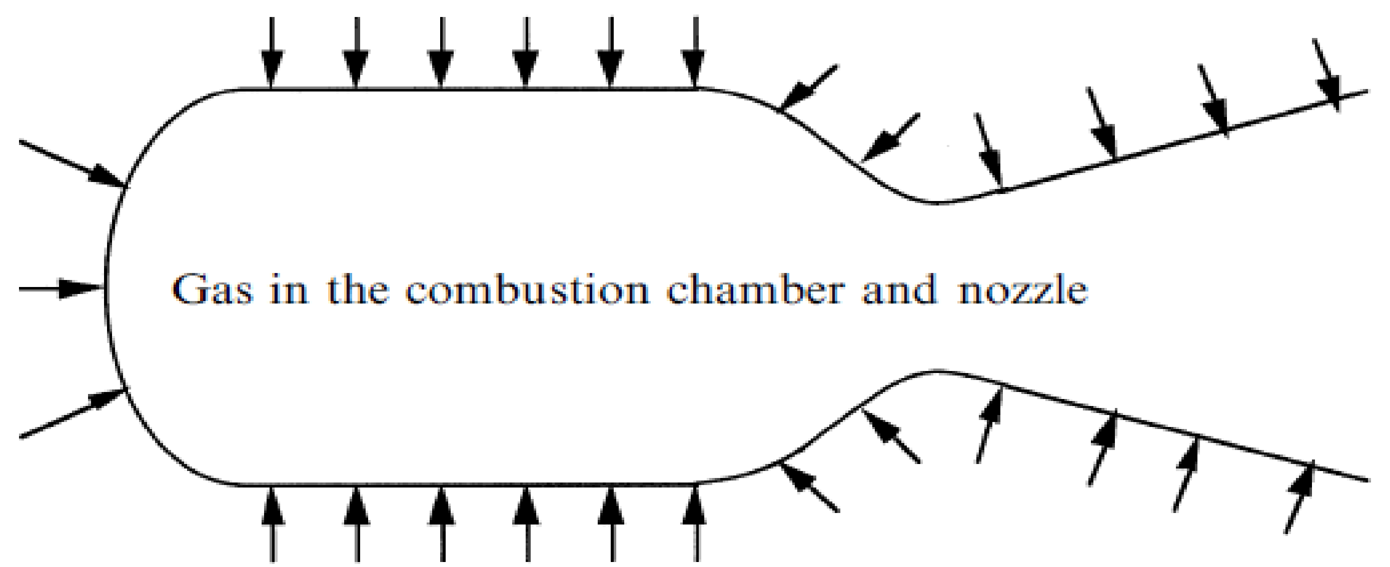
A solid fuelled rocket engine

Forces in the combustion chamber and exhaust nozzle



The figure represents the action of the gas pressure on the combustion chamber and the exhaust nozzle, which is the force which accelerates the rocket

Forces in the combustion chamber and exhaust nozzle



The figure represents the reaction of the walls of the combustion chamber and of the exhaust nozzle, acting on the gas contained by them, which is the force that accelerates the exhaust gas.

Forces in the combustion chamber and exhaust nozzle

The force accelerating the exhaust gas (the reaction of the walls),

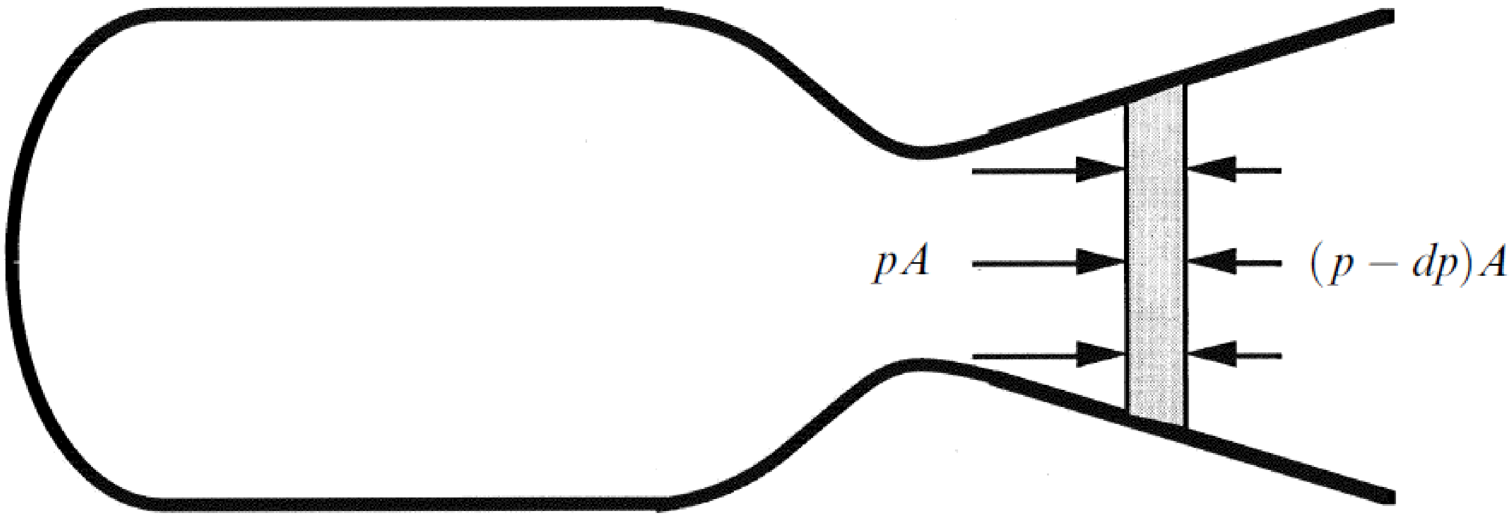
is equal to the surface integral of the pressure, taken over the whole

inner surface of the chamber and nozzle:

$$F = \oint p \, dA.$$

This is not the only force acting on the gas, there is also a retarding force

Forces in the combustion chamber and exhaust nozzle



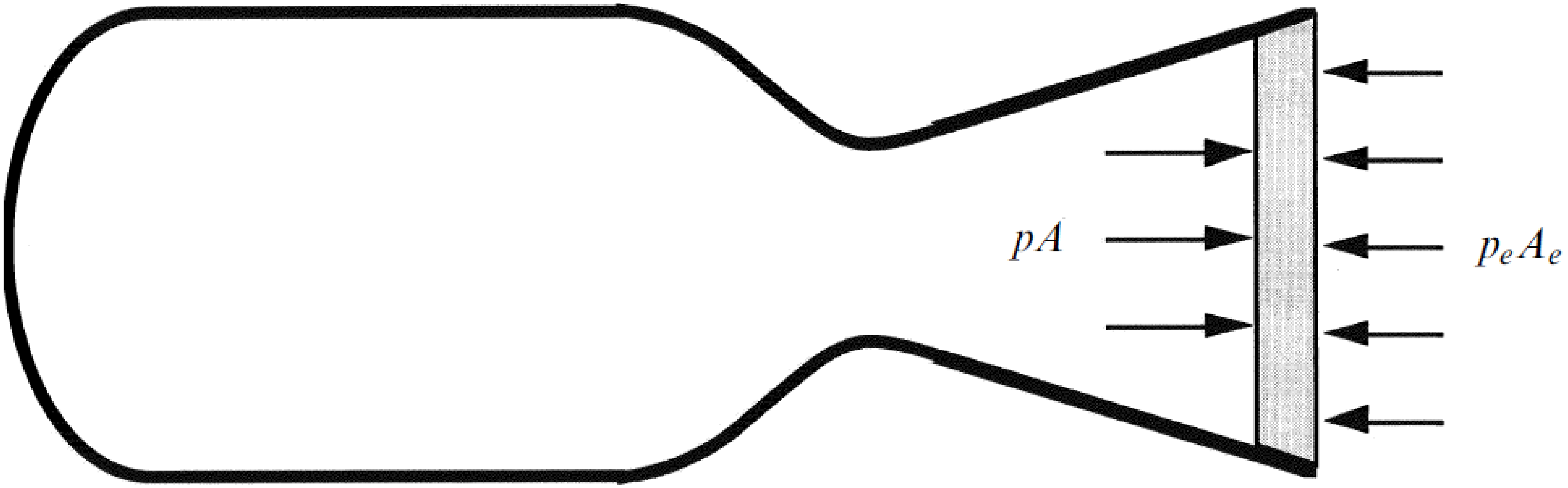
Considering the shaded portion of the exhaust stream, the net accelerating force acting on the shaded portion is

$$dF = pA - (p - dp)A$$

Where A is the cross-sectional area at any given point, and the pressure gradient is *dp/dx*. This is the force that accelerates the gas through the nozzle.

Forces in the combustion chamber and exhaust nozzle

For an element at the extreme end of the nozzle – the exit point



- The outward force is *pA*,
- but the retarding force is the pressure at the exit plane, which can be denoted by p_e, multiplied by the area at the exit plane, $A_e = p_e A_e$

The accelerating forces on the exhaust gases

The accelerating forces on the exhaust gases,

$$F_G = \oint p\, dA - p_e A_e = m u_e$$

where m is the mass flow rate through the nozzle, and
u_e is the exhaust velocity.

This is the force that accelerates the exhaust stream in the nozzle.

The accelerating forces on the rocket

The accelerating forces on the exhaust gases, the surface integral of the pressure, taken over the walls of the combustion chamber and nozzle:

$$F_R = \oint p \, dA$$

which is the force tending to accelerate the rocket.

Retarding force acting on the rocket due to atmospheric pressure

$$p_a A_e$$

where p_a is the atmospheric pressure and
A_e is the area of the exit plane

The net forces on the rocket- the thrust equation

The accelerating forces on the exhaust gases,

$$F_R = \oint p\, dA - p_a A_e$$

Substituting $\oint p\, dA$

$$F_R = m u_e + p_e A_e - p_a A_e$$

This is the thrust equation.,

By substituting $F_R = m v_e$,

The *effective exhaust velocity* becomes $v_e = u_e + \left(\frac{p_e - p_a}{m} \right)$

Launch Assists - Aircraft Assisted Launch

Lockheed L-1011 Stargazer launches Pegasus carrying the three Space Technology 5 satellites in the skies of California, 2006

Aircraft Assisted Launch

The Space Shuttle Endeavour and its 747 carrier aircraft soar over the California, 2012

The Magnetic Levitation

The Magnetic Levitation (MagLev) System evaluated at NASA’s Marshall Space Flight Center. Credit: NASA

Launch Assists - Catapults

Very high accelerations:

2000 – 100,000g
No biological organism can withstand such accelerations.

Spacecraft hardware has to be specially protected:
Adding mass, complexity and Costs

The relationship between catapult length ***l***, exit velocity ***v*** and acceleration ***a*** is given by

$$a = v^2 / 2.\, l$$

Catapults

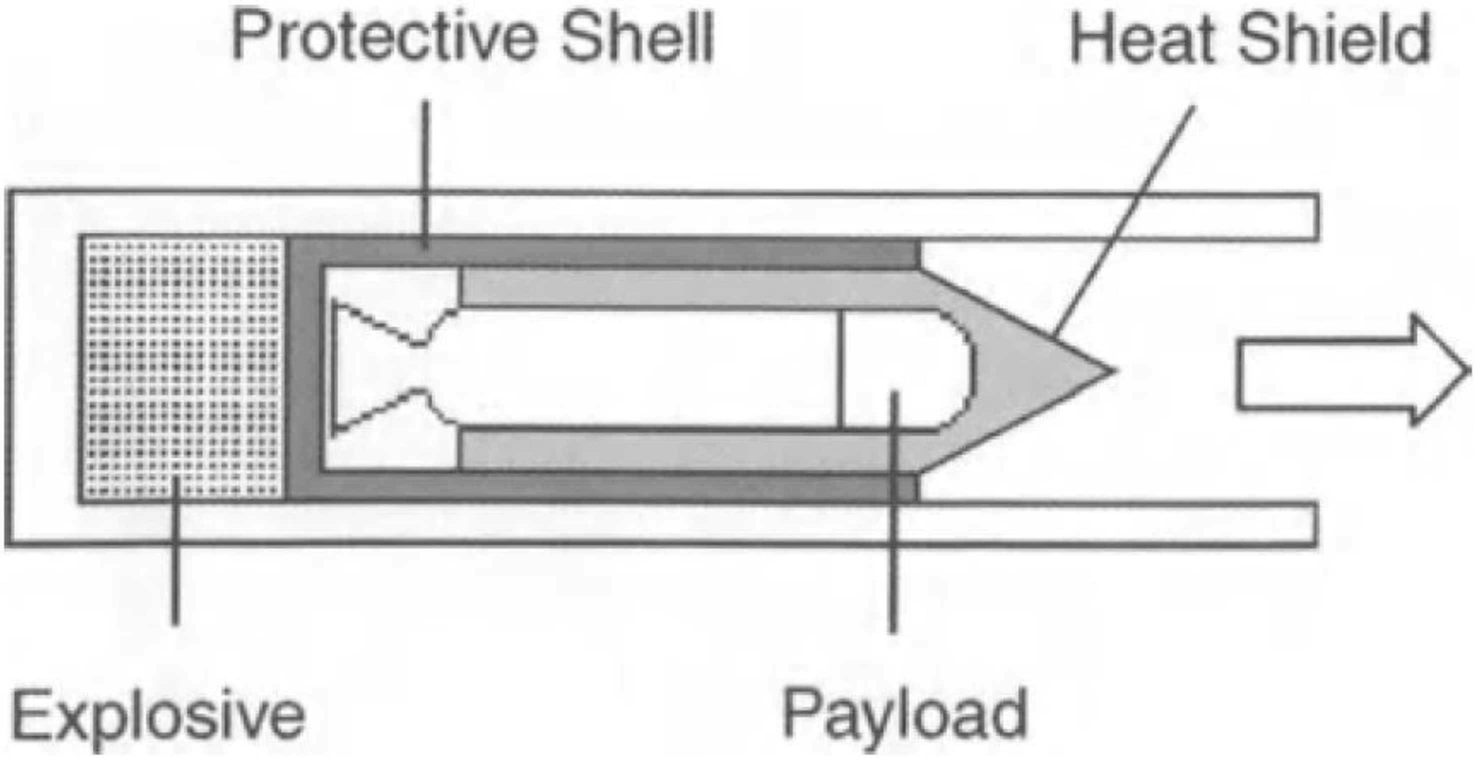
Heat Shields: Adds to the mass, reducing payload –

heat transfer to be considered

Environmental issues: Guns produce shockwave,

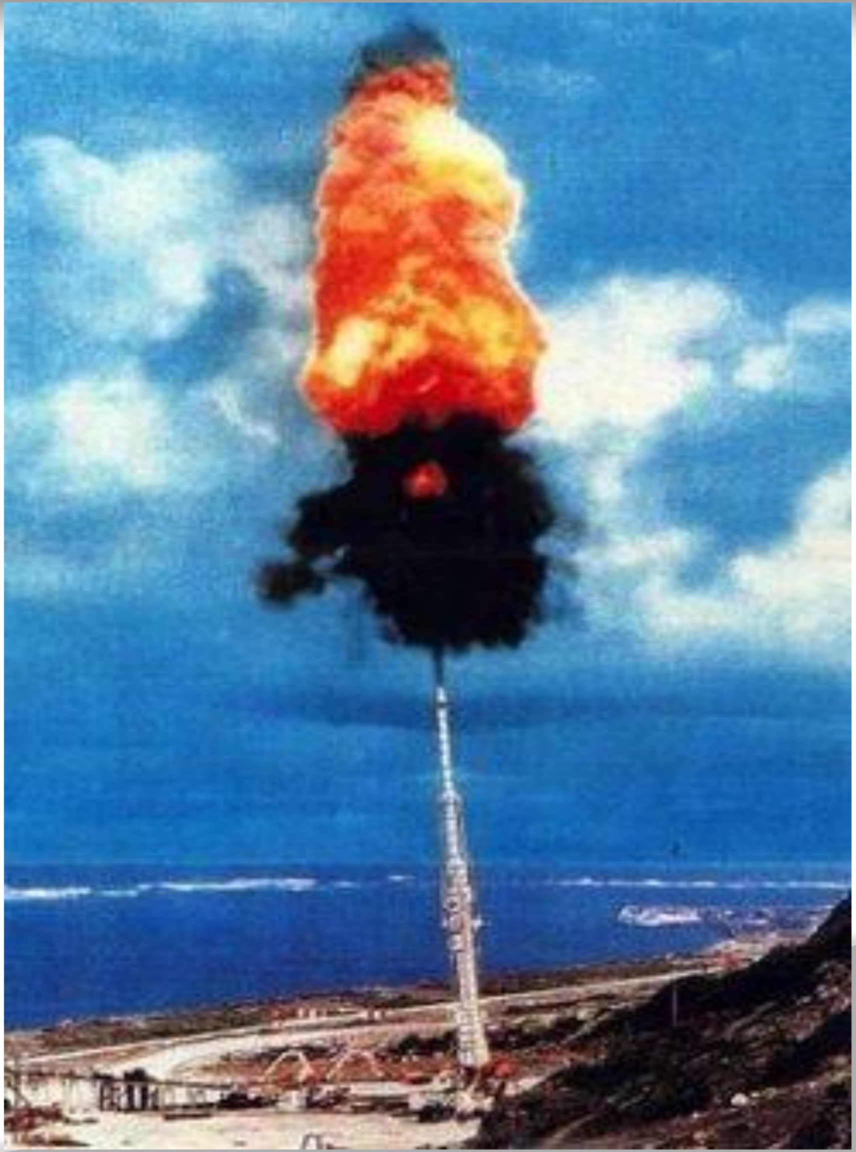
operating personnel and surroundings to be protected.

Gun Launch



Gun Launch

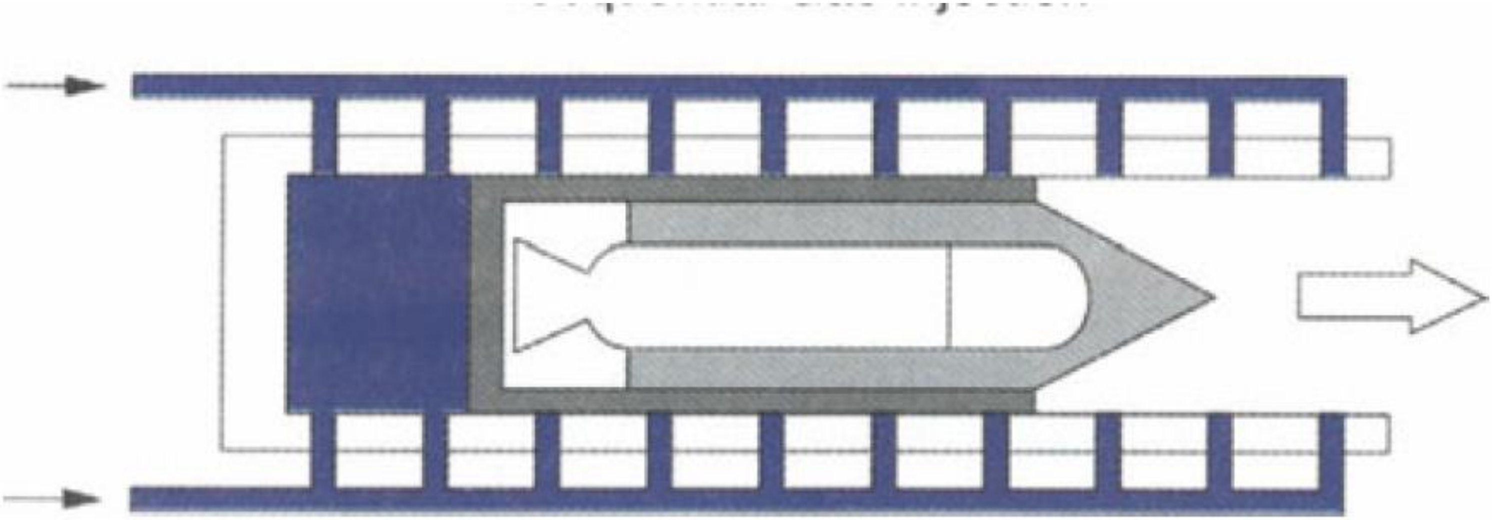
Gun Launch- HARP gun



High Altitude Research Program, US, 1960. 85 kg- 180 km

Gas Gun Launch- HARP gun

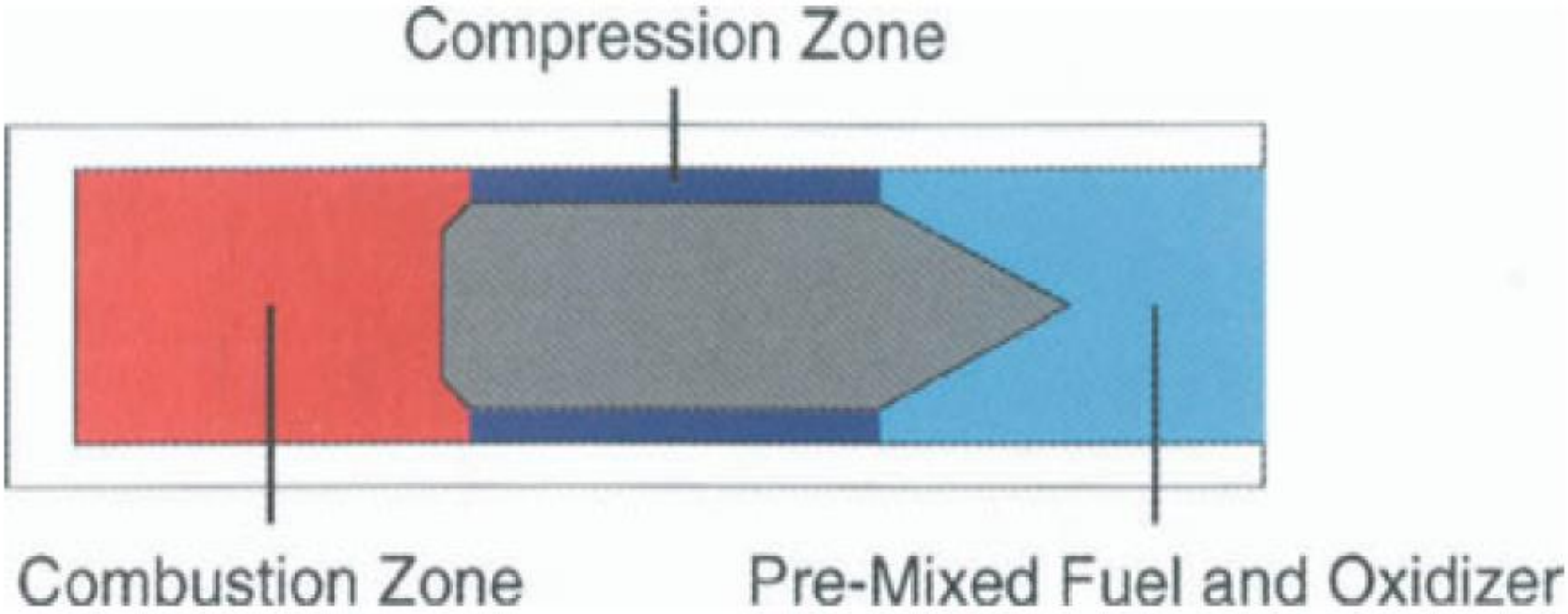
Highly compressed, low molecular weight gas (e.g. hydrogen or helium)



Super **H**igh **A**ltitude **R**esearch **P**roject, Lawrence Livermore National Laboratory in California, and became operational in December 1992.

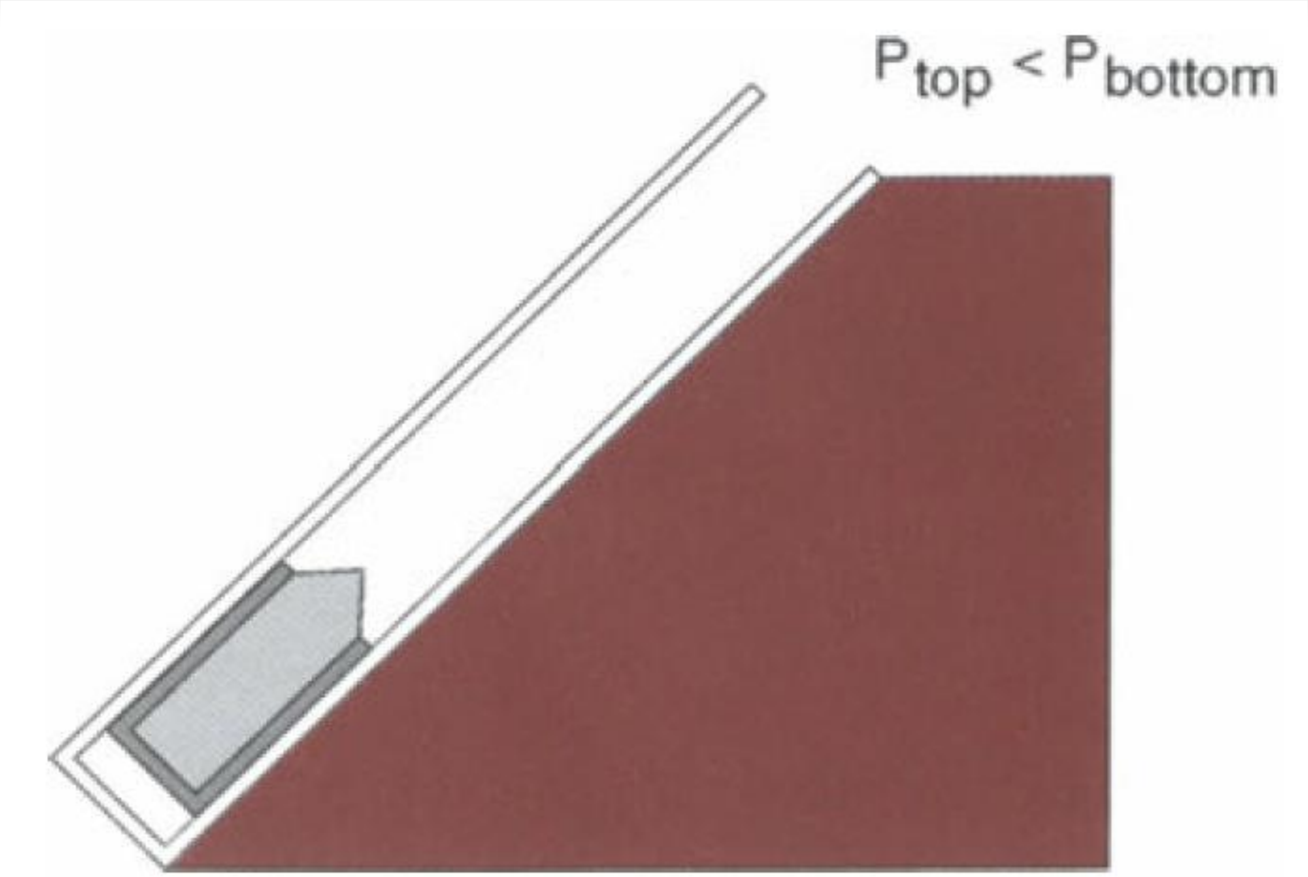
Capable -5.8 kg – 2.77 km/s, target 5000 kg – 7km/s-LEO

Ram accelerator



Premixed fuel and oxidizer: e.g. methane and oxygen
The projectile is injected with an initial velocity and compresses the gas at the end of the projectile, the gas is ignited and combustion starts.
4.29 kg – 1.48 km/s

Pneumatic Catapult



The tube would be placed alongside a mountain.
A difference in altitude of 2.1 km – would result in a pre. diff. of 0.25 bar, could produce exit velocities of 300 m/s

UNIT 2

FUNDAMENTALS OF ROCKET PROPULSION

CLOs	Course Learning Outcome
CLO 4	Explain the operating principle of the rocket engine and demonstrate the rocket equation.
CLO 5	Discuss the different Newton’s laws of motion and the relation of thrust generation to different laws of motion
CLO 6	Describe the different types of propulsion systems and preliminary concepts in nozzle less propulsion and air augmented rockets.

Rocket engine: A vehicle or device propelled by one or more rocket engines, especially such a vehicle designed to travel through space.

- A projectile weapon carrying a warhead that is powered and propelled by rockets.
- A projectile firework having a cylindrical shape and a fuse that is lit from the rear.

Missile: An object or weapon that is fired, thrown, dropped, or otherwise projected at a target; a projectile.

PROPELLANT

- Propellant is the chemical mixture burned to produce thrust in rockets and consists of a fuel and an oxidizer.
- A fuel is a substance that burns when combined with oxygen producing gas for propulsion.
- An oxidizer is an agent that releases oxygen for combination with a fuel.
- The ratio of oxidizer to fuel is called the mixture ratio. Propellants are classified according to their state - liquid, solid, or hybrid.
- The gauge for rating the efficiency of rocket propellants is specific impulse, stated in seconds.

Liquid Propellants

- In a liquid propellant rocket, the fuel and oxidizer are stored in separate tanks, and are fed through a system of pipes, valves, and turbo pumps to a combustion chamber where they are combined and burned to produce thrust.
- Liquid propellant engines are more complex than their solid propellant counter parts, however, they offer several advantages.
- By controlling the flow of propellant to the combustion chamber, the engine can be throttled, stopped, or restarted.

Solid Propellants

- Solid propellant motors are the simplest of all rocket designs. They consist of a casing, usually steel, filled with a mixture of solid compounds (fuel and oxidizer) that burn at a rapid rate, expelling hot gases from a nozzle to produce thrust.
- When ignited, a solid propellant burns from the center out towards the sides of the casing. The shape of the center channel determines the rate and pattern of the burn, thus providing a means to control thrust.
- Unlike liquid propellant engines, solid propellant motors cannot be shut down.
- Once ignited, they will burn until all the propellant is exhausted.

Hybrid Propellants

- Hybrid propellant engines represent an intermediate group between solid and liquid propellant engines.
- One of the substances is solid, usually the fuel, while the other, usually the oxidizer, is liquid.
- The liquid is injected into the solid, whose fuel reservoir also serves as the combustion chamber.
- The main advantage of such engines is that they have high performance, similar to that of solid propellants, but the combustion can be moderated, stopped, or even restarted.

Ignition System in Rockets

- Solid propellant ignition consists of a series of complex rapid events, which start on receipt of a signal (usually electric) and include heat generation, transfer of the heat from the igniter to the motor grain surface, spreading the flame over the entire burning surface area, filling the chamber free volume (cavity) with gas, and elevating the chamber pressure without serious abnormalities such as overpressures, combustion oscillations, damaging shock waves, hangfires (delayed ignition), extinguishment, and chuffing.

the ignition process is divided into three phases for analytical purposes:

Phase I, Ignition time lag: the period from the moment the igniter receives a signal until the first bit of grain surface burns.

Phase II, Flame-spreading interval: the time from first ignition of the grain surface until the complete grain burning area has been ignited.

Phase III, Chamber-filling interval: the time for completing the chamber filling process and for reaching equilibrium chamber pressure and flow.

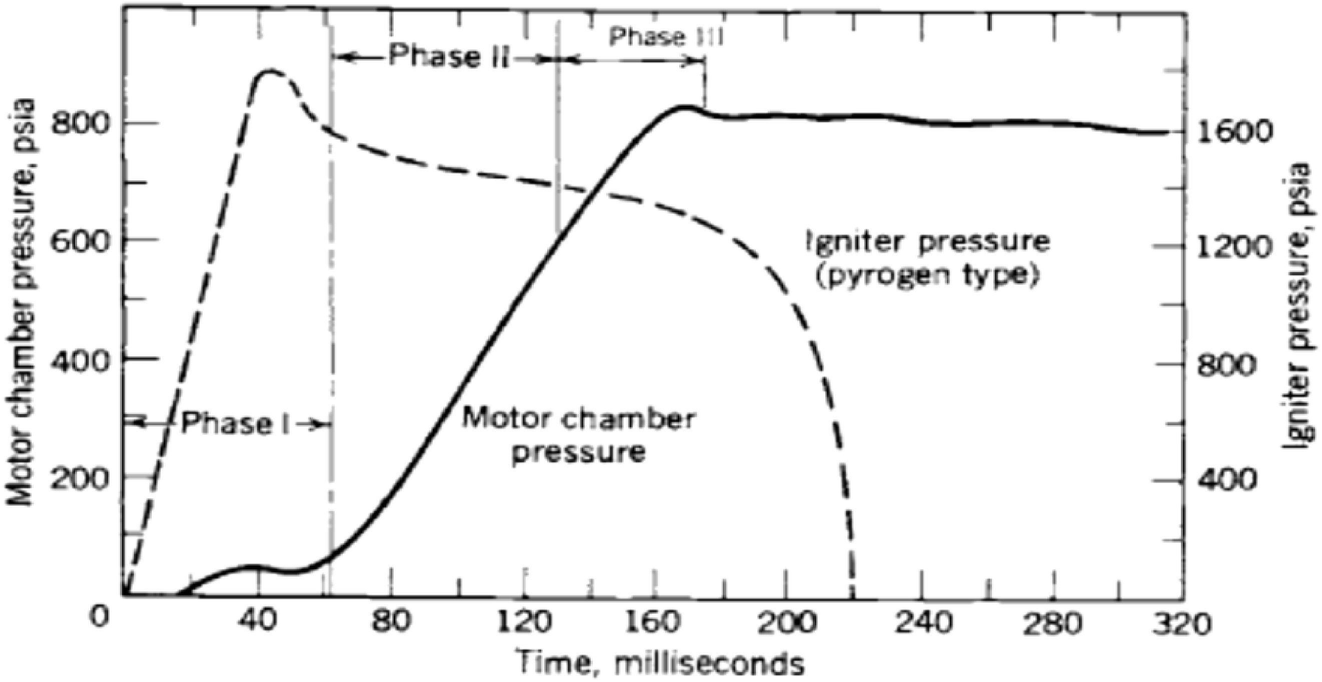


Fig. 2.1 Typical ignition pressure transient portion

TYPES OF IGNITERS

- Pyrotechnic Igniters:

- In industrial practice, pyrotechnic igniters are defined as igniters (other than pyrogen-type igniters as defined further on) using solid explosives or energetic propellant-like chemical formulations (usually small pellets of propellant which give a large burning surface and a short burning time) as the heat-producing material.
- This definition fits a wide variety of designs, known as bag and carbon igniters, powder can, plastic case, pellet basket, perforated tube, combustible case, jellyroll, string, or sheet igniters.

Pyrogen Igniters

- A pyrogen igniter is basically a small rocket motor that is used to ignite a larger rocket motor.
- The pyrogen is not designed to produce thrust. All use one or more nozzle orifices, both sonic and supersonic types, and most use conventional rocket motor grain formulations and design technology. Heat transfer from the pyrogen to the motor grain is largely convective, with the hot gases contacting the grain surface as contrasted to a highly radiative energy emitted by pyrotechnic igniters.

- Total Impulse :It is the thrust force F (which can vary with time) integrated over the burning time t.

$$I_t = \int_0^t F\,dt$$

Specific Impulse

- The specific impulse is the total impulse per unit weight of propellant. It is an important figure of merit of the performance of a rocket propulsion system, similar in concept to the miles per gallon parameter used with automobiles.
- A higher number means better performance.

ROCKET NOZZLE CLASSIFICATION

◉ Under-and Over-Expanded Nozzles:

- An under-expanded nozzle discharges the fluid at an exit pressure greater than the external pressure because the exit area is too small for an optimum area ratio.
- The expansion of the fluid is therefore incomplete within the nozzle, and must take place outside. The nozzle exit pressure is higher than the local atmospheric pressure.
- In an over-expanded nozzle the fluid attains a lower exit pressure than the atmosphere as it has an exit area too large for optimum.

NOZZLE CONFIGURATIONS

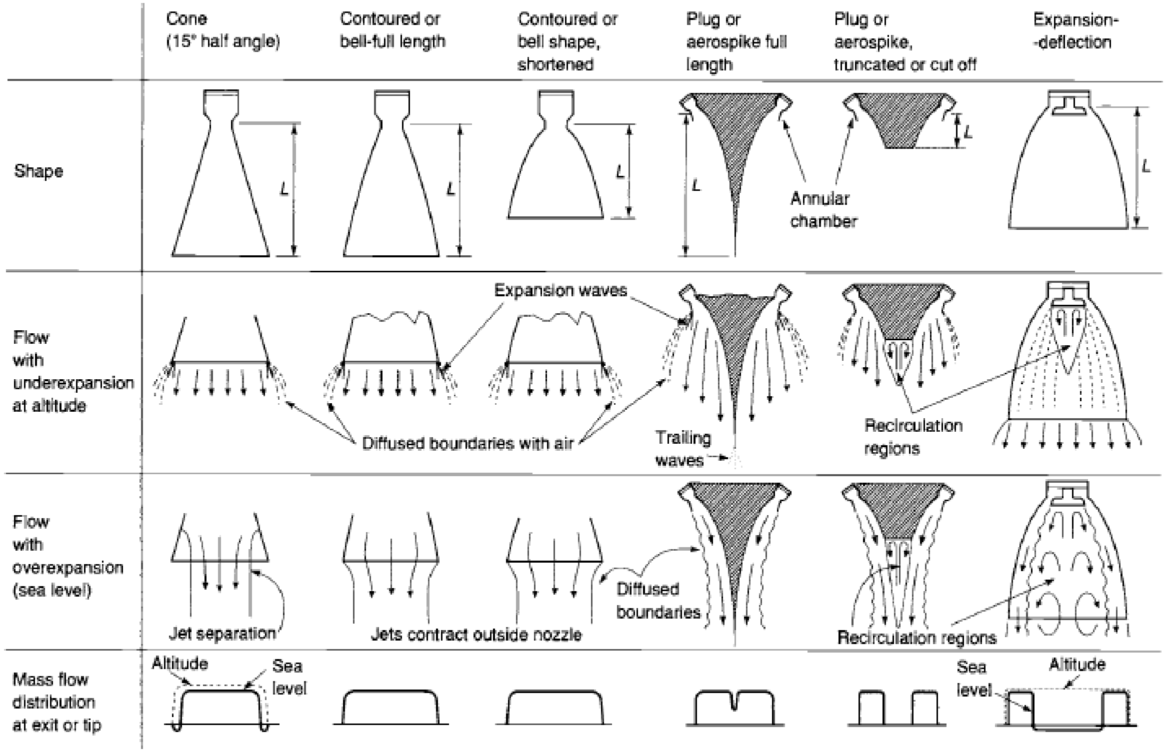


Figure 2.2 several nozzle configurations

TSIOLKOVSKY'S ROCKET EQUATION

- The **Tsiolkovsky rocket equation**, **classical rocket equation**, or **ideal rocket equation** (also known mistakenly as **delta-v**) is a mathematical equation that describes the motion of vehicles that follow the basic principle of a rocket: a device that can apply acceleration to itself using thrust by expelling part of its mass with high velocity and thereby move due to the conservation of momentum.

- The equation relates the delta-v (the maximum change of velocity of the rocket if no other external forces act) with the effective exhaust velocity and the initial and final mass of a rocket, or other reaction engine.
- For any such maneuver (or journey involving a sequence of such maneuvers):

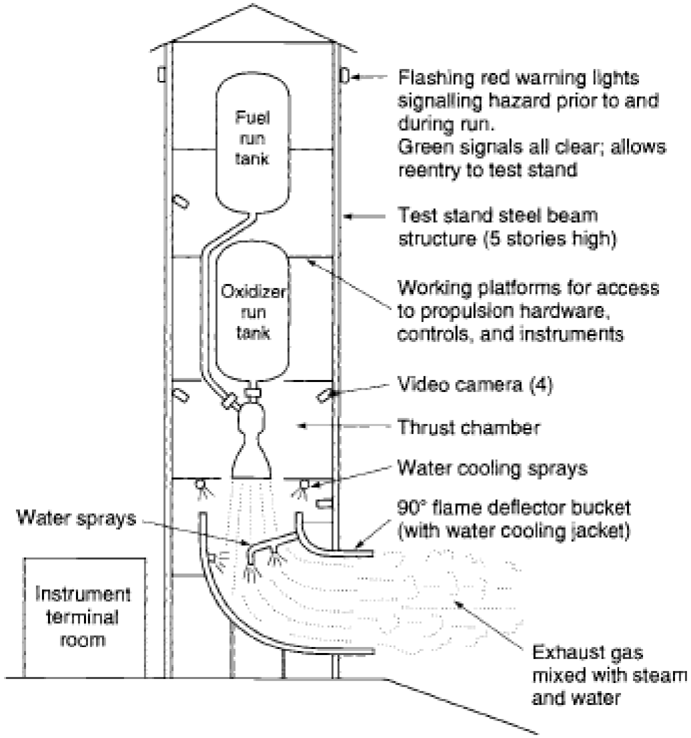
$$\Delta v = v_e \ln \frac{m_0}{m_f}$$

TEST FACILITIES AND SAFEGUARDS TES TEST FACILITIES AND SAFEGUARDS FACILITIES AND SAFEGUARDS

- For chemical rocket propulsion systems, each test facility usually has the following major systems or components:
- 1. A test cell or test bay where the article to be tested is mounted, usually in a special test fixture. If the test is hazardous, the test facility must have provisions to protect operating personnel and to limit damage in case of an accident.

TEST FACILITIES AND SAFEGUARDS TES TEST FACILITIES AND SAFEGUARDS FACILITIES AND SAFEGUARDS

- 2. An instrumentation system with associated computers for sensing, maintaining, measuring, analyzing, correcting, and recording various physical and chemical parameters. It usually includes calibration systems and timers to accurately synchronize the measurements.
- 3. A control system for starting, stopping, and changing the operating conditions.
- 4. Systems for handling heavy or awkward assemblies, supplying liquid propellant, and providing maintenance, security, and safety.



- Figure 2.3 typical static test stand for a large liquid propellant thrust chamber

SAFETY PROVISIONS IN A MODERN TEST FACILITY INCLUDE THE FOLLOWING

- 1. Concrete-walled blockhouse or control stations for the protection of
- personnel and instruments remote from the actual rocket propulsion location.
- 2. Remote control, indication, and recording of all hazardous operations and measurements; isolation of propellants from the instrumentation and control room.

SAFETY PROVISIONS IN A MODERN TEST FACILITY INCLUDE THE FOLLOWING

- 3. Automatic or manual water deluge and fire-extinguishing systems.
- 4. Closed circuit television systems for remotely viewing the test.
- 5. Warning signals (siren, bells, horns, lights, speakers) to notify personnel to clear the test area prior to a test, and an all-clear signal when the conditions are no longer hazardous.

INSTRUMENTATION AND DATA MANAGEMENT

- 1. Forces (thrust, thrust vector control side forces, short thrust pulses).
- 2. Flows (hot and cold gases, liquid fuel, liquid oxidizer, leakage).
- 3. Pressures (chamber, propellant, pump, tank, etc.).

INSTRUMENTATION AND DATA MANAGEMENT

- 4. Temperatures (chamber walls, propellant, structure, nozzle).
- 5. Timing and command sequencing of valves, switches, igniters, etc.
- 6. Stresses, strains, and vibrations (combustion chamber, structures, propellant lines, accelerations of vibrating parts) .

UNIT-3

SOLID ROCKET ROPULSION

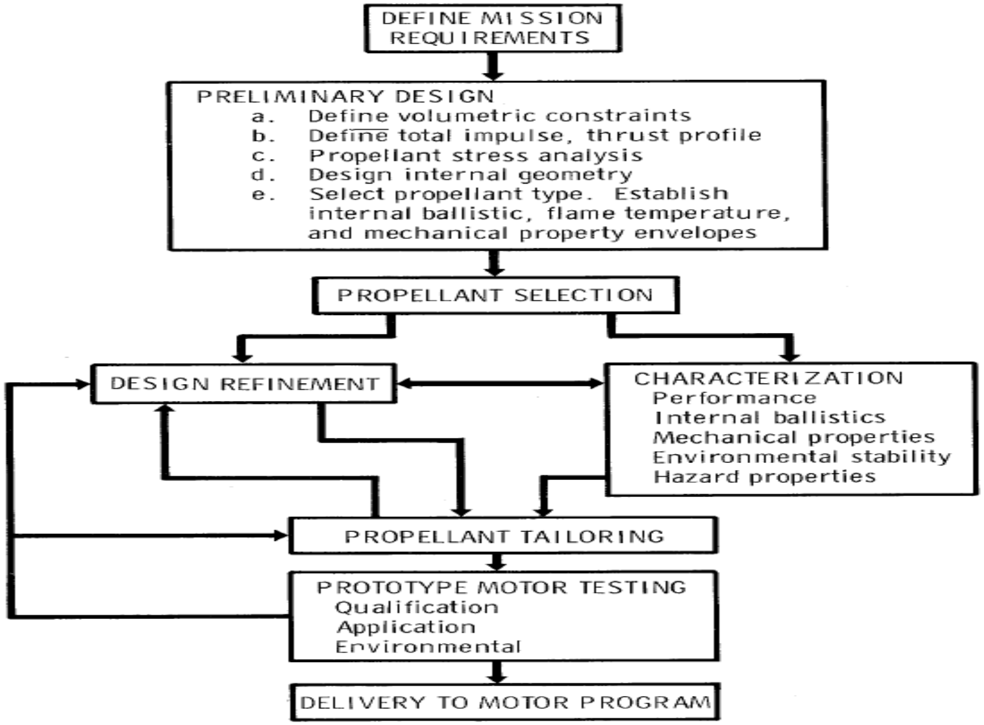
CLOs	Course Learning Outcome
CLO 7	Demonstrate the salient features of solid propellants rockets and estimate the grain configuration designs suitable for different missions.
CLO 8	Understand the erosive burning, combustion instability, and burners
CLO 9	Remember the applications and advantages of solid propellant rockets

INTRODUCTION

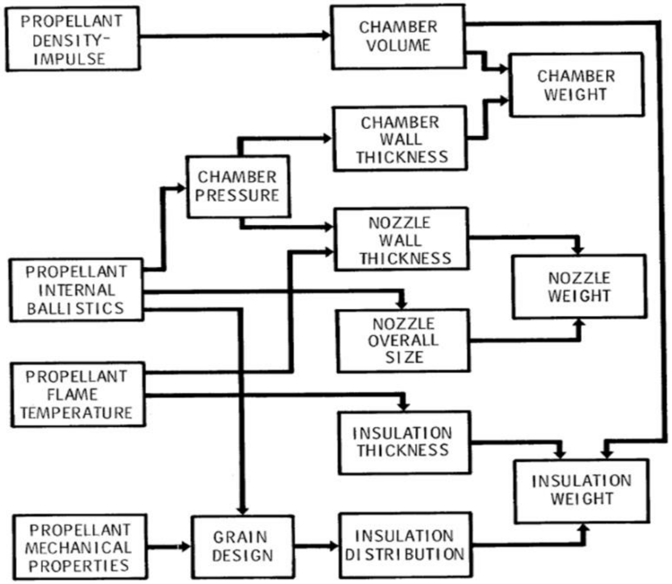
- Solid propellant motors are the simplest of all rocket designs. They consist of a casing, usually steel, filled with a mixture of solid compounds (fuel and oxidizer) that burn at a rapid rate, expelling hot gases from a nozzle to produce thrust.
- When ignited, a solid propellant burns from the center out towards the sides of the casing.

INTRODUCTION

- The shape of the center channel determines the rate and pattern of the burn, thus providing a means to control thrust.
- Unlike liquid propellant engines, solid propellant motors cannot be shut down.
- Once ignited, they will burn until all the propellant is exhausted.

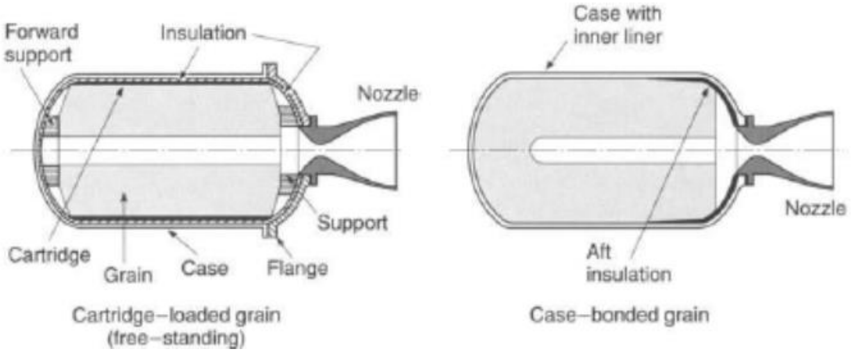


- Figure 3.1 propellant selection

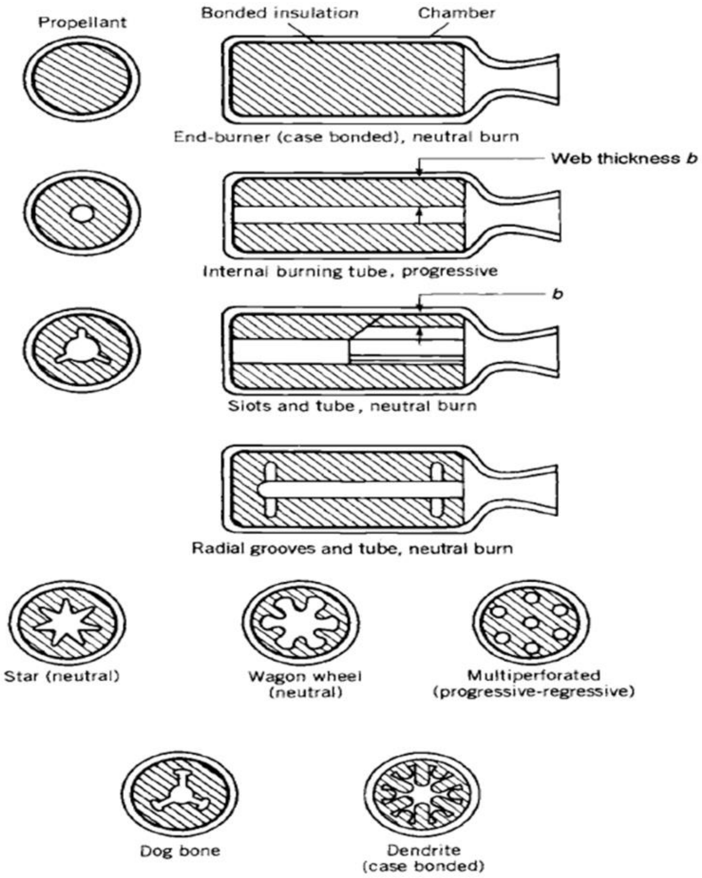


- Figure 3.2 influence of propellant properties

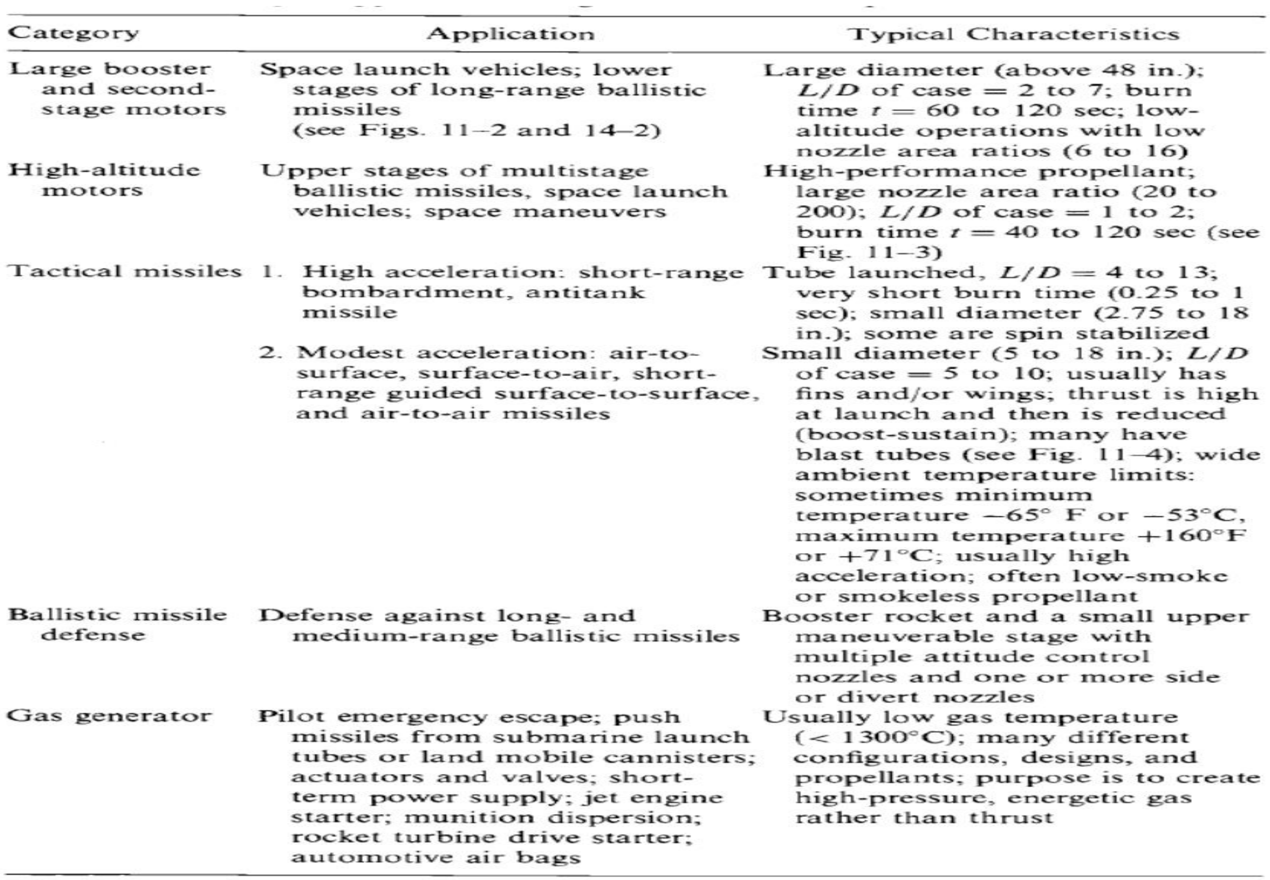
- **Propellant grain design considerations:**
- Add a burning rate catalyst, often called burning rate modifier (0.1 to
- 3.0% of propellant) or increase percentage of existing catalyst.
- Decrease the oxidizer particle size.
- Increase oxidizer percentage.
- Increase the heat of combustion of the binder and/or the plasticizer.
- Imbed wires or metal staples in the propellant.



- Figure 3.3 Simplified schematic diagrams of a free-standing (or cartridge-loaded) and a case-bonded grain.


Propellant
Bonded insulation
Chamber
End-burner (case bonded), neutral burn
Web thickness *b*
Internal burning tube, progressive
b
Slots and tube, neutral burn
Radial grooves and tube, neutral burn
Star (neutral)
Wagon wheel (neutral)
Multiperforated (progressive-regressive)
Dog bone
Dendrite (case bonded)

APPLICATIONS AND ADVANTAGES OF SOLID PROPELLANT ROCKETS.



Category	Application	Typical Characteristics
Large booster and second-stage motors	Space launch vehicles; lower stages of long-range ballistic missiles (see Figs. 11–2 and 14–2)	Large diameter (above 48 in.); L/D of case = 2 to 7; burn time t = 60 to 120 sec; low-altitude operations with low nozzle area ratios (6 to 16)
High-altitude motors	Upper stages of multistage ballistic missiles, space launch vehicles; space maneuvers	High-performance propellant; large nozzle area ratio (20 to 200); L/D of case = 1 to 2; burn time t = 40 to 120 sec (see Fig. 11–3)
Tactical missiles	1. High acceleration: short-range bombardment, antitank missile	Tube launched, L/D = 4 to 13; very short burn time (0.25 to 1 sec); small diameter (2.75 to 18 in.); some are spin stabilized
	2. Modest acceleration: air-to-surface, surface-to-air, short-range guided surface-to-surface, and air-to-air missiles	Small diameter (5 to 18 in.); L/D of case = 5 to 10; usually has fins and/or wings; thrust is high at launch and then is reduced (boost-sustain); many have blast tubes (see Fig. 11–4); wide ambient temperature limits: sometimes minimum temperature −65° F or −53°C, maximum temperature +160°F or +71°C; usually high acceleration; often low-smoke or smokeless propellant
Ballistic missile defense	Defense against long- and medium-range ballistic missiles	Booster rocket and a small upper maneuverable stage with multiple attitude control nozzles and one or more side or divert nozzles
Gas generator	Pilot emergency escape; push missiles from submarine launch tubes or land mobile cannisters; actuators and valves; short-term power supply; jet engine starter; munition dispersion; rocket turbine drive starter; automotive air bags	Usually low gas temperature (< 1300°C); many different configurations, designs, and propellants; purpose is to create high-pressure, energetic gas rather than thrust

UNIT 4
LIQUID AND HYBRID ROCKET PROPULSION

CLOs	Course Learning Outcome
CLO 10	Recognize the salient features of liquid propellant rockets, various feed systems and injectors.
CLO 11	Understand the thrust control cooling, heat transfer problems, combustion instability in liquid propellant rockets
CLO 12	Understand the peculiar problems associated with the operation of cryogenic engines in different missions.
CLO 13	Recognize the standard and reverse hybrid systems, combustion mechanism, applications, and limitations.

INTRODUCTION

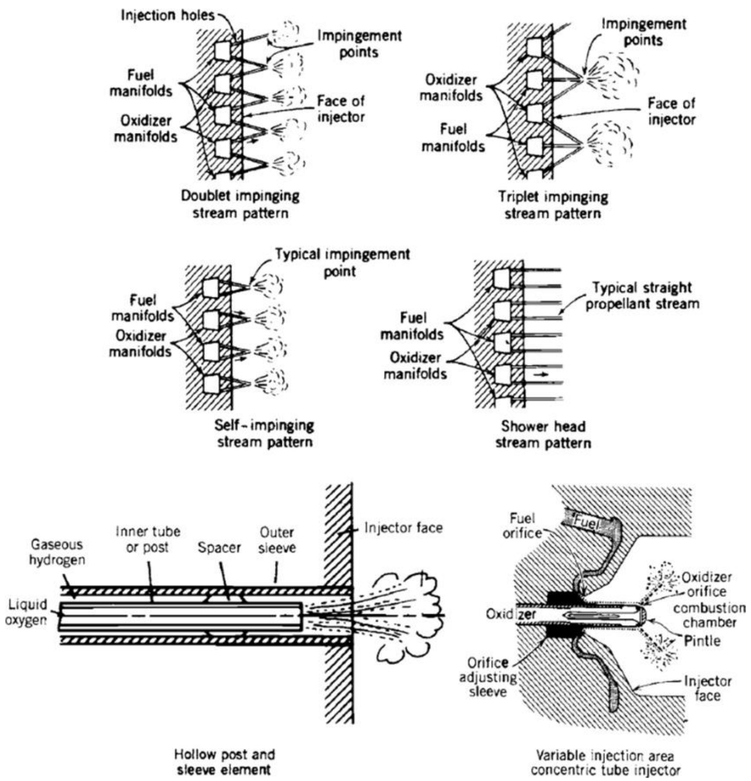
The propellants, which are the working substance of rocket engines, constitute the fluid that undergoes chemical and thermodynamic changes. The term liquid propellant embraces all the various liquids used and may be one of the following:

1. Oxidizer (liquid oxygen, nitric acid, etc.)
2. Fuel (gasoline, alcohol, liquid hydrogen, etc.).
3. Chemical compound or mixture of oxidizer and fuel ingredients, capable of self-decomposition.
4. Any of the above, but with a gelling agent.

SELECTION OF LIQUID PROPELLANTS

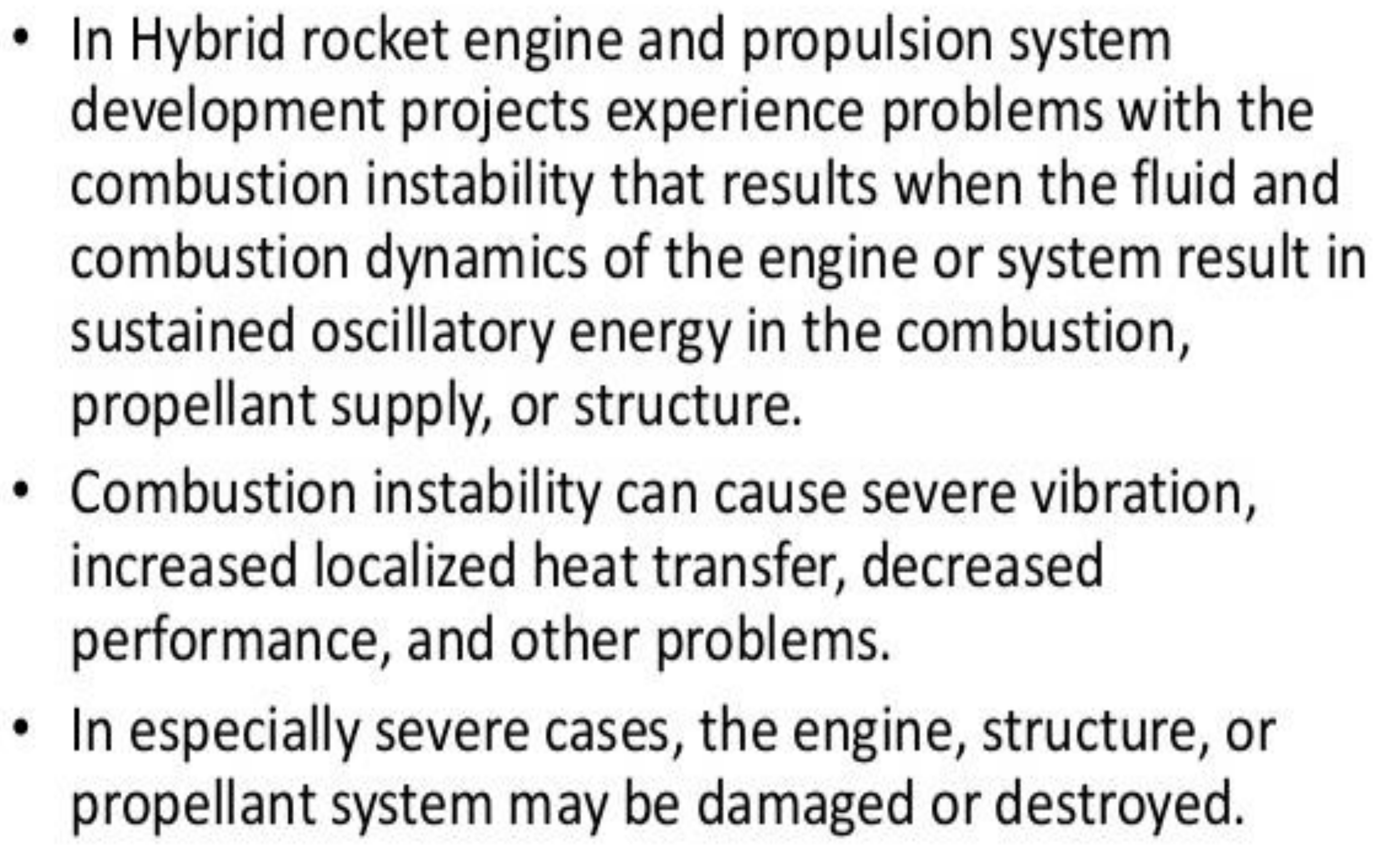
- Mission Definition
- Affordability (Cost)
- System Performance
- Survivability (Safety)
- Reliability
- Controllability
- Maintainability
- Geometric Constraints
- Prior Related Experience
- Operability
- Producibility
- Schedule
- Environmental Acceptability
- Reusability

INJECTOR



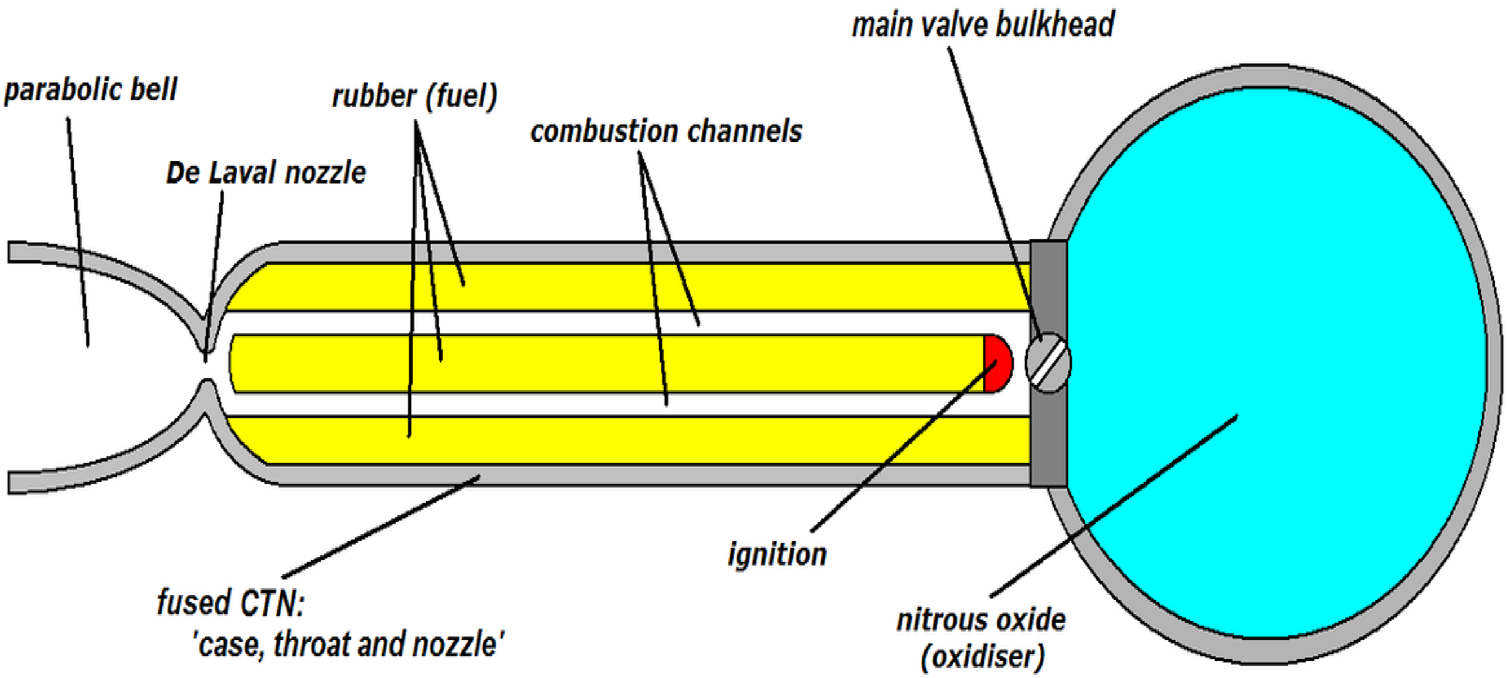
- Figure 4.1 Schematic Diagrams Of Several Injector Types.

Combustion Instability In Liquid Propellant Rockets



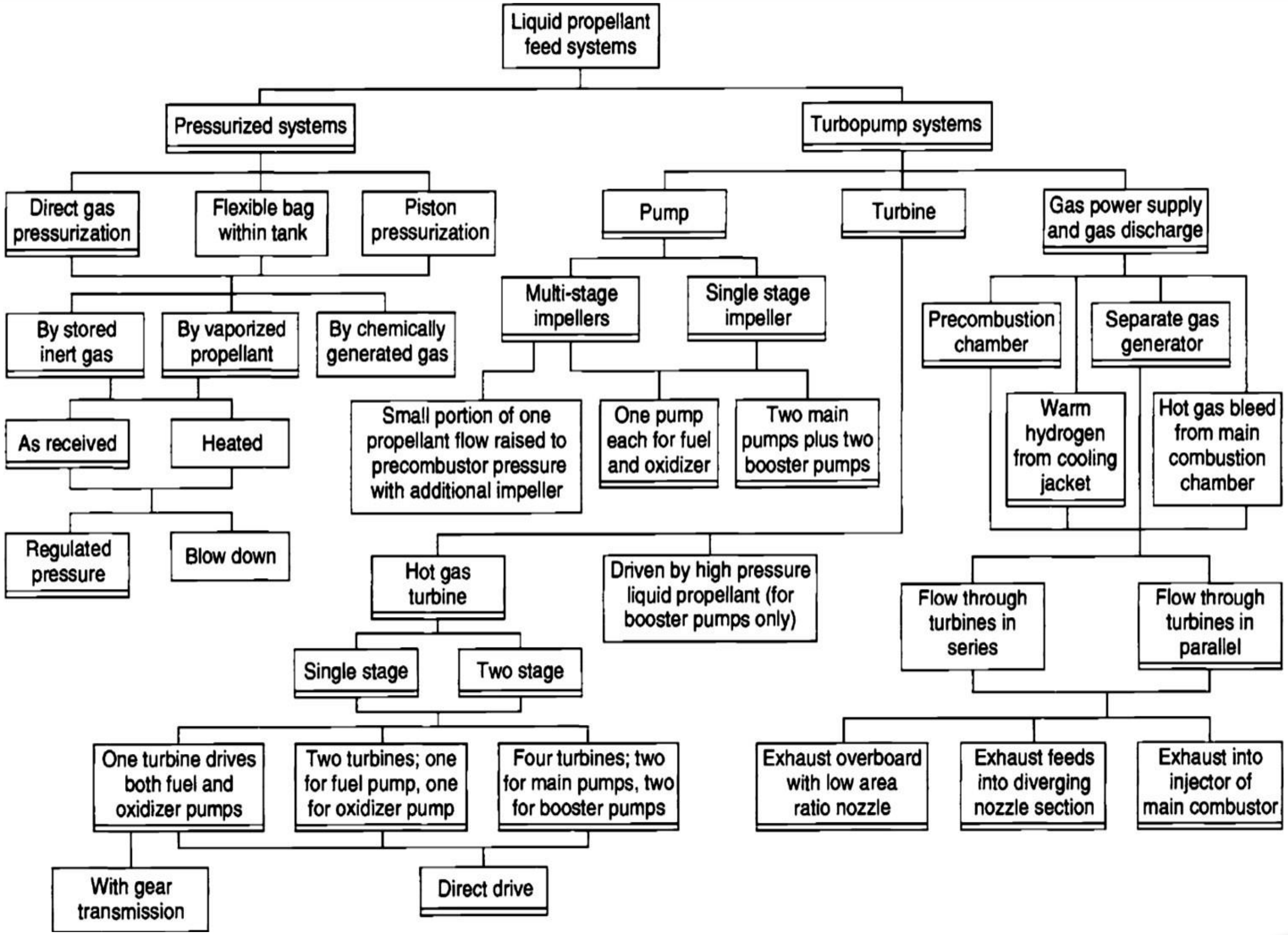
- In Hybrid rocket engine and propulsion system development projects experience problems with the combustion instability that results when the fluid and combustion dynamics of the engine or system result in sustained oscillatory energy in the combustion, propellant supply, or structure.
- Combustion instability can cause severe vibration, increased localized heat transfer, decreased performance, and other problems.
- In especially severe cases, the engine, structure, or propellant system may be damaged or destroyed.

Combustion Mechanism in Hybrid Propellant Rockets



- Figure 4.2 hybrid propellant

PROPELLANT FEED SYSTEMS



Liquid propellant feed systems

Pressurized systems

Turbopump systems

Direct gas pressurization

Flexible bag within tank

Piston pressurization

Pump

Turbine

Gas power supply and gas discharge

Multi-stage impellers

Single stage impeller

Precombustion chamber

Separate gas generator

By stored inert gas

By vaporized propellant

By chemically generated gas

Warm hydrogen from cooling jacket

Hot gas bleed from main combustion chamber

As received

Heated

Small portion of one propellant flow raised to precombustor pressure with additional impeller

One pump each for fuel and oxidizer

Two main pumps plus two booster pumps

Regulated pressure

Blow down

Hot gas turbine

Driven by high pressure liquid propellant (for booster pumps only)

Flow through turbines in series

Flow through turbines in parallel

Single stage

Two stage

One turbine drives both fuel and oxidizer pumps

Two turbines; one for fuel pump, one for oxidizer pump

Four turbines; two for main pumps, two for booster pumps

Exhaust overboard with low area ratio nozzle

Exhaust feeds into diverging nozzle section

Exhaust into injector of main combustor

With gear transmission

Direct drive

Problems Associated With Operation Of Cryogenic Engines

- The thrust comes from the rapid expansion from liquid to gas with the gas emerging from the motor at very high speed.
- The energy needed to heat the fuels comes from burning them, once they are gasses.
- Cryogenic engines are the highest performing rocket motors. Cryogenic engines are fundamentally different from electric motors because there isn't anything rotating in them. They're essentially reaction engines.
- By 'reaction' I'm referring to Newton's law: "to every action there is an equal and opposite reaction.

- The cryogenic (or rocket) engine throws mass in one direction, and the reaction to this is a thrust in the opposite direction.
- Therefore, to get the required mass flow rate, the only option was to cool the propellants down to cryogenic temperatures (below −183 °C [90 K], −253 °C [20 K]), converting them to liquid form.
- Hence, all cryogenic rocket engines are also, by definition, either liquid-propellant rocket engines or hybrid rocket engines Introduction to hybrid rocket propulsion-standard and reverse hybrid systems-combustion mechanism in hybrid propellant rockets applications and limitations.

Introduction to Hybrid Rocket Propulsion

- Rocket propulsion concepts in which one component of the propellant is stored in liquid phase while the other is stored in solid phase are called hybrid propulsion systems.
- Such systems most commonly employ a liquid oxidizer and solid fuel.
- Various combinations of solid fuels and liquid oxidizers as well as liquid fuels and solid oxidizers have been experimentally evaluated for use in hybrid rocket motors.

Advantages of a Hybrid Rocket Propulsion System

- (1) safety during fabrication, storage, or operation without any possibility of explosion or detonation;
- (2) start-stop-restart capabilities;
- (3) relatively low system cost;
- (4) higher specific impulse than solid rocket motors and higher density-specific impulse than liquid bipropellant engines; and
- (5) the ability to smoothly change motor thrust over a wide range on demand.

Disadvantages of a Hybrid Rocket Propulsion System

- (1) mixture ratio and, hence, specific impulse will vary somewhat during steady-state operation and throttling;
- (2) lower density-specific impulse than solid propellant systems;
- (3) some fuel sliver must be retained in the combustion chamber at end-of burn, which slightly reduces motor mass fraction; and
- (4) unproven propulsion system feasibility at large scale.

Applications

- Hybrid propulsion is well suited to applications or missions requiring throttling, command shutdown and restart, long-duration missions requiring storable nontoxic propellants, or infrastructure operations (manufacturing and launch) that would benefit from a non-self-deflagrating propulsion system.
- Such applications would include primary boost propulsion for space launch vehicles, upper stages, and satellite maneuvering systems.

Applications

- Many early hybrid rocket motor developments were aimed at target missiles and low-cost tactical missile applications .
- Other development efforts focused on high-energy upper-stage motors. In recent years development efforts have concentrated on booster prototypes for space launch applications.

Hybrid Rocket Configuration

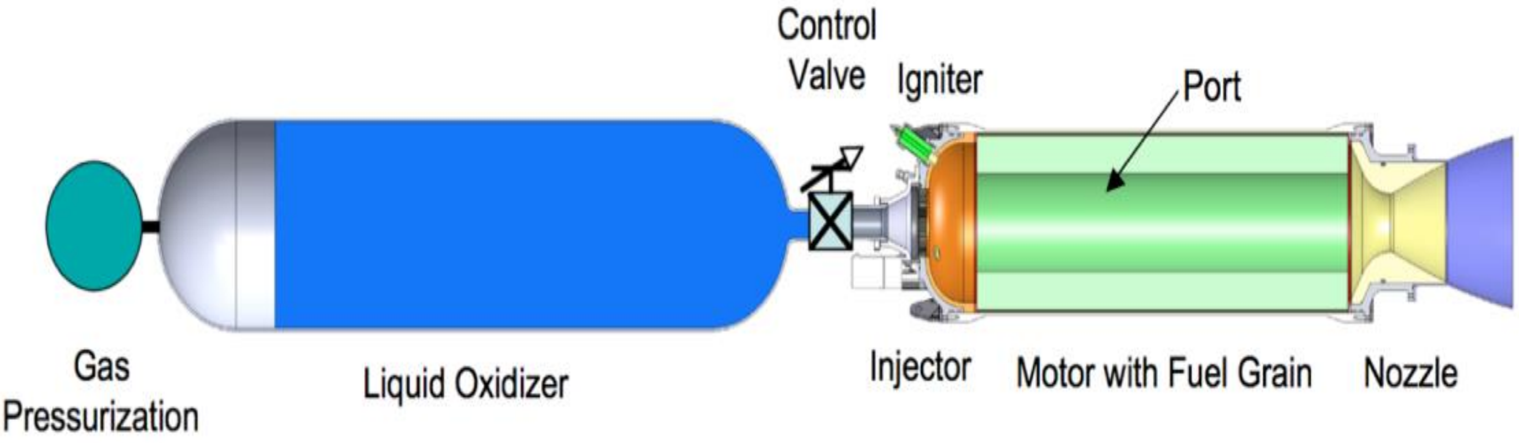


Figure:4.3 Schematic of a hybrid rocket motor

UNIT – 5

ADVANCED PROPULSION TECHNIQUES

CLOs	Course Learning Outcome
CLO 14	Understand the different types of Electric, Ion, and Nuclear propulsion systems.
CLO 15	Identify the future applications of the electric propulsion system

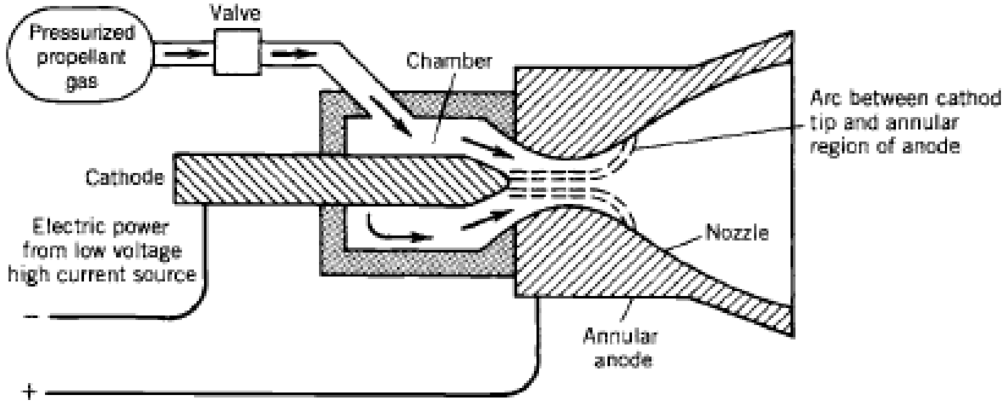
ELECTRIC ROCKET PROPULSION

In all electric propulsion the source of the electric power (nuclear, solar radiation receivers, or batteries) is physically separate from the mechanism that produces the thrust.

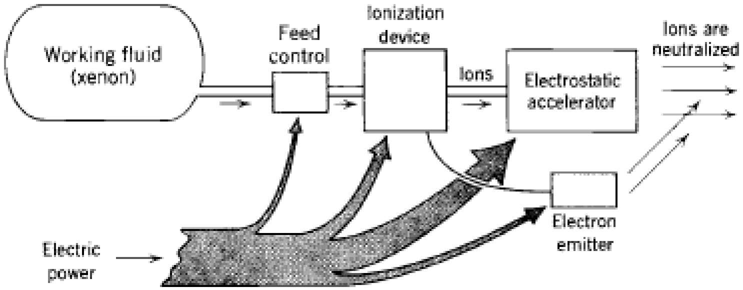
This type of propulsion has been handicapped by heavy and inefficient power sources. The thrust usually is low, typically 0.005 to 1 N.

In order to allow a significant increase in the vehicle velocity, it is necessary to apply the low thrust and thus a small acceleration for a long time (weeks or months).

- The two other types--the electrostatic or ion propulsion engine and the
- Electromagnetic or magneto plasma engine--accomplish propulsion by different principles and the thermodynamic expansion of gas in a nozzle, as such, does not apply. Both will work only in a vacuum. In an ion rocket a working fluid (typically, xenon) is ionized (by stripping off electrons) and then the electrically charged heavy ions are accelerated to very high velocities (2000 to 60,000 rn/sec) by means of electrostatic fields. The ions are subsequently electrically neutralized; they are combined with electrons to prevent the buildup of a space



- Figure 5.1 : Simplified Diagram of Arc Heating Electric Propulsion



- Figure. 5.2 Simplified Schematic Diagram Of A Typical Ion Rocket

PRINCIPLES OF ELECTRIC PROPULSION

- The basic principle of electric propulsion is to apply electrical energy to the propellant from an external power source.
- This can be done in several ways. The simplest is to heat the propellant with a hot wire coil, through which an electric current passes.
- This elementary approach, used in some commercial thrusters, is very successful.

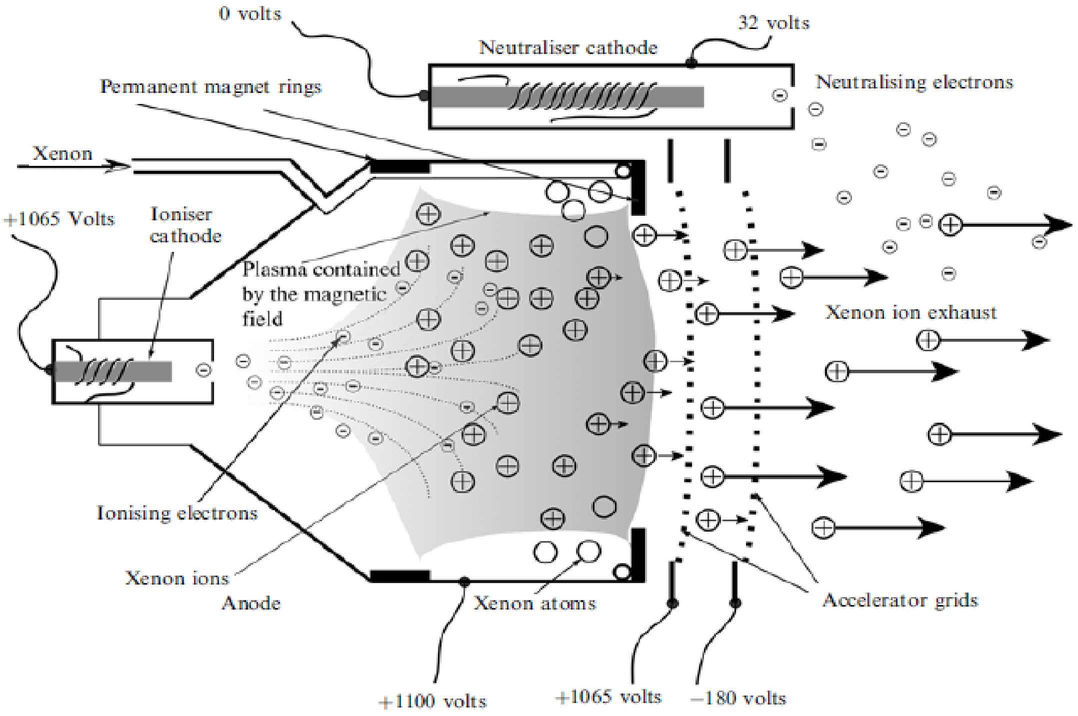
PRINCIPLES OF ELECTRIC PROPULSION

- More energy can be delivered from the electric current if an arc is struck through the propellant, which generates higher temperatures than the resistive approach and produces a higher exhaust velocity.
- Finally, electric or magnetic fields can be used directly to accelerate propellant ions to very high velocities, producing the highest exhaust velocity of all.

- These ion thrusters, and Kall effect thrusters are seen as the most promising for deep space applications, and they are already coming into commercial use for station keeping and interplanetary propulsion.
- While for a chemical rocket the link between energy supply and propellant simplifies analysis, for electrical propulsion the power supply introduces free parameters for which we have to make estimates when deriving expected vehicle performance.

ION PROPULSION

- This is the simplest concept„ propellant is ionised, and then enters a region of strong electric field, where the positive ions are accelerated. Passing through a grid, they leave the engine as a high-velocity exhaust stream.
- The electrons do not leave, and so the exhaust is positively charged. Ultimately this would result in a retarding field developing between the spacecraft and the exhaust, and so an electron current is therefore discharged into the exhaust to neutralize the spacecraft.
- The electrons carry little momentum, and so this does not affect the thrust.



- Figure 5.3 Schematic Diagram Of The NSTAR Ion Thruster

ION THRUSTER THEORY

- The theory of operation is also relatively simple, and because it is so different from that of a thermal rocket it is useful to include a brief description here, so that the strengths and limitations can be appreciated.
- As in all reaction propulsion systems, the thrust depends ultimately on the transfer of momentum from an exhaust stream to the vehicle.
- The exhaust velocity is straightforwardly given by the potential difference between the grids. Ions dropping through this potential difference each gain a fixed amount of energy, and this converts directly into a velocity.
- The other parameter in the thrust is the mass flow rate.

SOLAR CELLS

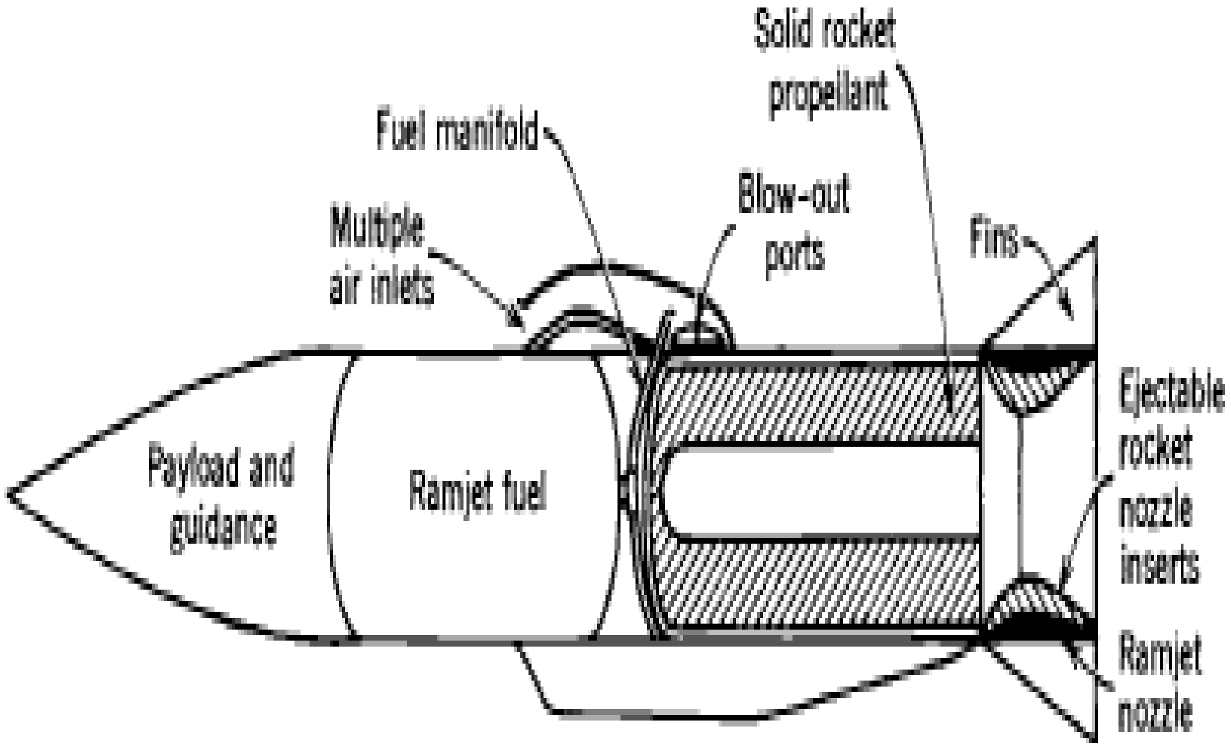
- The maximum efficiency of solar cells, in converting solar energy to electricity, ranges from 15 to 20% depending on the type. Typically, for a 30-kw array, the mass per kilowatt is about 13 kg.
- The areal extent would be about 210 m^2, achieved by deploying a folded structure, once in space.
- For lower power, 5−6 kw, a mass per kilowatt of 7 kg can be achieved. This reflects the mass needed for the structure of the larger deployable array.
- with improved solar cells, especially gallium arsenide, and the use of solar concentrators, which focus the sunlight collected by lightweight reflectors on to a smaller area of solar cells, a mass per kilowatt of about 3 kg is thought to be achievable.

APPLICATIONS OF ELECTRIC PROPULSION

- The different applications which currently make or may make use of Electric Propulsion Systems in the future, are:
- LEO (e.g. Earth Observation, Earth Science, constellations)
- MEO (e.g. Navigation)
- GEO (e.g. Telecommunications)
- Space Transportation (e.g. launcher kick stages, space tugs)
- Space Science, Interplanetary, and Space exploration.

NUCLEAR ROCKET ENGINES

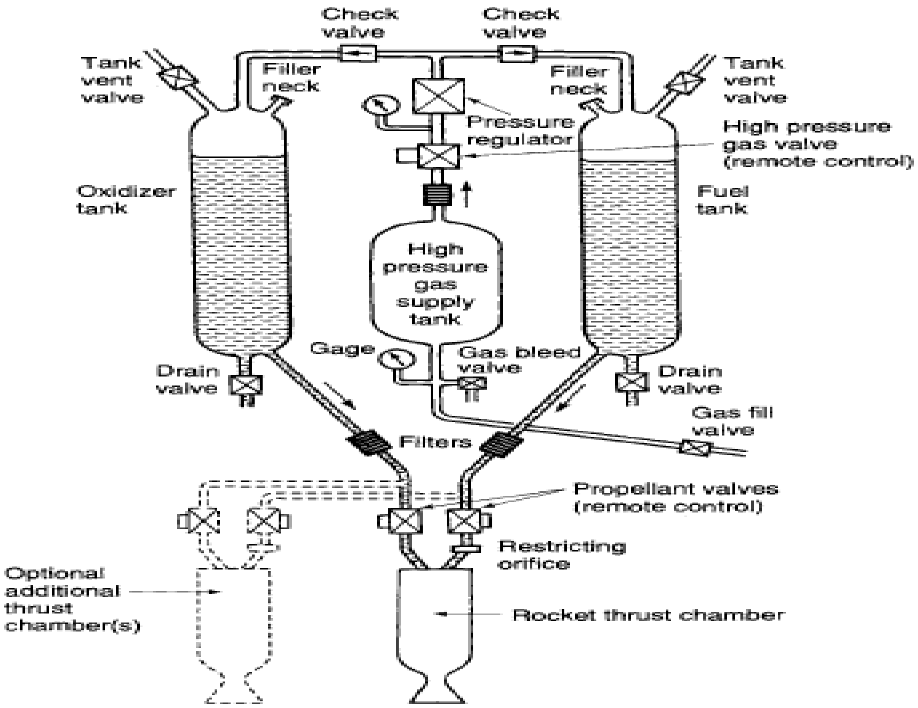
- In the nuclear fission reactor rocket, heat can be generated by the fission of uranium in the solid reactor material and subsequently transferred to the working fluid.).
- The nuclear fission rocket is primarily a high-thrust engine (above 40,000 N) with specific impulse values up to 900 sec.
- Fission rockets were designed and tested in the 1960s.
- Ground tests with hydrogen as a working fluid culminated in a thrust of 980,000 N (210,000 lb force) at a graphite core nuclear reactor level of 4100 MW with an equivalent altitude-specific impulse of 848 sec and a hydrogen temperature of about 2500 K.



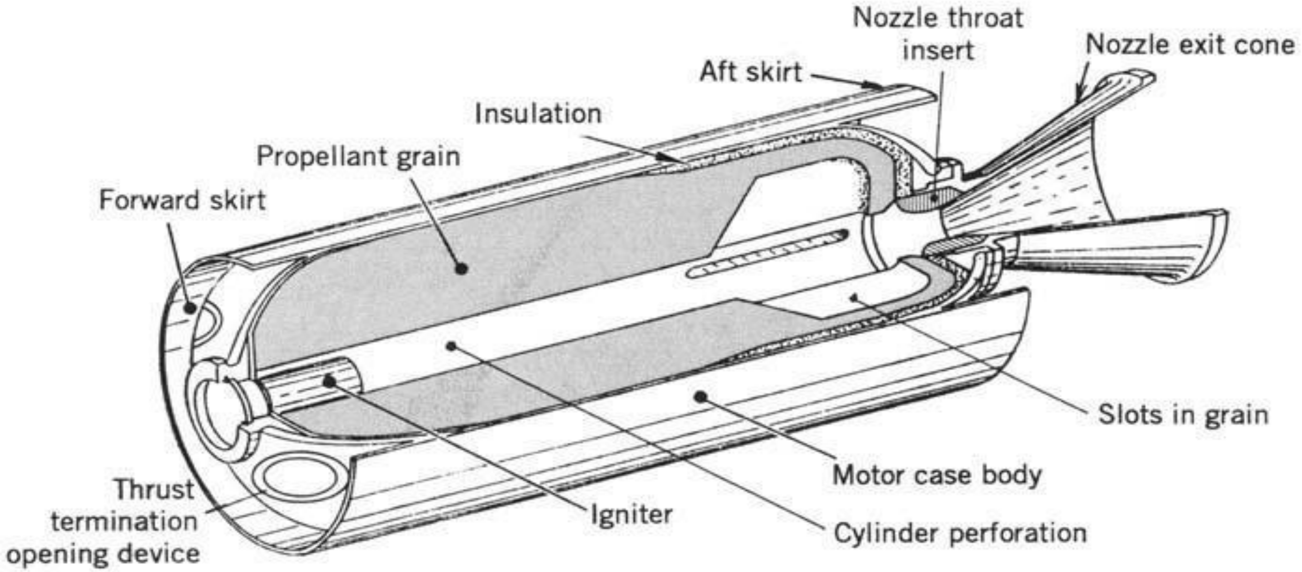
- Figure 5.4 : Elements Of An Air-Launched Missile With Integral Rocket-Ramjet Propulsion

CHEMICAL ROCKET PROPULSION

- The energy from a high-pressure combustion reaction of propellant chemicals, usually a fuel and an oxidizing chemical, permits the heating of reaction product gases to very high temperatures (2500 to 4100°C or 4500 to 7400°F).
- These gases subsequently are expanded in a nozzle and accelerated to high velocities (1800 to 4300 m/sec or 5900 to 14,100 ft/sec).
- Since these gas temperatures are about twice the melting point of steel, it is necessary to cool or insulate all the surfaces that are exposed to the hot gases.
- According to the physical state of the propellant, there are several different classes of chemical rocket propulsion devices.



- Figure5.5 : liquid propellant rocket engine with a gas pressure feed system.



- figure 5.6 :typical solid propellant rocket motor with the propellant grain bonded

Thank You