ROCKET AND MISSILES

B. Tech VIII semester

BY

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COURSE OBJECTIVES:

The course should enable the students to:	
I	Learn Fundamentals of rocket and missile systems, functions and disciplines and the full spectrum of rocket systems, uses and technologies
II	Understand the Fundamentals and uses of solid, liquid and hybrid rocket systems and differences between systems built as weapons and those built for commerce.
III	Explain the use of low and high fidelity performance modeling, including performance loss factors, Staging theory, performance and practices for multi-stage rockets.
IV	Discuss the reliability issues in rocket systems, and strategies to improve reliability, including random and systematic failures, non-linier reliability curves.

COURSE OUTCOMES (COs):

The course should enable the students to:	
CO 1	Describe the Classification of launch vehicles and missiles and its dynamics
CO 2	Differentiating the components of and the design considerations of solid and hybrid rocket systems and some design problems
CO 3	Understanding the concept of liquid propulsion system ,component classification and design problems in rocket systems
CO 4	Estimation of optimization techniques od navigation and guidance system in rockets ,missiles and its aerodynamics control systems
CO 5	Acquiring the knowledge on design, materials and testing of rockets space environment on the selection of materials for rockets and spacecraft

UNIT 1

ROCKET DYNAMICS

CLOs	Course Learning Outcome
CLO 1	List out the classification of launch vehicles and missiles, rocket systems, airframe component
CLO 2	Acquire the basic knowledge on forces and moments acting on a rocket, propulsion, aerodynamics, gravity of rocket missiles
CLO 3	Examine the equations of motion for three-dimensional motion through atmosphere and vacuum, earth's atmosphere, numerical problems

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 invader 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.

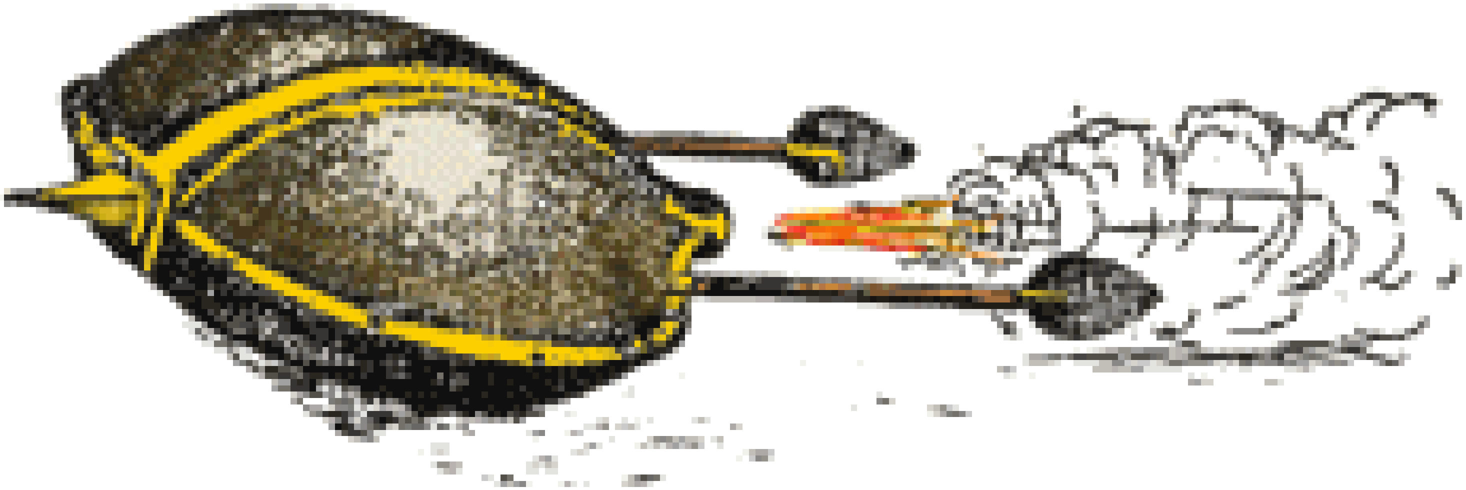


Figure 1.7 Surface Running Torpedo

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

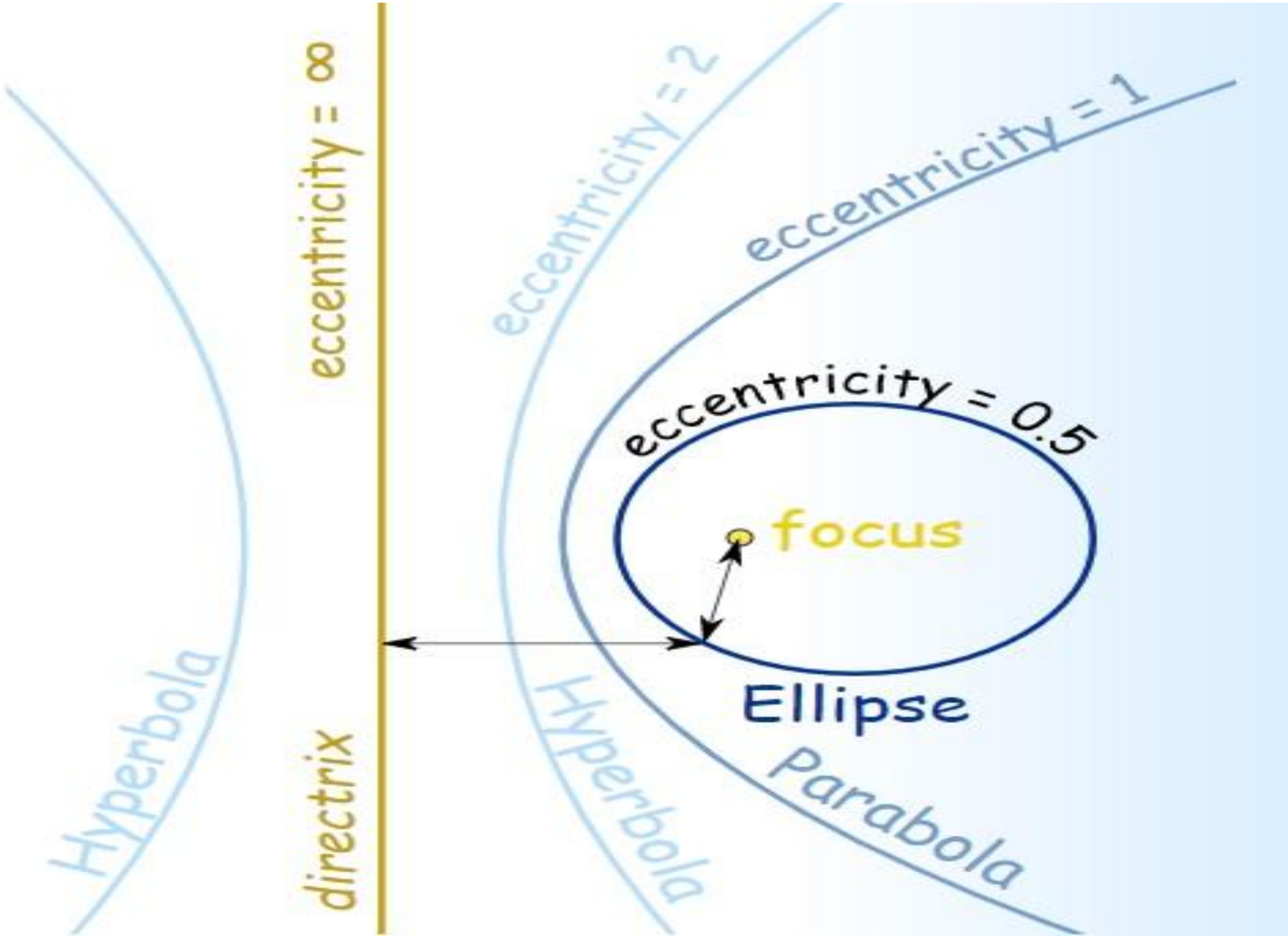
0 < **eccentricity** < 1 we get an ellipse,

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	$\geq$ 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:

$$h = MrV$$

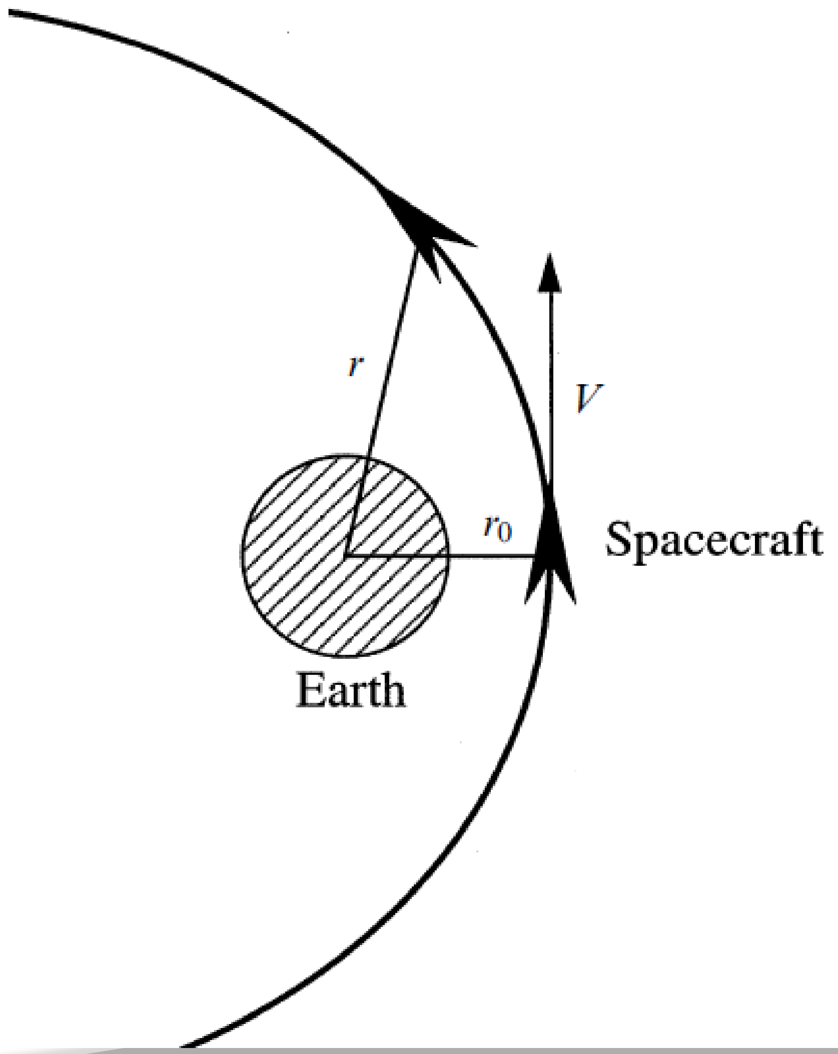
$$\varepsilon = \frac{h^2}{GM_\oplus M^2 r_0} - 1$$

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.

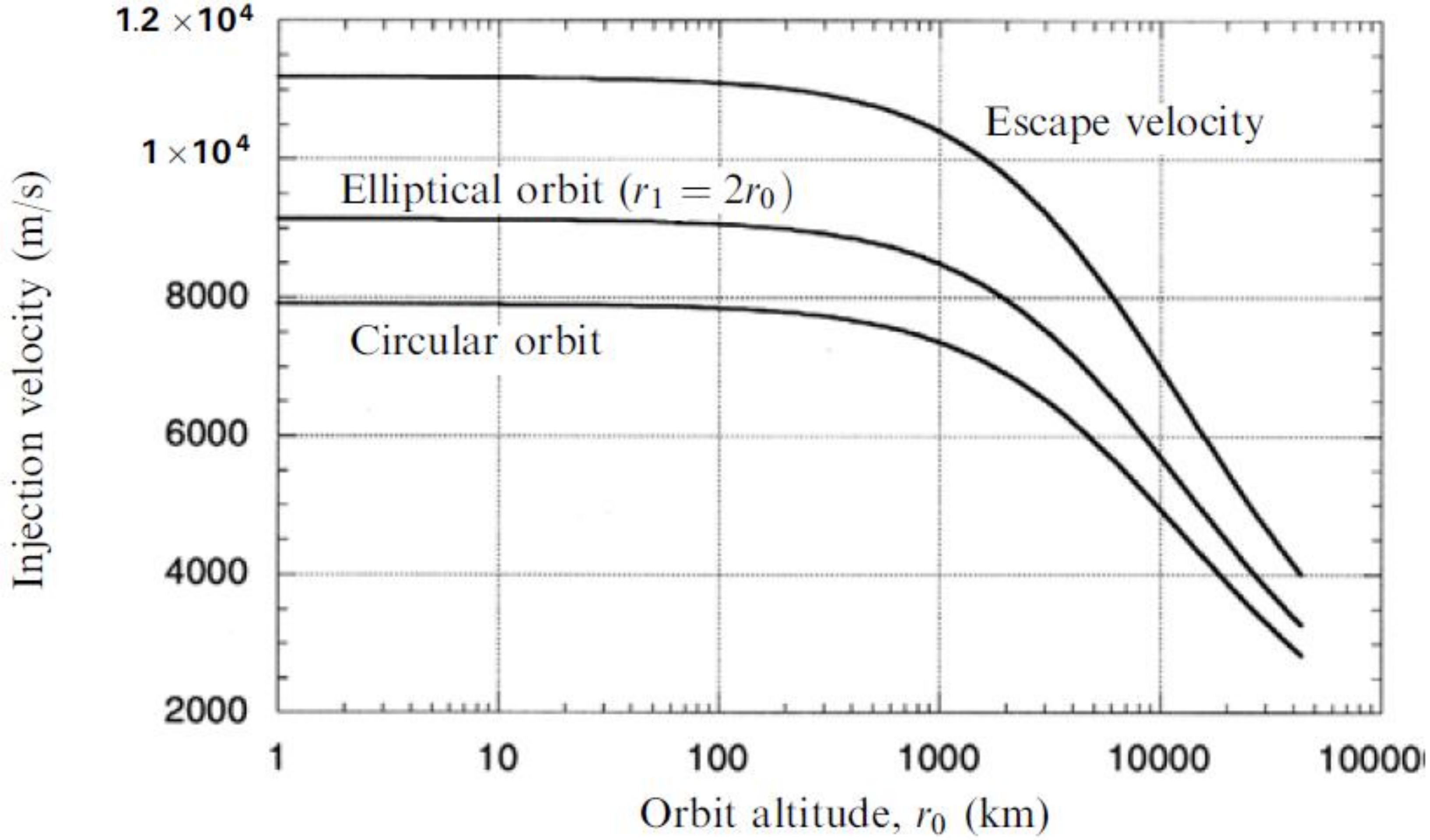
$$V_0 = \sqrt{\frac{GM_{\oplus}}{r_0}} \qquad \text{for a circular orbit}$$

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

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

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

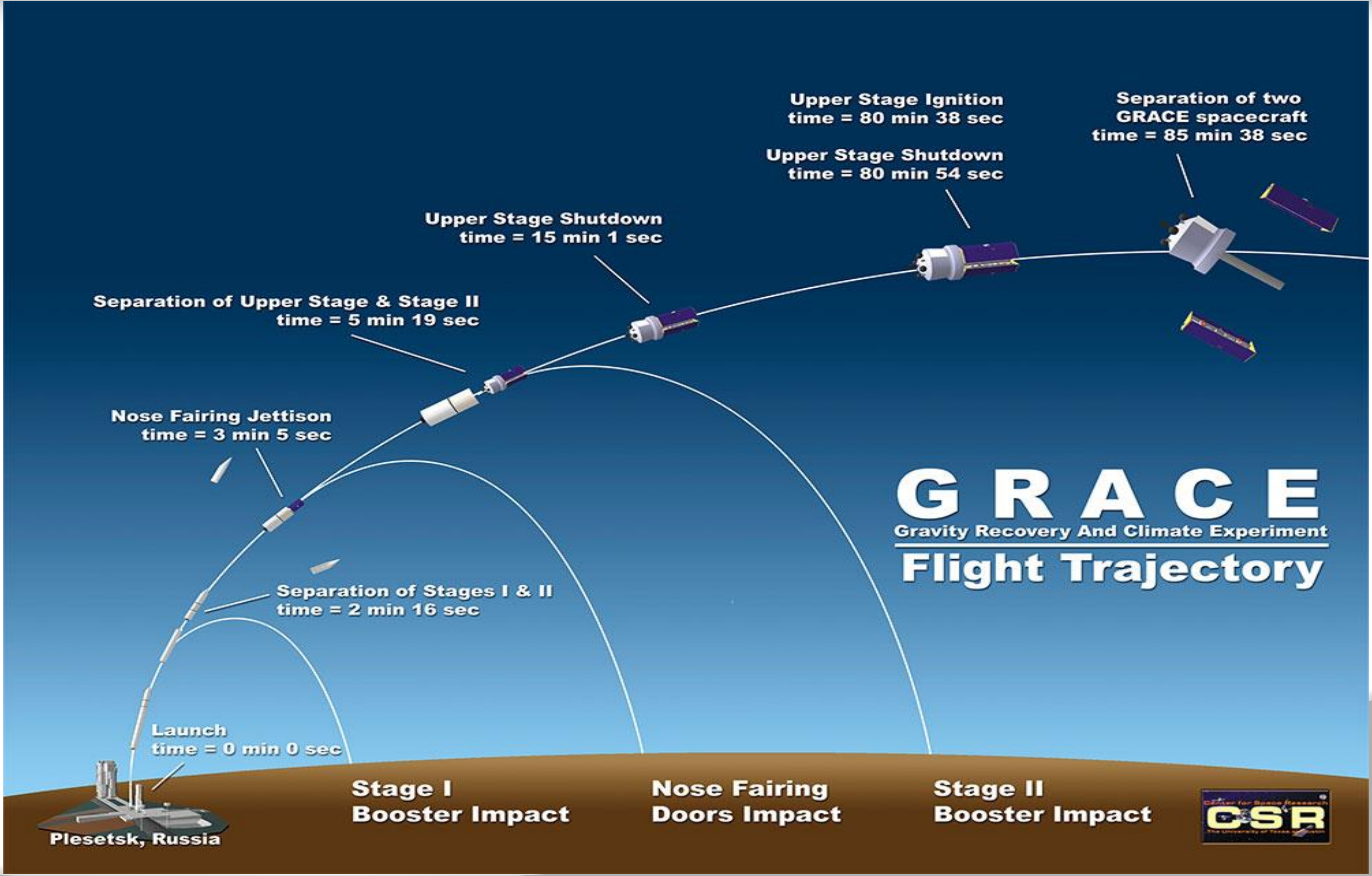
- Losses associated with this slowing are known as gravity drag, and can be minimized by executing the next phase of the launch, the **pitchover maneuver**, as soon as possible.

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

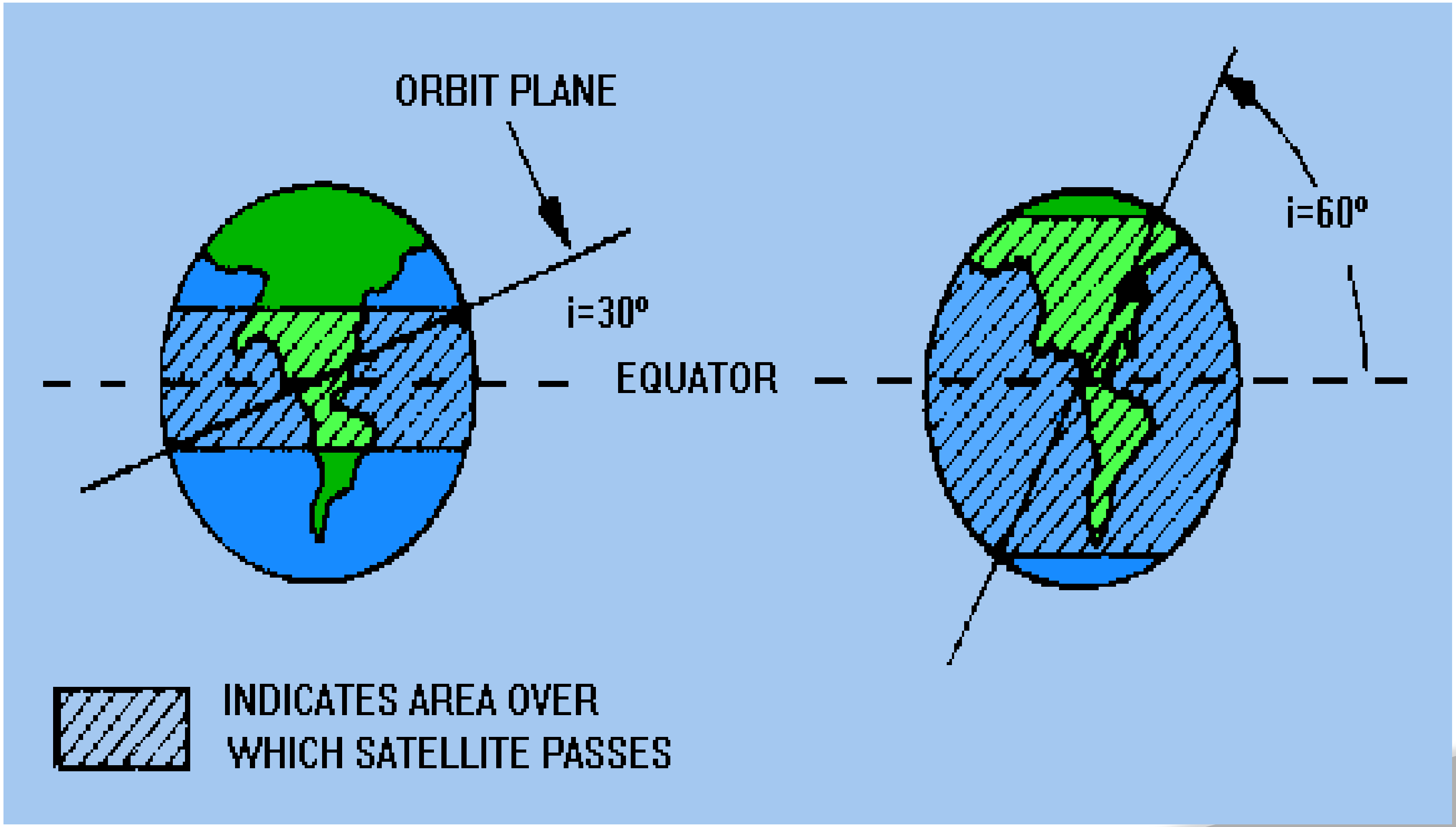
A decrease in velocity when a spacecraft is in circular orbit causes It to enter an elliptical orbit. The apogee is at the same altitude as the circular orbit, and the perigee is determined by the velocity decrease. At perigee, the S/C velocity > the corresponding new circular orbit, Further decrease 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 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 = $6.673\text{x}10^{(-11)}$ N·m^2/kg^2

m_E = the mass of the Earth ($5.98 \text{ x } 10^{24}$ 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.

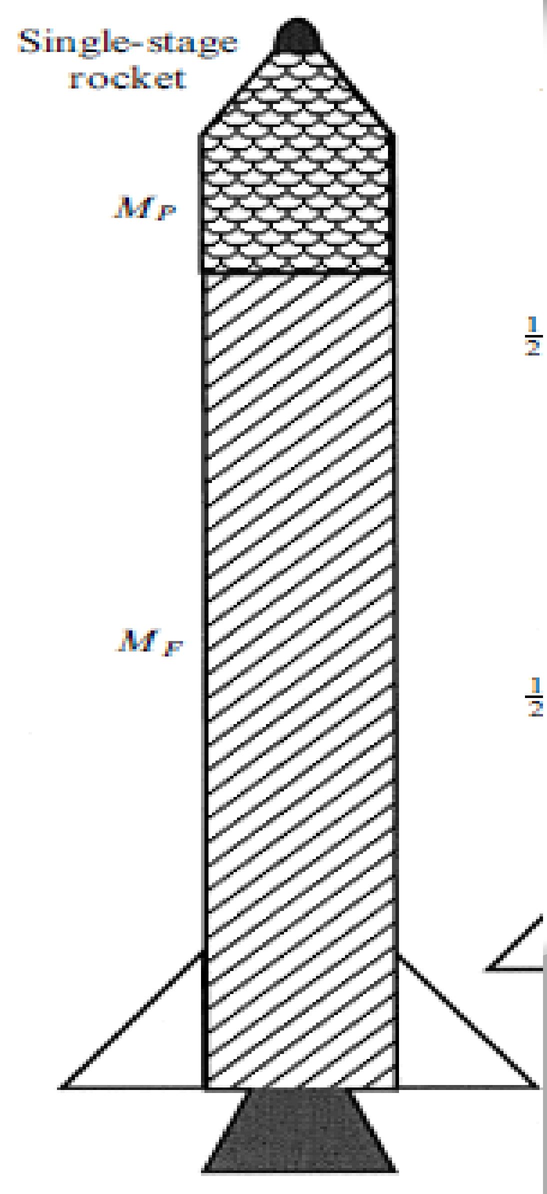
$$v = \sqrt{GM\left(\frac{2}{r} - \frac{1}{a}\right)} \qquad (elliptical\ \ orbit)$$

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

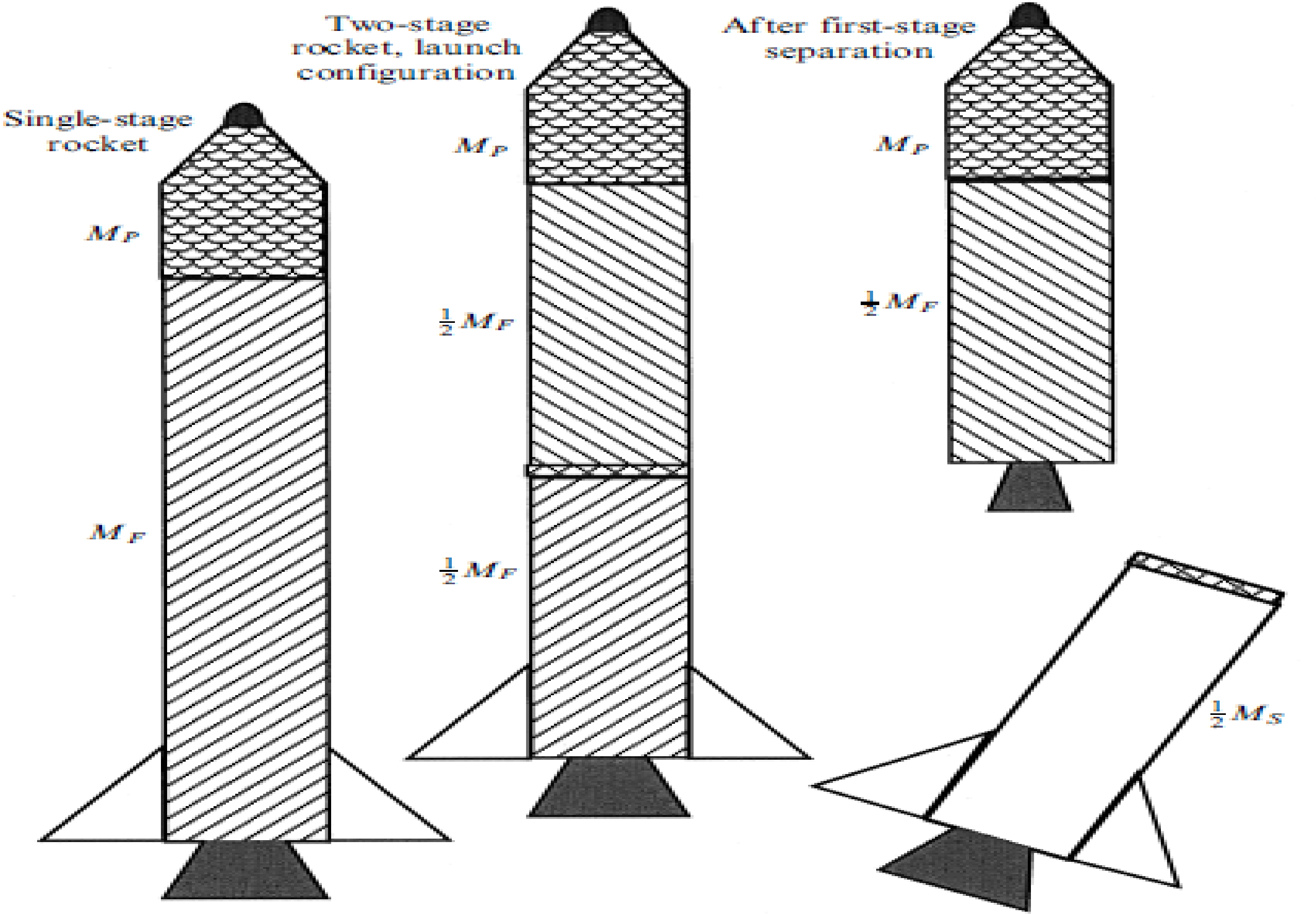
SSTO and TSTO (Multistage Rocket)

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-

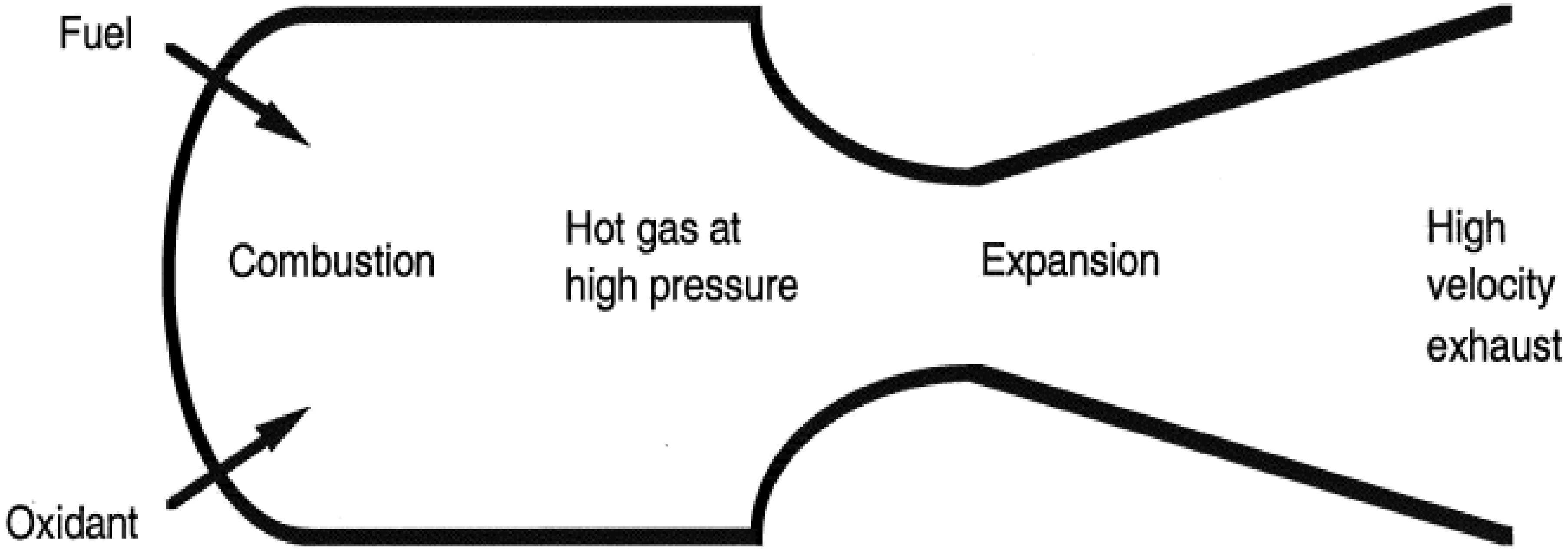
fuel and oxidiser, in the combustion chamber-into kinetic energy of

the emerging exhaust gas.

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

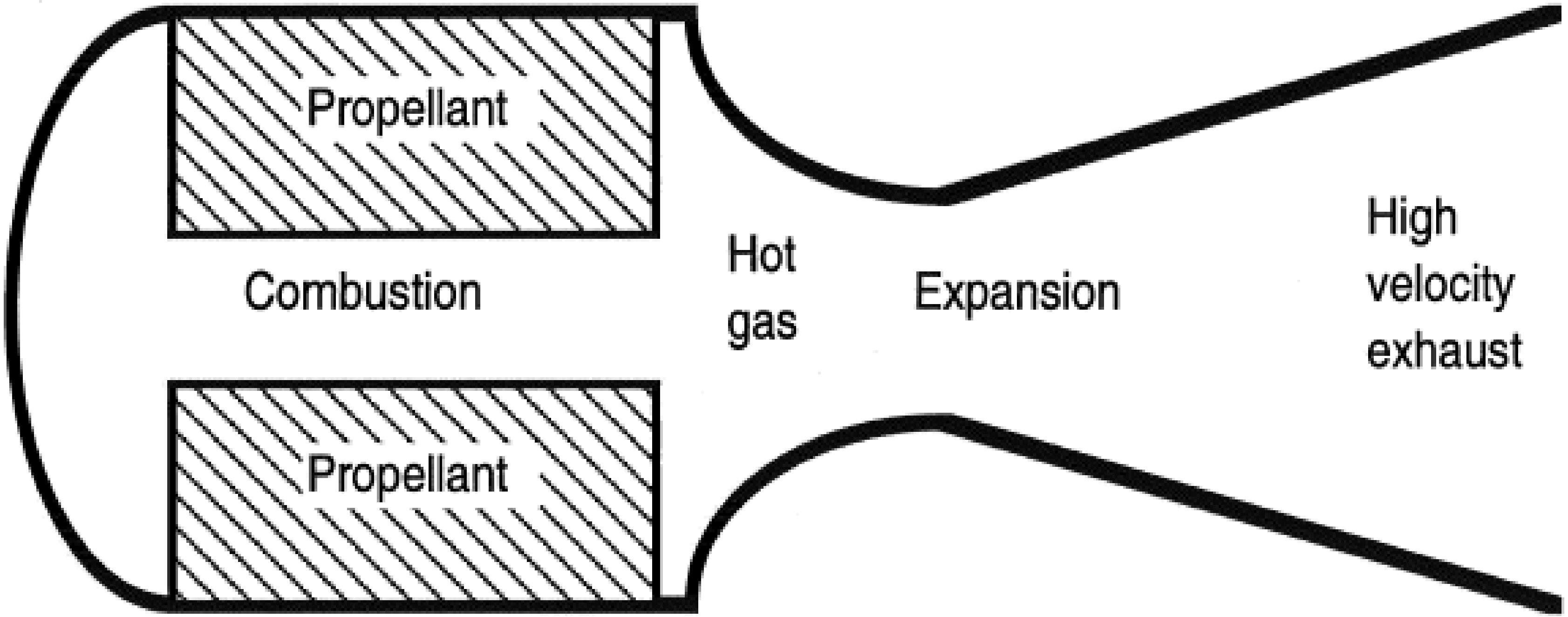
which accelerates the rocket.

The Basic Configuration



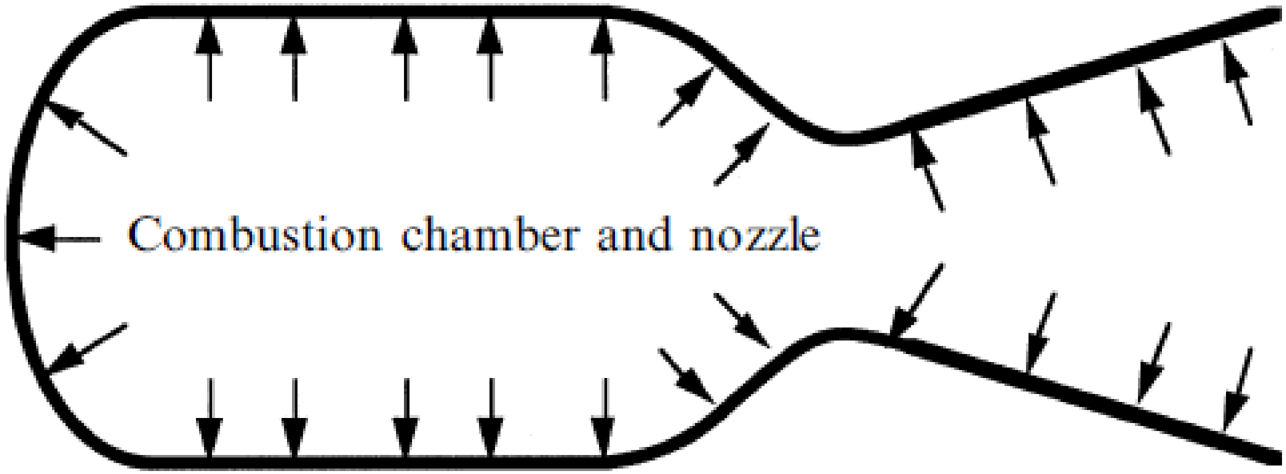
A liquid fuelled rocket engine

The Basic Configuration



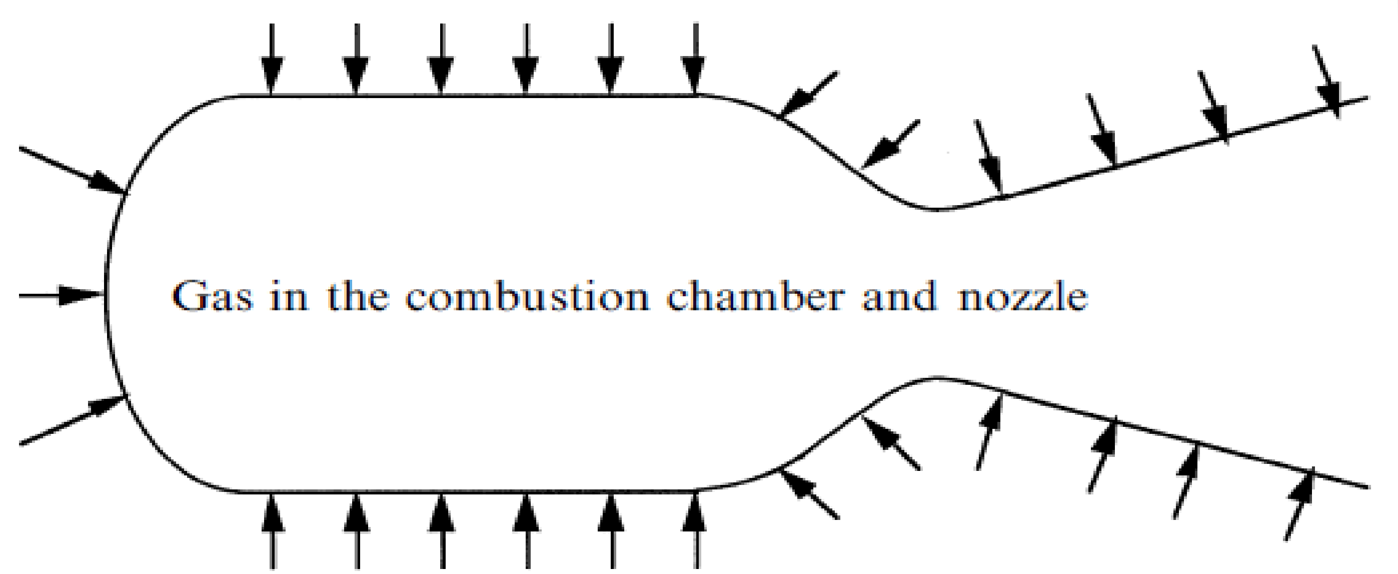
A solid fuelled rocket engine

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),

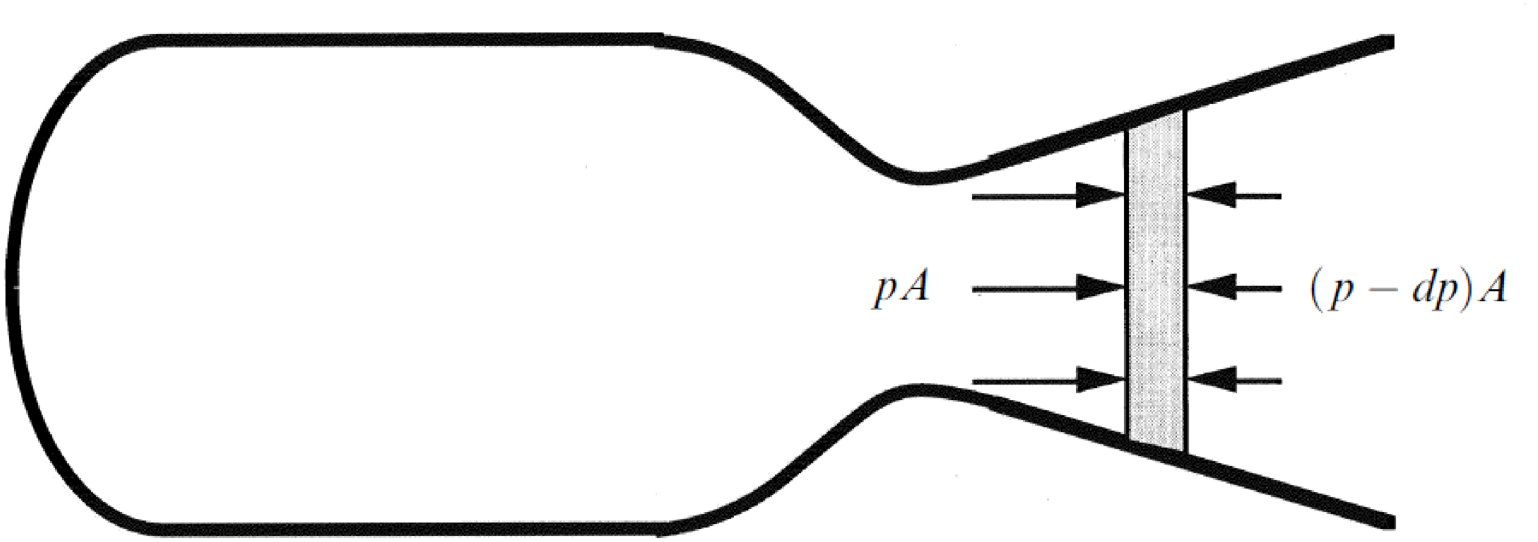
is equal to the surface integral of the pressure, taken over the whole

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



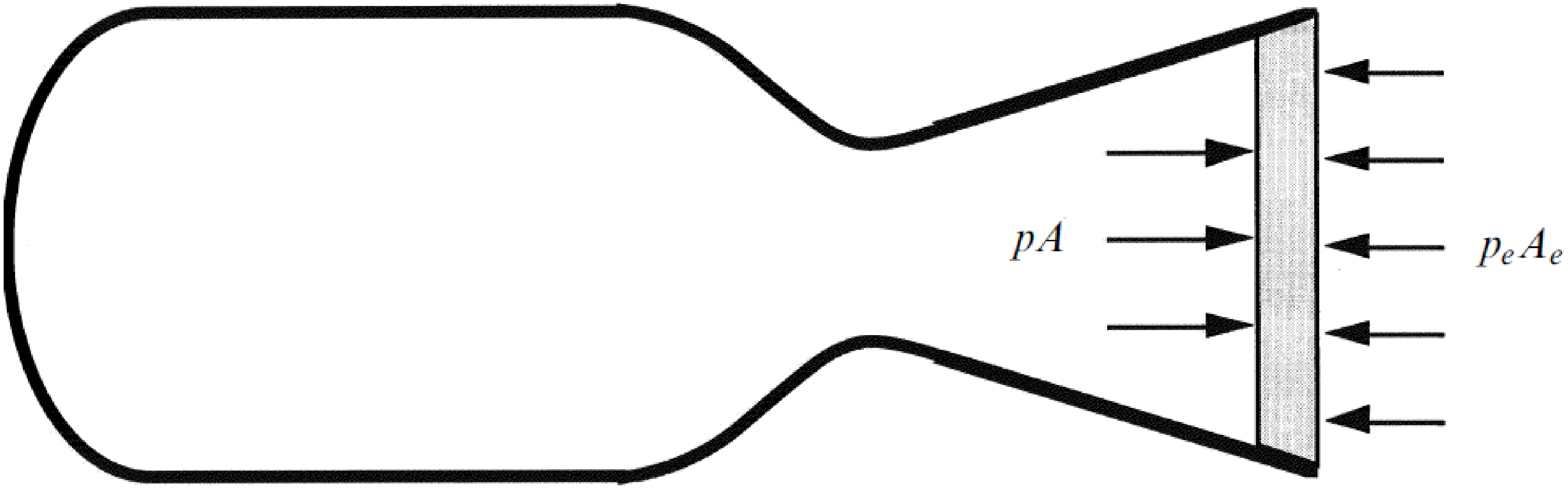
Considering the shaded portion of the exhaust stream, the net accelerating force acting on the shaded portion is

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

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

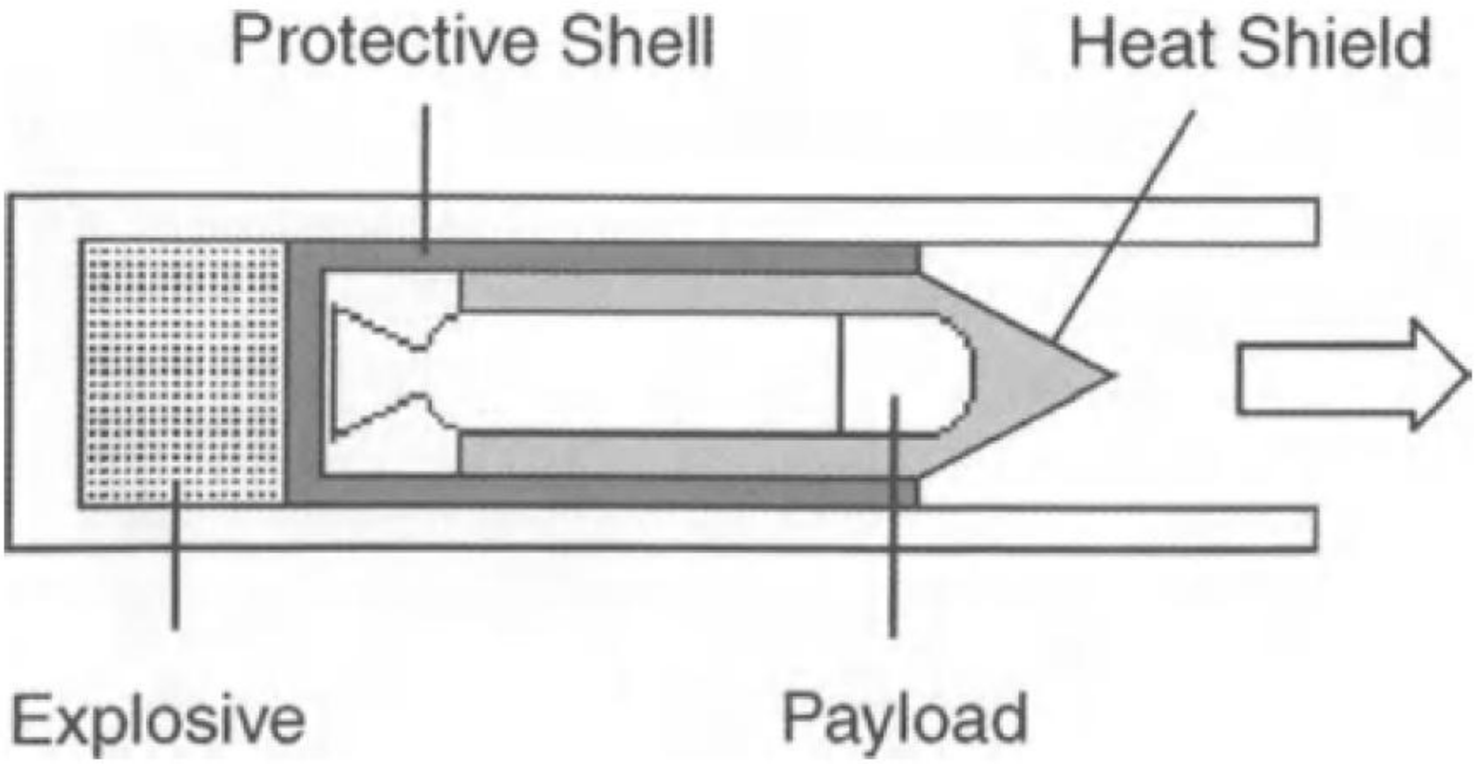
Heat Shields: Adds to the mass, reducing payload –

heat transfer to be considered

Environmental issues: Guns produce shockwave,

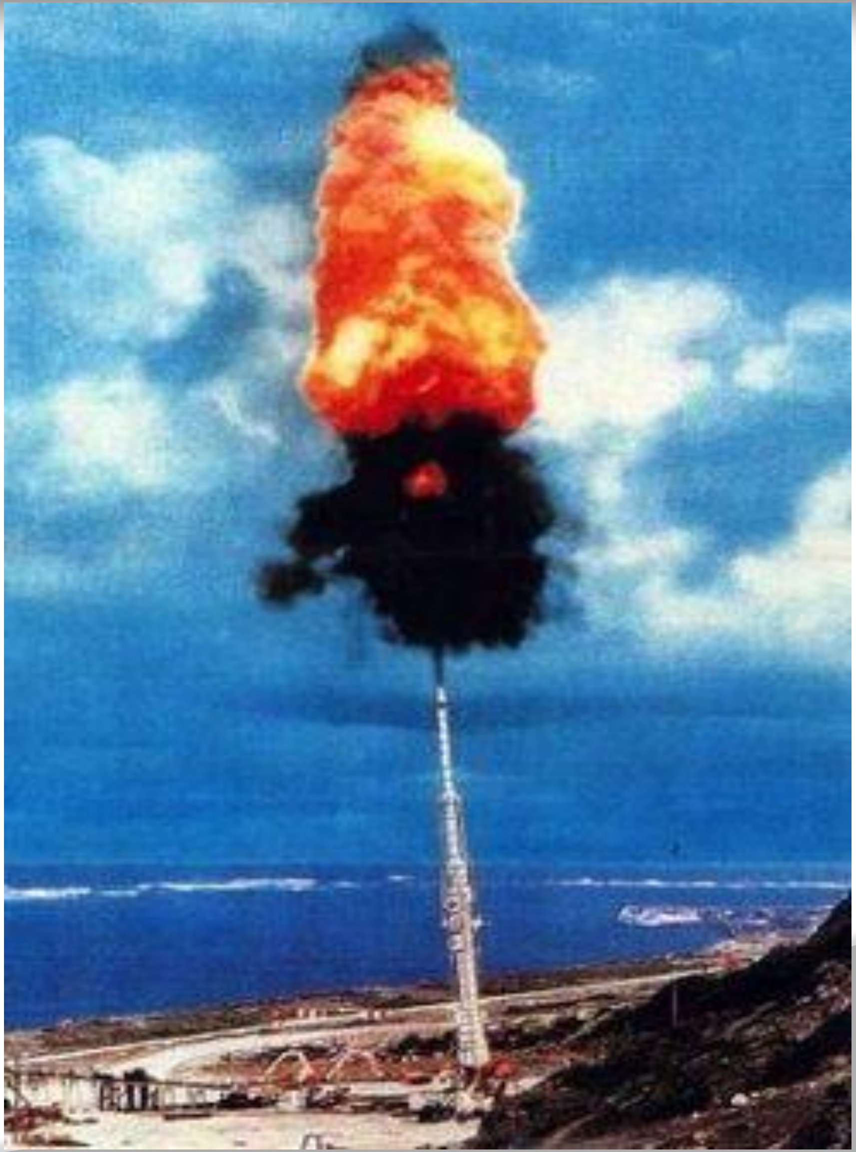
operating personnel and surroundings to be protected.

Gun Launch



Gun Launch

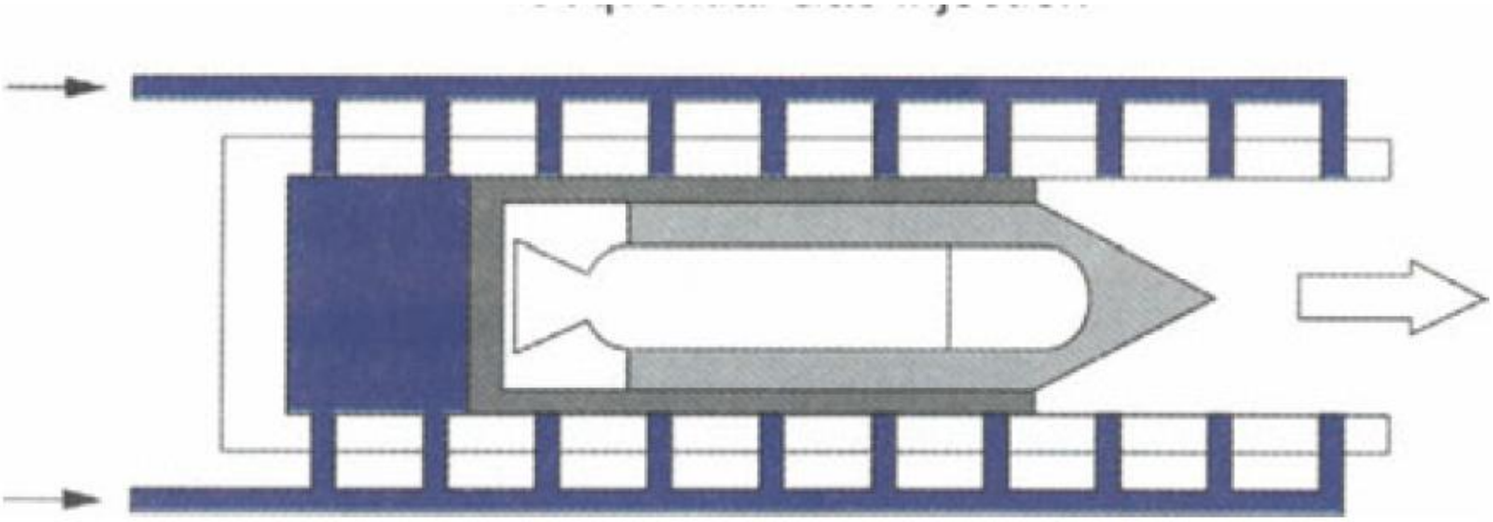
Gun Launch- HARP gun



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

Gas Gun Launch- HARP gun

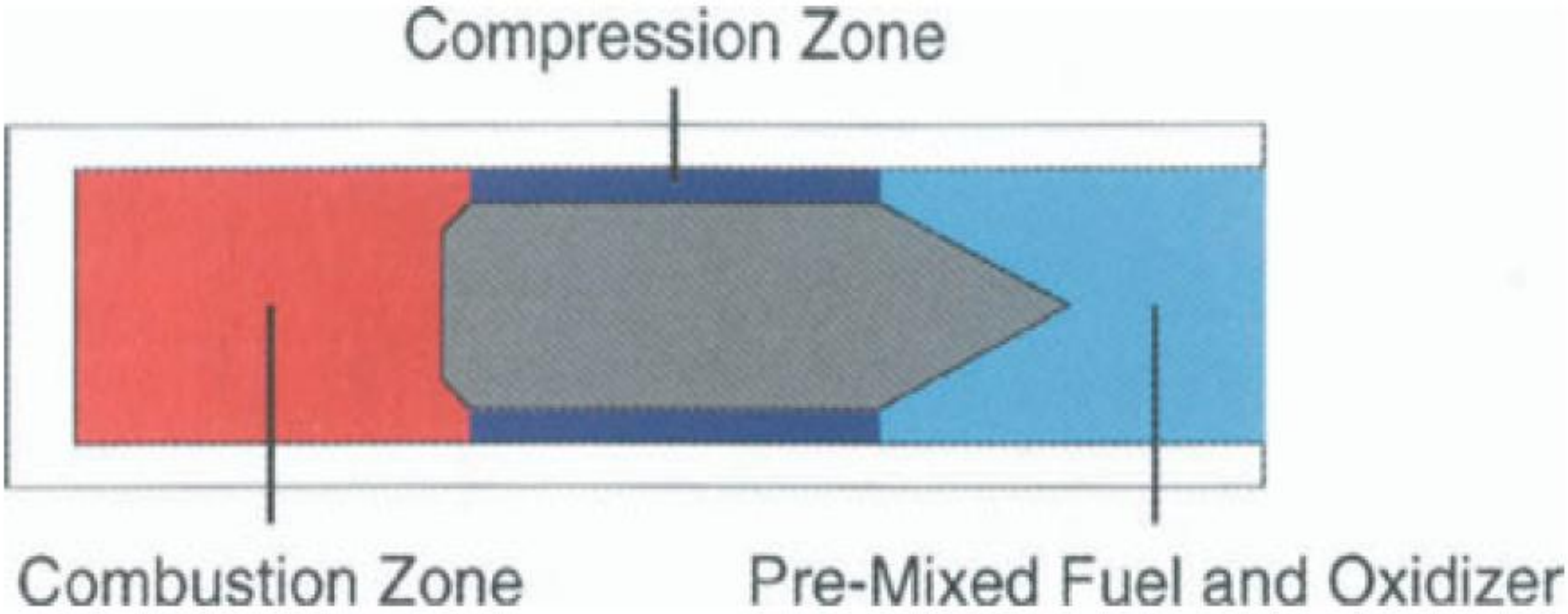
Highly compressed, low molecular weight gas (e.g. hydrogen or helium)



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

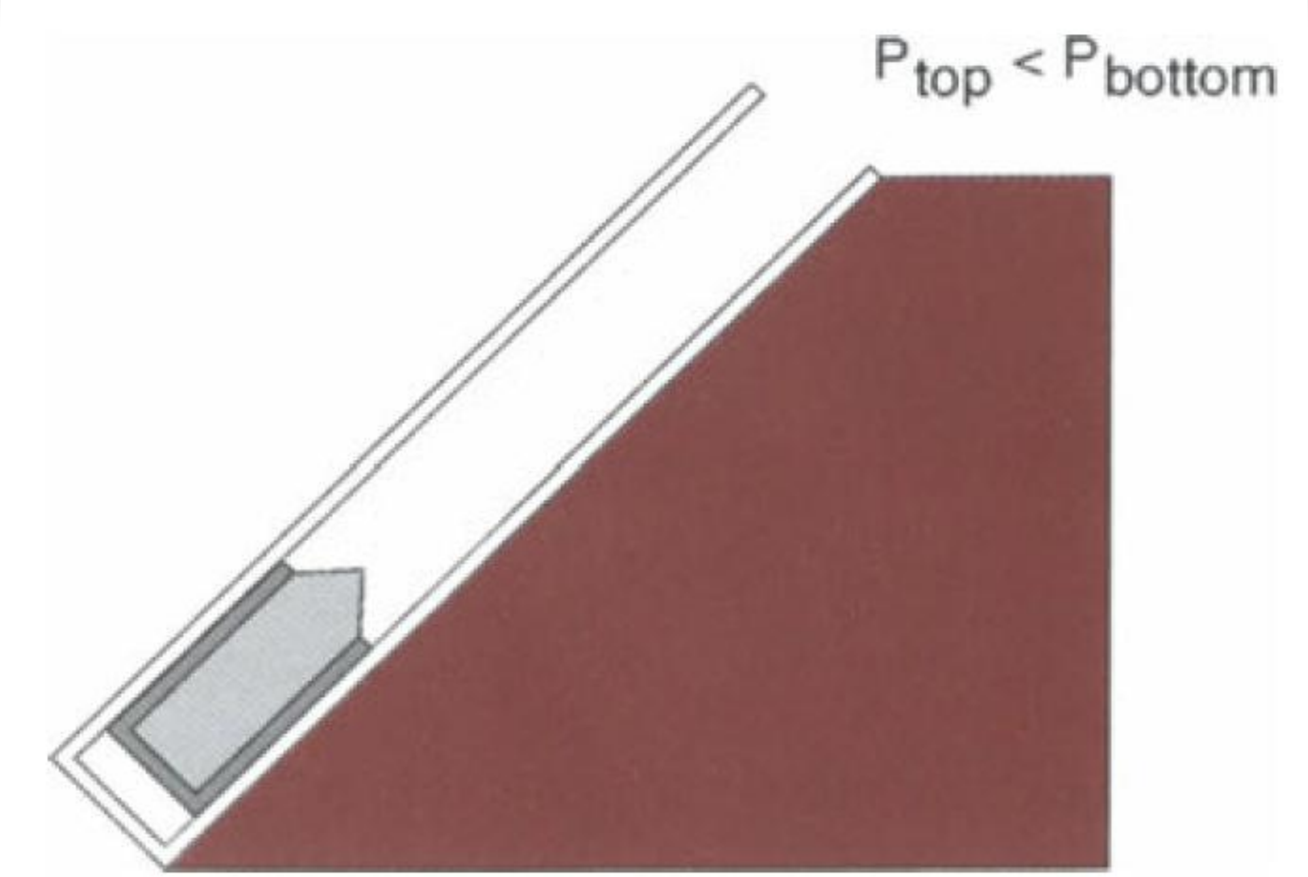
Capable -5.8 kg – 2.77 km/s, target 5000 kg – 7km/s-LEO

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

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

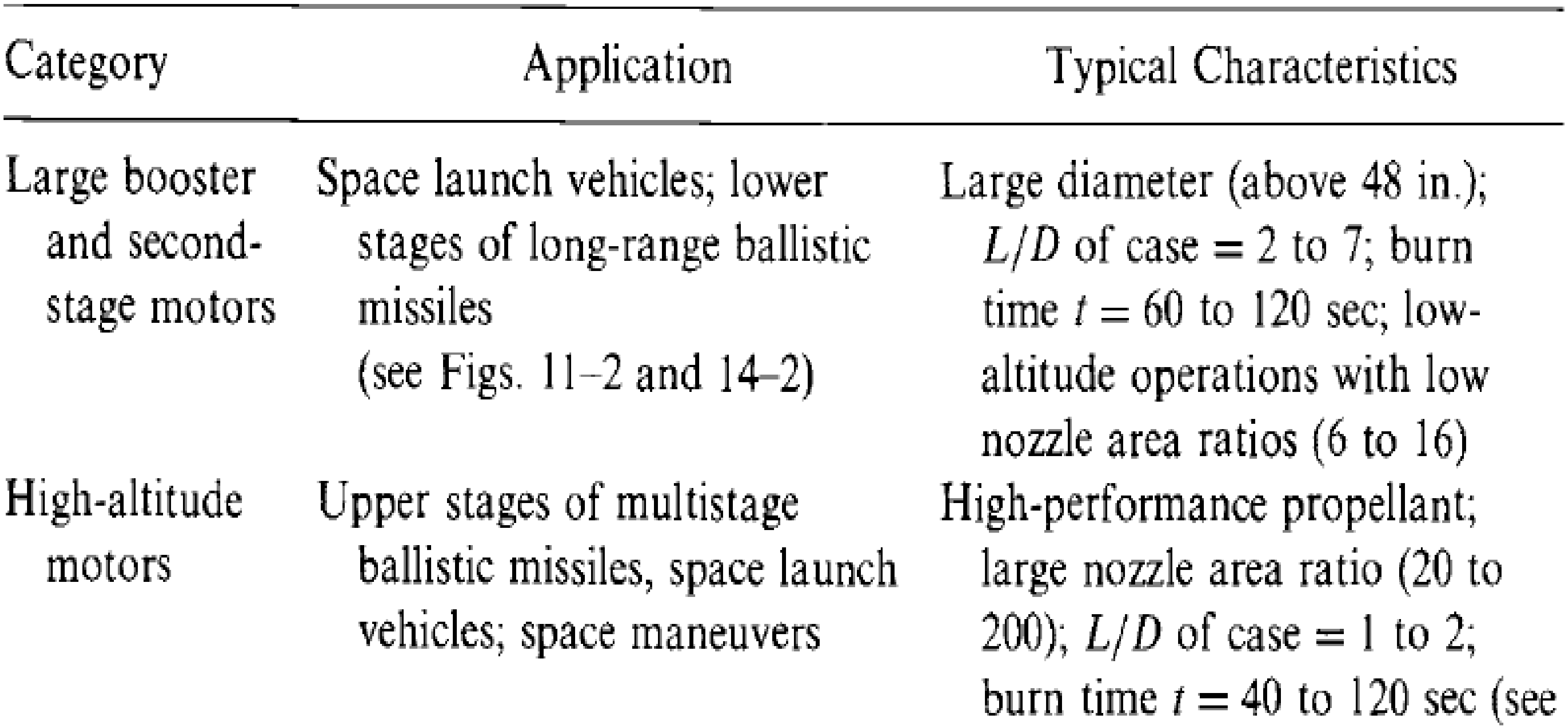
- The shape of the center channel determines the rate and pattern of the burn, thus providing a means to control thrust.
- Unlike liquid propellant engines, solid propellant motors cannot be shut down.
- Once ignited, they will burn until all the propellant is exhausted.

Salient Features of Solid Propellant Rockets

Applications:

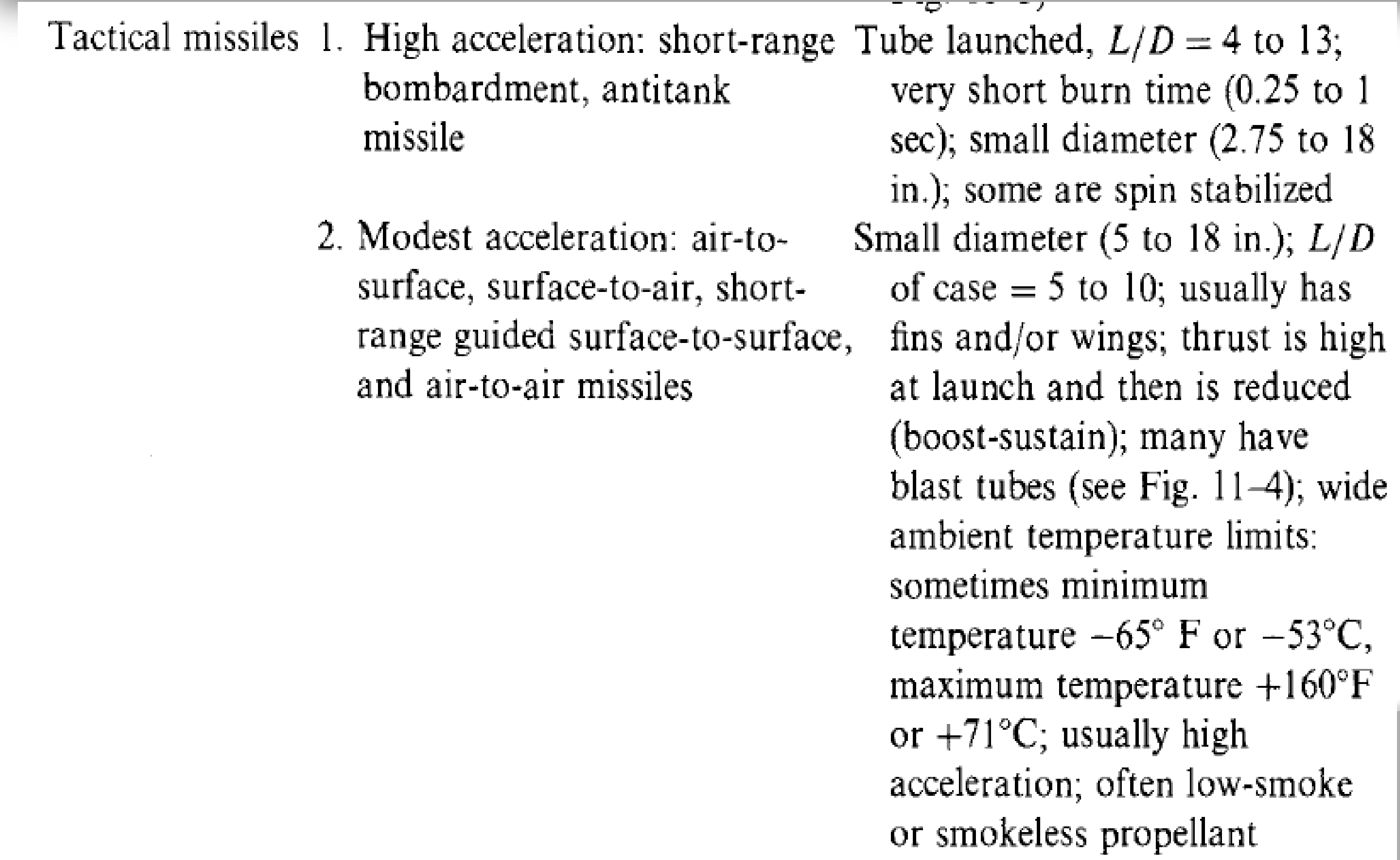
- The main propulsion system for small and medium launchers
- Third stage for orbital injection
- Used for elliptical orbital transfer
- As strap-on boosters for many modern heavy launchers

Salient features 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

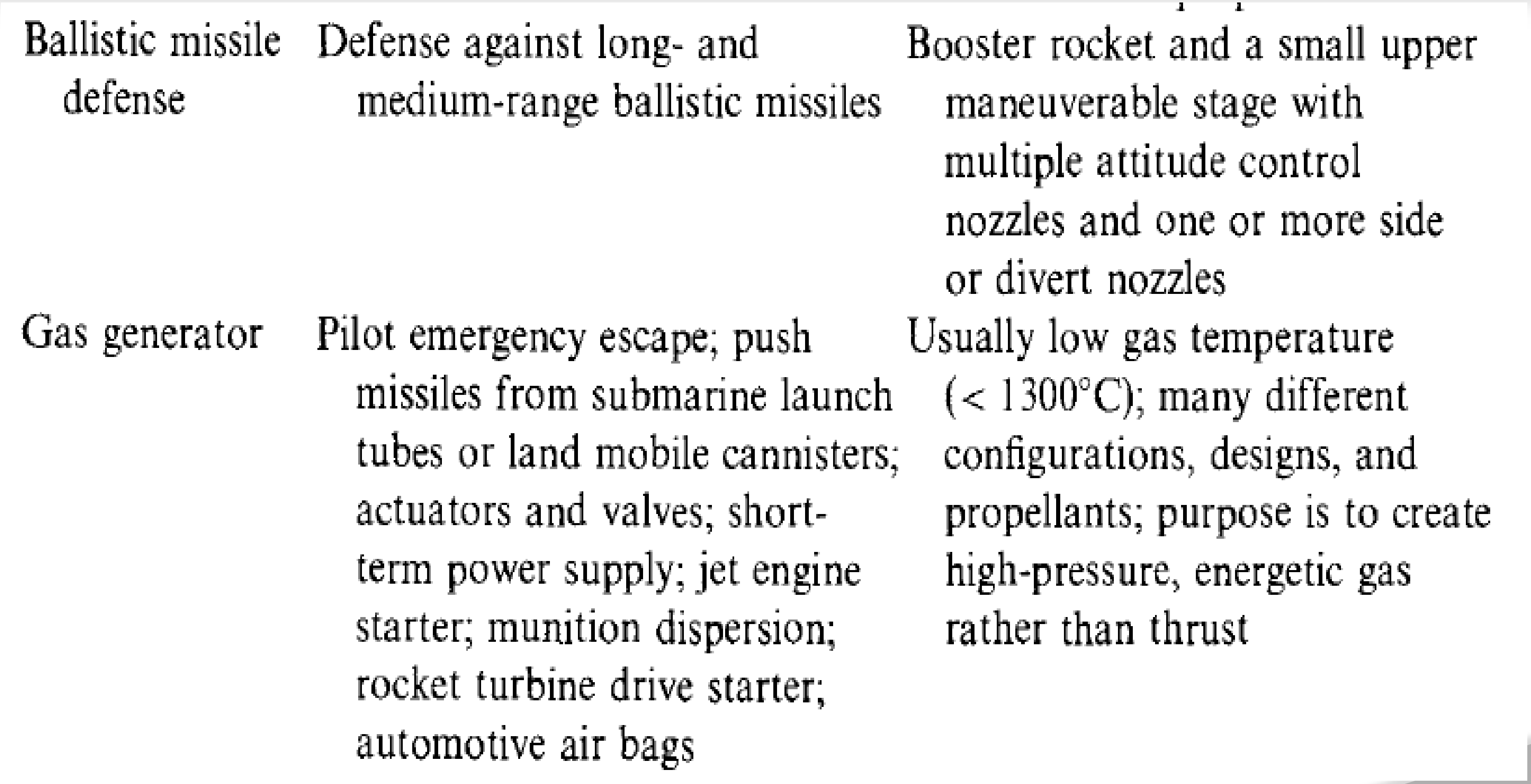
Salient features of solid propellant rockets



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

Reference: Rocket Propulsion Elements, George P Sutton, Page 422

Salient Features of Solid Propellant Rockets



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

Selection Criteria of Solid Propellants

There is a constant interplay of design and propellant tailoring efforts during the **motor design program**.

The ***System Analyst*** with the problem of imparting a given terminal velocity to a payload, *determines*

- the **total delivered impulse required** of the motor
- the desired *shape* of **thrust-time profile**
- the **volumetric constraints** on the motor

Selection Criteria of Solid Propellants

Within the dimensional constraints,

the ***Internal Ballistician*** works with

- a range of available **propellant density-impulses**
- **burning rates** to design ***internal geometry***,

  which will give the required volumetric loadings.
- works with the ***desired*** **thrust-time** profile at a **specific burning rate**.

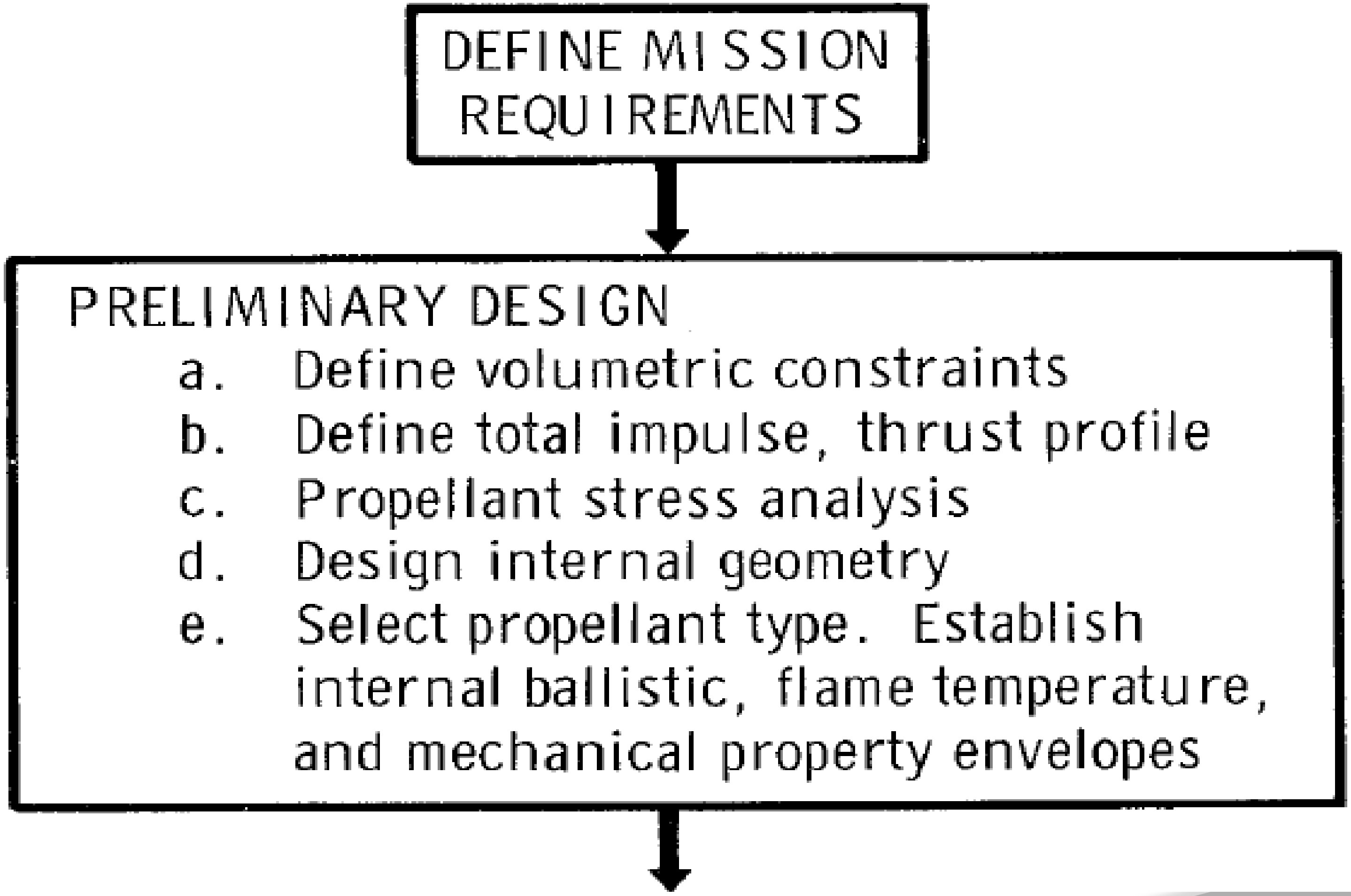
Selection Criteria of Solid Propellants

The ***Stress Analyst*** using assumed values of **mechanical properties for the propellant**, calculates viscoelastic stress concentrations in the grain geometry under all anticipated motor loadings and environments.

- *He defines an envelope of acceptable propellant mechanical properties*.

- The anticipated storage and handling conditions determine the **hazard, thermal stability, and storage stability** requirements for the propellant.

Selection Criteria of Solid Propellants

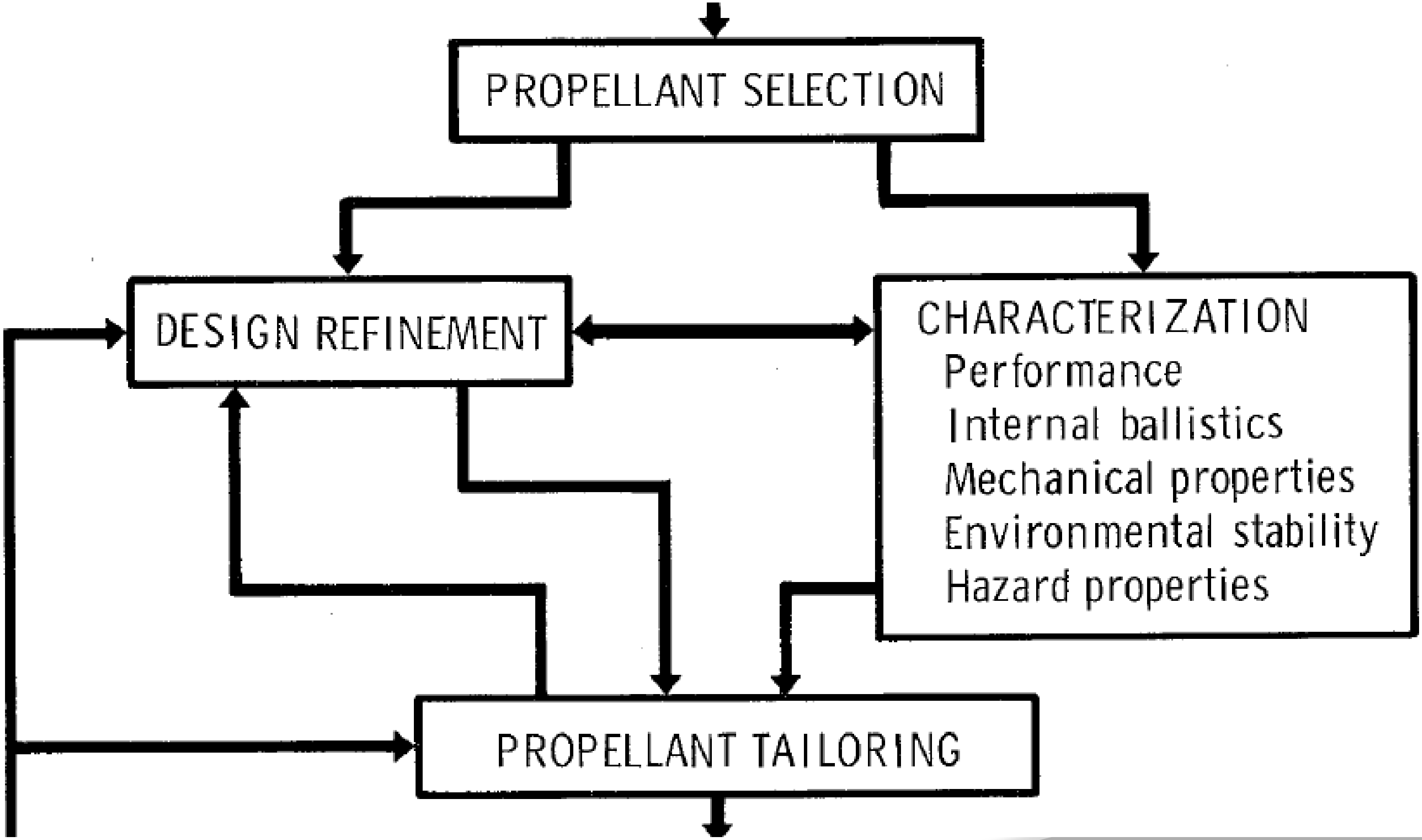


DEFINE MISSION REQUIREMENTS

PRELIMINARY DESIGN

a. Define volumetric constraints
b. Define total impulse, thrust profile
c. Propellant stress analysis
d. Design internal geometry
e. Select propellant type. Establish internal ballistic, flame temperature, and mechanical property envelopes

Selection Criteria of Solid Propellants



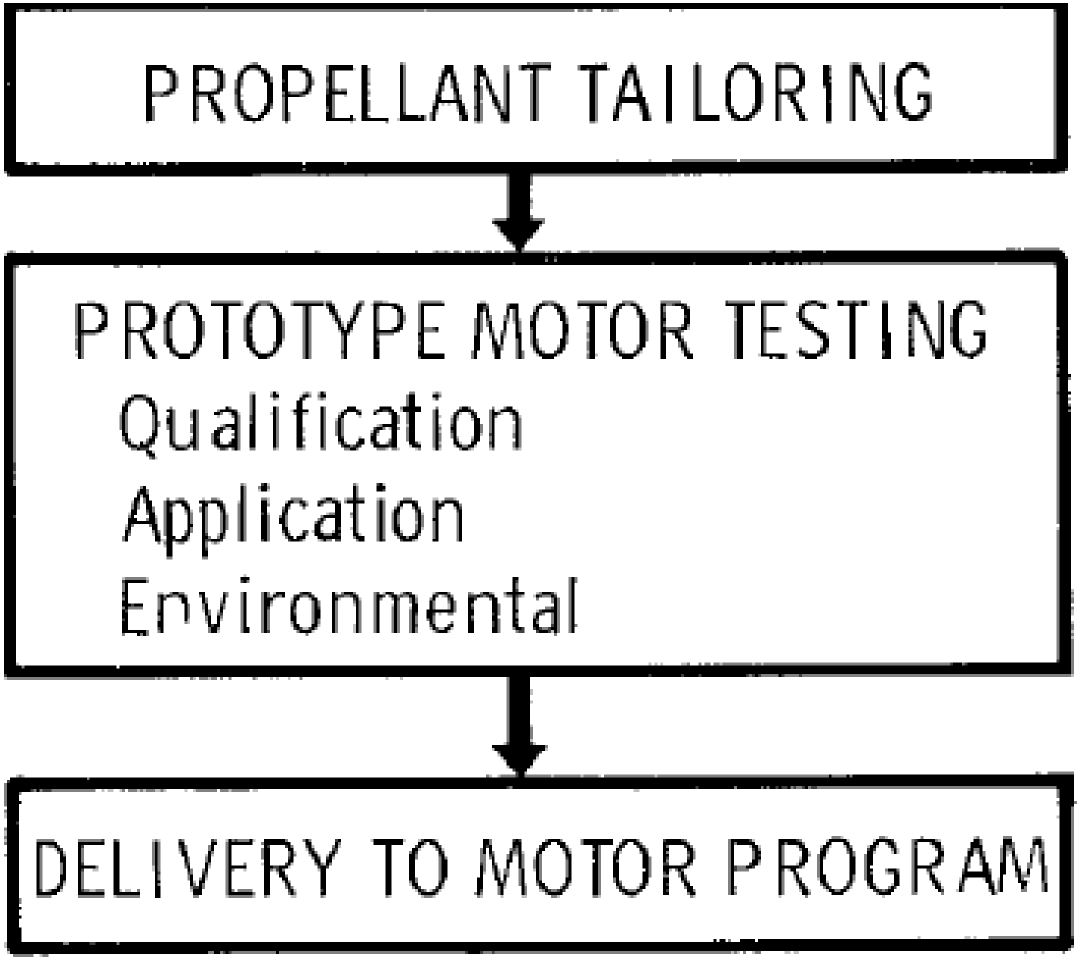
PROPELLANT SELECTION

DESIGN REFINEMENT

CHARACTERIZATION
- Performance
- Internal ballistics
- Mechanical properties
- Environmental stability
- Hazard properties

PROPELLANT TAILORING

Selection Criteria of Solid Propellants



PROPELLANT TAILORING

PROTOTYPE MOTOR TESTING

- Qualification
- Application
- Environmental

DELIVERY TO MOTOR PROGRAM

Reference: Solid Propellant Selection and Characterization, NASA-SP-8064, 1971

Selection Criteria of Solid Propellants

There are two families of solids propellants:

- **Homogeneous** and
- **Composite**.

Both types are dense, stable at ordinary temperatures, and easily storable.

Homogeneous propellants

Homogeneous propellants are

either *simple base* or *double base*.

- A **simple base** propellant consists of a single compound, usually **nitrocellulose**, which has both an oxidation capacity and a reduction capacity.

- **Double base** propellants usually consist of Nitrocellulose (NC) and Nitroglycerine (NG), to which a plasticizer is added.

- **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.

Propellants

- The **grain** is the *shaped mass of processed solid propellant* inside the rocket motor.
- The propellant material and geometrical configuration of the grain determine the motor performance characteristics.
- The propellant grain is a cast, molded, or extruded body and its appearance and feel is similar to that of hard rubber or plastic.
- A few rocket motors have more than one grain inside a single case or chamber and very few grains have segments made of different propellant composition (e.g., to allow different burning rates). However, most rockets have a single grain.

Types of Solid Propellants

There are two families of solids propellants:

- **Homogeneous** and
- **Composite**.

Both types are dense, stable at ordinary temperatures, and easily storable.

Homogeneous propellants

Homogeneous propellants are either *simple base* or *double base*.

- A **simple base** propellant consists of a single compound, usually **nitrocellulose**, which has both an oxidation capacity and a reduction capacity.
- **Double base** propellants usually consist of Nitrocellulose (NC) and Nitroglycerine (NG), to which a plasticizer is added.

Homogeneous propellants

Homogeneous propellants do not usually have specific impulses greater than about 210 seconds under normal conditions.

Their main asset is that they do not produce traceable fumes and are, therefore, commonly used in tactical weapons.

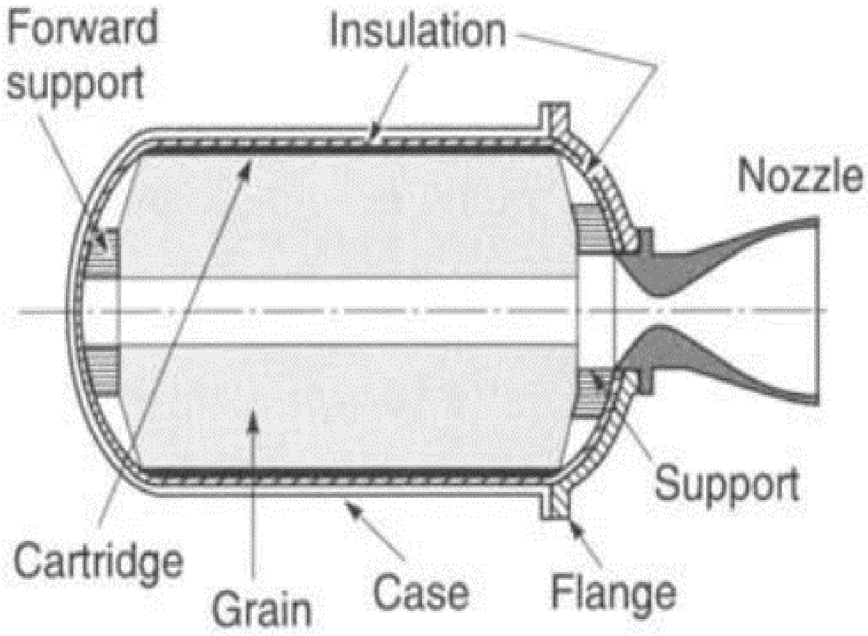
They are also often used to perform subsidiary functions such as jettisoning spent parts or separating one stage from another.

Composite propellants

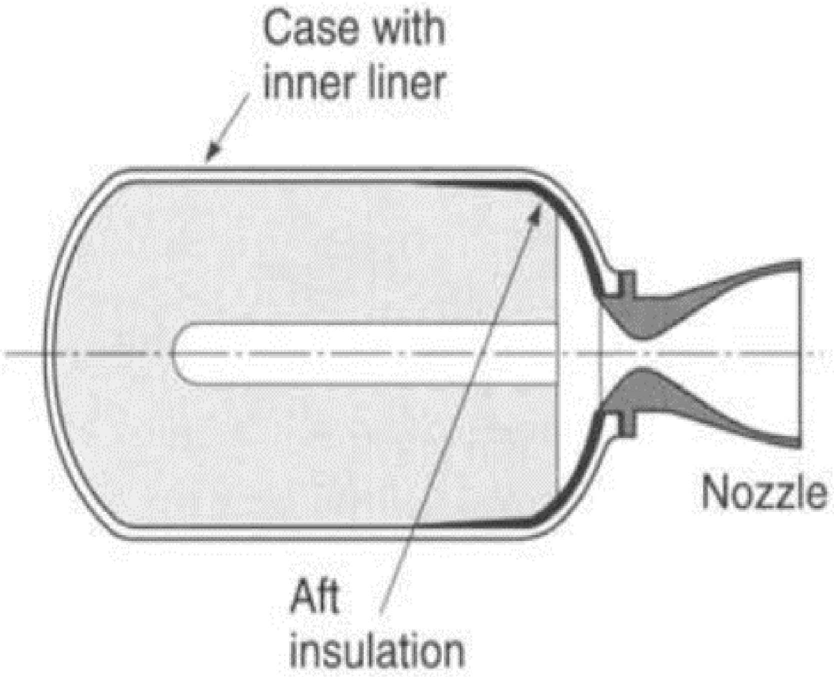
Composite propellants form a heterogeneous propellant grain with the oxidizer crystals and a powdered fuel (usually aluminum) held together in a matrix of synthetic rubber (or plastic) binder, such as Hydroxyl-terminated polybutadiene (HTPB).

Composite propellants are cast from a mix of solid (Ammonium perchlorate, AP crystals, A1 powder) and liquid (HTPB, Polypropylene glycol-PPG) ingredients. The propellant is hardened by crosslinking or curing the liquid binder polymer with a small amount of curing agent, and curing it in an oven, where it becomes hard and solid.

Grain- Methods of Holding Grain inside the Case



Cartridge–loaded grain (free–standing)



Case–bonded grain

Grains

Cartridge-loaded grains are used in some small tactical missiles and a few medium-sized motors. They often have a lower cost and are easier to inspect.

The **case-bonded grains** give a somewhat better performance, a little less inert mass (no holding device, support pads, and less insulation), a better volumetric loading fraction, are more highly stressed, and often somewhat more difficult and expensive to manufacture. Today almost all larger motors and many tactical missile motors use case bonding.

Grain- Terminology

Configuration: The shape or geometry of the initial burning surfaces of a grain as it is intended to operate in a motor.

Cylindrical Grain: A grain in which the internal cross section is constant along the axis regardless of perforation shape.

Neutral Burning: Motor burn time during which thrust, pressure, and burning surface area remain approximately constant , typically within about +15%. Many grains are neutral burning.

Perforation: The central cavity port or flow passage of a propellant grain; its cross section may be a cylinder, a star shape, etc.

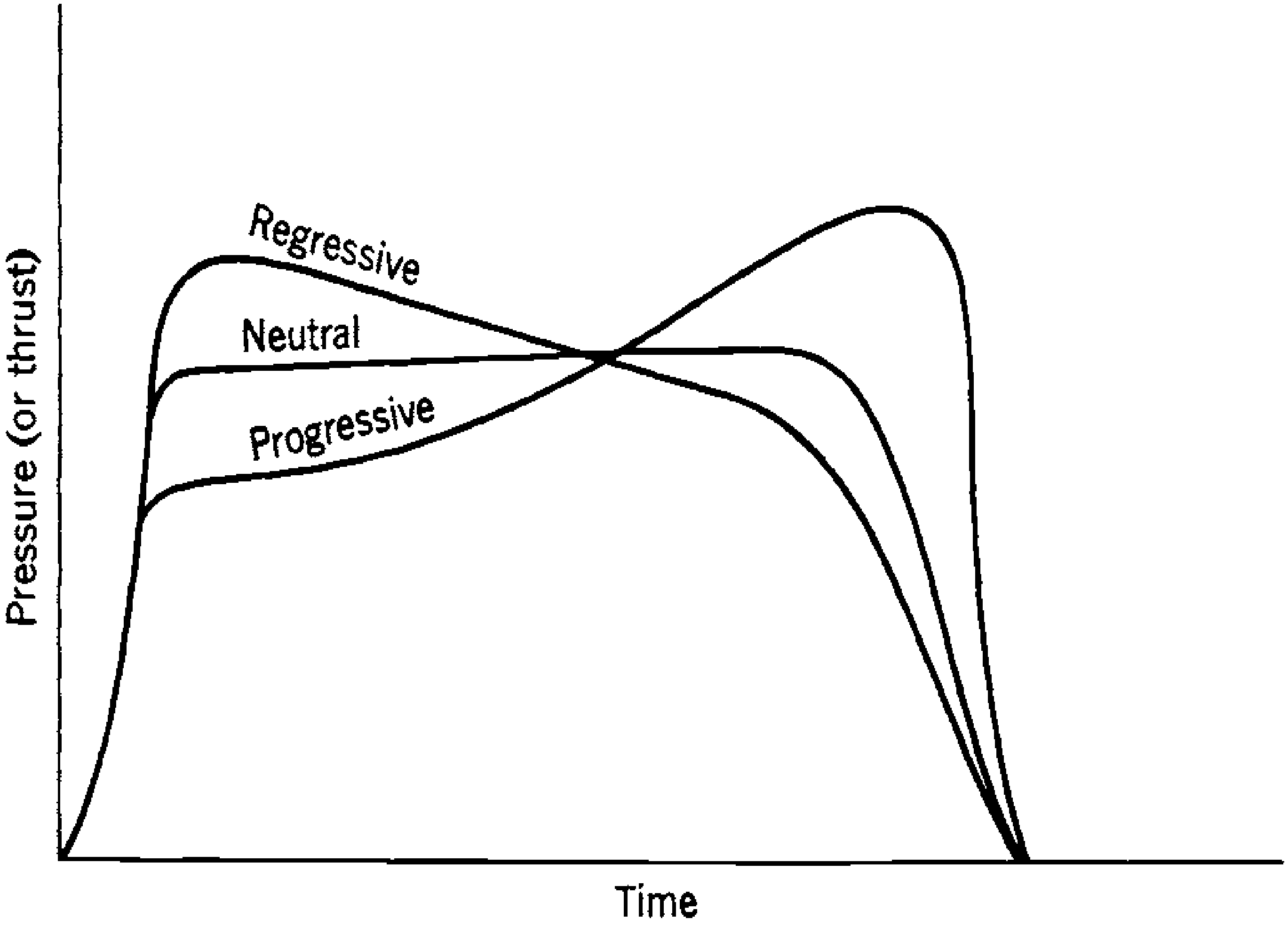
Grain- Terminology

Progressive Burning: Burn time during which thrust, pressure, and burning surface area increase.

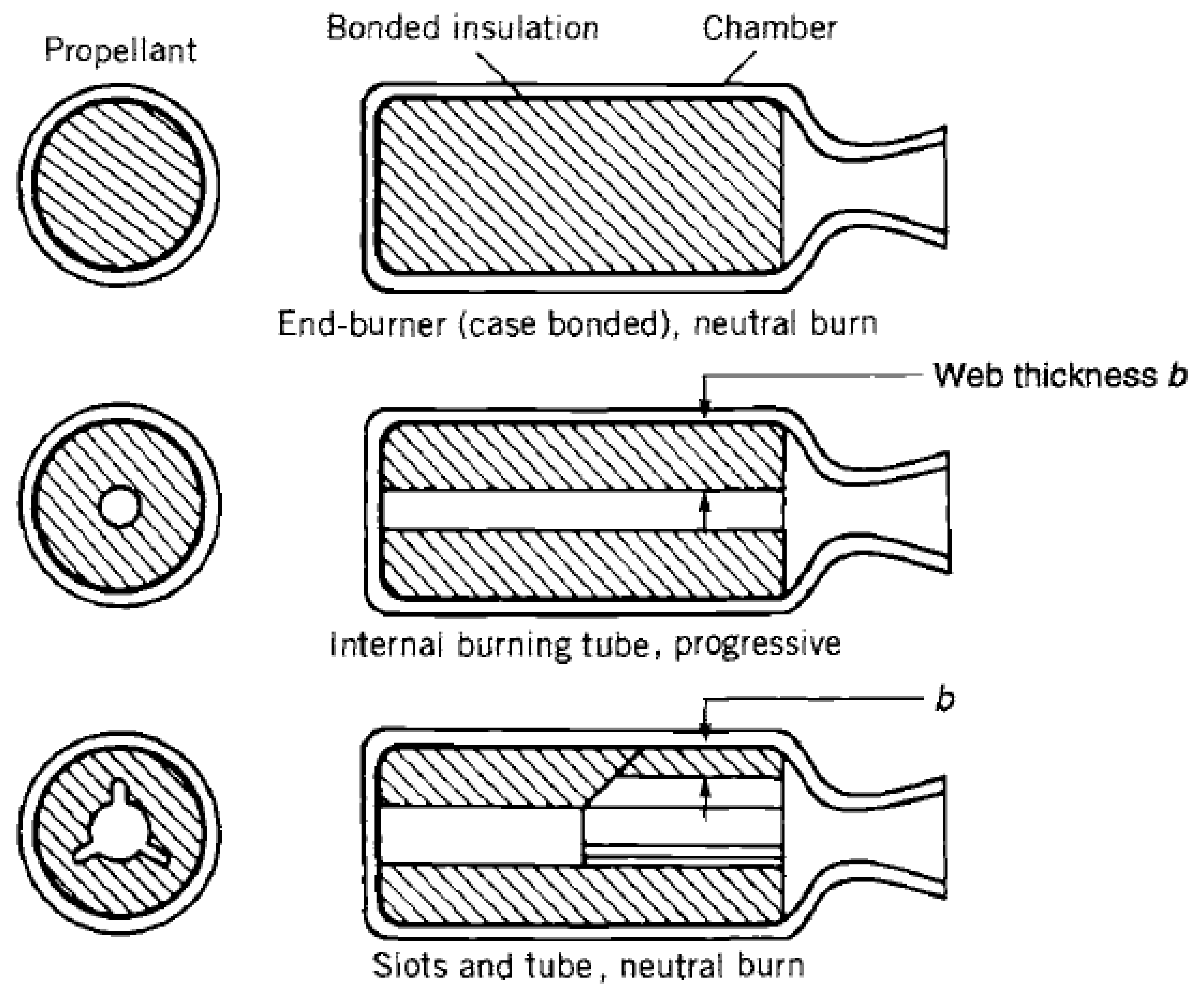
Regressive Burning: Burn time during which thrust, pressure, and burning surface area decrease.

Sliver: Unburned propellant remaining (or lost--that is, expelled through the nozzle) at the time of web burnout .

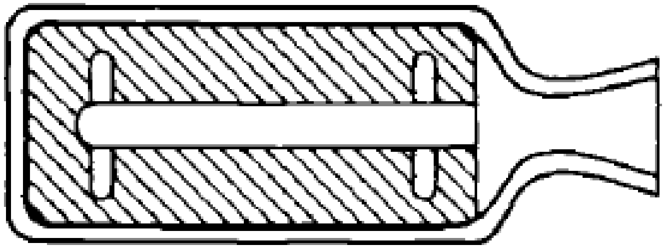
Grain- Terminology



Grain Configuration

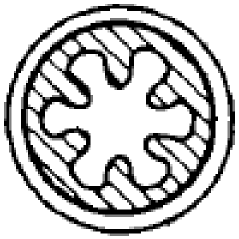


Grain Configuration

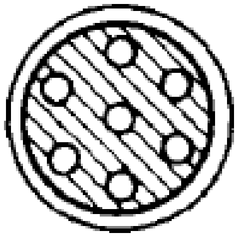


Radial grooves and tube, neutral burn

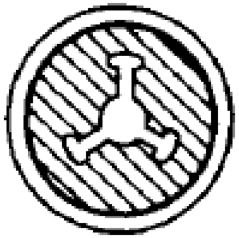
Star (neutral)



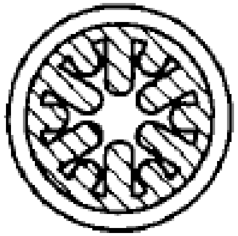
Wagon wheel
(neutral)



Multiperforated
(progressive-regressive)



Dog bone

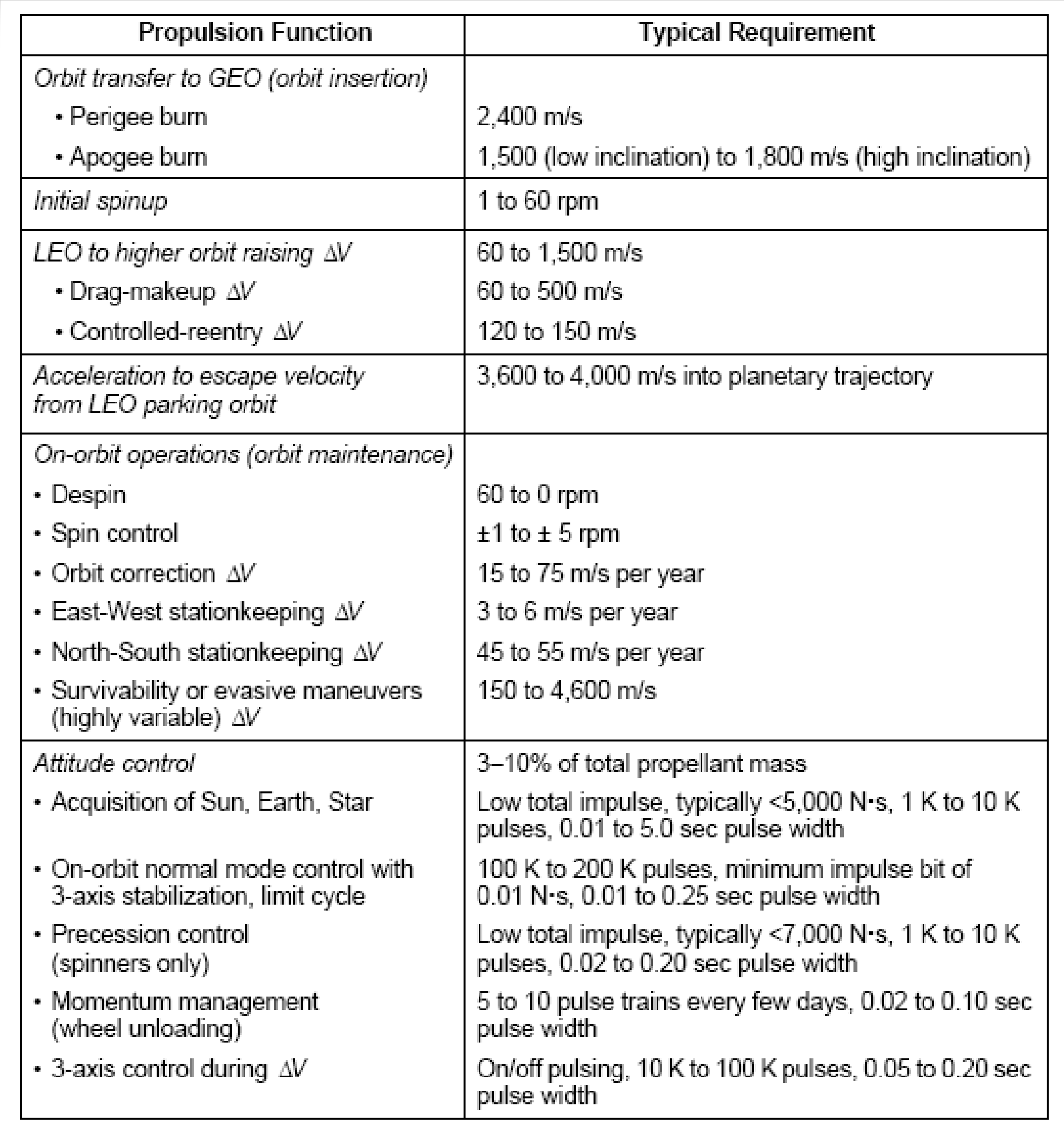


Dendrite
(case bonded)

Unit 3
Liquid Propellant Rockets

- Purpose of the propulsion subsystem
  - Transfer spacecraft from launch vehicle parking orbit to spacecraft mission orbit
  - Maintain and control spacecraft orbit
  - Maintain and control spacecraft attitude
- Types of spacecraft propulsion systems
  - Chemical
    - Liquid, Solid or Hybrid
  - Solar Electric
  - Nuclear
    - Thermal or Electric

Typical Propulsion Requirements



Propulsion Function	Typical Requirement
Orbit transfer to GEO (orbit insertion)	
• Perigee burn	2,400 m/s
• Apogee burn	1,500 (low inclination) to 1,800 m/s (high inclination)
Initial spinup	1 to 60 rpm
LEO to higher orbit raising ΔV	60 to 1,500 m/s
• Drag-makeup ΔV	60 to 500 m/s
• Controlled-reentry ΔV	120 to 150 m/s
Acceleration to escape velocity from LEO parking orbit	3,600 to 4,000 m/s into planetary trajectory
On-orbit operations (orbit maintenance)	
• Despin	60 to 0 rpm
• Spin control	±1 to ± 5 rpm
• Orbit correction ΔV	15 to 75 m/s per year
• East-West stationkeeping ΔV	3 to 6 m/s per year
• North-South stationkeeping ΔV	45 to 55 m/s per year
• Survivability or evasive maneuvers (highly variable) ΔV	150 to 4,600 m/s
Attitude control	3–10% of total propellant mass
• Acquisition of Sun, Earth, Star	Low total impulse, typically <5,000 N·s, 1 K to 10 K pulses, 0.01 to 5.0 sec pulse width
• On-orbit normal mode control with 3-axis stabilization, limit cycle	100 K to 200 K pulses, minimum impulse bit of 0.01 N·s, 0.01 to 0.25 sec pulse width
• Precession control (spinners only)	Low total impulse, typically <7,000 N·s, 1 K to 10 K pulses, 0.02 to 0.20 sec pulse width
• Momentum management (wheel unloading)	5 to 10 pulse trains every few days, 0.02 to 0.10 sec pulse width
• 3-axis control during ΔV	On/off pulsing, 10 K to 100 K pulses, 0.05 to 0.20 sec pulse width

Typical Propulsion Requirements

- Overview
- Rocket and Missile Fuels
  - Liquid Rocket
  - Solid Rocket
  - Hybrid Rocket
  - Etc…

LIQUID COMBUSTION CHAMBER OVERVIEW

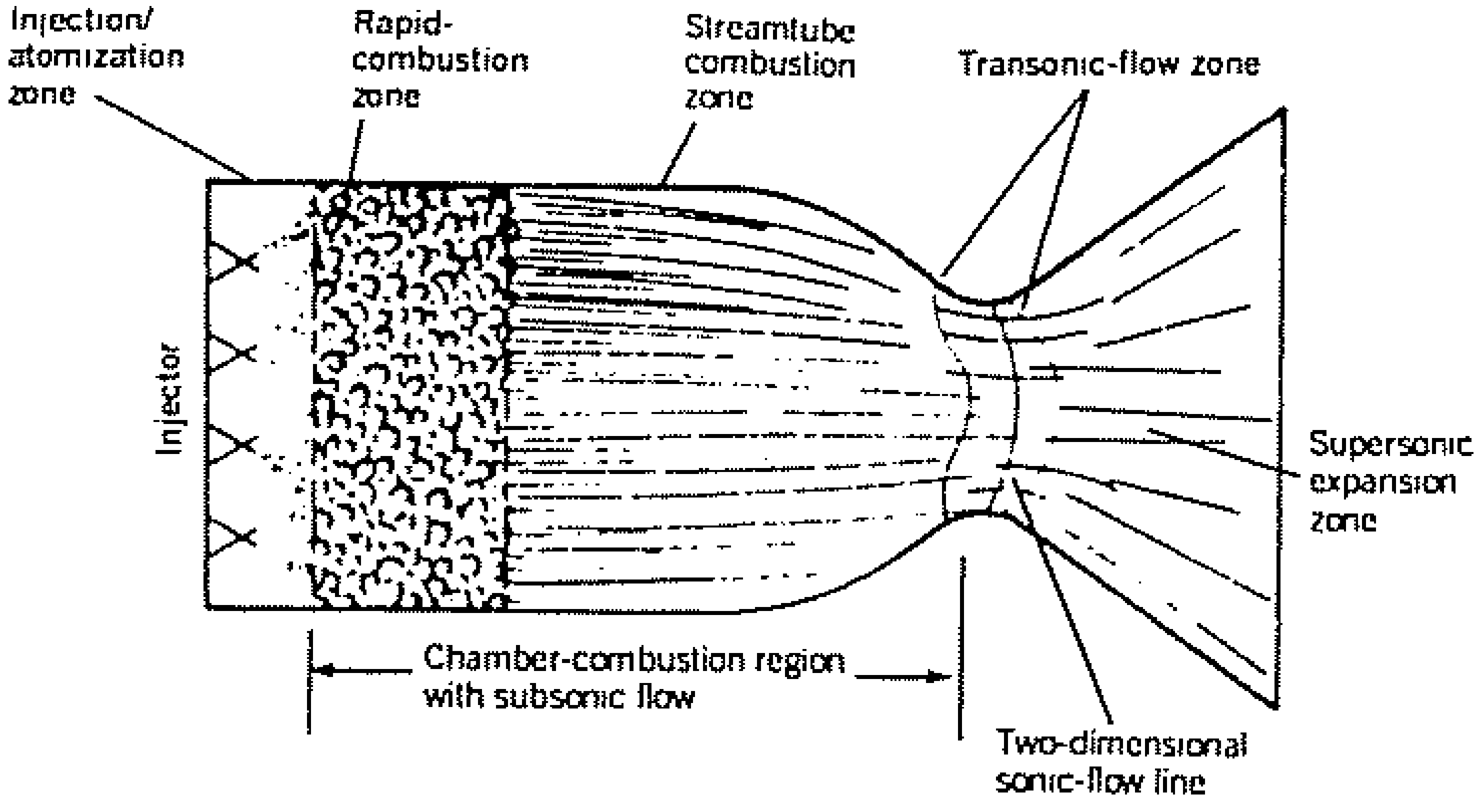


Fig. 9–1. *Division of combustion chamber into zones for analysis. (Reprinted with permission from Reference 9–1; copyright by AIAA.)*

SIZING OF COMBUSTOR LENGTH

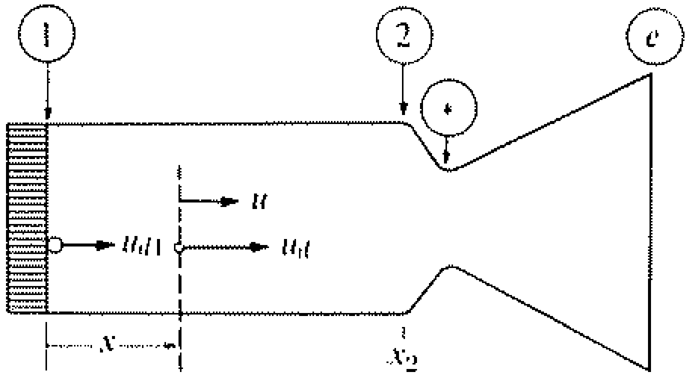


FIGURE 12.9 Idealized liquid-propellant combustor

Drop size
$$R = \frac{r}{r_0}, \tag{12.7}$$

Gas velocity
$$\omega = \frac{\rho u A_c}{\dot{m}}, \tag{12.8}$$

Drop velocity
$$\chi = \frac{\rho u_d A_c}{\dot{m}}, \tag{12.9}$$

Axial distance
$$\xi = \frac{x}{r_0^2} \frac{k}{c_p \rho_l} \frac{\rho A_c}{\dot{m}} \ln(1 + B), \tag{12.10}$$

Drag
$$\mathcal{S} = \frac{9}{2} \frac{c_p \mu}{k B}, \tag{12.11}$$

SIZING OF COMBUSTOR LENGTH

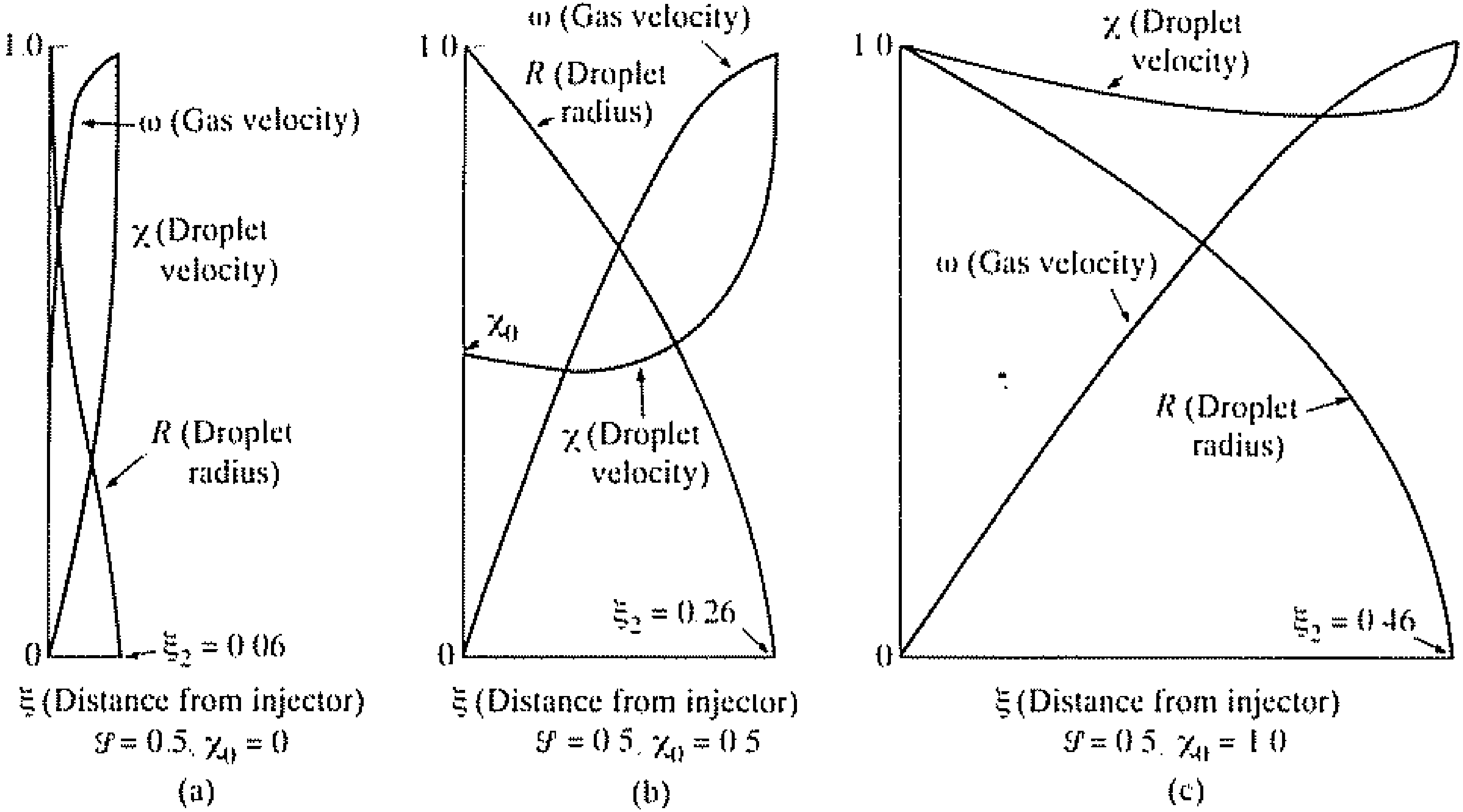
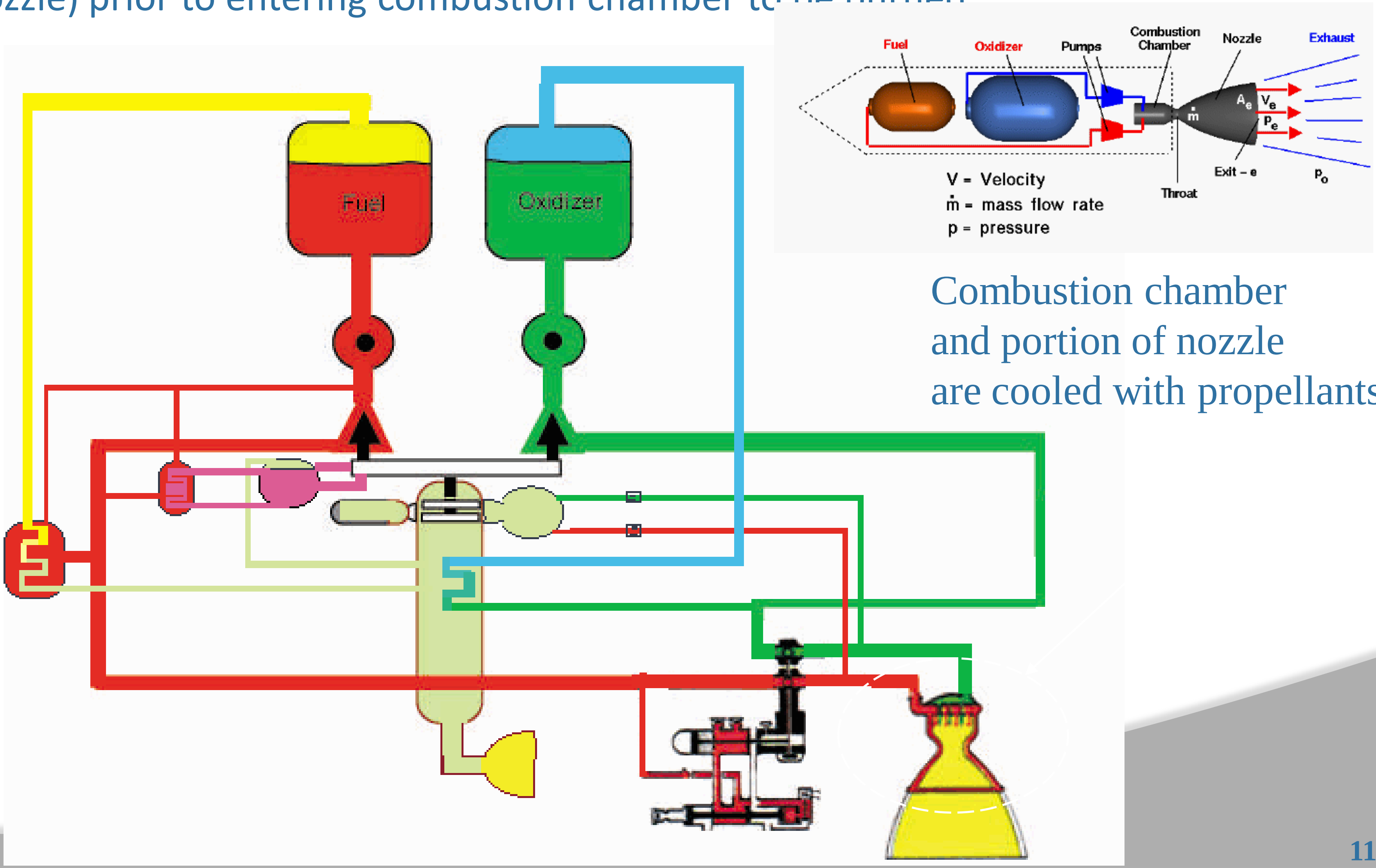


FIGURE 12.10 Effect of initial drop size on dimensionless combustor performance variables Variation of χ, ρ, and ω (defined by Eq (12 8) as a function of ξ for $\mathcal{S} = 0.5$ (Courtesy Spalding [10])

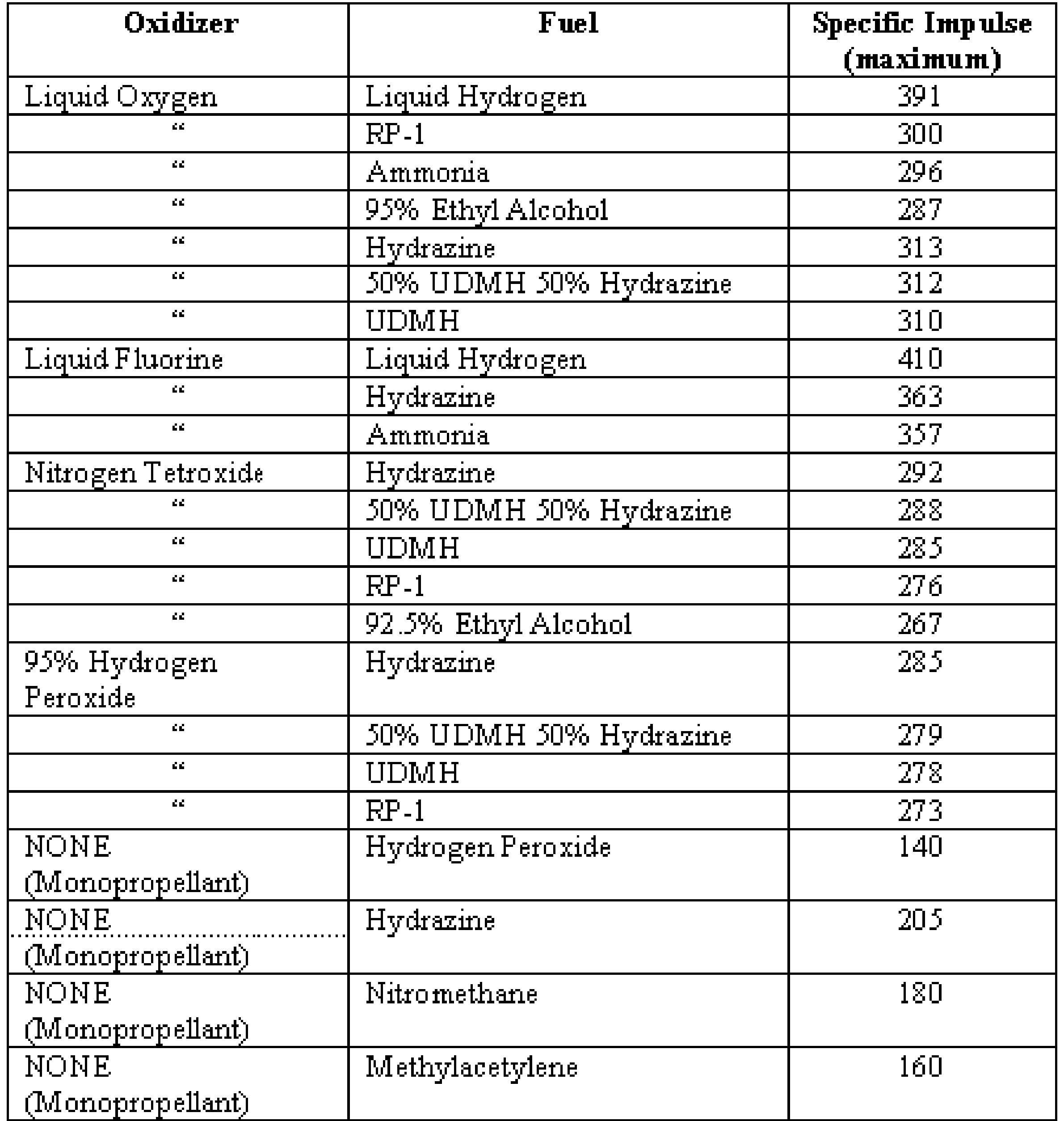
Liquid Propulsion System

Propellants are often used to cool portions of the rocket (combustion chamber and nozzle) prior to entering combustion chamber to be burned



Combustion chamber and portion of nozzle are cooled with propellants

COMMON LIQUID ROCKET FUELS



Oxidizer	Fuel	Specific Impulse (maximum)
Liquid Oxygen	Liquid Hydrogen	391
“	RP-1	300
“	Ammonia	296
“	95% Ethyl Alcohol	287
“	Hydrazine	313
“	50% UDMH 50% Hydrazine	312
“	UDMH	310
Liquid Fluorine	Liquid Hydrogen	410
“	Hydrazine	363
“	Ammonia	357
Nitrogen Tetroxide	Hydrazine	292
“	50% UDMH 50% Hydrazine	288
“	UDMH	285
“	RP-1	276
“	92.5% Ethyl Alcohol	267
95% Hydrogen Peroxide	Hydrazine	285
“	50% UDMH 50% Hydrazine	279
“	UDMH	278
“	RP-1	273
NONE (Monopropellant)	Hydrogen Peroxide	140
NONE (Monopropellant)	Hydrazine	205
NONE (Monopropellant)	Nitromethane	180
NONE (Monopropellant)	Methylacetylene	160

- **Most Common Liquid Oxidizers**
  - LOX
  - Hydrogen Peroxide
  - Nitric Acid
  - Nitrogen Tetroxide
  - Liquid Florine
- Most Common Liquid Fuels
  - Hydrocarbon fuels (RP1, kerosense, methane)
  - Liquid hydrogen
  - Hydrazine (also mono)
  - Unsymmetrical Dimethylhydrazine

Typical Propulsion Requirements

Maneuver	ΔV, km/s
Orbit transfer: LEO to GEO LEO to GEO GTO to GEO (1) GTO to GEO (2) LEO to Earth escape LEO to translunar orbit LEO to lunar orbit GTO to lunar orbit LEO to Mars orbit LEO to solar escape	3.95 (no plane change required) 4.2 (including plane change of 28 deg) 1.5 (no plane change required) 1.8 (incl. plane change of 28 deg.) 3.2 3.1 3.9 1.25-1.4 5.7 8.7
Orbit control: Station-keeping (GEO)	50-55 m/s per year
Orbit control: Drag compensation •alt.: 400-500 km •alt.: 500-600 km •alt.: >600 km	< 100 m/s per year max. (<25 m/s average) < 25 m/s per year max. (< 5 m/s average) < 7.5 m/s per year max.
Attitude control: 3-axis control	2-6 m/s per year
Auxiliary tasks: •Spin-up or despin •Stage or booster separation •Momentum wheel unloading	5-10 m/s per manoeuvre 5-10 m/s per manoeuvre 2-6 m/s per year

Typical Propulsion Requirements for INTELSAT V

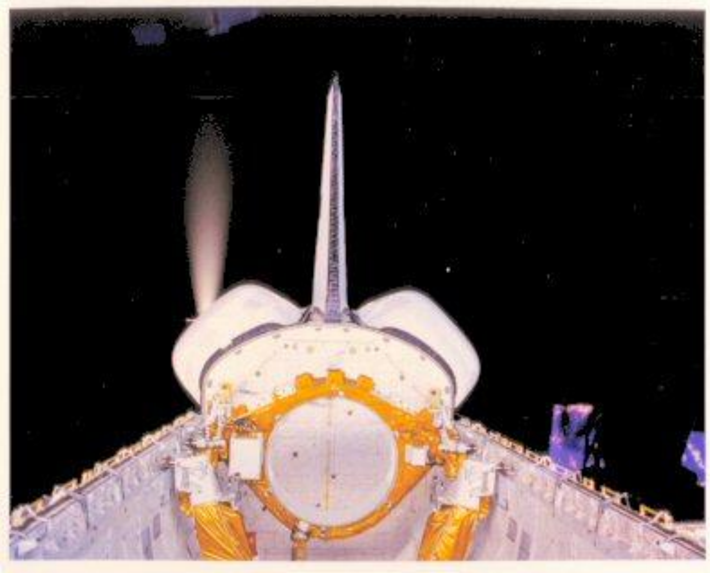
- Propellant mass of 168.9 kg required
  - Transfer orbit (7 kg)
    - Spin up, reorientation
  - Drift orbit (29.9 kg)
    - Reorientation, spin down
  - GEO (132 kg)
    - NS Station Keeping (106 kg)
    - EW Station Keeping (11.7 kg)
    - Attitude Maintenance (12.3 kg)
    - Disposal (2 kg)

Typical Propulsion Requirements for INTELSAT V

- ORBIT TRANSFER
  - INTELSAT V satellite has a Thiokol AKM that produces an average thrust of 56 kN (12,500 lbf) and burns to depletion in approximately 45 seconds.
- STATIONKEEPING AND ATTITUDE CONTROL
  - Array of four 0.44 N (0.1 lbf) thrusters for roll control,
  - Array of ten 2.0 N (0.45 lbf) thrusters for pitch and yaw control and E/W stationkeeping,
  - Array of two 22.2 N (5.0 lbf) thrusters for repositioning and reorientation.
  - Four 0.3 N (0.07 lbf) EHTs are used for N/S stationkeeping.
- The nominal mass of the spacecraft at beginning of life (BOL) is 1005 kg and the dry mass at end of life (EOL) is 836 kg. The difference of 169 kg represents the mass of the propellant for a design life of 7 years.

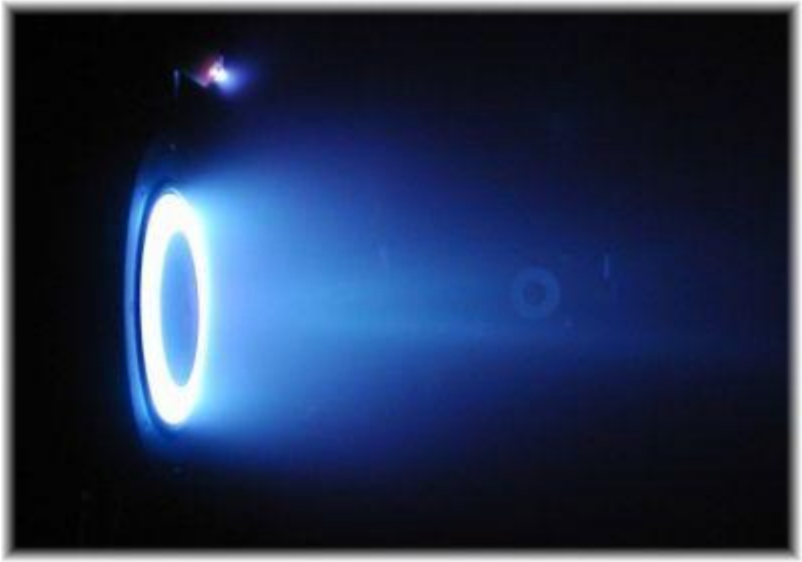
Chemical Propulsion

- Chemical reaction produces energy
  - Liquid
    - Bipropellant
      - Two reactants
        - Fuel and Oxidizer
        - MMH, UDMH, O_2, HNO_3, N_2O_4
    - Monopropellant
      - Single reactant
        - Catalyst
        - N_2H_4, H_2O_2
  - Solid
    - Fuel and oxidizer combined in a solid mixture (grain)
  - Hybrid
    - Typically a solid fuel and a liquid or gaseous oxidizer



Solar Electric Propulsion

- Several Classifications
  - Electrothermal
    - Resistojet
    - Arcjet
  - Electrostatic
    - Ion engine
  - Electromagnetic
    - Pulsed Plasma Thruster
    - Hall Effect Thruster
    - MPD

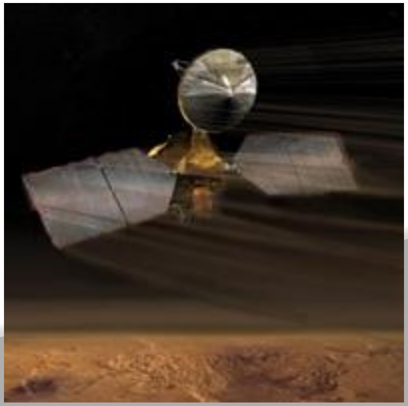


Nuclear Propulsion

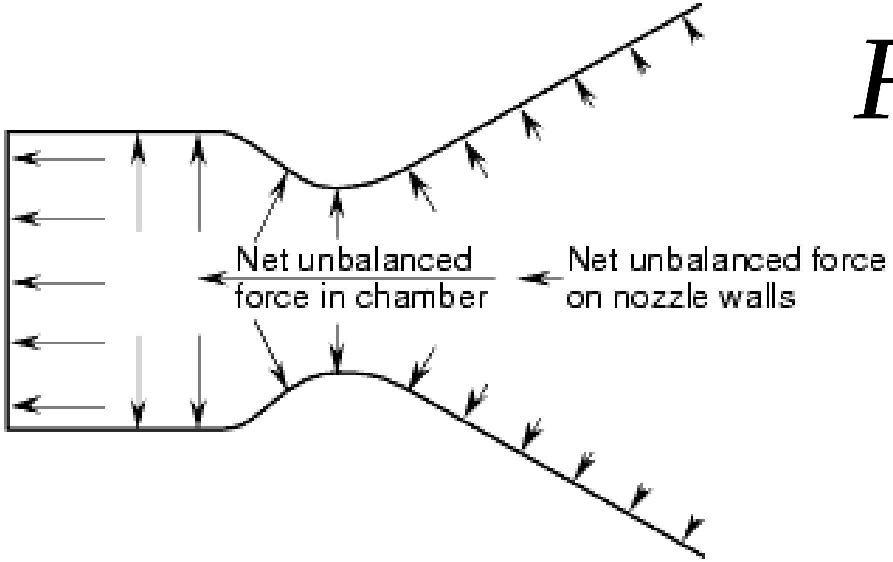
- Fission or Radioactive Isotope Decay
- Nuclear Thermal Propulsion (NTP)
  - Transfers heat produced by nuclear process into propellant gas
  - Propellant heating increases thrust and specific impulse
- Nuclear Electric Propulsion (NEP)
  - Uses heat produced by nuclear process to produce electric power
  - Electric power used to ionize and accelerate propellant

Propellant-less Propulsion

- Solar Sail
  - Uses solar pressure to generate thrust
  - Large, reflective surface area required
- Electrodynamic Tether
  - Uses Earth's (or other planet's) magnetic field to generate a force (with an electric current)
- Atmospheric Drag
  - Aerobraking
  - Re-entry



How a Thermodynamic Rocket Works



$$F = \dot{m}v_e + (p_e - p_a)A_e$$

m = mass flow rate (kg/sec)
v_e = propellant exhaust velocity (m/sec)
p_e = pressure at nozzle exit (Pa)
p_a = ambient pressure (Pa)
A_e = area of nozzle exit (m^2)

For Ideal Expansion ($p_e = p_a$):

$$F = \dot{m}v_e$$

Thank You