LECTURE NOTES

ON

LAUNCH VEHICLE MISSILE TECHNOLOGY

IV B. Tech II semester (JNTUH-R13)

Mr. Shiva Prasad U.
Assistant Professor

AERONAUTICAL ENGINEERING

INSTITUTE OF AERONAUTICAL ENGINEERING
(Autonomous)
DUNDIGAL, HYDERABAD - 500 043

UNIT-I
INTRODUCTION

1.1 Introduction

Launch vehicles are the rocket-powered systems that provide transportation from the earth's surface into the environment of space. In the early days of the U.S. civilian space program the term "launch vehicle" was used by NASA in preference to the term "booster" because "booster" had been associated with the development of the military missiles. "Booster" now has crept back into the vernacular of the Space Age and is used interchangeably with "launch vehicle."

Space Launch Vehicles

1.2 TYPES

1. EXPANDABLE

2. REUSABLE

Classification of Missile

Missiles are generally classified on the basis of their Type, Launch Mode, Range, Propulsion, Warhead and Guidance Systems.

Type:

1.CRUISE MISSILE

2. BALLISTIC MISSILE

Launch Mode:

Surface-to-Surface Missile

Surface-to-Air Missile

Surface (Coast)-to-Sea Missile

Air-to-Air Missile

Air-to-Surface Missile

Sea-to-Sea Missile

Sea-to-Surface (Coast) Missile

Short & Long range Ballistic Missiles

Anti-Tank Missile

Range:

Short Range Missile

Medium Range Missile

Intermediate Range Ballistic Missile

Intercontinental Ballistic Missile

Propulsion:

Solid Propulsion

Liquid Propulsion

Hybrid Propulsion

Ramjet

Scramjet

Cryogenic

Warhead:

Conventional

Strategic

Guidance Systems:

Wire Guidance

Command Guidance

Terrain Comparison Guidance

Terrestrial Guidance

Inertial Guidance

Beam Rider Guidance

Laser Guidance

RF and GPS Reference

1.3 On the basis of Type:

(i) Cruise Missile: A cruise missile is an unmanned self-propelled (till the time of impact) guided vehicle that sustains flight through aerodynamic lift for most of its flight path and whose primary mission is to place an ordnance or special payload on a target. They fly within the earth's atmosphere and use jet engine technology. These vehicles vary greatly in their speed and ability to penetrate defences.Cruise missiles can be categorised by size, speed (subsonic or supersonic), range and whether launched from land, air, surface ship or submarine.

Depending upon the speed such missiles are classified as:

1) Subsonic cruise missile

2) Supersonic cruise missile

3) Hypersonic cruise missile

Subsonic cruise missile flies at a speed lesser than that of sound. It travels at a speed of around 0.8 Mach. The well-known subsonic missile is the American Tomahawk cruise missile. Some other examples are Harpoon of USA and Exocet of France.

Subsonic & Supersonic Cruise Missiles

Supersonic cruise missile travels at a speed of around 2-3 Mach i.e.; it travels a kilometre approximately in a second. The modular design of the missile and its capability of being launched at different orientations enable it to be integrated with a wide spectrum of platforms like warships, submarines, different types of aircraft, mobile autonomous launchers and silos. The combination of supersonic speed and warhead mass provides high kinetic energy ensuring tremendous lethal effect. BRAHMOS is the only known versatile supersonic cruise missile system which is in service.

Hypersonic cruise missile travels at a speed of more than 5 Mach. Many countries are working to develop hypersonic cruise missiles. BrahMos Aerospace is also in the process of developing a hypersonic cruise missile, BRAHMOS-II, which would fly at a speed greater than 5 Mach.

(ii) Ballistic Missile: A ballistic missile is a missile that has a ballistic trajectory over most of its flight path, regardless of whether or not it is a weapon-delivery vehicle. Ballistic missiles are categorised according to their range, maximum distance measured along the surface of earth's ellipsoid from the point of launch to the point of impact of the last element of their payload. The missile carry a huge payload. The carriage of a deadly warhead is justified by the distance the missile travels. Ballistic missiles can be launched from ships and land based facilities. For example, Prithvi I, Prithvi II, Agni I, Agni II and Dhanush ballistic missiles are currently operational in the Indian defence forces.

1.4 On the basis of Launch Mode:

(i) Surface-to-Surface Missile: A surface-to-surface missile is a guided projectile launched from a hand-held, vehicle mounted, trailer mounted or fixed installation. It is often powered by a rocket motor or sometimes fired by an explosive charge since the launch platform is stationary.

(ii) Surface-to-Air Missile: A surface-to-air missile is designed for launch from the ground to destroy aerial targets like aircrafts, helicopters and even ballistic missiles. These missiles are generally called air defence systems as they defend any aerial attacks by the enemy.

(iii) Surface (Coast)-to-Sea Missile: A surface (coast)-to-sea missile is designed to be launched from land to ship in the sea as targets.

(iv)Air-to-Air Missile: An air-to-air missile is launched from an aircraft to destroy the enemy aircraft. The missile flies at a speed of 4 Mach.

(v) Air-to-Surface Missile: An air-to-surface missile is designed for launch from military aircraft and strikes ground targets on land, at sea or both. The missiles are basically guided via laser guidance, infrared guidance and optical guidance or via GPS signals. The type of guidance depends on the type of target.

(vi) Sea-to-Sea Missile: A sea-to-sea missile is designed for launch from one ship to another ship.

(vii) Sea-to-Surface (Coast) Missile: A sea-to-surface missile is designed for launch from ship to land based targets.

(viii) Anti-Tank Missile: An anti-tank missile is a guided missile primarily designed to hit and destroy heavily-armoured tanks and other armoured fighting vehicles. Anti-tank missiles could be launched from aircraft, helicopters, tanks and also from shoulder mounted launcher.

1.5 On the basis of Range:

This type of classification is based on maximum range achieved by the missiles. The basic classification is as follows:

(i) Short Range Missile

(ii) Medium Range Missile

(iii) Intermediate Range Ballistic Missile

(iv) Intercontinental Ballistic Missile

1.6 On the basis of Propulsion:

(i) Solid Propulsion: Solid fuel is used in solid propulsion. Generally, the fuel is aluminium powder. Solid propulsion has the advantage of being easily stored and can be handled in fuelled condition. It can reach very high speeds quickly. Its simplicity also makes it a good choice whenever large amount of thrust is needed.

(ii) Liquid Propulsion: The liquid propulsion technology uses liquid as fuel. The fuels are hydrocarbons. The storage of missile with liquid fuel is difficult and complex. In addition, preparation of missile takes considerable time. In liquid propulsion, propulsion can be controlled easily by restricting the fuel flow by using valves and it can also be controlled even under emergency conditions. Basically, liquid fuel gives high specific impulse as compared to solid fuel.

(ii) Hybrid Propulsion: There are two stages in hybrid propulsion - solid propulsion and liquid propulsion. This kind of propulsion compensates the disadvantages of both propulsion systems and has the combined advantages of the two propulsion systems.

(iii) Ramjet: A ramjet engine does not have any turbines unlike turbojet engines. It achieves compression of intake air just by the forward speed of the air vehicle. The fuel is injected and ignited. The expansion of hot gases after fuel injection and combustion accelerates the exhaust air to a velocity higher than that at the inlet and creates positive push. However, the air entering the engine should be at supersonic speeds. So, the aerial vehicle must be moving in supersonic speeds. Ramjet engines cannot propel an aerial vehicle from zero to supersonic speeds.

(iv)Scramjet: Scramjet is an acronym for Supersonic Combustion Ramjet. The difference between scramjet and ramjet is that the combustion takes place at supersonic air velocities through the engine. It is mechanically simple, but vastly more complex aerodynamically than a jet engine. Hydrogen is normally the fuel used.

(v) Cryogenic: Cryogenic propellants are liquefied gases stored at very low temperatures, most frequently liquid hydrogen as the fuel and liquid oxygen as the oxidizer. Cryogenic propellants require special insulated containers and vents which allow gas to escape from the evaporating liquids. The liquid fuel and oxidizer are pumped from the storage tanks to an expansion chamber and injected into the combustion chamber where they are mixed and ignited by a flame or spark. The fuel expands as it burns and the hot exhaust gases are directed out of the nozzle to provide thrust.

1.7 On the basis of Warhead:

(i) Conventional Warhead: A conventional warhead contains high energy explosives. It is filled with a chemical explosive and relies on the detonation of the explosive and the resulting metal casing fragmentation as kill mechanisms.

(ii) Strategic Warhead: In a strategic warhead, radio active materials are present and when triggered they exhibit huge radio activity that can wipe out even cities. They are generally designed for mass annihilation.

On the basis of Guidance Systems:

(i) Wire Guidance: This system is broadly similar to radio command, but is less susceptible to electronic counter measures. The command signals are passed along a wire (or wires) dispensed from the missile after launch.

(ii) Command Guidance: Command guidance involves tracking the projectile from the launch site or platform and transmitting commands by radio, radar, or laser impulses or along thin wires or optical fibres. Tracking might be accomplished by radar or optical instruments from the launch site or by radar or television imagery relayed from the missile.

(iii) Terrain Comparison Guidance: Terrain Comparison (TERCOM) is used invariably by cruise missiles. The system uses sensitive altimeters to measure the profile of the ground directly below and checks the result against stored information.

(iv)Terrestrial Guidance: This system constantly measures star angles and compares them with the pre-programmed angles expected on the missile's intended trajectory. The guidance system directs the control system whenever an alteration to trajectory is required.

(v) Inertial Guidance: This system is totally contained within the missile and is programmed prior to launch. Three accelerometers, mounted on a platform space-stabilised by gyros, measure accelerations along three mutually perpendicular axes; these accelerations are then integrated twice, the first integration giving velocity and the second giving position. The system then directs the control system to preserve the pre-programmed trajectory. This systems are used in the surface-to-surface missiles and in cruise missiles.

(vi)Beam Rider Guidance: The beam rider concept relies on an external ground or ship-based radar station that transmits a beam of radar energy towards the target. The surface radar tracks the target and also transmits a guidance beam that adjusts its angle as the target moves across the sky.

(vii) Laser Guidance: In laser guidance, a laser beam is focused on the target and the laser beam reflects off the target and gets scattered. The missile has a laser seeker that can detect even miniscule amount of radiation. The seeker provides the direction of the laser scatters to the guidance system. The missile is launched towards the target, the seeker looks out for the laser reflections and the guidance system steers the missile towards the source of laser reflections that is ultimately the target.

(viii) RF and GPS Reference: RF (Radio Frequency) and GPS (Global Positioning System) are examples of technologies that are used in missile guidance systems. A missile uses GPS signal to determine the location of the target. Over the course of its flight, the weapon uses this information to send commands to control surfaces and adjusts its trajectory. In a RF reference, the missile uses RF waves to locate the target.

1.8MISSIONS, ROLES, AND STRUCTURE OF THE MDA

A. MISSIONS

During the past 25 years, the mission of the missile defense program has evolved from (1) a technology program to determine the feasibility of ballistic missile defense to

(2) a technology development program to provide a shield over the United States against ballistic missiles to

(3) a program known as Global Protection Against Limited Strike, or GPALS, to protect the United States, its friends, and allies from a limited ballistic missile attack to

(4) a program to provide theater-based defenses against short- and mediumrange ballistic missiles and to thwart potential light attacks of long-range missiles from “rogue”-class adversaries to

(5) the current broad program of integrated sensor, interceptor, and command and control, battle management, and communications (C2BMC) capabilities.

The MDA was established in January 2002 to provide centralized management to develop and integrate these programs (of sensors, interceptors, command and control, and battle management) into a BMDS. The broad definition of the MDA’s current mission includes the need to develop and deploy a BMDS capable of defeating ballistic missiles of all ranges in all phases of flight to defend the United States, deployed forces, allies, and friends. To that end, DoDD 5134.9 of 9 October 2004, drawing on NSPD-23, defined the MDA’s mission as follows:

• To defend the United States, deployed forces, allies and friends from ballistic missile attacks of all ranges in all phases of flight.

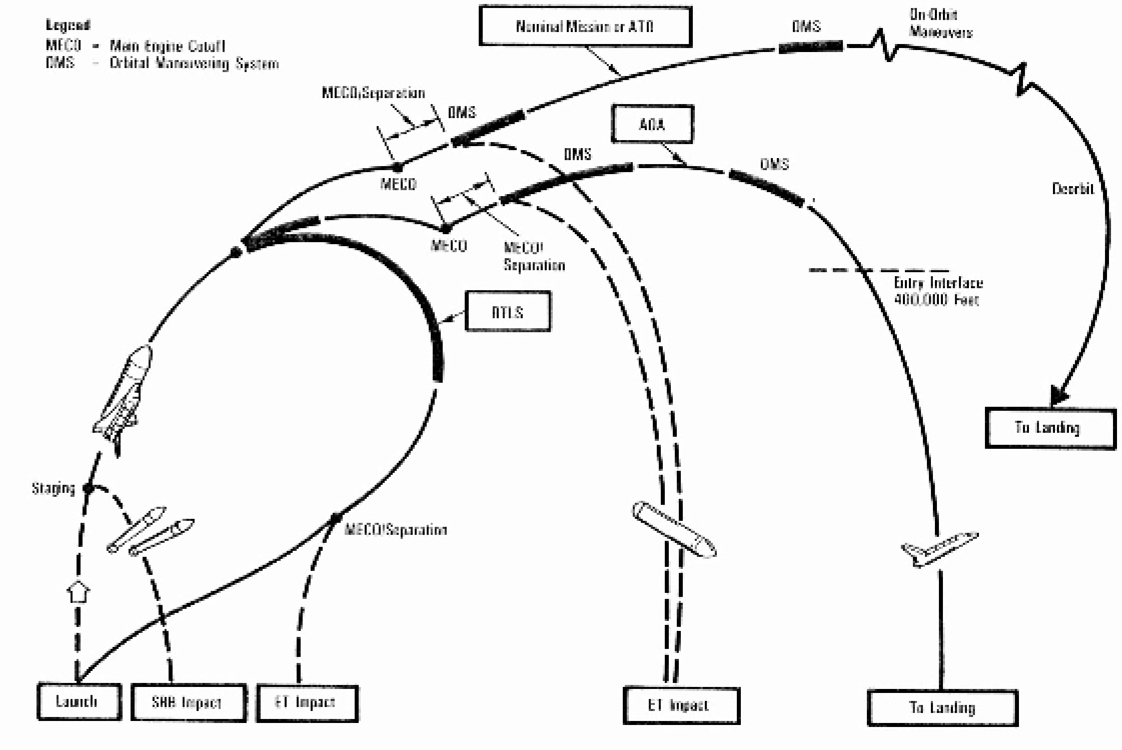
• To develop and deploy, as directed, a layered BMDS. • To enable the fielding of elements of the BMDS as soon as practicable.

• To provide capability in blocks, improving the effectiveness of fielded capability by inserting new technologies as they become available.

1.9 MISSION PROFILE

In the launch configuration, the orbiter and two solid rocket boosters are attached to the external tank in a vertical (nose-up) position on the launch pad. Each solid rocket booster is attached at its aft skirt to the mobile launcher platform by four bolts.

Emergency exit for the flight crew on the launch pad up to 30 seconds before lift-off is by slidewire. There are seven 1,200-foot- long slidewires, each with one basket. Each basket is designed to carry three persons. The baskets, 5 feet in diameter and 42 inches deep, are suspended beneath the slide mechanism by four cables. The slidewires carry the baskets to ground level. Upon departing the basket at ground level, the flight crew progresses to a bunker that is designed to protect it from an explosion on the launch pad.



Abort and Normal Mission Profile

At launch, the three space shuttle main engines-fed liquid hydrogen fuel and liquid oxygen oxidizer from the external tank-are ignited first. When it has been verified that the engines are operating at the proper thrust level, a signal is sent to ignite the solid rocket boosters. At the proper thrust-to-weight ratio, initiators (small explosives) at eight hold-down bolts on the solid rocket boosters are fired to release the space shuttle for lift-off. All this takes only a few seconds.

Maximum dynamic pressure is reached early in the ascent, nominally approximately 60 seconds after lift-off.

Approximately a minute later (two minutes into the ascent phase), the two solid rocket boosters have consumed their propellant and are jettisoned from the external tank. This is triggered by a separation signal from the orbiter.

The boosters briefly continue to ascend, while small motors fire to carry them away from the space shuttle. The boosters then turn and descend, and at a predetermined altitude, parachutes are deployed to decelerate them for a safe splashdown in the ocean. Splashdown occurs approximately 141 nautical miles (162 statute miles) from the launch site. The boosters are recovered and reused.

Meanwhile, the orbiter and external tank continue to ascend, using the thrust of the three space shuttle main engines. Approximately eight minutes after launch and just short of orbital velocity, the three space shuttle engines are shut down (main engine cutoff), and the external tank is jettisoned on command from the orbiter.

The forward and aft reaction control system engines provide attitude (pitch, yaw and roll) and the translation of the orbiter away from the external tank at separation and return to attitude hold prior to the orbital maneuvering system thrusting maneuver.

The external tank continues on a ballistic trajectory and enters the atmosphere, where it disintegrates. Its projected impact is in the Indian Ocean (except for 57-degree inclinations) in the case of equatorial orbits (Kennedy Space Center.launch) and in the extreme southern Pacific Ocean in the case of a Vandenberg Air Force Base launch.

Normally, two thrusting maneuvers using the two orbital maneuvering system engines at the aft end of the orbiter are used in a two-step thrusting sequence: to complete insertion into Earth orbit and to circularize the spacecraft's orbit. The orbital maneuvering system engines are also used on orbit for any major velocity changes.

In the event of a direct-insertion mission, only one orbital maneuvering system thrusting sequence is used.

The orbital altitude of a mission is dependent upon that mission. The nominal altitude can vary between 100 to 217 nautical miles (115 to 250 statute miles).

The forward and aft reaction control system thrusters (engines) provide attitude control of the orbiter as well as any minor translation maneuvers along a given axis on orbit.

1.10 Payload and Propulsion System

1.10.1 Propulsion system

There are four major components to any full scale rocket; the structural system, or frame, the payload system, the guidance system, and the **propulsion system**. The propulsion of a rocket includes all of the parts which make up the rocket engine; the tanks pumps, propellants, power head, and rocket nozzle. The function of the propulsion system is to produce thrust.

Thrust is the force which moves a rocket through the air and through space. Thrust is generated by the **propulsion system**of the rocket. Different propulsion systems develop thrust in different ways, but all thrust is generated through some application of Newton's third law of motion. For every action there is an equal and opposite reaction. In any propulsion system, a **working fluid** is accelerated by the system and the reaction to this acceleration produces a force on the system. A general derivation of the thrust equation shows that the amount of thrust generated depends on the mass flow through the engine and the exit velocity of the gas.

The study of rockets is an excellent way for students to learn the basics of forces and the response of an object to external forces. There are four major components to any full scale rocket; the structural system, or frame, the **payload system**, the guidance, and the propulsion system. On this page we show some types of payloads that are carried on rockets.

1.10.2 Payload

The **payload** of a rocket depends on the rocket's mission. The earliest payloads on rockets were fireworks for celebrating holidays. Some of the early ideas for booster staging were developed in an effort to loft fireworks as high as possible. During World War II, the fireworks were replaced by several thousand pounds of explosives on the German V2 rocket. Following World War II, many countries developed guided ballistic missiles armed with nuclear warheads for payloads. The same rockets were modified to launch satellites with a wide range of missions; communication, weather monitoring, spying, planetary exploration, and observation. On the figure we show a picture of the Hubble Space Telescope which has been used to explore deep space from low earth orbit.

1.11 Control and Guidance Requirements

There are four major components to any full scale rocket; the structural system or frame, the payload system, the **guidance system**, and the propulsion system. The **guidance system** of a rocket includes very sophisticated sensors, on-board computers, radars, and communication equipment. The guidance system has two main roles during the launch of a rocket; to provide **stability** for the rocket, and to **control** the rocket during maneuvers.

The motion of any object in flight is a combination of the translation of the center of gravity and the rotation of the object about its center of gravity. Many different methods have been developed to control rockets in flight. All of the control methods produce a torque about the rocket's center of gravity which causes the rocket to rotate in flight. Through an understanding of the forces acting on the rocket and the resulting motion, the rocket guidance system can be programmed to intercept targets, or to fly into orbit.

A stable rocket is one which naturally returns to its flight configuration when it is perturbed from that configuration. For simple rockets flying within the atmosphere, stability is assured if the aerodynamic forces acting through the center of pressure are kept below the rocket center of gravity. **Fins** located at the bottom of the rocket, or weight added to the top of the rocket help to establish this condition. For complex rockets, or for rockets flying above the atmosphere, stability can be provided by the guidance system, using the same methods employed for maneuvers.

On this slide, we show a picture of a Atlas rocket at the left and a picture of the Space Shuttle at the right. The Atlas rocket was developed in the late 1950's and used small **vernier rockets** on the sides of the missile to provide maneuvering and balance. The Space Shuttle was designed in the late 1970's and employed the more modern gimbaling of the main engines to provide for control during launch.

1.12 Performancemeasures, design, staging,

The study of rockets is an excellent way for students to learn the basics of forces and the response of an object to external forces. All rockets use the thrust generated by a propulsion system to overcome the weight of the rocket. For stomp rockets,bottle rockets, and model rockets, the aerodynamic drag and lift are also important forces acting on the rocket. For air-to-air and ground-to-air missiles, the aerodynamic forces are significant, but for satellite launchers, the aerodynamic forces are not as important because of the **flight trajectory** to orbit.

On this slide we show the major invents in the flight of a two stage launcher to orbit. Throughout the flight, the **weight** of the rocket is constantly changing because of the burning of the propellants. At **launch**, the thrust produced by the engine is greater than the weight of the rocket and the net force accelerates the rocket away from the pad. Unlike model rockets, full scale launchers rely on a sophisticated **guidance system** to balance and steer the rocket during its flight. The thrust of the rocket is gimbaled, or rotated, during the flight to produce maneuvers. Leaving the pad, the rocket begins a powered vertical ascent. The vehicle accelerates because of the high thrust and decreasing weight and rather quickly moves out of the thick atmosphere near the surface of the earth. Although the rocket is traveling supersonically, the drag on the vehicle is small because of the shape of the rocket and the lower air density at altitude. As the rocket ascends, it also begins to pitch over and its flight path becomes more inclined to the vertical.

Several minutes into the ascent, most launchers **discard** some of the weight of the rocket. This process is called staging and often includes the ignition of a second engine, or **upper stage**, of the launcher. The discarded first stage continues on aballistic flight back to earth. The first stage may be retrieved, as with the Space Shuttle solid rocket engines, or it may be completely discarded, as was done on the Apollo moon rockets. The lighter, upper stage continues to accelerate under the power of its engine and to pitch over to the horizontal. At a carefully determined altitude and speed the upper stage engine is **cut off** and the stage and payload are in orbit. The exact speed needed to orbit the earth depends on the altitude, according to a formula that was developed by Johannes Kepler in the early 1600's:

$V = sqrt(g_0 * Re^2 / (Re + h))$

where **V** is the velocity for a circular orbit, **g0** is the surface gravitational constant of the Earth (32.2 ft/sec^2), **Re** is the mean Earth radius (3963 miles), and **h** is the height of the orbit in miles. If the rocket was launched from the Moon or Mars, the rocket would require a different orbital velocity because of the different planetary radius and gravitational constant. For a 100 mile high orbit around the Earth, the orbital velocity is 17,478 mph.

Materials used for launch vehicles & missiles and their selection criteria.

1.13 Selection of Materials

High Specific Strength.
-High Specific Modulus.
-Fabrication Easiness.
Easy availability
-Critical requirements.
-Service Conditions.

1.14 Specific Requirements Under Adverse Conditions

High Pressure.

- High Temperature.
- Thermo-Structural needs.
- Soft Magnets.
- HED Permanent Magnets.
- Bi-metallics.
- Opto-Electronics.
- Electro-Optics.

1.15 Types of Materials

1. Structural Metallic Materials.
2. Composite Materials.
3. Thermo-Structural Materials.
4.Thermal Protection Materials.
5. Special Materials.
6. Chemicals.

UNIT-II

Solid Propellant Rocket Systems

2.1 Introduction

What is Rocket?

1.
    a. A rocket engine.
    b. A vehicle or device propelled by one or more rocket engines, especially such a vehicle designed to travel through space.
2. A projectile weapon carrying a warhead that is powered and propelled by rockets.
3. A projectile firework having a cylindrical shape and a fuse that is lit from the rear.

What is missile?

1. An object or weapon that is fired, thrown, dropped, or otherwise projected at a target; a projectile.
2. A guided missile.
3. A ballistic missile.

2.2 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.

2.3 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 counterparts, however, they offer several advantages. By controlling the flow of propellant to the combustion chamber, the engine can be throttled, stopped, or restarted.

A good liquid propellant is one with a high specific impulse or, stated another way, one with a high speed of exhaust gas ejection. This implies a high combustion temperature and exhaust gases with small molecular weights.

2.4 Solid propellant rocket motors and principal features

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.

There are two families of solids propellants: homogeneous and composite. Both types are dense, stable at ordinary temperatures, and easily storable.

2.5 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. It is difficult to make use of this concept for vary large thrusts, and thus, hybrid propellant engines are rarely built.

2.6 Ignition system in rockets

This section is concerned with the mechanism or the process for initiating the combustion of a solid propellant grain. 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, hang fires(delayed ignition), extinguishment, and chuffing. The *igniter* in a solid rocket motor generates the heat and gas required for motor ignition.

Motor ignition must usually be complete in a fraction of a second for all but the very large motors. The motor pressure rises to an equilibrium state in a very short time, as shown in Fig. 1. Conventionally, 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.

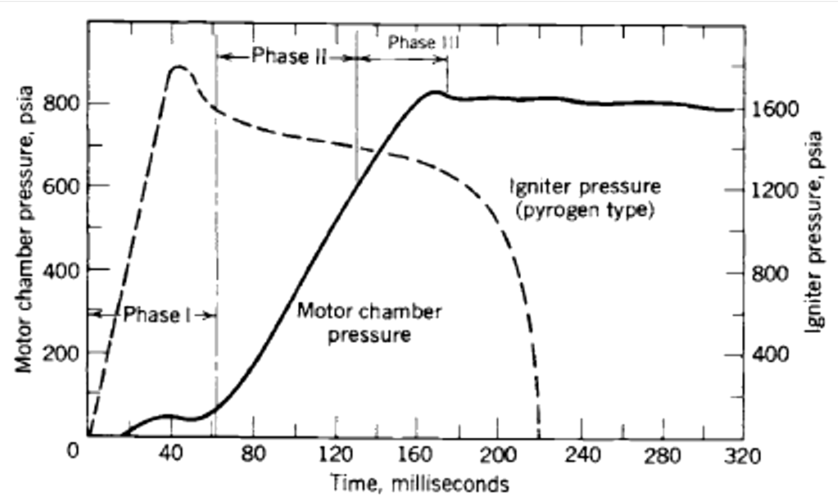


Figure 1 Typical ignition pressure transient portion of motor chamber pressure time trace with igniter pressure trace and ignition process phases shown. Electric signal is received a few milliseconds before time zero

The ignition will be successful once enough grain surface is ignited and burning, so that the motor will continue to raise its own pressure to the operating chamber pressure. The critical process seems to be a gas-phase reaction above the burning surface, when propellant vapors or decomposition products interact with each other and with the igniter gas products. If the igniter is not powerful enough, some grain surfaces may burn for a short time, but the flame will be extinguished.

Satisfactory attainment of equilibrium chamber pressure with full gas flow is dependent on (1) characteristics of the igniter and the gas temperature, composition and flow issuing from the igniter, (2) motor propellant composition and grain surface ignitability, (3) heat transfer characteristics by radiation and convection between the igniter gas and grain surface, (4) grain flame spreading rate, and (5) the dynamics of filling the motor free volume with hot gas.

Ignitability of a propellant is affected by many factors, including (1)the propellant formulation, (2) the initial temperature of the propellant grain surface, (3) the surrounding pressure, (4) the mode of heat transfer, (5) grain surfaceroughness, (6) age of the propellant, (7) the composition and hot solid particle content of the igniter gases, (8) the igniter propellant and its initial temperature, (9) the velocity of the hot igniter gases relative to the grain surface, and (10) the cavity volume and configuration. Fig. 2 and the ignition time becomes shorter with increases in bothheat flux and chamber pressure. If a

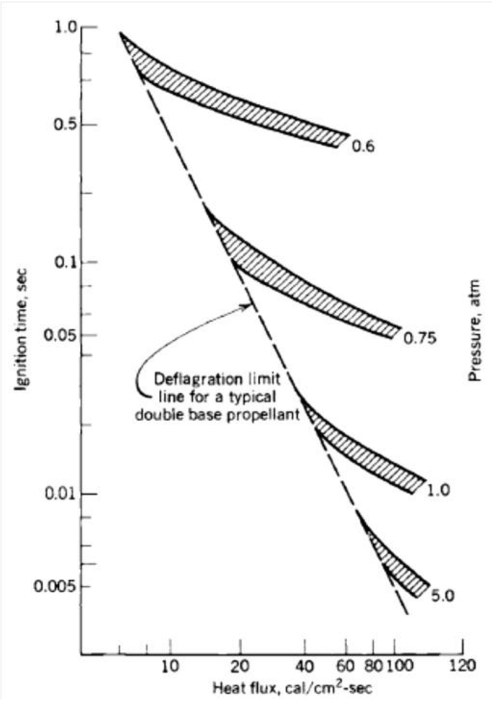


Figure 2 Propellant ignitability curves" effect of heat flux on ignition time for aspecific motor.

short ignition delay is required, then amore powerful igniter will be needed. The radiation effects can be significant in the ignition transient case. InSection 1.4 we describe ananalysis and design for igniters.

2.7Types of Igniters

In Section 1.3 the process of ignition was described. In this section we discuss specific igniter types, locations, and their hardware.Since the igniter propellant mass is small (often less than 1% of the motorpropellant) and burns mostly at low chamber pressure (low Is), it contributesvery little to the motor overall total impulse. It is the designer's aim to reducethe igniter propellant mass and the igniter inert hardware mass to a minimum,just big enough to assure ignition under all operating conditions.

Fig. 3 shows several alternative locations for igniter installations.When mounted on the forward end, the gas flow over the propellant surfacehelps to achieve ignition. With aft mounting there is little gas motion, particularlynear the forward end; here ignition must rely on the temperature,pressure, and heat transfer from the igniter gas. If mounted on the nozzle,the igniter hardware and its support is discarded shortly after the igniter hasused all its propellants and there is no inert mass penalty for the igniter case.There are two basic types: pyrotechnic igniters and pyrogen igniters; both arediscussed below.

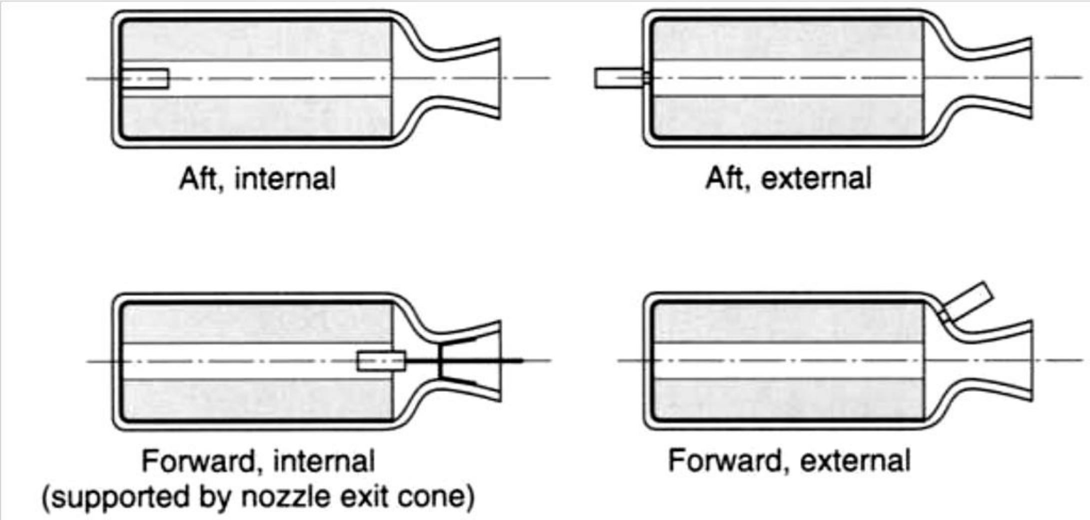


Figure 3 Simple diagrams of mounting options for igniters. Grain configurations are not shown.

2.8 Pyrotechnic Igniters

A special form of pyrotechnic igniter is the *surface-bonded* or *grain-mounted igniter*. Such an igniter has its initiator included within a sandwich of flat sheets; the layer touching the grain is the main charge of pyrotechnic. This form of igniter is used with multipulse motors with two or more end-burning grains. The ignition of the second and successive pulses of these motors presents unusual requirements for available space, compatibility with the grain materials, life, and the pressure and temperature resulting from the booster grain operation. Advantages of the sheet igniter include light weight, low volume, and high heat flux at the grain surface. Any inert material employed (such as wires and electric ceramic insulators) is usually blown out of the motor nozzle during ignition and their impacts have caused damage to the nozzle or plugged it, particularly if they are not intentionally broken up into small pieces.

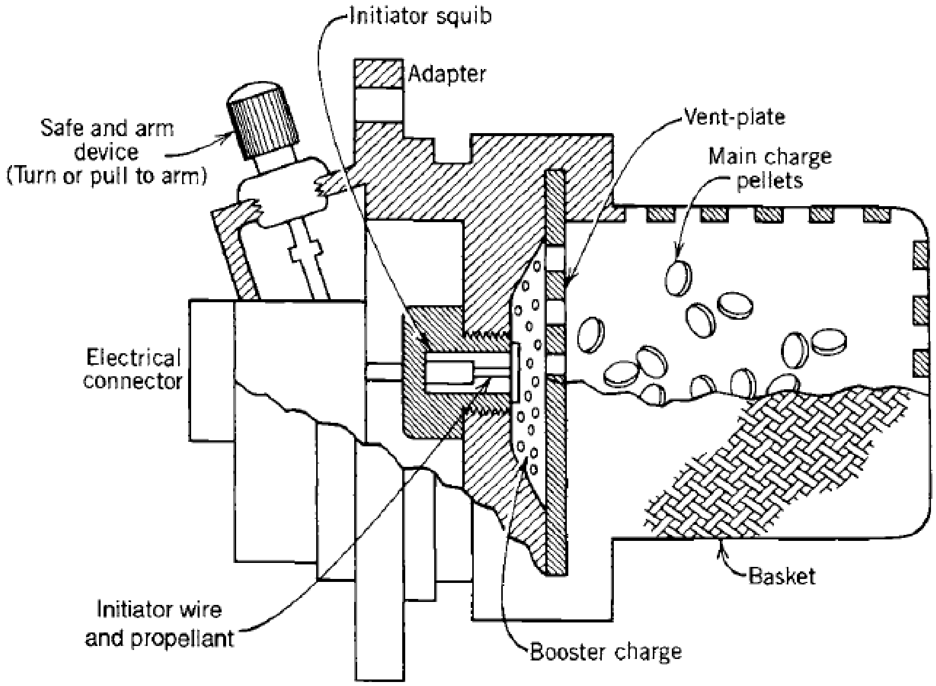


Figure 4 Typical pyrotechnic igniter with three different propellant charges that ignite in sequence.

2.9 Pyrogen Igniters

A pyrogen igniter is basically a small rocket motor that is used to ignite a largerrocket motor. The pyrogen is not designed to produce thrust. All use one ormore nozzle orifices, both sonic and supersonic types, and most use conventionalrocket motor grain formulations and design technology. Heat transferfrom the pyrogen to the motor grain is largely convective, with the hot gasescontacting the grain surface as contrasted to a highly radiative energy emittedby pyrotechnic igniters. Fig. 5illustrate rocket motorswith a typical pyrogen igniter. The igniter in Fig. 5.d has three nozzles and acylindrical grain with high-burn-rate propellant. For pyrogen igniters theinitiator and the booster charge are very similar to the designs used in pyrotechnicigniters. Reaction products from the main charge impinge on the surfaceof the rocket motor grain, producing motor ignition. Common practice onthe very large motors is to mount externally, with the pyrogen igniter pointingits jet up through the large motor nozzle. In this case, the igniter becomes apiece of ground-support equipment.

Two approaches are commonly used to safeguard against motor misfires, orinadvertent motor ignition; one is the use of the classical *safe and arm device*and the second is the *design of safeguards* into the initiator. Energy for unintentionalignition--usually a disaster when it happens--can be (1) static electricity,(2) induced current from electromagnetic radiation, such as radar, (3)induced electrical currents from ground test equipment, communication apparatus,ornearby electrical circuits in the flight vehicle, and (4) heat, vibration,or shock from handling and operations. Functionally, the safe and arm deviceserves as an electrical switch to keep the igniter circuit grounded when notoperating; in some designs it also mechanically misaligns or blocks the ignitiontrain of events so that unwanted ignition is precluded even though the initiatorfires. When transposed into the *arm* position, the ignition flame can be reliablypropagated to the igniter's booster and main charges.

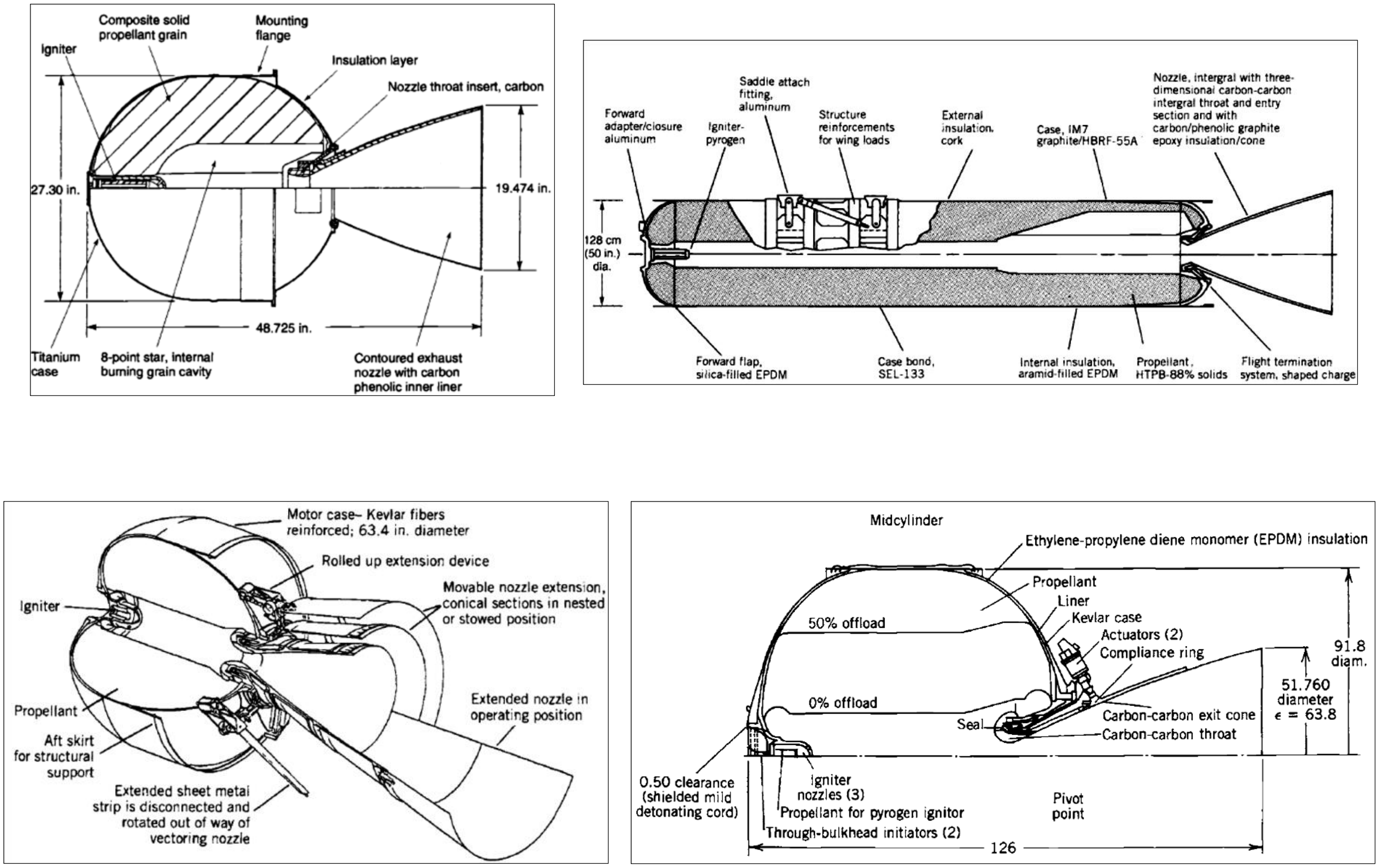


Figure 5a. (top left), b. (top right), c. (lower left) d. (lower right) illustrate rocket motors with a typical pyrogen igniter

Electric initiators in motor igniters are also called squibs, glow plugs, primers,and sometimes headers; they always constitute the initial element in theignition train and, if properly designed, can be a safeguard against unintendedignition of the motor. Three typical designs of initiators are shown in Fig. 6.Both (a) and (b) structurally form a part of the rocket motor case andgenerically are headers. In the integral diaphragm type (a) the initial ignitionenergy is passed in the form of a shock wave through the diaphragm activatingthe acceptor charge, with the diaphragm remaining integral. This same principleis also used to transmit a shock wave through a metal case wall or a metalinsert in a filament-wound case; the case would not need to be penetrated andsealed. The header type (b) resembles a simple glow plug with two high-resistancebridgewires buried in the initiator charge. The exploding bridgewiredesign (c) employs a small bridgewire (0.02 to 0.10 mm) of low-resistancematerial, usually platinum or gold, that is exploded by application of a highvoltagedischarge.

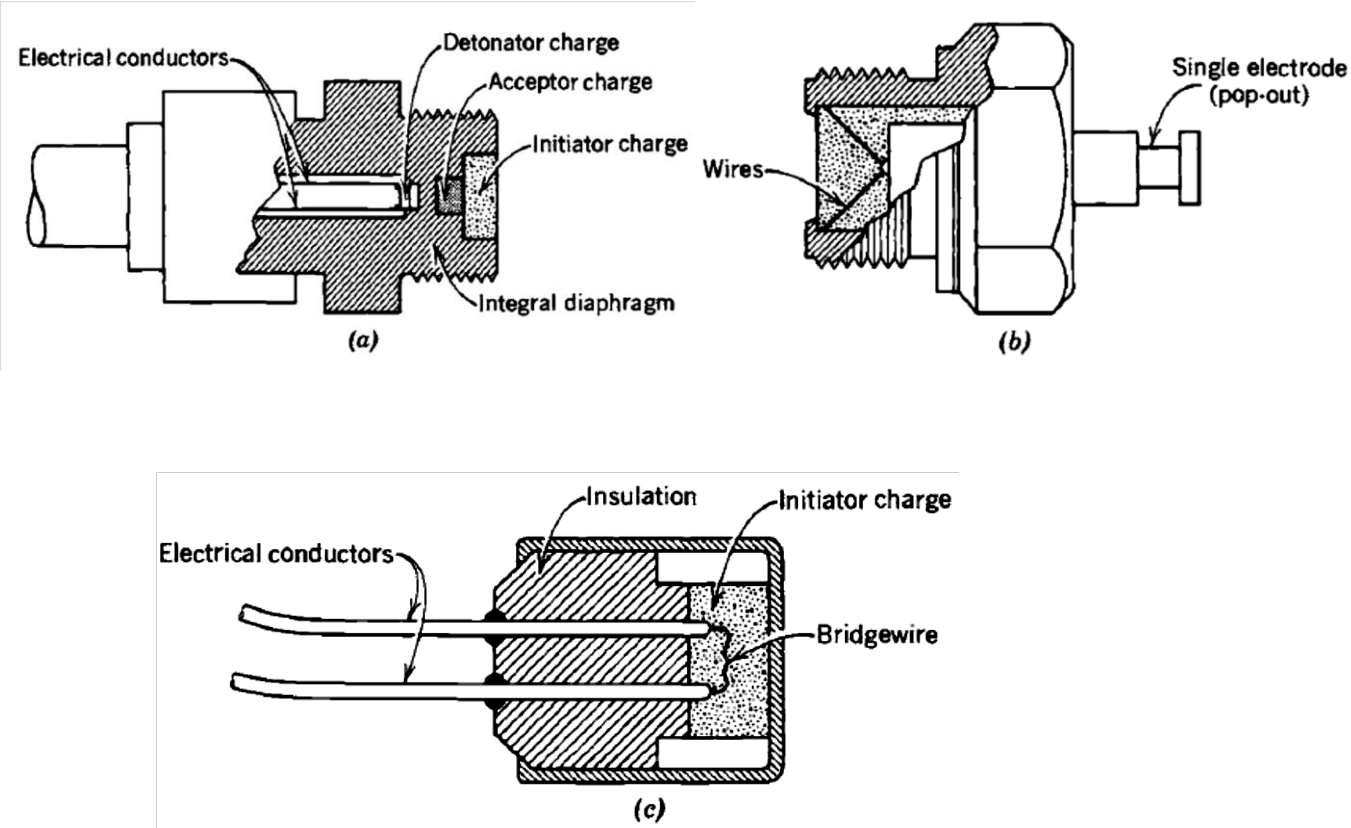


Figure 6 Typical electric initiators; (a) integral diaphragm type; (b) header type with double bridgewire; (c) exploding bridgewire type.

The safeguard aspect of the initiator appears as a basic design feature in theform of (1) minimum threshold electrical energy required for activation, (2)voltage blockage provisions (usually, air gaps or semiconductors in the electricalcircuit), or (3) responsiveness only to a specific energy pulse or frequencyband. Invariably, such safeguards compromise to some degree the safety providedby the classical safe and arm device.

A new method of initiating the action of an igniter is to use laser energy tostart the combustion of an initiator charge. Here there are no problems withinduced currents and other inadvertent electrical initiation. The energy from asmall neodymium/YAG laser, external to the motor, travels in fiber-optical glass cables to the pyrotechnic initiator charge. Sometimes anoptical window in the case or closure wall allows the initiator charge to beinside the case.

2.10Igniter design considerations

The basic theories of initiating ignition, heat transfer, propellant decomposition,deflagration, flame spreading, and chamber filling are common to thedesign and application of pyrotechnic and pyrogen igniters. In general, themathematical models of the physical and chemical processes that must beconsidered in the design of igniters are far from complete and accurate.

Analysis and design of igniters, regardless of the type, depend heavily onexperimental results, including past successes and failures with full-scalemotors. The effect of some of the important parameters has become quitepredictable, using data from developed motors. For example, Fig. 7isof benefit in estimating the mass of igniter main charge for motors of varioussizes (motor free volume). From these data,

$$m = 0.12(V_F)^{0.7}$$

where m is the igniter charge in grams and $V_F$is the motor free volume in cubicinches or the void in the case not occupied by propellant. A larger igniter massflow means a shorter ignition delay. The ignition time events were shown inFig. 7.

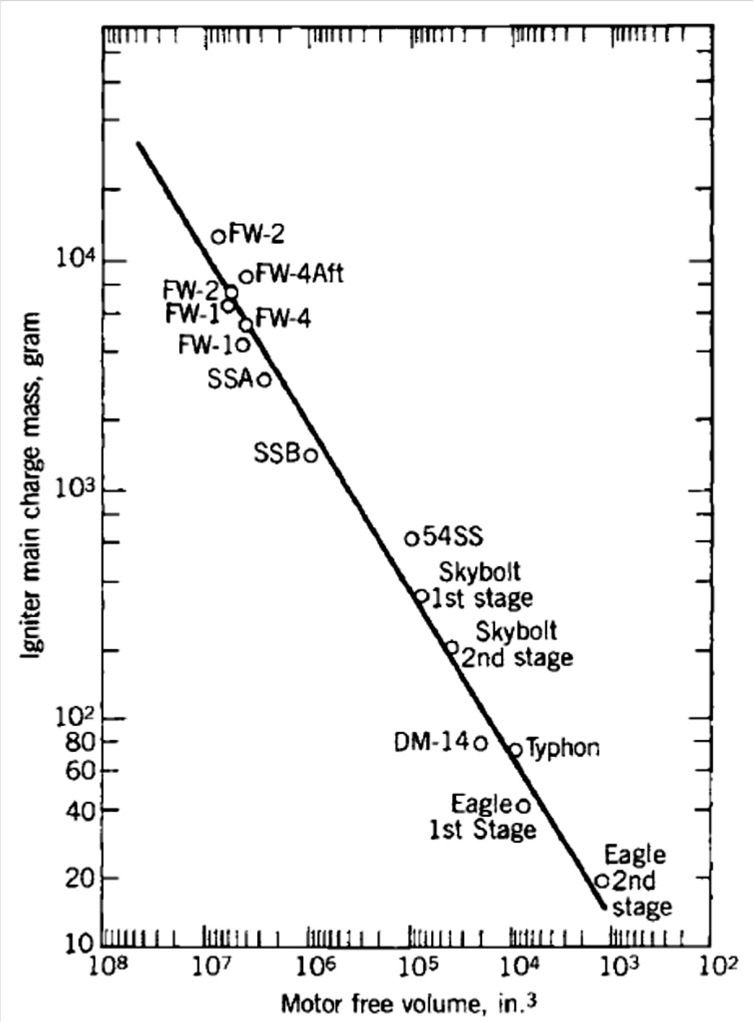


Figure 7 Igniter charge mass versus motor free volume, based on experience with various-sized rocket motors using AP/A1 composite propellant.

2.11Combustion System of Solid Rockets

The combustion in a solid propellant motor involves exceedingly complexreactions taking place in the solid, liquid, and gas phases of a heterogeneousmixture. Not only are the physical and chemical processes occurring duringsolid propellant combustion not fully understood, but the available analyticalCombustion models remain oversimplified and unreliable. Experimental observationsof burning propellants show complicated three-dimensional micro- structures, a three-dimensional flame structure, intermediate products in theliquid and gaseous phase, spatially and temporally variant processes, aluminumagglomeration, nonlinear response behavior, formation of carbon particles, andother complexities yet to be adequately reflected in mathematical models.

A typical flame for an AP/A1/HTPB* propellant looks very different, as seenin Fig. 9. Here the luminous flame seems to be attached to the burning surface, even at low pressures. There is no dark zone.

The flame structure appears to be one-dimensional. Theburning rate of this propellant decreases when the RDX percentage is increasedand seems to be almost unaffected by changes in RDX particle size. Muchwork has been done to characterize the burning behavior of different propellants.

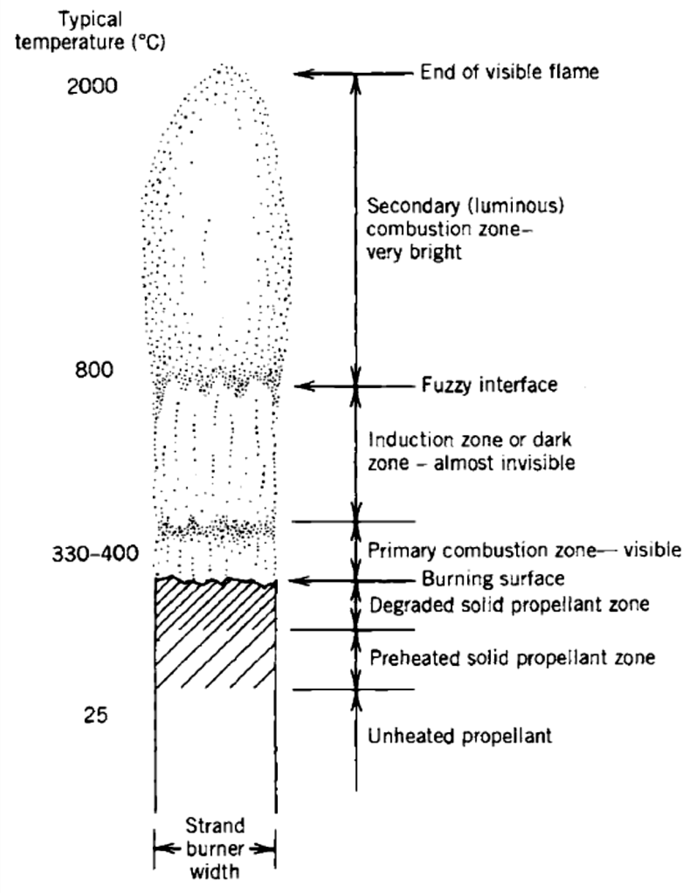


Figure 8 Schematic diagram of the combustion flame structure of a double-base propellant as seen with a strand burner in an inert atmosphere.

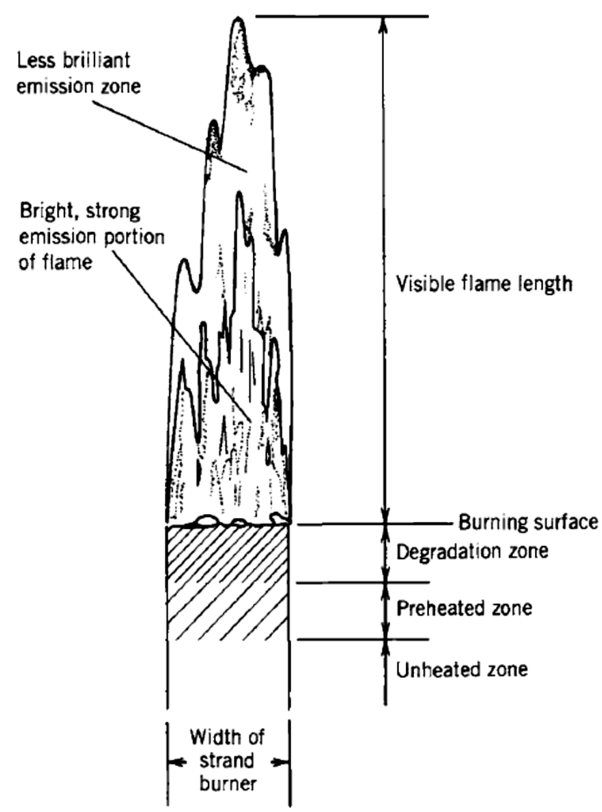


Figure 9 Diagram of the flickering, irregular combustion flame of a compositepropellant (69% AP, 19% A1, plus binder and additives) in a strand burner with aneutral atmosphere.

The burning rate of all propellants is influenced by pressure , the initial ambient solid propellant temperature, the burn ratecatalyst, the aluminum particle sizes and their size distribution, and to a lesserextent by other ingredients and manufacturing process variables.

Erosive burningis basically an accelerated combustion phenomenon stimulated byincreased heat transfer and erosion by local high velocities.

2.12 Propellants, Composition, Properties

Thousands of combinations of fuels and oxidizers have been tried over the years. Some of the more common and practical ones are:

Cryogenic

Liquid oxygen (LOX, O2) and liquid hydrogen (LH2, H2) – Space Shuttle main engines, Ariane 5 main stage and the Ariane 5 ECA second stage, the BE-3 of Blue Origin's New Shepard, the first and second stage of the Delta IV, the upper stages of the Ares I, Saturn V's second and third stages, Saturn IB, and Saturn I as well as Centaur rocket stage, the first stage and second stage of the H-II, H-IIA, H-IIB, and the upper stage of the GSLV.

Liquid oxygen (LOX) and liquid methane (CH4) – the in-development Raptor (SpaceX) and BE-4 (Blue Origin) engines.

Semi-cryogenic

- Liquid oxygen (LOX) and kerosene or RP-1 – Saturn V's first stage, Zenit rocket, R-7-derived vehicles including Soyuz, Delta, Saturn I, and Saturn IB first stages, Titan I and Atlas rockets, Falcon 1 and Falcon 9
- Liquid oxygen (LOX) and carbon monoxide (CO) – proposed for a Mars hopper vehicle (with a specific impulse of approximately 250 s), principally because carbon monoxide and oxygen can be straightforwardly produced by Zirconia electrolysis from the Martian atmosphere without requiring use of any of the Martian water resources to obtain Hydrogen.

Hypergolic

- T-Stoff (80% hydrogen peroxide, H_2O_2 as the oxidizer) and C-Stoff (methanol, CH_3OH, and hydrazine hydrate, $N_2H_4 \bullet n(H_2O)$ as the fuel) – used for the Hellmuth-Walter-WerkeHWK 109-509A, -B and -C engine family used on the Messerschmitt Me 163B Komet, an operational rocket fighter plane of World War II, and Ba 349 *Natter* manned VTO interceptor prototypes.
- Nitric acid (HNO_3) and kerosene – Soviet BI-1 and MiG I-270 rocket fighter prototypes, Scud-A, aka SS-1 SRBM

Liquid rockets have been built as monopropellant rockets using a single type of propellant, bipropellant rockets using two types of propellant, or more exotic tripropellant rockets using three types of propellant.

Bipropellant liquid rockets generally use a liquid fuel, such as liquid hydrogen or a hydrocarbon fuel such as RP-1, and a liquid oxidizer, such as liquid oxygen. The engine may be a cryogenic rocket engine, where the fuel and oxidizer, such as hydrogen and oxygen, are gases which have been liquefied at very low temperatures.

Liquid-propellant rockets can be throttled (thrust varied) in realtime, and have control of mixture ratio (ratio at which oxidizer and fuel are mixed); they can also be shut down, and, with a suitable ignition system or self-igniting propellant, restarted.

Liquid propellants are also sometimes used in hybrid rockets, in which a liquid oxidizer is combined with a solid fuel.

2.13Injector

The functions of the injector are similar to those of a carburetor of an internalcombustion engine. The injector has to introduce and meter the flow of liquidpropellants to the combustion chamber, cause the liquids to be broken up intosmall droplets (a process called atomization), and distribute and mix the propellantsin such a manner that a correctly proportioned mixture of fuel andoxidizer will result, with uniform propellant mass flow and composition overthe chamber cross section. This has been accomplished with different typesofinjector designs and elements; several common types are shown in Fig. 1andcomplete injectors are shown in Fig. 2.

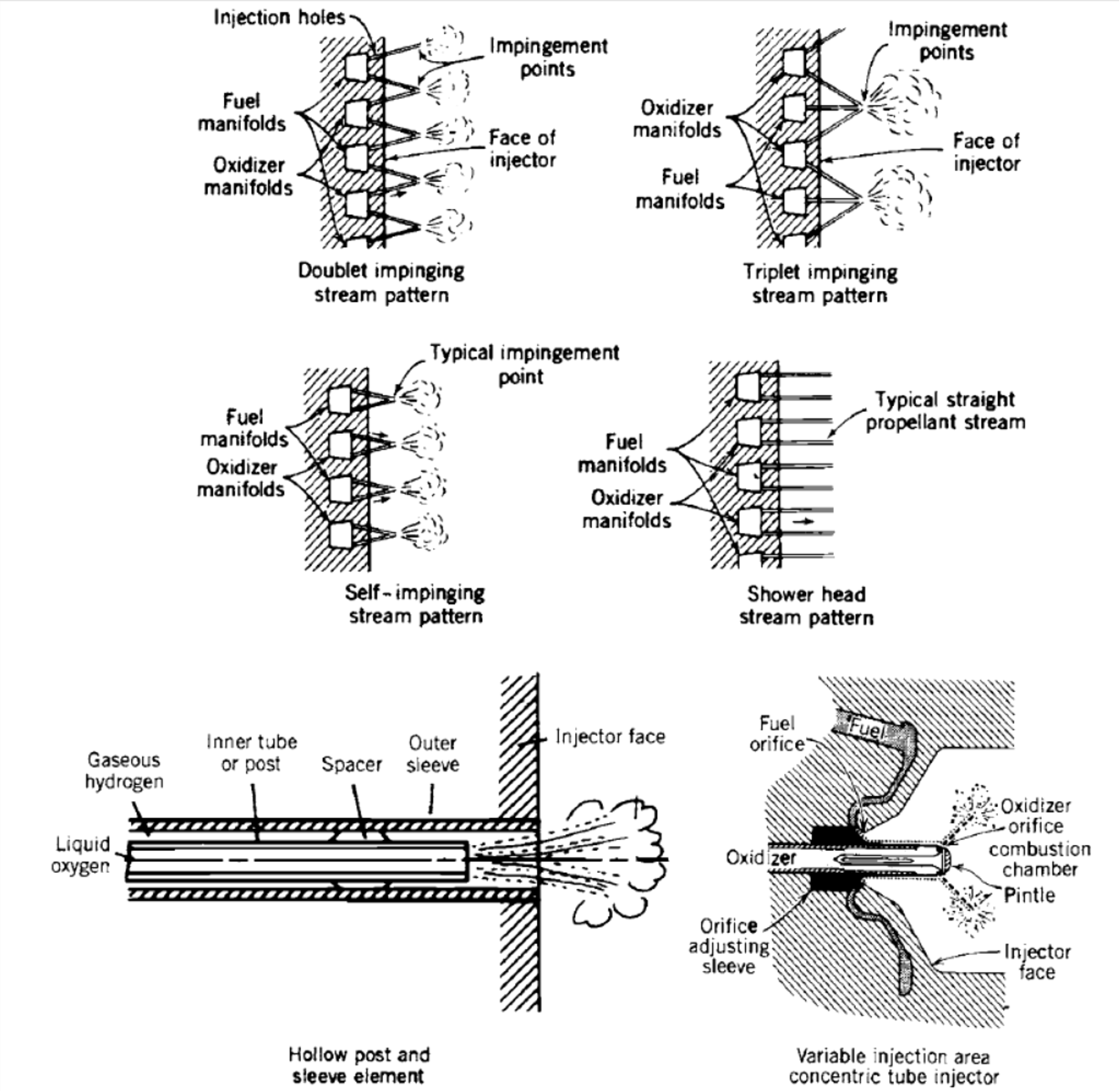


Figure 3 Schematic diagrams of several injector types. The movable sleeve type variable thrust injector

The SSME injector uses 600 concentric sleeveinjection elements; 75 of them have been lengthened beyond the injector face toform cooled baffles, which reduce the incidence of combustion instability.

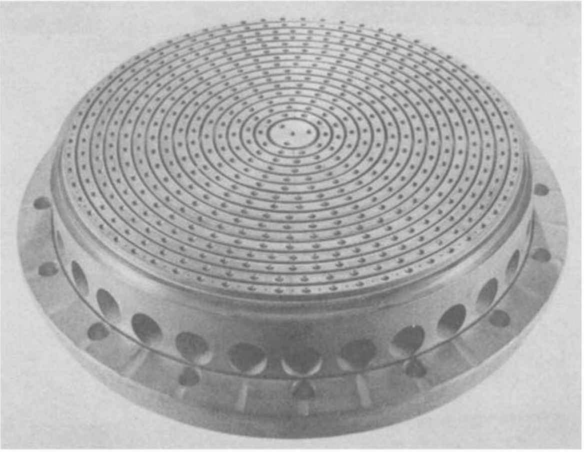


Figure 4 Injector with 90° self-impinging (fuel-against-fuel and oxidizer-againstoxidizer)-type countersunk doublet injection pattern. Large holes are inlets to fuelmanifolds. Pre-drilled rings are brazed alternately over an annular fuel manifold orgroove and a similar adjacent oxidizer manifold or groove.

The original method of making injection holes was to carefully drill them andround out or chamfer their inlets. This is still being done today. It is difficult toalign these holes accurately (for good impingement) and to avoid burrs andsurface irregularities. One method that avoids these problems and allows a largenumber of small accurate injecton orifices is to use multiple etched, very thinplates (often called platelets) that are then stacked and diffusion bondedtogether to form a monolithic structure as shown in Fig. 3. The photo-etchedpattern on each of the individual plates or metal sheets then provides not onlyfor many small injection orifices at the injector face, but also for internal distributionor flow passages in the injector and sometimes also for a fine-meshfilter inside the injector body. The platelets can be stacked parallel to or normalto the injector face. The finished injector has been called the platelet injector andhas been patented by the Aerojet Propulsion Company.

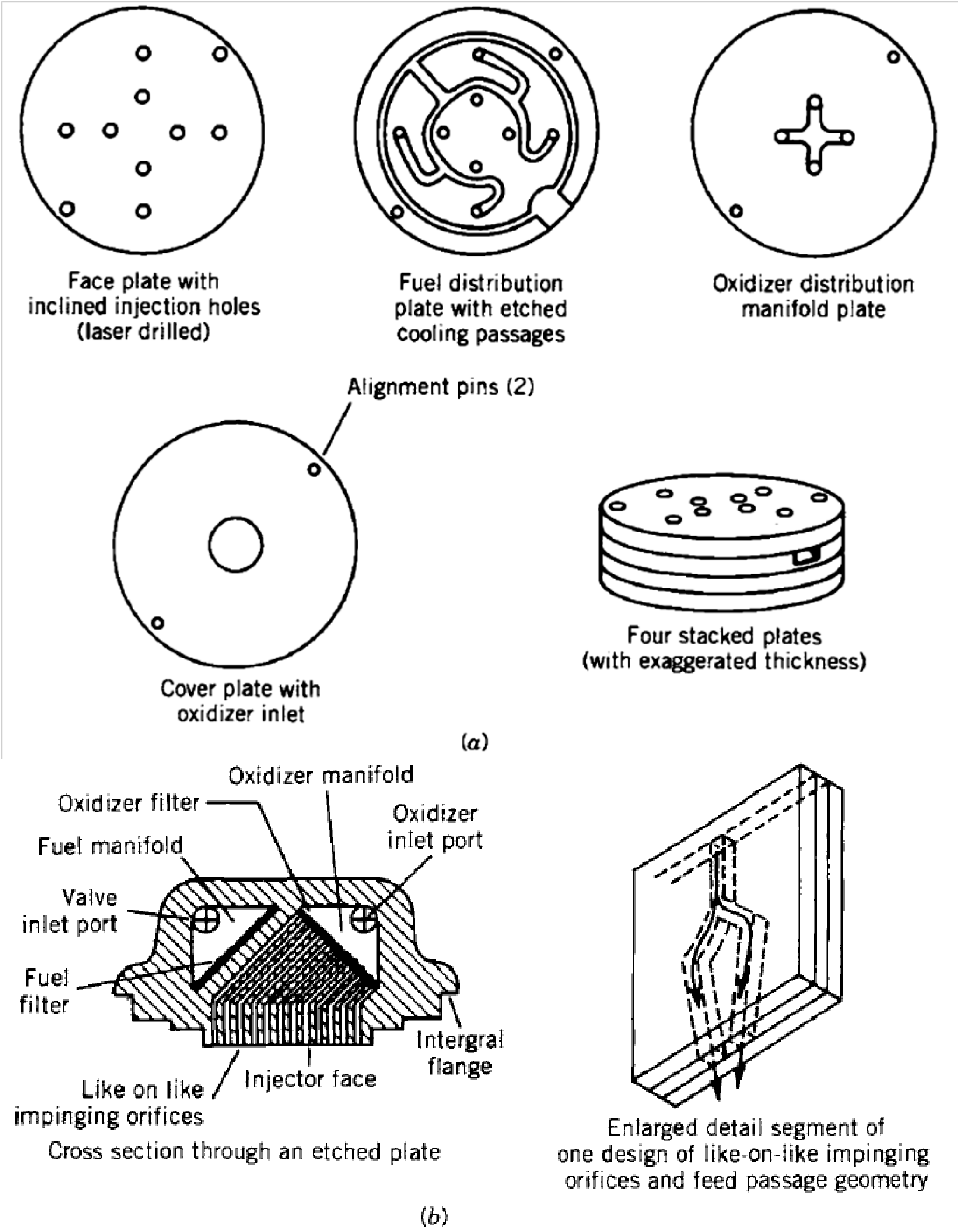


Figure 5 Simplified diagrams of two types of injector using a bonded platelet construction technique: (a) injector for low thrust with four impinging unlike doubletliquid streams; the individual plates are parallel to the injector face; (b) Like-on-likeimpinging stream injector with 144 orifices; plates are perpendicular to the injector face.

2.14Propellant Feed Systems

The propellant feed system has two principal functions: to raise the pressure ofthe propellants and to feed them to one or more thrust chambers. The energyfor these functions comes either from a high-pressure gas, centrifugal pumps,or a combination of the two. The selection of a particular feed system and itscomponents is governed primarily by the application of the rocket, duration, number or type ofthrust chambers, past experience, mission, and by general requirements ofsimplicity of design, ease of manufacture, low cost, and minimum inert mass.A classification of several of the more important types of feed system is shownin Fig. 4 and some are discussed in more detail below. All feed systems havepiping, a series of valves, provisions for filling and removing (draining andflushing) the liquid propellants, and control devices to initiate, stop, and regulatetheir flow and operation.

2.14.1Propellant Feed Lines &Valves

Valves control the flows of liquids and gases and pipes conduct these fluids tothe intended components. There are no rocket engines without them. There aremany different types of valves. All have to be reliable, lightweight, leakproof,and must withstand intensive vibrations and very loud noises. Table 1givesseveral key classification categories for rocket engine valves. Any one enginewill use only some of the valves listed here.The art of designing and making valves is based, to a large extent, onexperience. Often the design details, such as clearance, seat materials, oropening time delay present development difficulties. With many of these valves,any leakage or valve failure can cause a failure of the rocket unit itself. Allvalves are tested for two qualities prior to installation; they are tested forleaks--through the seat and also through the glands--and for functionalsoundness or performance.

The propellant valves in high thrust units handle relatively large flows at high service pressures. Therefore, the forces necessary to actuate the valves are large. Hydraulic or pneumatic pressure, controlled by pilot valves, operates the larger valves; these pilot valves are in turn actuated by asolenoid or a mechanical linkage. Essentially this is a means of power boost.

Two valves commonly used in pressurized feed systems are *isolationvalves*(when shut, they isolate or shut off a portion of the propulsionsystem) and *latch valves;* they require power for brief periods during movements,such as to open or shut, but need no power when latched orfastened into position.

A very simple and very light valve is a *burst diaphragm.* It is essentially acircular disk of material which blocks a pipeline and is designed so that it willfail and burst at a predetermined pressure differential. Burst diaphragms arepositive seals and prevent leakage, but they can be used only once. The
German *Wasserfall*antiaircraft missile used four burst disks; two were inhigh pressure air lines and two were in the propellant lines.Figure 5 shows a main liquid oxygen valve. It is normally closed, rotary
actuated, cryogenic, high pressure, high flow, reusable ball valve, allowingcontinuousthrotting, a controlled rate of opening through a crank and hydraulicpiston (not shown), with a position feedback and anti-icing controls.

Pressure regulators are special valves which are used frequently to regulategas pressures. Usually the discharge pressure is regulated to a predeterminedstandard pressure value by continuously throttling the flow, using a piston,flexible diaphragm, or electromagnet as the actuating mechanism.

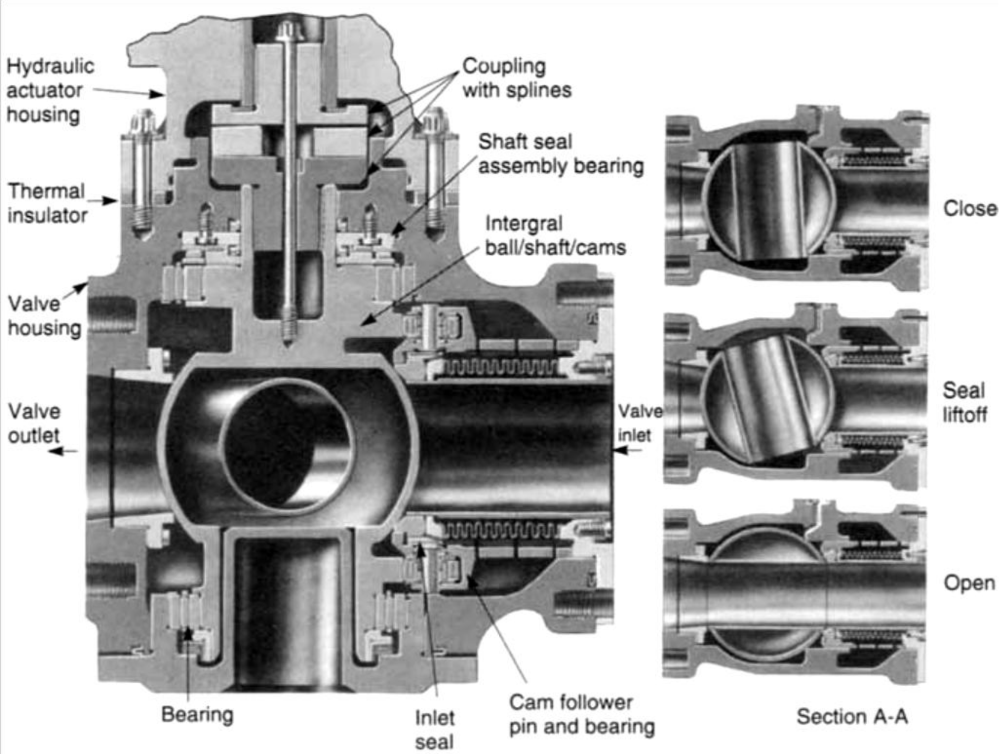


Figure 6 The SSME main oxidizer valve is a low-pressure drop ball valve representative of high-pressure large valves used in rocket engines. The ball and its integralshaft rotate in two bearings. The seal is a machined plastic ring spring-loaded by abellows against the inlet side of the ball. Two cams on the shaft lift the seal a shortdistance off the ball within the first few degrees of ball rotation. The ball is rotated by aprecision hydraulic actuator (not shown) through an insulating coupling.

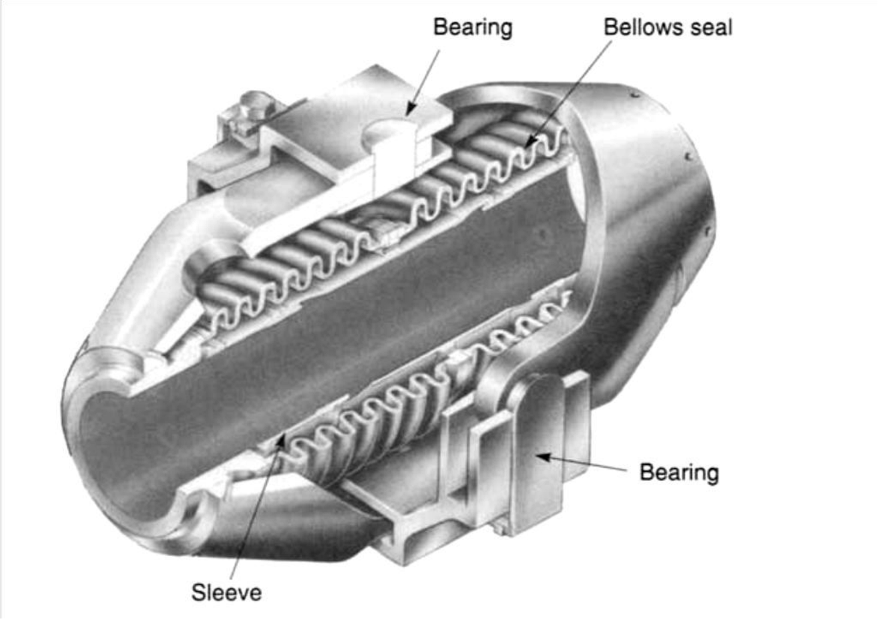


Figure 7 Flexible high-pressure joint with external gimbal rings for a high-pressurehot turbine exhaust gas.

2.14.2 Turbine feed systems

The basic operational principle for a turbine is to remove energy from a fluid by a transfer ofangular momentum between the fluid and rotating element. The changes in angular momentum require changes in tangential velocity. The turbine consists of stationary and rotating elements as shown in Figure 7. The rotating blades on a turbine disk decrease the fluid tangential velocity while the stationary blades increase the fluid tangential velocity. Two types of energy conversions explain the turbine flow process: 1) expansion process where the pressure is converted to the velocity and 2) potential energy converted to the kinetic energy and thus to the shaft power.

The turbine requirements are defined by the selected engine power cycle. The engine power balance provides the turbine-drive gas type, flow rate, inlet temperature, inlet pressure, and pressure ratio across the turbine. Once the turbine requirements have been determined and the pump horsepower requirements are known, the turbine design and sizing analysis can begin. A generalized approach for turbine design can listed as follows. First, the hot gas supply properties (e.g. inlet temperature, specific heat, and specific heat ratio) are determined. Second, the isentropic spouting velocity C_o and turbine disk size/pitch velocity are calculated. Third, the type of turbine for achieving the optimal turbine efficiency is determined. Fourth, the pump requirements are balanced. Fifth, the turbine design parameters are compared with engine power balance predictions. The turbine design process is a highly iterative process in order to satisfy the engine requirements as well as satisfy the turbine performance, materials, stress, and dynamic requirements.

2.17 Propellant slosh

In fluid dynamics, **slosh** refers to the movement of liquid inside another object (which is, typically, also undergoing motion). Strictly speaking, the liquid must have a free surface to constitute a **slosh dynamics** problem, where the dynamics of the liquid can interact with the container to alter the system dynamics significantly. Important examples include propellant slosh in spacecraft tanks and rockets (especially upper stages), and cargo slosh in ships and trucks transporting liquids (for example oil and gasoline). However, it has become common to refer to liquid motion in a completely filled tank, i.e. without a free surface, as "fuel slosh". Such motion is characterized by "inertial waves" and can be an important effect in spinning spacecraft dynamics. Extensive mathematical and empirical relationships have been derived to describe liquid slosh. These types of analyses are typically undertaken using computational fluid dynamics and finite element methods to solve the fluid-structure interaction problem, especially if the solid container is flexible. Relevant fluid dynamics non-dimensional parameters include the Bond number, the Weber number, and the Reynolds number.

Slosh is an important effect for spacecraft, ships, and some aircraft. Slosh was a factor in the recent Falcon 1 second test flight anomaly, and has been implicated in various other spacecraft anomalies, including a near-disaster with the Near Earth Asteroid Rendezvous (NEAR Shoemaker) satellite.

2.18 Spacecraft effects

Liquid slosh in microgravity is relevant to spacecraft, most commonly Earth-orbiting satellites, and must take account of liquid surface tension which can alter the shape (and thus the eigenvalues) of the liquid slug. Typically, a large part of the mass fraction of a satellite is liquid propellant at/near Beginning of Life (BOL), and slosh can adversely affect satellite performance in a number of ways. For example, propellant slosh can introduce uncertainty in spacecraft attitude (pointing) which is often called jitter. Similar phenomena can cause pogo oscillation and can result in structural failure of space vehicle.Another example is problematic interaction with the spacecraft Attitude Control System (ACS), especially for spinning satellites which can suffer resonance between slosh and nutation, or adverse changes to the rotational inertia.

2.19 Practical effects

Sloshing or shifting cargo, water ballast, or other liquid (e.g. from leaks or firefighting) can cause disastrous capsizing in ships due to free surface effect; this can also affect trucks and aircraft.

The effect of slosh is used to limit the bounce of a roller hockey ball. Water slosh can significantly reduce the rebound height of a ball but some amounts of liquid seem to lead to a resonance effect. Many of the balls for roller hockey commonly available contain water to reduce the bounce height.

Shortly after it reached orbit in August 1969, NASA’s spin-stabilized Applications Technology Satellite 5 (ATS5) began to wobble, sending the spacecraft into an unplanned flat spin and crippling the mission. It was later found that this event was caused by excessive fuel slosh, creating a long-standing concern about this phenomenon.

Spinning is a well-established method for stabilizing a spacecraft or launch vehicle upper stage with a minimum of hardware, complexity, and expense. Fuel slosh reduces the rotational kinetic energy of a spinning space vehicle, however, leading to a growing *nutation* (wobble) that can undermine its gyroscopic stability. As the ATS5 mission demonstrated, failure to understand the effect of fuel slosh can have serious consequences.

2.20 Propellant Tanks

In liquid bipropellant rocket engine systems propellants are stored in one ormore oxidizer tanks and one or more fuel tanks; monopropellant rocket enginesystems have, of course, only one set of propellant tanks. There are also one ormore high-pressure gas tanks, the gas being used to pressurize the propellanttanks. Tanks can be arranged in a variety of ways, and the tank design can beused to exercise some control over the change in the location of the vehicle'scenter of gravity. Typical arrangements are shown in Fig. 9. Because thepropellant tank has to fly, its mass is at a premium and the tank material istherefore highly stressed. Common tank materials are aluminum, stainlesssteel, titanium, alloy steel, and fiber-reinforced plastics with an imperviousthin inner liner of metal to prevent leakage through the pores of the fiberreinforcedwalls.

There are several categories of tanks in liquid propellant propulsion systems:

1. For pressurized feed systems the propellant tanks typically operate at anaverage pressure between 1.3 and 9 MPa or about 200 to 1800 lbf/in. 2.These tanks have thick walls and are heavy.

2. For high-pressure gas (used to expel the propellants) the tank pressuresare much higher, typically between 6.9 and 69 MPaor 1000 to 10,000 lbf/in^2. These tanks are usually spherical for minimum inert mass. Severalsmall spherical tanks can be connected together and then they are relativelyeasy to place within the confined space of a vehicle.

3. For turbo-pump feed systems it is necessary to pressurize the propellanttanks slightly (to suppress pump cavitation as explained in Section 10.1)to average values of between 0.07 and 0.34 MPa or 10 to 50 lbf/in 2. Theselow pressures allow thin tank walls, and therefore turbopump feed systemshave relatively low tank weights.

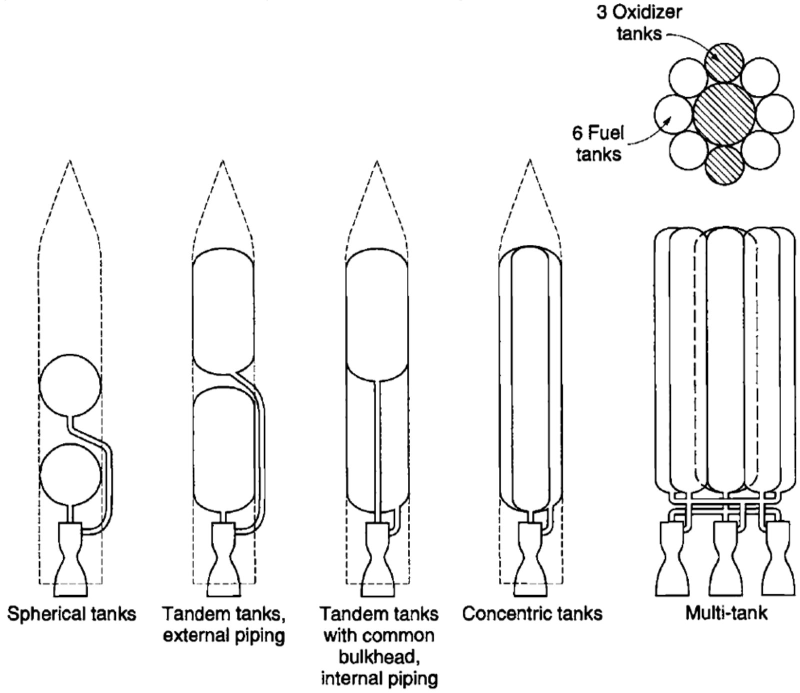


Figure 8 Typical tank arrangements for large turbopump-fed liquid propellant rocket engines.

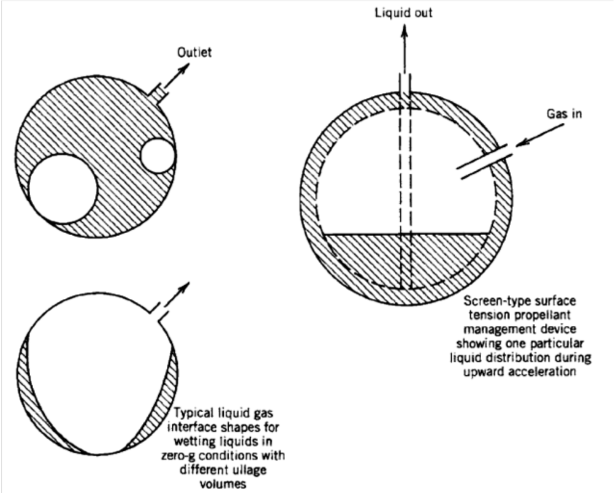


Figure 10 Ullage bubbles can float around in a zero-gravity environment; surface tension device can keep tank outlet covered with liquid.

Liquid propellant tanks can be difficult to empty under side accelerations, zerog,or negative-g conditions during flight. Special devices and special types oftanks are needed to operate under these conditions. Some of the effects that have to be overcome are described below.

Separation is needed for these reasons:

1. It prevents pressurizing gas from dissolving in the propellant. Dissolved pressurizing gas dilutes the propellant, reduces its density as well as itsspecific impulse, and makes the pressurization inefficient.
2. It allows hot and reactive gases (generated by gas generators) to be used for pressurization, and this permits a reduction in pressurizing system mass and volume. The mechanical separation prevents a chemical reactionbetween the hot gas and the propellant, prevents gas from beingdissolved in the propellant, and reduces the heat transfer to the liquid.
3. In some cases tanks containing toxic propellant must be vented without spilling any toxic liquid propellant or its vapor. For example, in servicing a reusable rocket, the tank pressure needs to be relieved without venting or spilling potentially hazardous material.

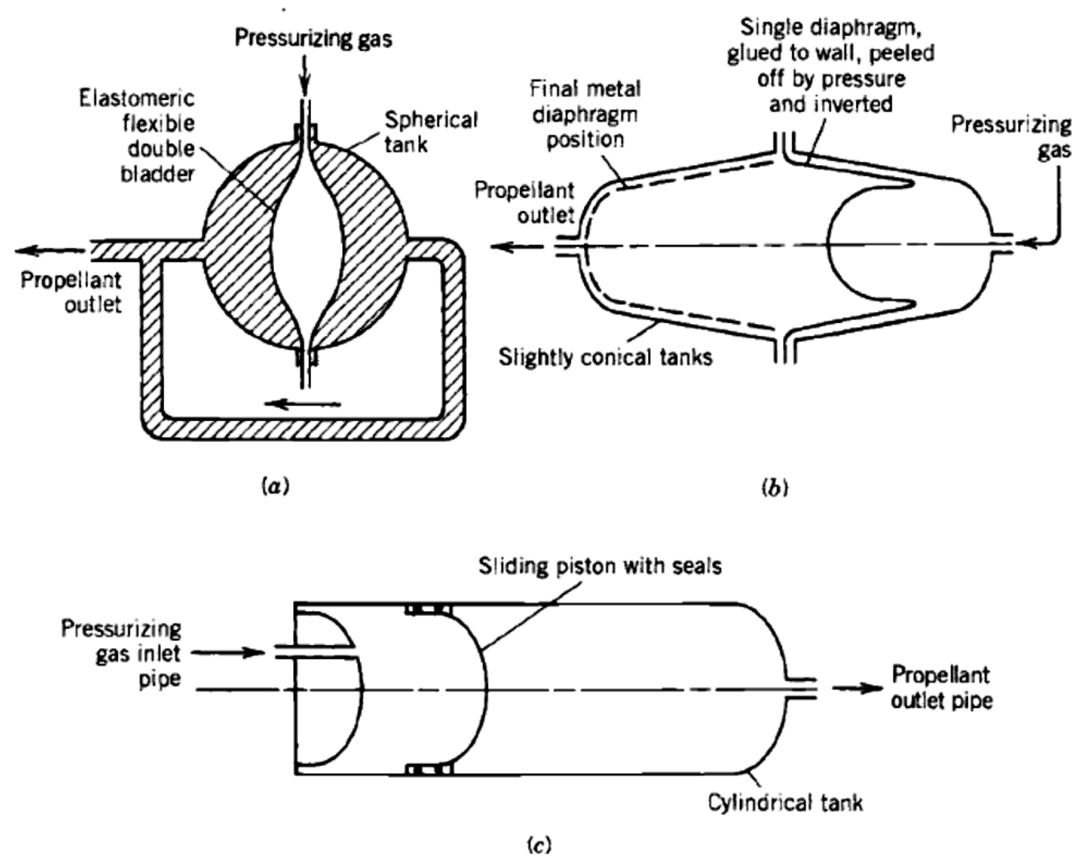


Figure 11 Three concepts of propellant tanks with positive expulsion: (a) inflatabledual bladder; (b) rolling, peeling diaphragm; (c) sliding piston. As the propellant volumeexpands or contracts with changes in ambient temperature, the piston or diaphragm willalso move slightly and the ullage volume will change during storage.

UNIT-III
AERODYNAMICSOFROCKETSANDMISSILES

3.1 Introduction

Aerodynamics of Missiles dynamics with slender bodies having different taper ratios and the geometric profiles to and the trajectory types will be discussed in this unit.

3.1.1 On the basis of Type:

(i) Cruise Missile: A cruise missile is an unmanned self-propelled (till the time of impact) guided vehicle that sustains flight through aerodynamic lift for most of its flight path and whose primary mission is to place an ordnance or special payload on a target. They fly within the earth's atmosphere and use jet engine technology. These vehicles vary greatly in their speed and ability to penetrate defences.Cruise missiles can be categorised by size, speed (subsonic or supersonic), range and whether launched from land, air, surface ship or submarine.

Depending upon the speed such missiles are classified as:

1) Subsonic cruise missile

2) Supersonic cruise missile

3) Hypersonic cruise missile

Subsonic cruise missile flies at a speed lesser than that of sound. It travels at a speed of around 0.8 Mach. The well-known subsonic missile is the American Tomahawk cruise missile. Some other examples are Harpoon of USA and Exocet of France.

Figure 1. Subsonic and Supersonic Cruise Missiles

Supersonic cruise missile travels at a speed of around 2-3 Mach i.e.; it travels a kilometre approximately in a second. The modular design of the missile and its capability of being launched at different orientations enable it to be integrated with a wide spectrum of platforms like warships, submarines, different types of aircraft, mobile autonomous launchers and silos. The combination of supersonic speed and warhead mass provides high kinetic energy ensuring tremendous lethal effect. BRAHMOS is the only known versatile supersonic cruise missile system which is in service.

Hypersonic cruise missile travels at a speed of more than 5 Mach. Many countries are working to develop hypersonic cruise missiles. BrahMos Aerospace is also in the process of developing a hypersonic cruise missile, BRAHMOS-II, which would fly at a speed greater than 5 Mach.

(ii) Ballistic Missile: A ballistic missile is a missile that has a ballistic trajectory over most of its flight path, regardless of whether or not it is a weapon-delivery vehicle. Ballistic missiles are categorised according to their range, maximum distance measured along the surface of earth's ellipsoid from the point of launch to the point of impact of the last element of their payload. The missile carry a huge payload. The carriage of a deadly warhead is justified by the distance the missile travels. Ballistic missiles can be launched from ships and land based facilities. For example, Prithvi I, Prithvi II, Agni I, Agni II and Dhanush ballistic missiles are currently operational in the Indian defence forces.

3.2 Components of Rockets and Missiles

Airframe
o Flight Control System
o Guidance System
oFuzeo Warhead
o Propulsion System

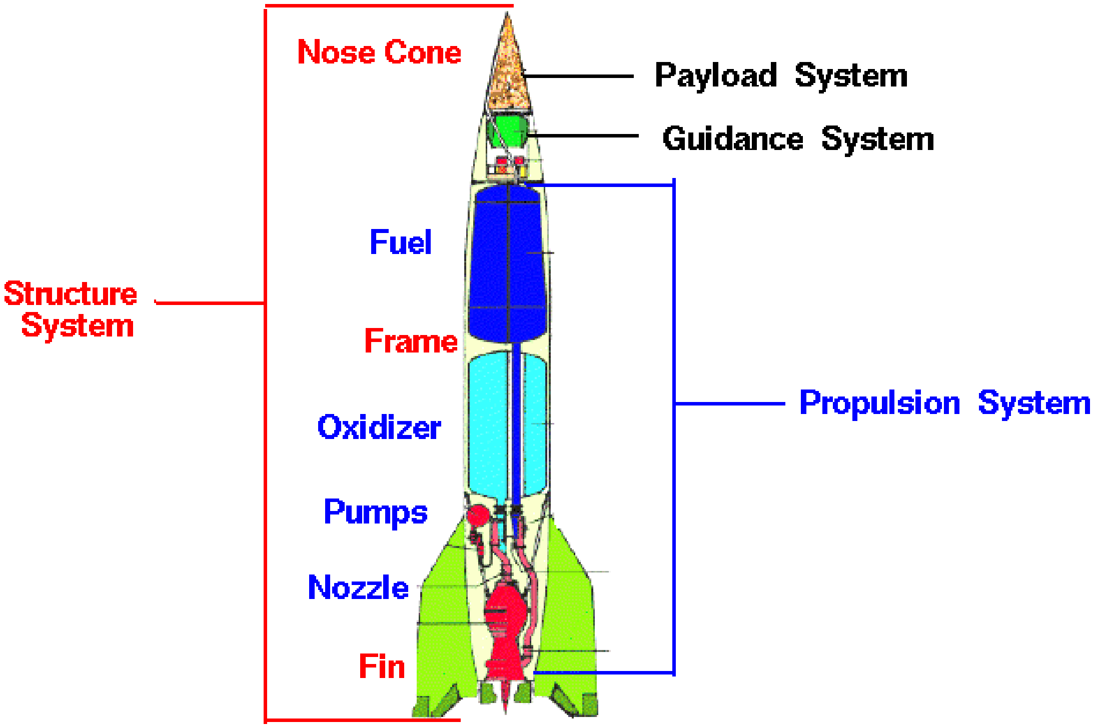


Fig. 2 Components of a missile

The study of rockets is an excellent way for students to learn the basics of forces and the response of an object to external forces. In flight, a rocket is subjected to the forces of weight, thrust, and aerodynamics. On this slide, we have removed the outer "skin" so that we can see the parts that make a rocket. There are many parts that make up a rocket. For design and analysis, engineers group parts which have the same function into systems. There are four major systems in a full scale rocket; the structural system, the payload system, the guidance system, and the propulsion system.

The structural system, or frame, is similar to the fuselage of an airplane. The frame is made from very strong but lightweight materials, like titanium or aluminum, and usually employs long "stringers" which run from the top to the bottom which are connected to "hoops" which run around around the circumference. The "skin" is then attached to the stringers and hoops to form the basic shape of the rocket. The skin may be coated with a thermal protection system to keep out the heat of air friction during flight and to keep in the cold temperatures needed for certain fuels and oxidizers. Fins are attached to some rockets at the bottom of the frame to provide stability during the flight.

The payload system of a rocket depends on the rocket's mission. The earliest payloads on rockets were fireworks for celebrating holidays. The payload of the German V2, shown in the figure, was several thousand pounds of explosives. Following World War II, many countries developed guided ballistic missiles armed with nuclear warheads for payloads. The same rockets were modified to launch satellites with a wide range of missions; communications, weather monitoring, spying, planetary exploration, and observatories, like the Hubble Space Telescope. Special rockets were developed to launch people into earth orbit and onto the surface of the Moon.

The guidance system of a rocket may include very sophisticated sensors, on-board computers, radars, and communication equipment to maneuver the rocket in flight. Many different methods have been developed to control rockets in flight. The V2 guidance system included small vanes in the exhaust of the nozzle to deflect the thrust from the engine. Modern rockets typically rotate the nozzle to maneuver the rocket. The guidance system must also provide some level of stability so that the rocket does not tumble in flight.

As you can see on the figure, most of a full scale rocket is propulsion system. There are two main classes of propulsion systems, liquid rocket engines and solid rocket engines. The V2 used a liquid rocket engine consisting of fuel and oxidizer (propellant) tanks, pumps, a combustion chamber with nozzle, and the associated plumbing. The Space Shuttle, Delta II, and Titan III all use solid rocket strap-ons.

The various rocket parts described above have been grouped by function into structure, payload, guidance, and propulsion systems. There are other possible groupings. For the purpose of weight determination and flight performance, engineers often group the payload, structure, propulsion structure (nozzle, pumps, tanks, etc.), and guidance into a single empty weight paramter. The remaining propellant weight then becomes the only factor that changes with time when determining rocket performance.

3.3 Forces on a Rocket

In order to understand the behaviour of rockets it is necessary to have a basic grounding in physics, in particular some of the principles of statics and dynamics. This section considers the forces acting on a rocket, and how they affect its performance. In particular, the section looks at the linear and rotational behaviour of a rocket. Forces Newton's second law leads to the well-known equation:

Force = mass x acceleration Expressed mathematically it can take one of several equivalent forms: 2 2 dt d r m dt dv F = ma = m = Most basic text books leave the concept of force at this point, possibly illustrating the idea of acceleration as being a change of velocity over time.

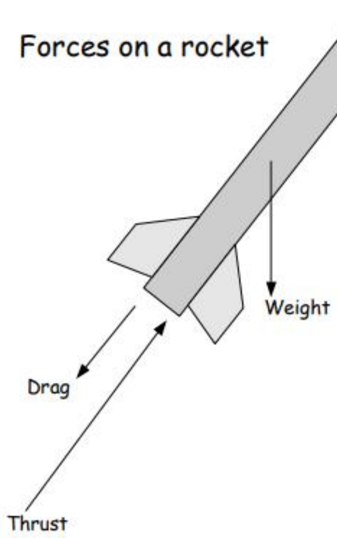


Fig. 3 Forces acting on a rocket body

The conventional view of a model rocket is to consider three forces acting on a rocket: thrust, drag and weight. Weight Drag Thrust Forces on a rocket. The forces on a rocket vary throughout the flight. At a basic level the weight reduces as propellant is consumed, the thrust changes depending on the burn profile, and drag increases with the square of the velocity. Most model rocket flights take place within a few thousand meters of the Earth, however in higher altitude flights other "constants" start to change. Air density, used to calculate drag, changes with temperature and hence with altitude. Even gravity reduces slightly as a rocket moves away from the Earth. Our Newton's second law equation starts to look complex as it contains nothing which is constant.

3.4 Methods of describing aerodynamic forces and moments

The study of rockets is an excellent way for students to learn the basics of forces and the response of an object to external forces. The motion of an object in response to an external force was first accurately described over 300 years ago by Sir Isaac Newton, using his three laws of motion. Engineers still use Newton's laws to design and predict the flight of full scale rockets.

Forces are vector quantities having both a magnitude and a direction. When describing the action of forces, one mustaccount for both the magnitude and the direction. In flight, a rocket is subjected to four forces; weight, thrust, and theaerodynamic forces, lift and drag. The magnitude of the weight depends on the mass of all of the parts of the rocket. The weight force is always directed towards the center of the earth and acts through the center of gravity, the yellow dot on the figure. The magnitude of the thrust depends on the mass flow rate through the engine and the velocity and pressure at the exit of the nozzle. The thrust force normally acts along the longitudinal axis of the rocket and therefore acts through the center of gravity. Some full scale rockets can move, or gimbal, their nozzles to produce a force which is not aligned with the center of gravity. The resulting torque about the center of gravity can be used to maneuver the rocket. The magnitude of the aerodynamic forces depends on the shape, size, and velocity of the rocket and on properties of the atmosphere. The aerodynamic forces act through the center of pressure, the black and yellow dot on the figure. Aerodynamic forces are very important for model rockets, but may not be as important for full scale rockets, depending on the mission of the rocket. Full scale boosters usually spend only a short amount of time in the atmosphere.

In flight the magnitude, and sometimes the direction, of the four forces is constantly changing. The response of the rocket depends on the relative magnitude and direction of the forces, much like the motion of the rope in a "tug-of-war" contest. If we add up the forces, being careful to account for the direction, we obtain a net external force on the rocket. The resulting motion of the rocket is described by Newton's laws of motion.

Although the same four forces act on a rocket as on an airplane, there are some important differences in the application of the forces:

1. On an airplane, the lift force (the aerodynamic force perpendicular to the flight direction) is used to overcome the weight. On a rocket, thrust is used in opposition to weight. On many rockets, lift is used to stabilize and control the direction of flight.
2. On an airplane, most of the aerodynamic forces are generated by the wings and the tail surfaces. For a rocket, the aerodynamic forces are generated by the fins, nose cone, and body tube. For both airplane and rocket, the aerodynamic forces act through the center of pressure (the yellow dot with the black center on the figure) while the weight acts through the center of gravity (the yellow dot on the figure).
3. While most airplanes have a high lift to drag ratio, the drag of a rocket is usually much greater than the lift.
4. While the magnitude and direction of the forces remain fairly constant for an airplane, the magnitude and direction of the forces acting on a rocket change dramatically during a typical flight.

3.5 Lateral/Directional Stability Derivatives

In this chapter we will be concerned with methods for predicting the streamline directions behind a lifting surface, alone or in combination with a body. This knowledge is necessary for the determination of the aerodynamic characteristics of any aerodynamic shape, such as a -tail, immersed in the flow. For this purpose the direction of the streamlines

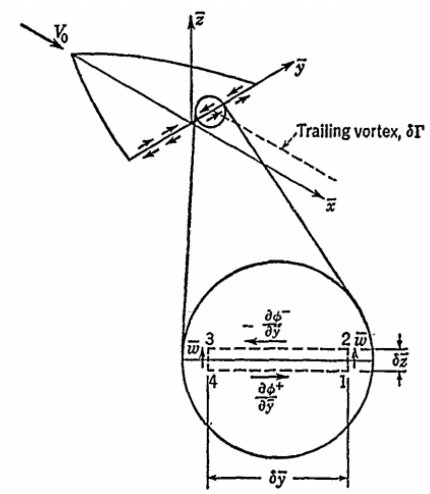


Fig.4 Wind Axes and side wash at the Trailing edge of the wing

will be specified with respect to the system of wind axes shown in Fig. 6-1. Let the components of the streamline velocity V with respect to the missile be $\bar{u}$, $\bar{v}$, and $\bar{w}$ along the positive axes of $\bar{x}$, $\bar{y}$, and $\bar{z}$, respectively. Then the downwash angle ε and the side-wash angle σ are defined to be

$$\epsilon = -\arctan\frac{\bar{w}}{\bar{u}} \approx \frac{-\bar{w}}{V}$$

$$\sigma = \arcsin\frac{\bar{v}}{V} \approx \frac{\bar{v}}{V}$$

Body-upwash and downwash in missiles. Rocket dispersion, re-entry body design considerations

3.6 Lift and Drag Forces, Drag Estimation

3.6.1 Aerodynamic Lift

$$C_L = \frac{L}{qA}$$

Lift coefficient is a dimensionless, area and dynamic pressure normalized form of lift

- For aircraft the area "A" used is the wing wetted area

- For wingless missiles or space launch vehicles it is customary to use the cross-section area of the vehicle body

- Lift coefficient will depend on

3.6.2 Aerodynamic Drag

$$C_D = \frac{D}{qA}$$

Just as with the lift coefficient:

- Lift coefficient is a dimensionless, area and dynamic pressure normalized form of lift

- For aircraft the area “” used is the wing wetted area

- For wingless missiles or space launch vehicles it is customary to use the cross-section area of the vehicle body

- Drag coefficient will depend on

Just as with the lift coefficient:

- Lift coefficient is a dimensionless, area and dynamic pressure normalized form of lift

- For aircraft the area “A” used is the wing wetted area

- For wingless missiles or space launch vehicles it is customary to use the cross-section area of the vehicle body

3.7 DRAG ESTIMATION

A procedure for estimating the drag co-efficient of rockets and artillery projectiles, with or without fins, is stated briefly. It is based partly on theory, partly on empirical data. Since the effect of yaw is neglected, the results apply only to small yaws.

The drag coefficient C_D- is assumed to consist of three principal parts; the wave drag coefficient C_{Dw} the base drag coefficient C_{Db} and the friction drag coefficientC_{Df}. Besides, there is interference efforts, which may be represented by an interference drag coefficientC_{Db}. The whole is the sum of its parts:

$C_D = C_{Dw} + C_{Dw} + C_{Dw} + C_{Dw}$

If ρ denotes the air density, d is the diameter of the cylindrical part of the body(or the caliber) and u the velocity of the missile relive to the air, the drag is

$$D = C_D \rho d^2 u^2$$

Nominal trajectory – Trajectory simulated with the design input Differences between the real and predicted values due to manufacturing measurement atmospheric modeling errors These lead to errors between the positions of a desired and a real impact point. Estimation of these errors is very important. Methods of estimation Root Mean Square Method Monte Carlo method Method of Co-variance matrix method: Dispersion computation for a short range ballistic missile

3.8 BOOST PHASE

Primary sources :– Launcher dynamics – Ignition shock, acoustics, vibration Launcher deflection,– inadequate structural rigidity Launcher tip-off effect – finite length launcher – CG shift and pitching down – rate gyro measurement Launcher setting errors – inclined launchers – Elevation and azimuth – sensitive at higher elevations Vertical launchers – verticality alignment, azimuth alignment Rocket motor weight– propellant, structure – tolerances in the design, Rocket CG measurement inaccuracy and variation during the flight Variation in rocket motor performance - temperature effect on propellant – composition - ISP, burn rate Guidance Navigation and control systems performance variation - , accelerometer and gyroscopes hardware specification and mounting errors software errors control system functional response and valve operational delays Thrust and fin misalignments – longitudinal axis, nozzle alignment, fin mounting errors, structural bending

Wind effects – Head / Tail winds and Cross winds – measurement accuracy, wind variability between the time of measurement and the time of launch Aerodynamic coefficients estimation accuracy – theoretical / wind tunnel

3.9 FLIGHT - REENTRY PHASE

Separation system / weapon delivery system performance characteristics Effect of aerodynamic heating Ballistic coefficient estimation W/ (C_d.A) Reentry guidance and control errors

Monte Carlo method of dispersion Simulate the rocket trajectory with nominal data – DRn, CRn Each input parameter is selected randomly in the defined ranges and used in the simulation - Random number generator software. Few thousands of simulations are made calculate the impact point deviation – δ DR and δ CR Statistical estimate of the dispersion is made. Takes more computer time – few thousands of simulation Realistic estimate

3.10 Re-entry body design considerations

Since almost all astronauts experience some level of sensory disturbance during reentry and landing, and since these detrimental effects would likely be exacerbated if traveling in a spacecraft whose design deviates considerably from that of a conventional aircraft, seat position is a critical element to consider in the design of AUTOMATED PILOTED Mission:

Controlled landing w/parafoil& skids Human: Upright w/ FOV to minimize vestibular disturbances Mission: Parafoil to reduce velocity Human: Reclined for parachute shock Mission: Low L/D for stability, safety, and simplicity Human: Reclined for cardiovascular distress piloted spacecraft. Furthermore, human constraints should be considered early in the design process, rather than retrofitted at a later stage, and thus prone to unnecessary compromises. An integrated approach to spacecraft design that addresses factors driven by sensorydisturbance mitigation, mission constraints, andother human concerns described in this paper, would help to ensure the safety and success of future missions. With the current focus on space exploration within NASA and space tourism in the private sector, the concepts presented here are applicable to numerous immediate and future goals of human space flight. Future related work should include determining the effects of long duration exposure to partialg (e.g., 0.16g on the lunar surface or 0.38g for Mars) on human cardiovascular, musculoskeletal andvestibular systems. Transitioning between these fractional gravity environments and 0g orbital flight, with ultimate high g reentry and return to 1g on Earth presents unique concerns for piloted spacecraft designs.

UNIT-lV
DYNAMICS& ATTITUDE CONTROL OF ROCKETS & MISSILES

4.1 Tsiolskovsky's Rocket Equation

The forces on a rocket change dramatically during a typical flight. This figure shows a derivation of the change in velocity during powered flight while accounting for the changing mass of the rocket. During powered flight the propellants of the propulsion are constantly being exhausted from the nozzle. As a result, the weight of the rocket is constantly changing. In this derivation, we are going to neglect the effects of aerodynamic lift and drag.

Newton’s second law of motion:

$$\frac{dMu}{dt} = F = Veq\frac{dmp}{dt} \tag{1}$$

$$Mdu + \cancel{udM} = Veqdmp \tag{2}$$

$$>u=0 \tag{3}$$

$$Mdu = -V_{eq}dM \tag{4}$$

$$du = -Veq\frac{dM}{M} \tag{5}$$

$$\Delta u = \ -V_{eq}\log\ \ (M)|_{mf}^{me} \tag{6}$$

4.2 Derivation of the Rocket Equation

A large fraction (typically ~90%) of the mass of a chemical rocket is propellant, thus it is important to consider the change in mass of the vehicle as it accelerates. The goal is to arrive at an expression which relates the change in velocity of a rocket to the change in its mass as well as any external forces that are acting on it. The analysis is performed using Newton’s 2nd Law, Equation 7, which states that the time rate of change of momentum is equal to the sum of the forces acting on the system.

$$\sum\vec{F} = \frac{d}{dt}\left(m\vec{V}\right) \tag{7}$$

The resulting expression is called the Rocket Equation and it may be used to relate specific impulse to the performance of a rocket. There are several ways to do this by applying conservation of momentum, and each text book has its own way of presenting this derivation.

4.3 Derivation using the Differential Momentum Theorem

The first step is to apply the momentum theorem differentially to a rocket in accelerating flight. The rocket system is shown in the figure below and is the same as that of Figure 1 and 2 of Mechanics and Thermodynamics of Propulsion. In the figures below the coordinate system is aligned to the axis of the rocket and parallel to both the direction of flight and the direction of the exhaust velocity. The positive direction is aligned with the direction of flight and gravity acts perpendicular to the Earth's center and at an angle □ relative to the body attached coordinate system.

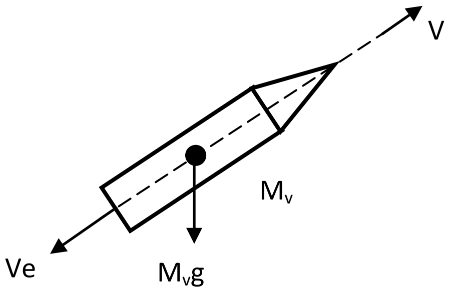


Fig.1 System at t

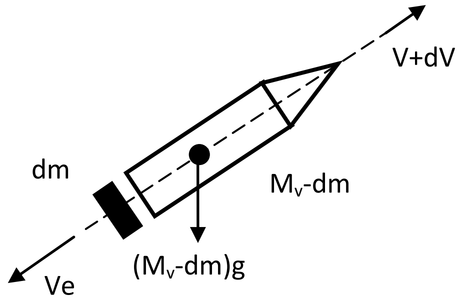


Fig. 2 System (Rocket + Expelled Mass) at t + dt

The basic idea is that at time t the rocket has a mass M_v and is traveling at a velocity (as measured by an *inertial* observer) of V. Note that both M_v and V are functions of time. During a small time increment, dt, the rocket has expelled a small mass, dm, such that at time t+dt, the mass of the rocket is M_v-dm. The small mass, dm, is expelled from the rocket at a velocity, Ve, *relative* to the rocket. The expulsion of this mass during the time dt leads to an increase in the velocity of the rocket such that V(t+dt)=V(t)+dV. The table below summarizes each of these terms:

Table 1: Summary of Initial and Final System Momentum in Inertial Frame

	Time	Mass	Velocity	Momentum
Rocket	t	M_v	V	M_vV
Rocket Only	t + dt	M_v- dm	V + dV	(M_v- dm)(V + dV)
Expelled Mass Only	t + dt	dm	V + dV - Ve	dm(V + dV - Ve)

Pay careful attention to the final velocity and momentum of the expelled mass. The point to notice is that this velocity must be expressed in an *inertial* system. An observer stationed on the rocket would measure the velocity and momentum of the expelled mass as Ve and dmVe, respectively. However, recall that Equation 7 must be applied in an inertial reference frame, such as an observer located on the ground. An observer stationed on the ground would measure the velocity of the expelled mass as the vector sum of the velocity of the rocket (traveling in the positive direction) and the velocity of the expelled mass (traveling in the negative direction) relative to the rocket at time t+dt as V+dV-Ve..

Now write these terms as the change in momentum of the system from the final state (t+dt) and the initial state (t), where the system is the rocket plus incremental mass.

$$momentum_{final} = (M_V - dm)(V + dV) + dm(V + dV - V_e) \qquad 8$$

$$momentum_{initial} = M_V V \qquad 9$$

$$momentum_{final} - momentum_{initial} = M_V dV - V_e dm \qquad 10$$

Equation 7 can now be rewritten as:

$$\sum \vec{F} dt = M_v dV - V_e dm \qquad 11$$

Compare Equation 12 to the result of a control volume analysis and you will find that the result is, of course, identical. We can now look at two important cases involving the expressions for the change in momentum of the rocket system.

4.3.1 No external surface or body forces acting on the rocket vehicle

In this case Equation 7 is equal to zero, and we can solve this expression for dV:

$$dV = \frac{V_e dm}{M_V} \qquad 12$$

Also note that the incremental mass that was ejected from the vehicle may be written as:

$$dm = \dot{m} dt = -\frac{dM_V}{dt} dt \qquad 13$$

In this expression $\dot{m}$ is the propellant mass flow rate, and this expression simply says that the change in mass of the vehicle during dt (which is decreasing, hence the negative sign) is equal to the mass of the expelled mass dm. This makes sense from the conservation of mass standpoint. Putting Equation 7 into Equation 6 gives:

$$dV = -\frac{V_e}{M_V}\left(\frac{dM_V}{dt} dt\right) = -V_e \frac{dM_V}{M_V} \qquad 14$$

Here we again make the assumption that the exit velocity of the ejected mass is a constant. This expression is now ready for integration. The limits of integration on the left integral are from the initial velocity to the final velocity and the limits of integration for the expression on the right hand side of the equal sign are from the initial mass to the final mass. This is shown below:

$$\int_{V_0}^{V_f} dV = -V_e \int_{M_0}^{M_f} \frac{dM_V}{M_V} \qquad 15$$

$$V_{final} - V_{inital} = \Delta V = -V_e \ln\left(\frac{M_{final}}{M_{initial}}\right) = V_e \ln\left(\frac{M_{initial}}{M_{final}}\right) \qquad 16$$

The final mass, M_{final}, is sometimes referred to as the burnout mass, and as its name implies this is the mass of the rocket when all the fuel as been expended. We can define a ratio, R, that relates the initial mass to the final, burnout mass of the rocket as:

$$R \equiv \frac{M_{initial}}{M_{burnout}} \tag{17}$$

Putting this expression into equation 8, gives:

$$\Delta V = V_e \ln R \tag{18}$$

Again, recall the assumptions on Equation 17. No forces (pressure, drag, gravity, etc.) are acting on the vehicle.

4.3.2 External surface and body forces acting on the rocket vehicle

In this case we will consider pressure forces of the non-deal expansion, as well as gravity and drag acting on the rocket. The sum of these forces is expressed below:

$$\sum F = (P_e - P_a)A_e - D - M_V g \cos\theta \tag{19}$$

I have represented the drag force simply by D. The last term on the right hand side is the gravity term, and a valid question to ask is: What is the correct mass to use in this term? As we shall discuss below, the final result must be solved by integration over time and the mass of the vehicle should be updated at each time step, dt. One could use the mass at the beginning of the time step (which is done above), the end of the time step (M_V-dm) or an average of these two, which would be expressed as (M_V-dm/2). If the time step is sufficiently small, accurate results will be obtained in all cases.

Equation 7 holds exactly for the case with external forces, but the difference in momentum between the initial and final state of the system is not zero. The difference between the final momentum and the initial momentum of the system is equal to the impulse $\sum Fdt$. We can express this as:

$$M_V dV - V_e dm = [(P_e - P_a)A_e - D - M_V g \cos\theta]dt \tag{20}$$

Again apply Equation 12 and rearrange some terms to yield:

$$M_V dV = [(P_e - P_a)A_e + \dot{m}V_e - D - M_V g \cos\theta]dt \tag{21}$$

Next we can combine the pressure and momentum flux terms to an equivalent velocity, c:

$$c = V_e + \left(\frac{P_e - P_a}{\dot{m}}\right)A_e \tag{22}$$

For the case where the exhaust pressure, pe, is equal to the ambient pressure, pa, we have:

$$dV = -V_e \frac{dM_V}{M_V} - \frac{D}{M_V} dt - g \cos\theta dt \qquad 23$$

For the case where pe ≠ pa, replace Ve with c from Equation 23. Equation 24 is called the Rocket Equation. Neglecting drag and assuming vertical flight:

$$dV = -V_e \frac{dM_V}{M_V} - gdt \qquad 24$$

Integrating we arrive at:

$$V = -V_e \ln\left(\frac{M_{final}}{M_{initial}}\right) - gt \qquad 25$$

This is exactly the set of expressions derived above.

One other interesting aspect is to relate Equation 26 to the specific impulse, which is defined as the thrust divided by the fuel weight flow:

$$I_{sp} = \frac{T}{\dot{m}g} \approx \frac{\dot{m}V_e}{\dot{m}g} = \frac{V_e}{g} \qquad 26$$

Substituting Equation 27 into Equation 26, we arrive at another useful form of the Rocket Equation:

$$V = g\left[I_{sp} \ln\left(\frac{M_{initial}}{M_{final}}\right) - t\right] \qquad 27$$

We can view equation 26 as being similar to the Breguet Range Equation for aircraft. It presents the overall dependence of the principal performance parameters for a rocket (velocity, V), on the efficiency of the propulsion system (Isp), and the structural design (ratio of the total mass to structural mass – since the initial mass is the fuel mass plus the structural mass and the final mass is only the structural mass).

4.4
Verticalmotionintheearth'sgravitationalfield,inclinedmotion,flightpathatconstantpit changle

Throws are bodies' movements, which take place near the Earth and which trajectories could be vanished with regard to the Earth's proportions. We will also suppose that there is neither any other force affecting the bodies than the gravity force nor the air resistance. So we suppose that the movements take place in vacuum.

We can observe free fall and compound movements (throws) in the Earth's homogenous gravity field. These movements are composed of free fall and uniform rectilinear movement. We divide them by the movement's direction:

1. Vertical throw downwards
2. Vertical throw upwards
3. Horizontal throw
4. Oblique throw upwards

4.4.1 Free fall

The easiest movement in the Earth's gravity field is the free fall. The free fall is uniformly accelerated movement with gravity acceleration g and with zero initial velocity. The free fall is a part of all the complicated movements in the Earth's homogenous gravity field.

These formulas are for the instantaneous velocity and trajectory of the free fall:

$V = g.t$ 28

$$S = \frac{gt^2}{2}$$ 29

4.4.2 Vertical throw upwards

Vertical throw upwards is composed of free fall and uniform rectilinear movement upwards. For example, the ball, which a tennis player throws before service, a stone blowing up from a volcano etc. These formulas hold for the instantaneous velocity v, travel s in time t:

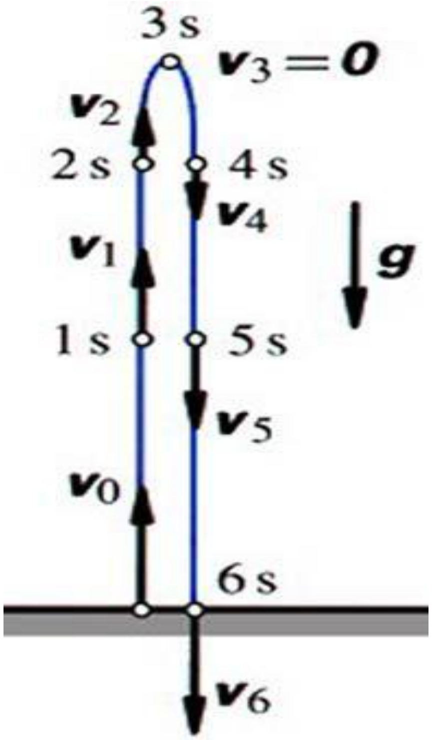


Fig. 3 vertically thrown upwards and free fall of object

$V = V_o - gt$ 30

$$S = V_o t - \frac{gt^2}{2} \qquad 31$$

The part of the vertical throw upwards when a mass point rises is called climb; the mass point performs uniformly slowed-down movement during it. The climb finishes when the instantaneous velocity equals zero, after it starts the free fall. The time when the mass point rises is the time of the climb T, and the mass point rises in the height H.
The trajectory of vertical throw upwards is in fact a line. The climb and the freefall are separated for clearness in the picture.

$$H = v_o T - \frac{1}{2} g T^2 \qquad 32$$

$$H = v_o \frac{v_o}{g} - \frac{1}{2} g \frac{v_o^2}{g^2} \qquad 33$$

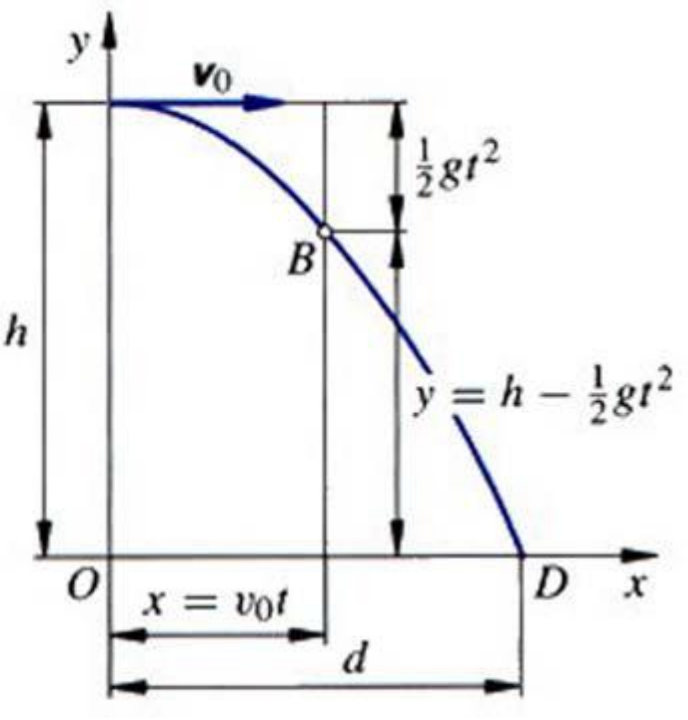
$$H = \frac{v_o^2}{2g} \qquad 34$$

Vertical throw downwards is composed of free fall and uniform rectilinear movement downwards. It is uniformly accelerated movement with $\boldsymbol{g}$ acceleration and initial velocity $\boldsymbol{v_0}$. These movements happen when we throw a stone into a chasm. The difference between this and a free fall is that we only let the stone fall down from a rest position by the free fall ($v_0 = 0$ m.s^{-1}).

4.4.3 Horizontal throw

Horizontal throw is composed of free fall and uniform rectilinear movement, whose direction is horizontal with the Earth's surface. The trajectory is a part of a parabola with apex in the place of the throw's start. Examples: effluent liquid from horizontally held hose, a marble, which goes over a horizontal table's edge.

The throw's length depends on the initial velocity $\boldsymbol{v_0}$ and on the height H, from which the body was thrown. We have to divide the movement in two parts – horizontal and vertical – to find out the mass point position.
The vertical movement is a free fall from the H height and the horizontal movement is a uniform rectilinear movement. We can determine the instantaneous position and velocity as a sum of these two movements, the instantaneous height h and the distance from the point of landing d.



$$d = v_o t$$

$$\mathrm{d} = \mathrm{v}_0 \cdot \mathrm{t} \qquad \mathrm{h} = \mathrm{H} - \frac{\mathrm{g} \cdot \mathrm{t}^2}{2} \qquad \mathrm{T} = \sqrt{\frac{2 \cdot \mathrm{H}}{\mathrm{g}}} \qquad \mathrm{D} = \mathrm{v}_0 \cdot \sqrt{\frac{2 \cdot \mathrm{H}}{\mathrm{g}}}$$

We can also determine the instantaneous velocity of the horizontal throw as a vector sum of the vertical and the horizontal velocity, where the horizontal velocity is the initial velocity and vertical one conforms to the free fall.

4.5 Body's movements in central Earth's gravitational field

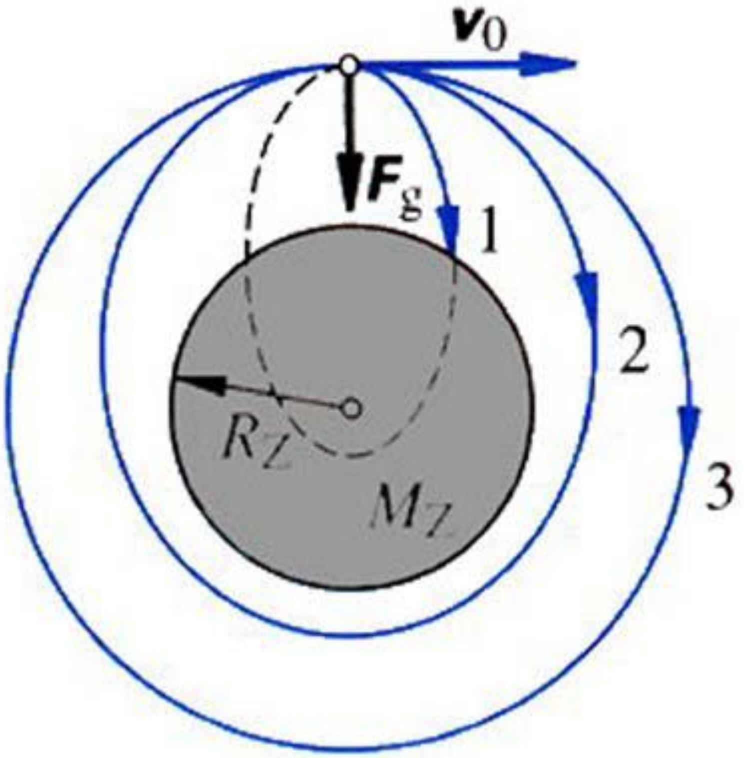
Throws are bodies' movements in a homogenous gravity field. We have to consider the gravity field as central for the movements of rockets, satellites or spaceships. The satellites' trajectories depend on its velocity.

4.5.1 Circular rate

1) Quite small initial velocity – the body is moving on an ellipse before it hit the Earth's surface. The part of the ellipse rises with the initial velocity.

2) The body does not hit the Earth in bigger initial velocities, but it circumscribes the whole ellipse.

3) If the initial velocity is a circular velocity $\boldsymbol{v_k}$, the body circumscribes a circle with a centre in the Earth's centre. The Earth's gravitational force $\boldsymbol{F_g}$and the centrifugal force $\boldsymbol{F_0}$ are in balance.



$$F_g = F_o$$

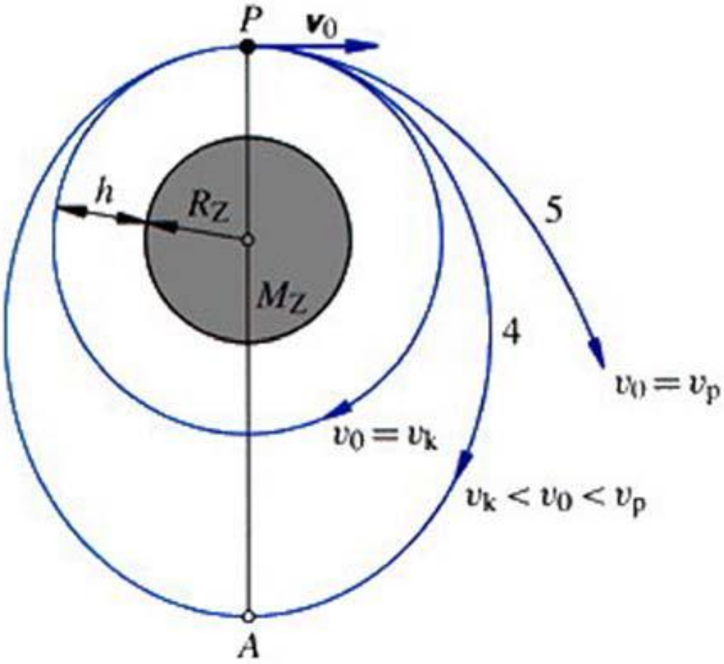
$$\kappa \cdot \frac{m \cdot M_Z}{(R_Z + h)^2} = \frac{m \cdot v_K^{2}}{R_Z + h}$$

$$v_K = \sqrt{\frac{\kappa \cdot M_Z}{R_Z + h}}$$

The value of the circular velocity $v_k$near the Earth’s surface is 7,9 $km \cdot s^{-1}$

4.5.2 Escape velocity

The trajectory is elliptical in bigger initial velocities again. The ellipse's plane goes through the Earth's centre, where it is its focus. The **P** point, where the distance from the Earth is the smallest, is called *perigee*, the **A** point, where the distance from the Earth is the biggest, is called *apogee*. With rising velocity the ellipse is more oblong.



The trajectory changes in a parabola in initial velocity and the body recedes from the Earth. The velocity $v_p$is called parabolic, escape. For the mentioned v_k= 7,9 km.s^{-1} is v_p= 11,2 km.s^{-1}.

$$v_p = v_k \cdot \sqrt{2}$$

Before the body reaches hyperbolic speed, it is moving in the Sun's gravitational field. When it reaches this velocity it leaves the Solar system.

4.6 Multistage Rocket Equations

Equations for model rocketeers - how to accurately predict speed and altitude for your multistage rocket from weight, diameter, motor thrust and impulse. If you're here I take it you're serious and looking for answers so let's get right to it. I'm assuming you've read and understand the single-stage equations.

4.6.1 First Stage

The equations to find velocity after first stage boost are the same as single stage boost, that is

$$k = \frac{1}{2}\rho C_d A$$

$$q = \sqrt{\frac{T - mg}{k}}$$

$$x = \frac{2kq}{m} = 2\frac{\sqrt{(T - mg)\cdot k}}{m}$$

$$t = \frac{I}{T}$$

$$v = q\frac{1 - e^{-xt}}{1 + e^{-xt}}$$

$$y_1 = \frac{-m}{2k}\ln\left(\frac{T - mg - kv^2}{T - mg}\right)$$

notice I call the distance travelled during the first stage boost "y1" instead of "yb". I do that because I'm going to call the second stage distance "y2", the third stage distance "y3" and in general, the boost stages are now called "yn".

4.6.2 Upper stages

For each stage after the first, you use a generalized version of these equations. First, set

- v0 equal to the end velocity (v) from the last stage
- m equal to the mass of the rocket after the previous stage has been ejected
- I equal to the impulse for the new stage
- T equal to the thrust for the new stage
- k stays the same as it was for the first stage

The following equations don't change but you recalculate with the new values of m, I and T:

$$q = \sqrt{\frac{T - mg}{k}}$$

$$x = \frac{2kq}{m}$$

$$t = \frac{I}{T}$$

Incidentally, the term "q", which is used because it makes the computation easier, also happens to be the terminal velocity for the rocket under thrust. So once you’ve computed q, you know how close your rocket comes to reaching terminal velocity (the point at which the wind resistance equals thrust, that is, you can’t GO faster than this). For single stage rockets this is no big deal because you never come close, but for multistage rockets, you may very nearly reach terminal velocity during boost.

The next term, s, is new for the upper stages:

$$s = \frac{q + v_0}{q - v_0}$$

Then the next two equations are slightly different for the upper stages. Notice that if v0 = 0, these equations become the same as the first stage, or single stage, equations, exactly as they should:

$$v = q\frac{s - e^{-xt}}{s + e^{-xt}}$$

$$y_n = \frac{-m}{2k}\ln\left(\frac{T - mg - kv^2}{T - mg - kv_0^2}\right)$$

The velocity v that you calculate here is the actual velocity of the rocket at the end of the boost phase. The altitude yn is the distance covered only during this boost phase, that is, you have to add up all the y's to get the total altitude the rocket will go.

4.7 Rocket Thrust Vector Control

Thrust Vector Control or Thrust Vectoring is a technology that deflects the mean flow of an engine jet from the centerline in order to transfer some force to the aimed axis. By that imbalance, a momentum is created and used to control the change of attitude of the aircraft. Among other things, thrust vectoring greatly improves maneuverability, even at high angles of attack or low speeds where conventional aerodynamic control surfaces lose all effectiveness. Thrust Vector Control is currently achieved by complex arrays of mechanical actuators capable of modifying the geometry of the nozzle and thus defect the flow. This variable geometry greatly increases weight and maintenance to the engine, and therefore limits the benefits from vectoring the thrust.

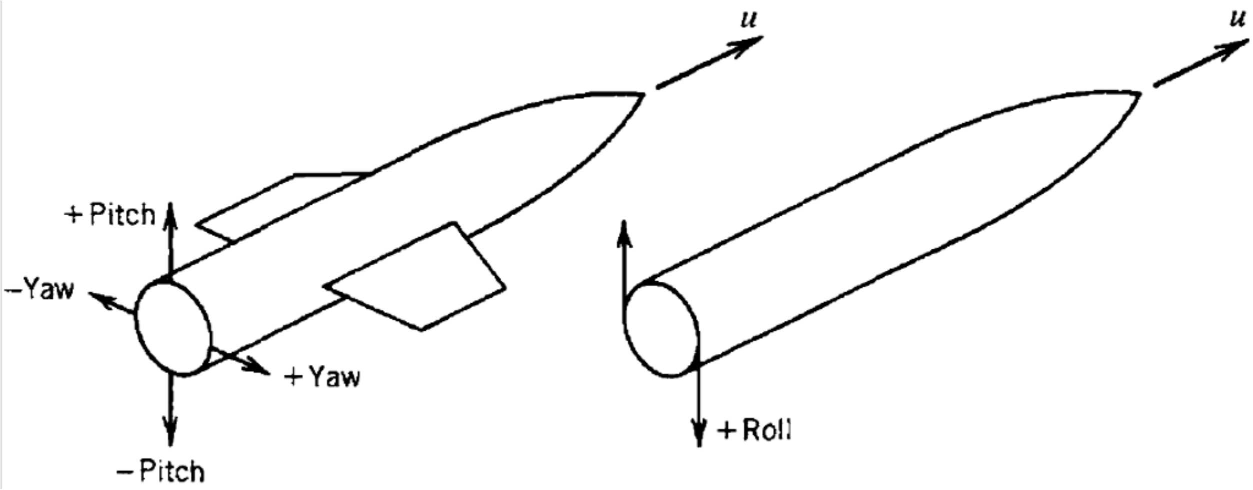


Figure 9 Moments applied to a flying vehicle.

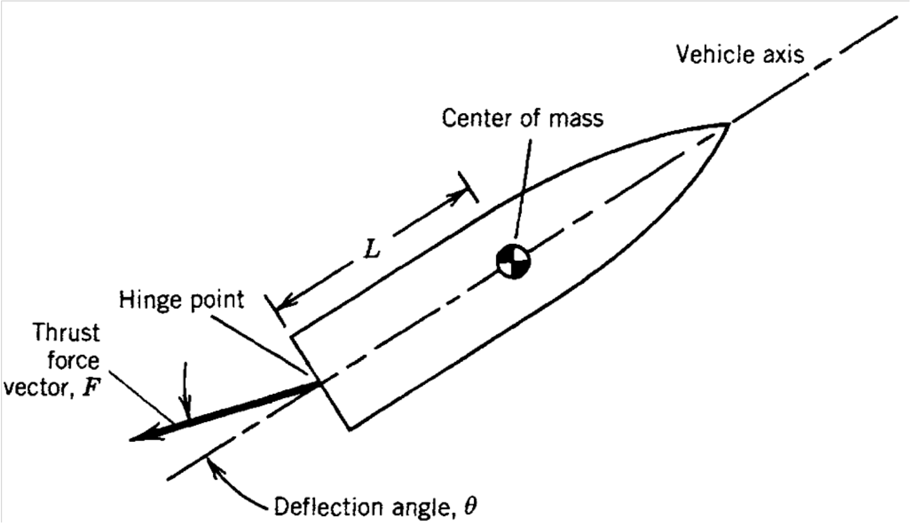


Figure 10 The pitch moment applied to the vehicle is *FL* sin θ.

4.8 Methods of Thrust Vector Control

Many different mechanisms have been used successfully. They can be classified into four categories:

1. Mechanical deflection of the nozzle or thrust chamber.
2. Insertion of heat-resistant movable bodies into the exhaust jet; theseexperience aerodynamic forces and cause a deflection of a part of theexhaust gas flow.
3. Injection of fluid into the side of the diverging nozzle section, causing an asymmetrical distortion of the supersonic exhaust flow.
4. Separate thrust-producing devices that are not part of the main flow through the nozzle.

4.9 Thrust Termination

Thrust termination is a concept specific to solid-fuel rockets. Unlike their liquid-fueled brethren, you cannot 'stop' a solid-fuel rocket easily. In the former, you can simply starve the motor of fuel and/or oxidizer; however, once you have ignited a solid-fueled rocket motor, it will continue to burn until all of its fuel has been consumed. The problem arises when you need to stop producing thrust *before* the motor has reached that point.

Probably the most famous modern examples of solid-fuel engines, the Space Shuttle's Solid Rocket Boosters, solve this problem quite simply. When the STS detects that the SRBs are about to burn out (by dropping chamber temperatures) it jettisons them using pyrotechnics so as to ensure that they do not burn down unevenly and imbalance it. They are then retrieved, refurbished and reused if possible. However, this solution only works if the solid rocket is mounted on the exterior of your vehicle. If the vehicle in question is a 'top stack' instead of a 'side stack' like the Shuttle - in other words, it has stages mounted atop each other in turn - then how can you get rid of the lowest stages as they approach the end of their burn?

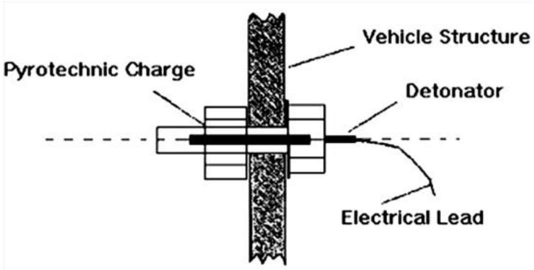
The problem is compounded if the vehicle needs a particular amount of boost from each stage, perhaps because its position and trajectory varies before launch. The most common version of this type of vehicle is a ballistic missile. In such cases, solid-fuel rockets are desirable due to their low maintenance and high shelf life - but in order to hit its target, the missile *must* be able to stop burning its main stage motor(s) with some precision in order to avoid 'overthrowing' its warheads. The first system to run into this problem was the first major SLBM in service, the United States' Polaris Fleet Ballistic Missile. At the time of its development (1956-1959) major ICBMs were liquid-fuel - however this was not practical aboard ship.

4.10 Separation Techniques

In designing separation mechanisms, the following factors must be considered: (1)adequate clearance between the separating bodies; (2) shock transmission to thepayload or structure of the continuing body; (3) damage to or contamination of thecontinuing body by debris resulting from the operation of the separation mechanism;and (4) the ability of the mechanism to withstand the natural and inducedenvironments encountered during service.

There are several methods of stage separation:
1. Explosive bolts.
2. Rods and springs.
3. Separation rockets.
4. Pneumatic separation.

4.10.1 Explosive bolts



Explosive bolts are used to join launch vehicle components that are meant to eventually come apart,fig. 2. On command, they blow apart and allow the components to separate. Explosive boltssecure stages and fairing shells to each other. They also activate the latches, which tie the vehicle tothe pad. Explosive bolts are often used in conjunction with rods and springs and separation rockets.

Figure 11 Explosive bolt

4.10.2 Rods and springs

Rods and springs are a low-stress, safe method of separating stages from each other or satellites fromupper stages, fig. 3. A spring-loaded rod pushes the components apart as soon as explosive bolts havereleased them. Rods and springs separate the solid rocket boosters from the Delta and H1 vehicles. Satellites are frequently deployed from the shuttle cargo bay using rods and springs.

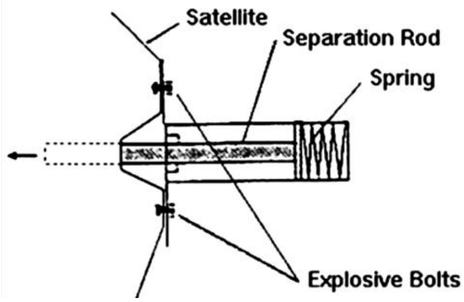
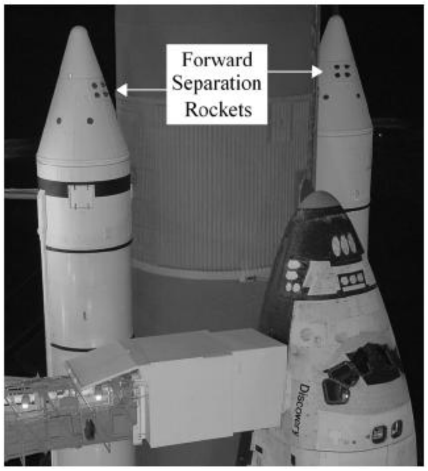


Figure 12 Rod and spring

4.10.3 Separation rockets

Separation rockets immediatelyaccelerate launch vehicle stages awayfrom each other or solid rocket boosters away from the core vehicle, fig's. 4 and 5. Theyare used where safety depends on rapid separation. The Ariane 4 uses eight rockets to separate thefirst and second stages. Separation rockets also push the solid rocket boosters away from the Titanand shuttle vehicles. In the case of the shuttle, eight 22,000 lb. thrust rockets separate the solids fromthe main tank.



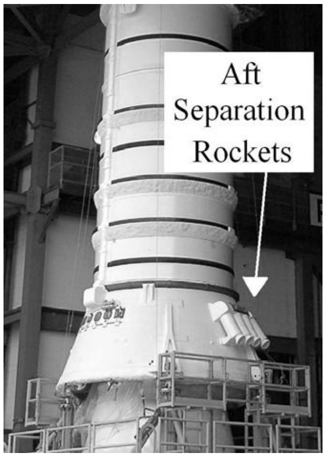


Figure 4 Shuttle separation rockets (forward) **Figure 5** Shuttle separation rockets

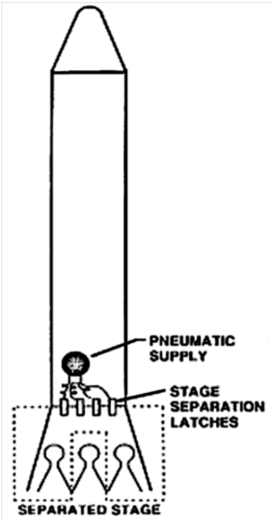
4.10.4 Pneumatic separation

Pneumatic separation involves a compressed gas, which actuates a piston that directly pushes components apart or triggers a latch mechanism. There are two types of pneumatic systems:

1. Hot gas.
2. Cold gas.

Hot Gas

Hot gas systems employ a gas generator that provides the high pressure gas for the actuators.



Cold Gas
Cold gas systems store an inert pressurant (helium, nitrogen) in a spherical tank that supplies multiple actuators. Cold gas systems are capable of long-term storage and don't need to be preloaded on the pad (fig. 6).

Figure 6 Cold gas separation

4.11 Stage separation dynamics

The dynamics of body separation, as it was suggested by many researchers, represents an inverse process of the perfectly plastic impact of the two perfectly inelastic bodies. During the separation, which lasts for a very short time interval τ, the body undergoes a relaxation which causes the energy of deformation (potential energy) to be transformed into kinetic energies of the separated and the remainder bodies. This additional kinetic energy causes the relative motion of the separated and remainder bodies. The separation forces and torques which act between the separated and remainder bodies give the separation impulses and separation moments. From this we can regard the separated and remainder body as one complex system. Then the separation impulses and moments between these bodies are internal within that system. It is this fact that the law of conservation of the momentum and angular momentum of the system can be applied. The linear momentum of the body before the separation and the sum of the linear momenta of two parts after the separation remain invariable. Also, the angular momentum of the body before the separation and the sum of angular momenta of two parts after the separation remain invariable.

Using the afore mentioned assumptions and the principles of dynamics, the velocity and angular velocity of the remainder body after the separation are obtained. Namely, the body with mass M and velocity of mass center $\mathbf{v}_S$has the linear momentum$\mathbf{K}_1 = M\mathbf{v}_S$. If the separated mass m moves with velocity $\mathbf{v}_{S2}$, its linear momentum is $m\mathbf{v}_{S2}$. The remainder mass $M - m$ has the unknown velocity $\mathbf{v}S1$and the corresponding linear momentum $(M - m)\mathbf{v}_{S1}$. Using the fact that the linear momentum of the body before separation and of the system after separation is invariant, we obtain

$$M\mathbf{v}_S = m\mathbf{v}_{S2} + (M - m)\mathbf{v}_{S1}. \qquad \text{Eq.4.11.1}$$

Solving the relation (1), the velocity of mass center$\mathbf{v}S1$ of the remainder body is determined. Before the separation, the angular momentum relating to a fixed point O (Fig. 1) is

$$\mathrm{L}_o = \mathbf{r}_S \mathrm{X} \mathbf{M}\mathbf{v}_\mathbf{s} + \mathbf{L}_\mathbf{s}. \qquad \text{Eq.4.11.2}$$

Where $\mathbf{r}_S$is the position vector of the mass center S of the whole body and $\mathbf{L}_S$ is the angular momentum of the body related to the mass center S. After the mass separation, the angular momentum of the remainder body relating to the fixed point O is

$$\mathbf{L}o_1 = \mathbf{r}_{S1} \times (M - m)\mathbf{v}_{S1} + \mathbf{L}_{S1}. \qquad \text{Eq.4.11.3}$$

and of the separated body

$$\mathbf{L}_{o2} = \mathrm{r}_{s2} \mathrm{X}\ \mathrm{m}\mathbf{v}_{s2} + \mathrm{L}_{s2,} \qquad \text{Eq.4.11.4}$$

where$\mathbf{L}_{S1}$ is the angular momentum of the remainder body relating to the mass center S_1; $\mathbf{L}_{S2}$ is the angular momentum of the separated body relating to its mass center S_2; $\mathbf{r}_{S1}$ and $\mathbf{r}_{S2}$ are the position vectors of the mass center of the remainder body and separated body, respectively. Regarding the assumption that the two bodies form one complex system, it is stated that the angular moment a of the body before and after mass separation are equal, $\mathbf{L}_O = \mathbf{L}_{O1} + \mathbf{L}_{O2}$,

$\mathbf{r}_s X M\mathbf{v}_s + \mathbf{L}_s = \mathbf{r}_{s1} X (M-m)\mathbf{v}_{s1} + \mathbf{L}_{s1} + \mathbf{r}_{s2} X m\mathbf{v}_{s2} + L_{s2}$ Eq.4.11.5

From Fig. 1, the relations between the position vectors are

$\mathbf{r}_{s1} = r_s + \mathbf{SS}_1$, $\mathbf{r}_{s2} = \mathbf{r}_s + \mathbf{SS}_{2.}$ Eq.4.11.6

Substituting (6) into (5), the following relation is obtained

$\mathbf{r}_s X [M\mathbf{v}_s - (M - m)\mathbf{v}_{s1} - m\mathbf{v}_{s2}] + \mathbf{L}_s = SS_1 X (M - m)\mathbf{v}_{s1} + L_{s1} +$
$SS_2 X m\mathbf{v}_{s2} + \mathbf{L}_{s2}$ Eq.4.11.7

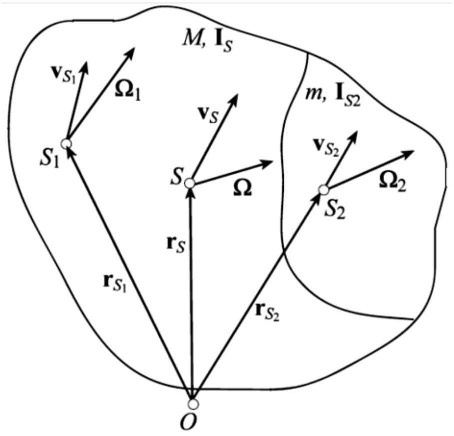


Figure 8 Body separation—position vectors, velocities and angular velocities of the system

Due to relation (1), (7) transforms to

$L_s = L_{s1} + L_{s2} + SS_1 X (M - m)\mathbf{v}_{s1} + SS_2 X m\mathbf{v}_{s2.}$ Eq.4.11.8

In general, the angular moment a before and after mass separation are $\mathbf{L}_S = \mathbf{I}_S\Omega$, $\mathbf{L}_{S1} = \mathbf{I}_{S1}\boldsymbol{\Omega}_1$ and $\mathbf{L}_{S2} = \mathbf{I}_{S2}\boldsymbol{\Omega}_2$, where Ω,Ω_1 and Ω_2 are, respectively, the angular velocities of the whole body, remainder and separated body before mass separation; $\mathbf{I}_S$, $\mathbf{I}_{S1}$, and $\mathbf{I}_{S2}$are inertia tensors for the whole body, remainder and separated body for mass centers S,S_1, and S_2, respectively. Using the relation (8), the angular velocity of the remainder body is determined. The relations (1) and (8) represent the principles of moment a and angular moment a variation of the system during mass separation. According to these equations, the velocity of mass center $\mathbf{v}_{S1}$ and angular velocityΩ_1 of the remainder body for dis-continual mass separation are calculated.

UNIT-V
ROCKETTESTING

5.1 Types of Tests

Before any rocket propulsion systems are put into operational use, they are subjected to several different types of tests, many of which are outlined below in the approximate sequence in which they are normally performed.

1. Manufacturing inspection and fabrication tests on individual parts (dimensional inspection, pressure tests, X-raying, leak checks, electric continuity tests, electromechanical checks, etc.). These tests are usually done at the factory.

2. Component tests (functional and operational on igniters, nozzles, insulation, valves, controls, injectors, structures, tanks, motor cases, thrust chambers, turbo pumps, thrust-vector control, etc.). May need special equipment/facilities.

3. Static rocket propulsion system tests (with complete propulsion system) on a test stand:
(*a*) Complete propulsion system tests (under rated conditions, off-design conditions, with intentional variations in environment or calibration);
(*b*) With liquid propellants a partial or simulated rocket operation (for proper function, calibration, ignition, operation—often without establishing full thrust or operating for the full duration); for reusable or restartable rocket propulsion systems this can include several starts, long-duration endurance tests, and post operational inspections and reconditioning;
(c) Some tests on chemical propulsion systems and nearly all tests on electrical propulsion systems are performed in large vacuum facilities that simulate the high-altitude rarified atmosphere conditions.

4. Static vehicle tests (when rocket propulsion system is installed in a restrained, non-flying vehicle or stage) on a vehicle test stand.

5. Flight tests: (*a*) with a specially instrumented or new propulsion system in a developmental flight test vehicle; (*b*) with a production vehicle.

Each of these five types of tests can be performed on at least three basic program types:

1. Research on and development or improvement of a new (or modified) rocket propulsion system, its propellants, materials, or components.

2. Evaluation of the suitability of a new (or modified) rocket engine or novel rocket motor for an alternate specified application or for flight readiness.

3. Production proof tests and quality assurance of existing operational rocket propulsion systems.

5.2 Test Facilities and Safeguards

For chemical rocket propulsion systems, each test facility usually has the followingmajor systems or components:

1. A *test cell* or *test bay* where the article (a rocket propulsion system or a thrust chamber) 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 accidents or explosions.

2. An *instrumentation system* with associated computers for sensing, maintaining, measuring, analyzing, correcting, and recording the 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 during tests.

4. Systems for handling and lifting heavy or awkward assemblies, for supplying (or removing) liquid propellant, and for providing maintenance, security, and safety.

5. For highly *toxic propellants* and *toxic plume gases* the capture of hazardous gases or vapors has been required (by firing inside a closed duct system) to remove most or all of the hazardous ingredients (e.g., by wet scrubbing and/or chemical treatment), allowing the release of the nontoxic portion of the exhaust gases and the safe disposal of the toxic solid or liquid residues.

6. In some tests specialized equipment and unique facilities are needed to conduct static testing under various environmental conditions or under simulated emergency conditions.

5.3 Monitoring the Environment and Controlling Toxic Materials

Open-air testing of chemical rocket propulsion systems frequently requires measurement and control of exhaust cloud concentrations and gas movement in the surrounding areas for safeguarding personnel and the environment. Most test and launch facilities have several stations (both inside and outside the facilities) for collecting and measuring air samples before, during, and after testing. Toxic clouds of exhaust gases (some with particulates) can result from normal rocket operation or from vapors or reaction gases from unintentional propellant spills, or from fire borne gases, explosions, or from the intentional destruction of vehicles in flight or rockets on the launch stand. Environmental government regulations usually limit themaximum local concentration or the total quantity of toxic gas or particulates that can be released to the atmosphere. One method of control is for tests with discharges of moderately toxic gases or products to be postponed until favorable weather and wind conditions are present.

5.4 Instrumentation and Data Management

In the last few decades, considerable progress has been made in instrumentation and data management. For further study the reader is referred to standard textbooks on instruments and computers used in testing. Some of the physical quantities commonly measured during rocket propulsion testing are:

1. Forces (thrust, thrust vector control side forces, short thrusting pulses).
2. Flows (hot and cold gases, liquid fuels, liquid oxidizers, leaks).
3. Pressures (chamber, propellant, pump inlet/outlet, tank, etc.).
4. Temperatures (chamber or case walls, propellant, structure, nozzle).
5. Timing and command sequencing of valves, switches, igniters, full pressure attainments, and others.
6. Stresses, strains, and vibrations (combustion chamber, structures, solid propellants, liquid propellant lines, local accelerations of vibrating parts) Also, thermal growths.
7. Movements and positions of parts (valve stems, gimbal position, deflection of parts under load or heat).
8. Voltages, frequencies, and currents in electrical or control subsystems.
9. Visual observations (flame configuration and color, test article failures, explosions) using high-speed cameras or video cameras.
10. Special quantities such as propellant strains, turbo-pump shaft speeds, liquid levels in propellant tanks, burning rates, flame luminosities, sound pressures and/or exhaust gas composition.
11. Ambient air conditions (pressure, temperature wind speed and direction, toxic gas content) at stations in the test facility area and also at stations downwind of the test area.

5.5 Post Accident Procedures

In the testing of any rocket propulsion system there will invariably be failures, particularly when some of the operating parameters are close to their limit. With each failure comes an opportunity to learn more about the design, materials, propulsion performance, fabrication methods, and/or the test procedures. A careful and thorough investigation of each failure is needed to learn the likely causes in order to identify remedies or fixes to prevent similar failures in the future. The lessons to be learned from these failures are perhaps some of the most important benefits of development testing. A formalized postaccident approach is often used, particularly if the failure had a major impact, such as high cost, major damage, or personnel injury. Any major failure (e.g., the loss of a space launch vehicle or severe damage to a test facility) often causes the program to be stopped and further testing or flights put on hold until failure causes are determined and remedial actions have been taken to prevent a recurrence.

5.6 Space launch vehicle launches procedures

Of utmost concern immediately after a major failure are the needed steps to respond to the emergency. These may include giving first aid to injured personnel, bringing the propulsion system and/or the test facilities to a safe/stable condition, limiting further damage from chemical hazards to the facility or theenvironment, working with local fire departments, medical or emergency maintenance staff or ambulance personnel, and debris clearing crews, and quickly providing factual statements to the management, the employees, the news media, and the public. It also includes controlling access to the facility where the failure has occurred and preserving evidence for the subsequent investigation. All test personnel, particularly the supervisory people, need to be trained not only in preventing accidents and minimizing any impact of a potential failure, but also on how to best respond to the emergency.