# SPACE :

## THE FINAL FRONTIER


Astronomy Club,
IIT Kanpur

Summer Projects- 2021

**MIDTERM REPORT**

ASTRO
IIT KANPUR

# MENTORS:

**Sunny K. Bhagat[sunny@iitk.ac.in]**

**Mubashshir Uddin[muddin@iitk.ac.in]**

**Varun Singh[varunsng@iitk.ac.in]**

# Participants:

| | |
|---|---|
| *rhansda20* | ojsig20 |
| *pritesh20* | parthb20 |
| *ganeshk20* | yashika20 |
| *sameers20* | srai20 |
| *sshikha20* | rajverma20 |
| *aditj20* | numrao20 |
| *anupsingh20* | akushwaha20 |
| *nallani20* | kajald20 |
| *ananyau20* | rohans20 |
| *anubhat20* | atharvad20 |
| *gpmilind20* | ananyap20 |
| *saikrishna20* | sarvagyaj20 |

# History of Rockets

## 1 Introduction

Today's rockets are remarkable collections of human ingenuity that have their roots in the science and technology of the past . It has been a fascinating subject for the scientific community. They are natural outgrowths of terribly thousands of years of experimentation and research. The data reporting the first use of of true rockets was in in 1232. At that time, the Chinese and Mongols were at the war. The fire arrows used were a simple form of solid propellant rocket.

### 1.1 Tsilokovsky's Contribution

In 1903, high school mathematics teacher Konstantin E. Tsiolkovsky (1857–1935), inspired by Verne and Cosmism, published *The Exploration of Cosmic Space by Means of Reaction Devices*. The Tsiolkovsky Equation—the principle that governs rocket propulsion—is named in his honour . He also advocated the use of liquid hydrogen and oxygen for propellant, calculating their maximum exhaust velocity.

$$\Delta v = v_e ln \frac{m_0}{m_f} \tag{1}$$

Here, $\Delta v$ is the change in speed of rocket, $v_e$ is exhaust velocity, $m_0$ is the initial while $m_f$ is the final rocket mass. He also published the a theory of multistage of rockets in 1929.

### 1.2 Goddard's contribution

In 1912, Robert Goddard, concluded that conventional solid-fuel rockets needed to be improved in three ways.

- The fuel should be burned in a small combustion chamber, instead of building the entire propellant container to withstand the high pressures.
- The rockets could be arranged in stages which will make them lose unnecessary load in middle of flight.
- The exhaust speed could be greatly increased by using a DE naval nozzle.

He combined and put forward these concepts in 1914. Goddard worked on developing solid propellant rockets since 1914, and demonstrated a light battlefield rocket to the US Army Signal Corps only five days before the signing of the armistice that ended World War 1. He also developed gyroscope system for flight control of rockets. After his death NASA has named its first space flight complex as Goddard Space Flight Center in his honour.

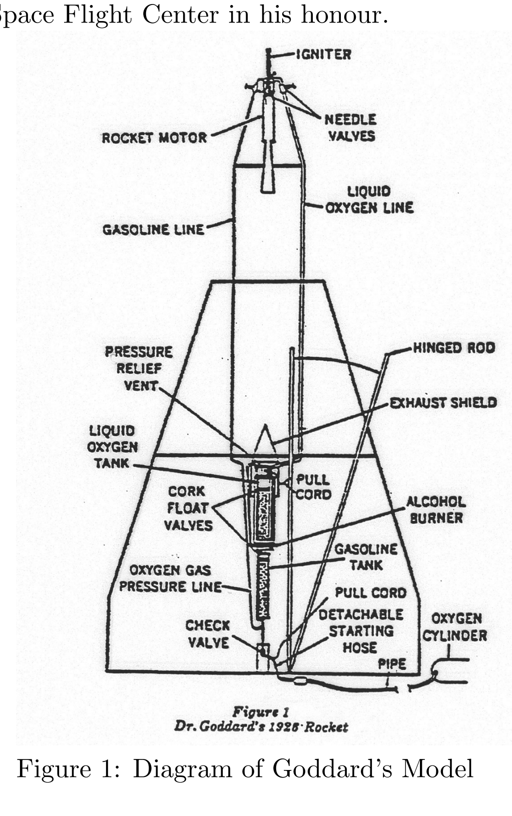



Figure 1: Diagram of Goddard's Model

### 1.3 Modernisation in Rocketry

Following developments by Goddard,rocketry was revolutionised but scientists had to still figure out to send the rockets to space. Rapid developments began when Germany realised the potential of the rockets as weapons in World War 2 through its V-2 rockets. A rocket was first used to send something in space on the Sputnik mission, which launched a Soviet satellite on Oct 4, 1957. Rocketry reached its pinnacle when it carried humans to the moon on July 16, 1969.

# Design

## 2 Payload

*Payload is the carrying capacity of an aircraft or launch vehicle, usually measured in terms of weight. Depending on the nature of the flight or mission, the payload of a vehicle may include cargo, passengers, flight crew, munitions, scientific instruments or experiments, or other equipment.* Extra fuel, when optionally carried, is also considered part of the payload. The payload system of a rocket depends on the rocket's mission. The earliest payloads on rockets were fireworks for celebrating holidays according to Chinese history (including the story of man strapped to a chair containing explosives XD). 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 and advanced scientific rovers and crafts to the outer solar system and beyond..

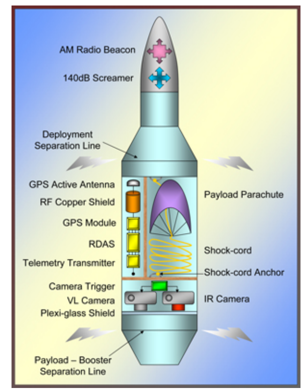


Figure 2: Payload

## 3 Fairing

The spacecraft and upper stage are housed within the payload fairing, which usually has a diameter more than that of the second or third stage. During the early portion of the boost phase when the aerodynamic forces from the atmosphere could affect the rocket, faring plays a crucial role:

- Protection in lower Atmosphere
- Protection against biospheric contamination
- Protection against heat

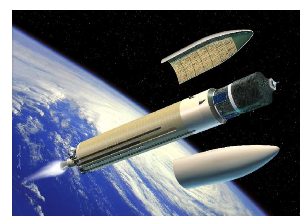


Figure 3: Fairing

Although faring may add extra weight to the rocket (which is negligible in comparison to the payload capacity), it's benefits outweigh the cons. Also as stated by the European Space Agency, "Once the launcher leaves the Earth's atmosphere, approximately three minutes after liftoff, the fairing is jettisoned. This lightens the remaining launcher's load as it loses approximately two tonnes of this no-longer required structure"

## 4 Body

*The structural system, or body, of a rocket is similar to the fuselage of an airplane.* As you can see on the figure, most of a full scale rocket is propulsion system surrounded by the frame:

## 4.1 Frame

Figure 4: Frame

The frame is made from very strong but light weight 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:

## 4.2 Propellant & Fuel Tank(s)

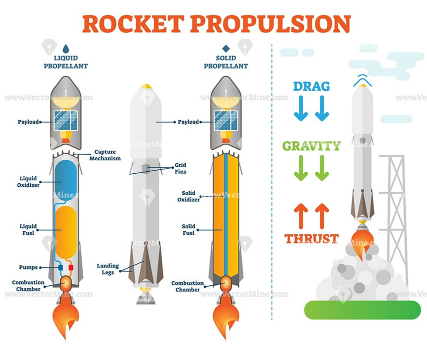



Figure 5: Rocket Propulsion

Rocket propellant is the reaction mass of a rocket. This reaction mass is ejected at the highest achievable velocity from a rocket engine to produce thrust. The energy required can either come from the propellants themselves, as with a chemical rocket, or from an external source, as with ion engines. This reaction mass is stored in the Fuel Tanks of the rocket, that account for more than 70% volume of a rocket (No kidding!).
***Liquid Propellant*** is the most widely used fuel in a rocket. Liquid oxygen is the most common cryogenic liquid oxidizer propellant for spacecraft rocket applications, usually in combination with liquid hydrogen, kerosene or methane. Liquid-fueled rockets have higher specific impulse than solid rockets and are capable of being throttled, shut down, and restarted. Only the combustion chamber of a liquid-fueled rocket needs to withstand high combustion pressures and temperatures. This propellant is pushed into the rocket engines by means of tubes.

For the side-thrusters in heavy rockets that can carry immense payload to space, ***solid fuel*** is preferred as solid propellant rockets are much easier to store and handle than liquid propellant rockets. High propellant density makes for compact size as well. These features plus simplicity and low cost make solid propellant rockets ideal for military and space applications.

***Ion thrusters*** ionize a neutral gas and create thrust by accelerating the ions (or the plasma) by electric and/or magnetic fields. Mainly, heavy elements such as Xe (Xenon) are used. Also, Ion thrusters can be operated and stored for a longer duration than either the solid or liquid propellants.

But of course, we need Engines to utilise the complete potential of these fuels:

## 4.3 Rocket Engine

This is the main component of the rocket. Yup, the one that is responsible for actually "lifting-off" the rocket from the ground to reach into space. 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 engines may or may not use oxidiser (i.e. they may take oxidiser intake via air from the atmosphere).

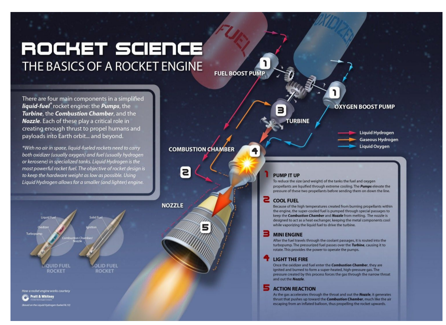



Figure 6: Rocket Engine

# 5 Fins

The technical definition of a Fin is: *A surface used to give directional stability to any object moving through a fluid such as water or air.* In short, fins provide maneuverability and stability to the rocket in the upper atmosphere. The size of the fins, their shape, the number to use and their placement on rocket are all questions that can be answered only by experimentation. Fins and other aerodynamic properties are tested in wind tunnels at high wind speeds. More about the aerodynamic impact of fins later in the document.

# Aerodynamics

## 6 Introduction

Rockets tend to break the sound barrier very fast and often when they haven't even left the lower atmosphere. The fins should be optimized for supersonic flight and ideally stay within the Mach Cone. There is always an optimum point and design style. In general, larger the fin, the more drag but the more stable. Thus drag and flow dynamics become extremely crucial in making of rockets. Following we discuss what are shock waves and how do they affect Rockets.

## 7 Definition

A shock wave is a propagating disturbance that moves faster than the local speed of sound in the medium.It carries energy and can propagate through a medium but is characterized by an abrupt, nearly discontinuous, change in pressure, temperature, and density of the medium.

## 8 Cause

Shock waves are formed when a pressure front moves at supersonic speeds(Speed more than that of sound) and pushes the air surrounding it. At that particular region, sound waves travelling against the flow reach a point where they are unable to travel any further upstream, and the pressure progressively develops at that particular region and a high-pressure shock wave rapidly forms.

## 9 Properties

Shock waves are not conventional sound waves; a shock wave takes the form of a very sharp change in the gas properties and is heard as a very loud noise. Over longer distances, it can change from a nonlinear wave into a linear wave, deteriorating into a conventional sound wave as the air is heated and the wave's energy is lost. A sound similar to that of created by a sonic boom is heard, which is usually produced by the supersonic flight of an aircraft.

## 10 Types of Shock Waves

- OBLIQUE SHOCK
- NORMAL SHOCK
- CROSSED SHOCK WAVES

### 10.1 Oblique Shock

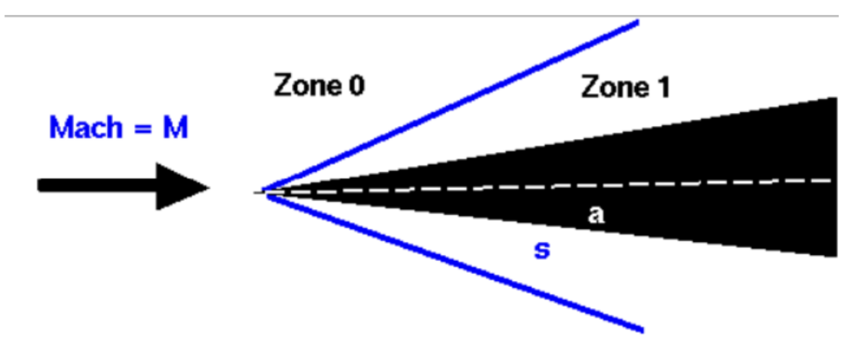



Figure 1: Oblique Shock

If the shock wave is inclined to the flow direction it is called an Oblique Shock.The flow changes and oblique shocks occur downstream of a nozzle if the expanded pressure is different from free stream conditions. For the Mach number change across an oblique shock there are two possible solutions; one supersonic and one subsonic.For normal conditions,supersonic solution is considered.

### 10.2 Normal Shock Waves

If the shock wave is perpendicular to the flow direction it is called a Normal Shock .It occurs in front of a supersonic object if the flow is turned by a large amount and the shock cannot remain attached to the body. The normal shock significantly increases the drag in a vehicle traveling at a supersonic speed. This property was utilized in the design of the return capsules during space missions such as the Apollo program, which needed a high amount of drag in order to slow down during atmospheric reentry.

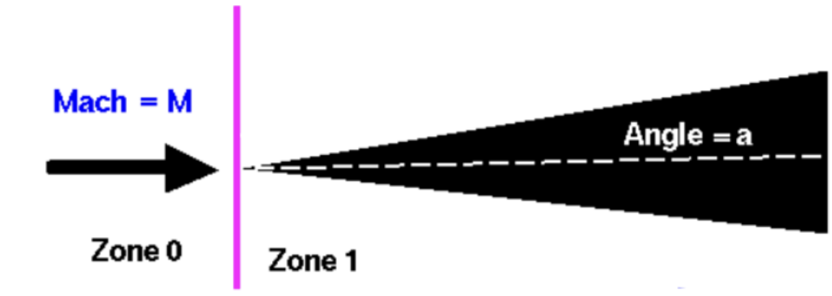



Figure 2: Normal Shock

### 10.3 Crossed Shock Waves

When two or more surfaces are there the shock waves generated due to it cross each other and the resultant is a third shock wave,called a Crossed Shock Wave. The shocks generated by the two wedges intersect at some point in the flow.In all of the shock reflections and intersections the Mach number of the flow is decreased

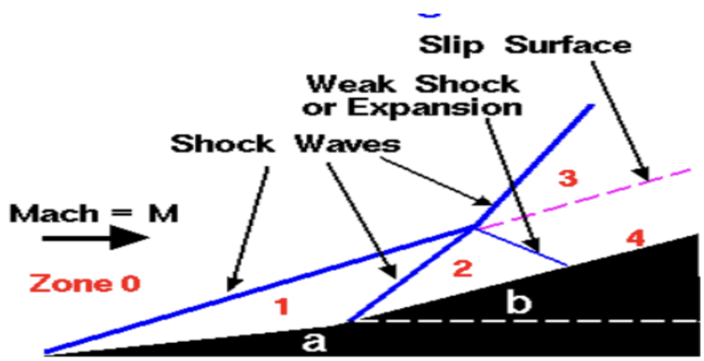



Figure 3: Crossed Shock

# Stability

## 11 Introduction:

Rockets stability is the key to control the whole path of the mission. Every mission has some specific goals and desire the rocket to fly in a defined and safe trajectory or path, therefore maintaining the stability of the rocket is a must to steer the rocket in its path.

Stability of rocket is broadly decided by the location of points of Center of gravity ($C_g$) and center of pressure ($C_p$). Centre of gravity ($C_g$) of a rocket is the point where the whole weight of the rocket can be averagely considered. And center of pressure ($C_p$) is the point where all the air pressure forces appear to concentrate.

# 12 Stability Criterion:

Like any object, rockets can rotate about their center of gravity ($C_g$). During the flight, even a small gust of wind or thrust can cause instabilities and can cause the rocket to 'wobble', and can change the complete course of flight. Whenever the rocket is inclined to its actual path, lift forces combining with drag act through the center of pressure ($C_p$). These forces exert torques about the center of gravity ($C_g$) and in the direction so that it counteracts the disturbance caused by wind or other air pressures.

The most important point of concentration is that the rockets should be engineered in a way such that the constantly rising position of $C_p$ should always be below $C_g$ to maintain the counteracting nature of torques caused by lift and drag. Stability increases as the distance between $C_p$ and $C_g$ increases. The lift and the drag forces move the nose back towards the flight direction. Engineers call this as a restoring action/force because the forces 'restore' the vehicle to its initial condition and nullify the action of disturbing forces to maintain the stability.

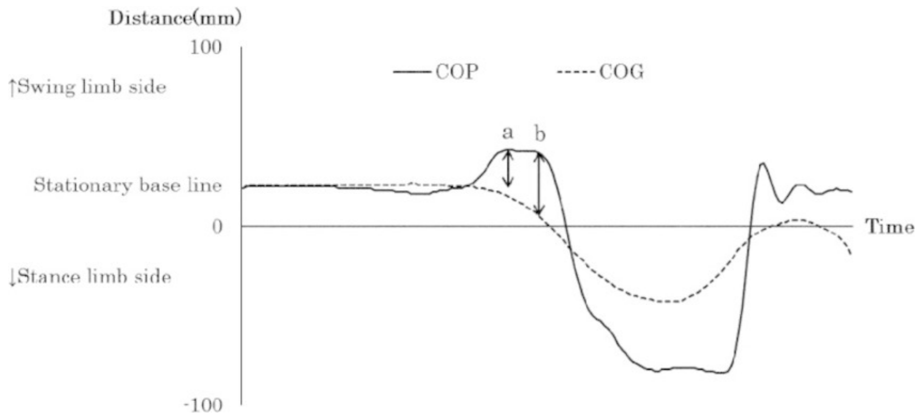



Figure 4: Centre of pressure and Centre of gravity versus time plot

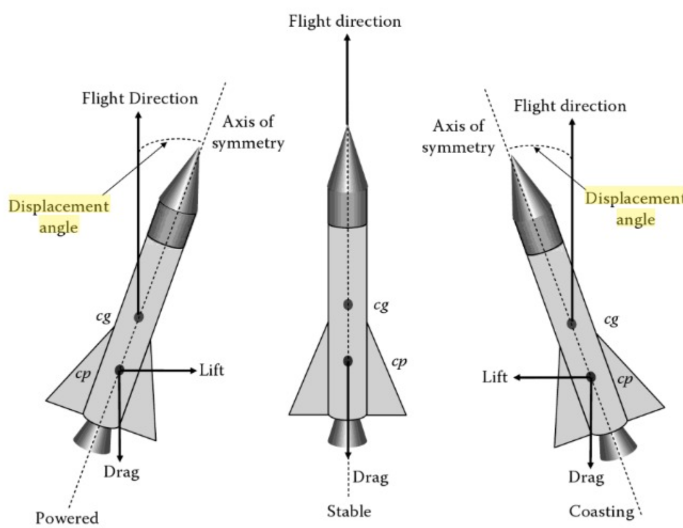



Figure 5: Positions of Centre of Pressure and Centre of Gravity in Rocket

As we can see int the figure 1, there certain strands of time where the $C$P is above $C$g which leads to instability in the flight which is counteracted and handled by engines.

A restoring force exists for the rocket because the center of pressure ($C_p$) is below the center of gravity($C_g$). If $C$P is above Cg at any time of flight, the lift and drag forces maintain their directions but the direction of the torque generated by the forces are reversed. This is called a de-stabilizing action/force. Any small disturbance in such condition can cause the rocket to completely loose its trajectory. One of the most trusted way to ensure stability is to add fins to the design so as to ensure that $C_p$ remains below $C_g$ throughout.

# Re-Entry

## 13 Re-entry

As much as going to space fascinates people, re-entry of spacecraft is one of the most important part of a space mission. In early days, rockets were not that powerful and only could obtain sub–orbital hops. But our modern rockets are capable of obtaining higher earth orbits.

### 13.1 Modes of re-entry

- **Ballistic re-entry:** It is like normal projectile motion. The only forces involved in it are gravity and drag. While re-entering vehicle heats up rapidly and experiences extreme g-force. In ballistic re-entry the vehicle spends very less time in the atmosphere, so it needs high deceleration. This high deceleration and extreme g-force make this kind of re-entry very unsuitable for human flights.

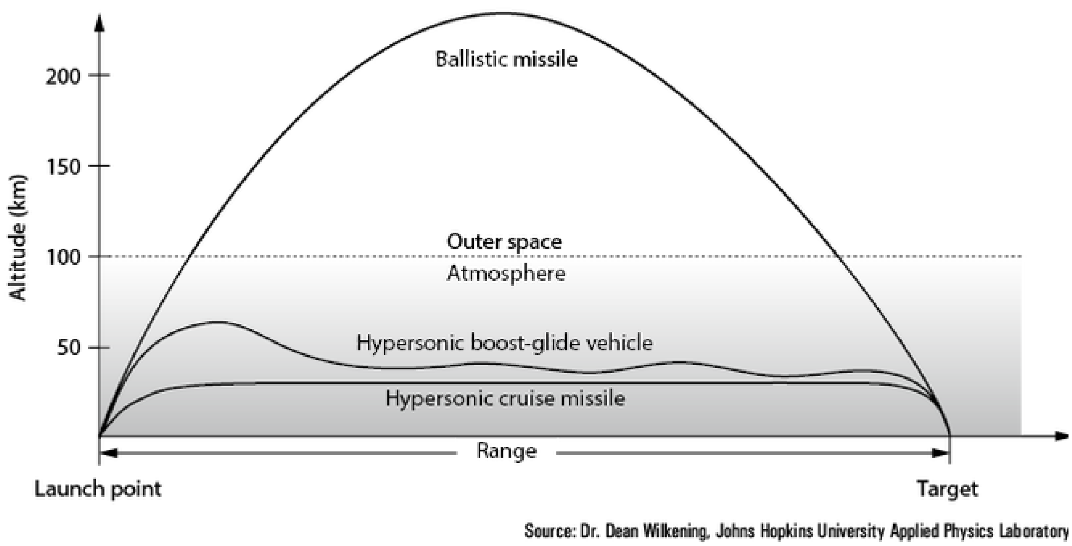



Figure 6: Ballistic trajectory (**?** )

- **Aerodynamic re-entry:** In addition to the gravity and drag force the spacecraft also introduces other forces while re-entering, to increase flight duration in atmosphere. During re-entry the spacecraft bleeds off most of its velocity in upper atmosphere and then plunges into the lower atmosphere with a lower velocity. Velocity, generated heat and experienced g-force during re-entry is lesser than that of ballistic re-entry which makes it more befitting for a crewed mission.

### 13.2 Factors during re-entry

- **Deceleration:** The structure and payload of spacecraft control its maximum deceleration. If it had a higher deceleration it will slow down rapidly and heat-up quickly and experience too much drag. But if a craft has a very low deceleration and it doesn't slow down enough then it may bounce off to the space.(**?** )

- **Heating:** During re-entry pods move with hyper-sonic speed which doesn't give time to the air in front of the pod to move aside and create friction. This air compression generates heat. The temperature can go up to 5000℃-6000℃. In fact, the compression generates shock waves, which causes heat to form plasma. This shock region is produced at a distance from the craft which is proportional to the curvature of the heating surface. So, temperature of the pod is not that high ( 1000℃-1200℃). Some air which escapes from the side, cause friction to the upper part of the pod.

### 13.3 Heat-shields: safety measurements

Heat-shields are designed to protect the spacecraft from excessive heat generated during re-entry. Heat-shields uses mainly two mechanisms: *thermal insulation* and *radiative cooling*. Some of the heat-shields used in modern rockets:

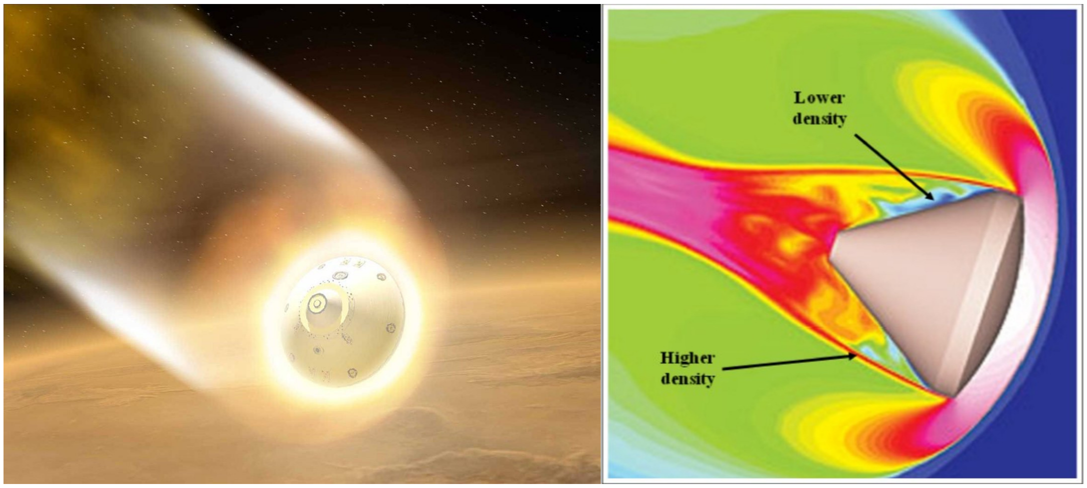



Figure 7: Heat during re-entry (? )

- **Insulation blankets:** The primary purpose of these are to protect the crew from engine noise and high temperature. These are lightweight, flexible, easier to maintain, replaceable and they firmly hold onto the body. They are particularly used for the fuselage wall cavities of the spacecraft, where the temperature is comparably below 649°C.
- **Insulation tiles:** These reusable insulation tiles are made from pure quartz sand. It prevents heat transfer to the underlying orbiter aluminium skin and structure. These tiles are very poor heat conductors and used where temperature is below 1260℃. These tiles are not mechanically fastened to the vehicle, but glued. So, they have a tendency to fall off which can be sometimes catastrophic.

Figure 8: Insulation blankets and insulation tiles (? )

- **Reinforced carbon-carbon:** These are made from carbon fibres reinforced in matrix of graphite. It can withstand re-entry temperature up to 1510℃ and comparably heavy and stronger than the tiles. Usually used on wing leading edges and nose cap, where the craft experience very high temperature.
- **Ablative heat shields:** An ablative heat shield consists of pyrogenic material when heated up it produces certain gases. When the outer surface is heated to a gas, it burns off, which then carries the excess heat away. Some models used in space -missions:

  1. SLWA
  2. AVOCOAT
  3. PICA

- **Regenerative cooling:** This method is thought for cooling the combustion chamber. As, the propellants used in rockets are often cryogenic it can be passed through tubes, channels around the combustion chamber to cool the engines. But still it's an experimental technology.

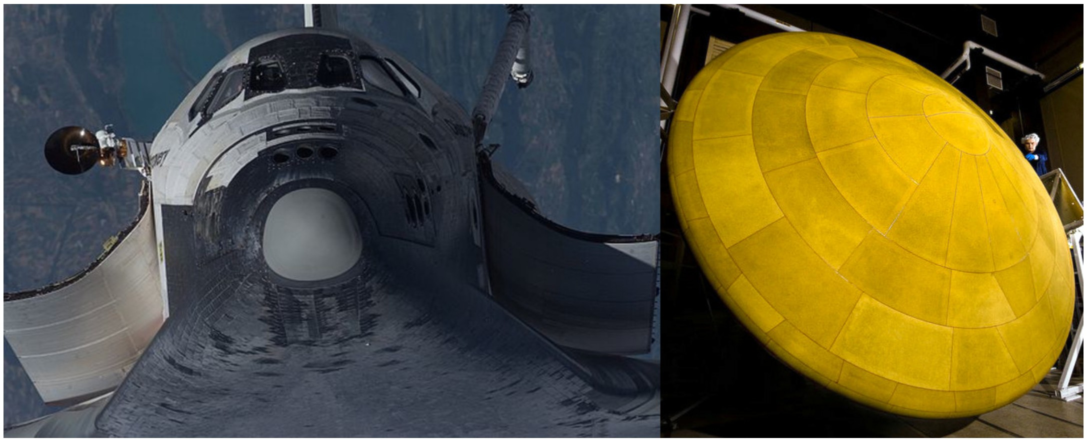


Figure 9: RCC used on nose cone of a vehicle and PICA (**?** )

# Rocket Equation

## 14 Rocket Equations

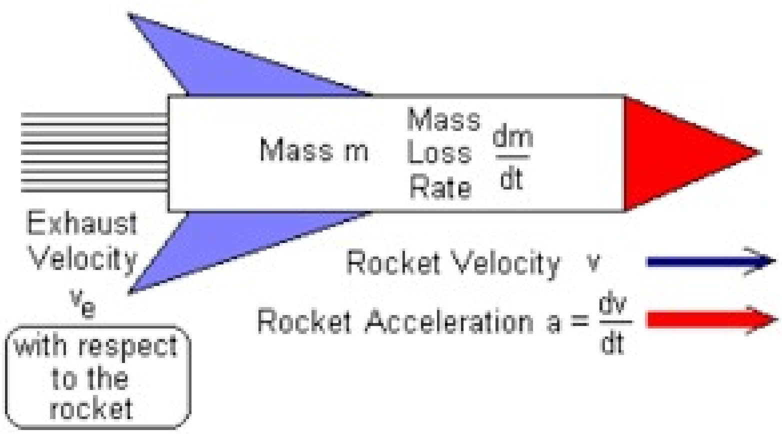
### 14.1 Ideal case

The two major considerations for ideal rocket equation taken are:-

- Conservation of mass
- Conservation of momentum

thus we get,

$$M.(\frac{dv}{dt}) = \frac{dM}{dt}.(-v_{ex}) \tag{1}$$




*where $M$ is the* ***mass of the rocket*** *and $v_{ex}$ is the velocity of the dm mass of the propellant i.e.* ***exhaust velocity****.*

On further solving equation (i),we get,

$$\Delta V = V_{ex}.ln(\frac{M_o}{M_f}) \tag{2}$$

[$v_{ex}$ is somewhat constant at steady state arrival]

here, $M_o$–**initial mass of rocket**, $M_f$**-final mass of rocket** and $v$ is the destination velocity i.e, orbital velocity where the rocket is supposed to land.

We can also get the **mass of the propellant**, $\Delta M$ required for the entire journey by the formula below:-

$$\frac{\Delta M}{M} = 1 - e^{(\frac{-\Delta v}{v_{exhaust}})} \tag{3}$$

# 15 Specific Impulse

In the language of ROCKET SCIENCE, specific impulse, $I_{sp}$ can be defined as "the efficient use of propellants in rockets/spacecrafts and fuels in jet engines". It is thus the measure of how proficiently a reaction mass creates thrust.

## 15.1 Formulation

$$I_{sp} = lim_{\Delta t \to 0} \frac{F_{thrust}.\Delta t}{M_p.g_o} \tag{4}$$

*$M_p$ is the mass of propellant and $F_{thrust}$ is the thrust.*

The above formula could be used to get the destination velocity $V$ as well which is given by:-

$$\Delta V = I_{sp}.g_o.ln(\frac{M_o}{M_f}) \tag{5}$$

NOTE: $1 - (\frac{M_o}{M_f})$ is the **mass ratio of payload**.

# 16 Non- Ideal Scenarios

## 16.1 Inclusion of the effect of gravity

Once the factor of gravity is incorporated, the rocket equations undergo a drastic change. Everything once again starts from the baseline i.e., Newton's Laws of Motions with the consideration of acceleration due to gravity, $g$ along with the thrust produced by the propellants.

Thus by using $a = \frac{dv}{dt}$ and thrust $= -c.(\frac{dm}{dt})$, the velocity of the rocket can be easily calculated as:

$$v = c(ln\frac{1}{\mu} - \frac{1-\mu}{n}) \tag{6}$$

where constant $\mu$ is equal to '**propellant mass fraction**' and $n$ is equal to $(\frac{F_{thrust}}{m_o g})$.The above expression could be integrated to get the displacement $z$ of the rocket.

At the burn-out time (when all propellant is consumed), rocket will coast in free flight and would follow some trajectory. Hence, we can obtain the **energy per unit mass**, $E$ as a function of $\mu$ by satisfying the Kepler's laws.

$$E = \frac{v^2}{2} + gz \tag{7}$$

Since $0<\mu<1$, $1\text{-}\mu - ln(\frac{1}{\mu})$ is negative. Hence reducing $n$ implies applying smaller thrust for a longer time, which gradually, deteriorates the final energy of the payload. To overcome this problem, we define an **Initial Ideal Impulsive Velocity ($V_o$)** and an **Equivalent Real Impulsive Velocity ($V_{eq}$)**, *where impulsive means at the ground level without much gravitational potential.*

$$(v_o)_{eq} = c\sqrt{(ln\frac{1}{\mu})^2 + \frac{1-\mu-ln(1/\mu)}{n}} \tag{8}$$

On comparing the (**change in Impulsive velocity with respect to ideal impulsive velocity**) with the '$n$' value for various values of $\mu$, we observe that as $n$ decreases, $\mu$ starts to increase making a curve.

| | $\mu = 0.7$ | $\mu = 0.5$ | $\mu = 0.3$ |
|---|---|---|---|
| $n = 1.5$ | 0.3628 | 0.3188 | 0.2676 |
| $n = 3$ | 0.1615 | 0.1444 | 0.1235 |
| $n = 10$ | 0.0456 | 0.0410 | 0.0354 |

Figure 10: Values of $\mu$ and $n$ taken

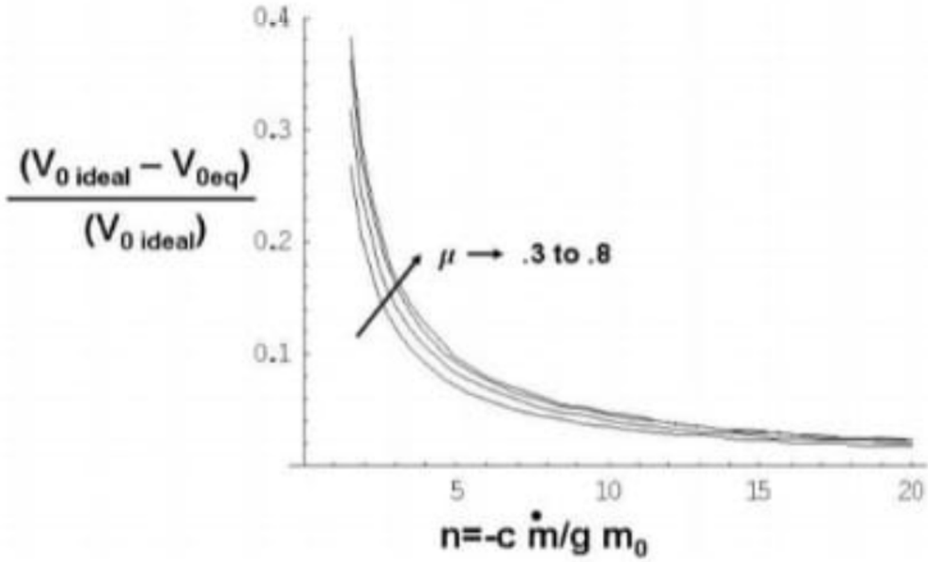



Figure 11: $(\frac{V_{oideal}-V_{oeq}}{V_{oideal}})$ *v/s 'n' curve*

Hence by by simple calculations we can easily measure the exchange in the impulsive velocities and the the graph shown below.

## 16.2 Gravity along with Drag

The effect of the drag force, $D$, is harder to quantify. It turns out that for many important applications drag effects are very small. The drag force is characterized in terms of a drag coefficient, $C_D$. Thus,

$$D = \frac{1}{2}\rho v^2 A C_D \tag{9}$$

where $A$ is the cross-sectional area of the rocket. The air density changes with altitude $z$, and may be approximated by, width=0.4centerrocket 2

$$\rho = \rho_o e^{-z/H} \tag{10}$$

where $H \approx 8000$ m is the so-called "scale height" of the atmosphere, and $\rho_o$ is the air density at sea level.
It is interesting to note that the effect of drag, losses contrary to what one might believe, is usually quite small, and it is often reasonable to ignore it in a first calculation. In order to see the importance of $D$ versus the effect of gravity, we can estimate the value of the ratio $(\frac{D}{mg})$.

**Let's take an example:** At conditions typical for maximum drag, $\rho \approx 0.25\ kg/m^3$ and $v = 700 m/s$. Considering a rocket of 12,000 $kg$ with a cross section of $A = 1m^2$ and $C_D = 0.2$, we have,

$$\frac{\rho A C_D v^2}{2mg} = 0.021 \tag{11}$$

which indicates that the drag force is only about 2% of the gravity force.

# SSTO + DSTO

## 17 SSTO

Single-Stage-to–Orbit commonly known as SSTO vehicle, was the first proposed launch vehicle to peep into outer space. It reaches Orbit From the surface of a body using only propellants and fluids without expending tanks, engines, or other major hardware. Notable single stage to orbit concepts include Skylon, the DC-X, the Lockheed-Martin X-33, and the Roton SSTO. These vehicles are much easier to achieve on extraterrestrial bodies with weaker gravitational fields and lower atmospheric pressure than Earth, such as the Moon and Mars. They have been acquired from the Moon, the Apollo program's Lunar Module, by several robotic spacecraft of the SovietLuna program.

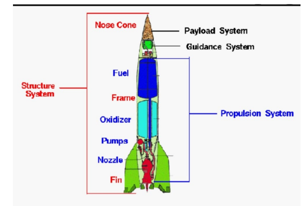



Fig-1: Structure of a SSTO vehicle

## 18 WHY STAGING?

The weight of the propellants is the major contributor to the rocket's weight. As the propellants are burned off during powered ascent, a larger proportion of the vehicle's weight becomes the near-empty tankage and structure required when the vehicle was fully loaded. Thus, the concept of staging has been used to lighten the vehicle's weight to achieve orbital velocity and discard a portion of the vehicle in the process after the burnout.

## 19 DSTO

A double-stage-to-orbit launch vehicle is a spacecraft premised on the concept of a reusable launch system using two rocket stages, each containing its own engines and propellant - provide propulsion consecutively to achieve orbital velocity. The two stages are designed so that the first stage is reusable while the second is expendable. The first stage in the rocket helps in accelerating the vehicle, at liftoff. At burnout of the fuel in first stage, the second stage steadily separates from it and continues to orbit using the fuel of its own. Nowadays, developments are taking place to make them somewhat reusable by retrieving the first stage components. One such example is Falcon 9, which achieved the first-stage reuse of an orbital vehicle.

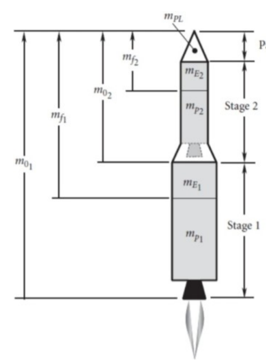



Fig-2: Structure of a DSTO vehicle

## 20 MATHEMATICAL ASPECT

$m_e$- structural part of the rocket stage(empty mass)
$m_p$ - mass of the propellant
$m_{pl}$ - mass of the payload
$m_i$ - mass of the initial mass
$m_f$ - final mass of rocket after burnout
$m_i = m_e + m_p + m_p l$

Certain dimensionless ratios have been defined for a meaningful comparison between the performance of the rocket and its stages.

1. Mass Ratio : the ratio between full initial mass of the stage of the rocket and final mass of the rocket stage, once at burnout - all of its fuel has been consumed. The equation for this ratio is:

$$\eta = \frac{m_e + m_p + m_{pl}}{m_e + m_p l} \tag{12}$$

2. Structural Coefficient : the ratio between the mass of structural part of the rocket stage, and the combined mass of the structural part of the rocket stage and propellant mass used in the stage, as shown in this equation:

$$\epsilon = \frac{m_e}{m_e + m_p} \tag{13}$$

3. Payload Ratio : the ratio between the payload mass and the combined mass of structural part of the rocket stage and the propellant, as shown in this equation :

$$\lambda = \frac{m_{pl}}{m_e + m_p} \tag{14}$$

4. Propellant Mass Fraction : the ratio between the propellant mass and full initial mass of the rocket, as shown in this equation :

$$\zeta = \frac{m_p}{m_i} = \frac{m_i - m_f}{m_i} = 1 - \frac{m_f}{m_i} \tag{15}$$

It can be easily observed that they are dependent on each other and, on further calculations following relation is obtained :

$$\eta = \frac{1+\lambda}{\epsilon+\lambda} \tag{16}$$

These performance ratios can also be used as references for the efficiency of the rocket during performing optimizations and comparing configurations for analysis.

*In Restricted Staging, all stages are similar with each stage having the same specific impulse $I_{sp}$,same structural coefficient $\epsilon$ , same payload ratio $\lambda$ and hence same mass ratio $\eta$.

## 21 SSTO vs DSTO

The main advantage of SSTO's over DSTO's is that they can be made fully reusable, i.e., they can be sent to orbitals and can be reused many times on return, thus reducing the launch costs to a great extent. On the other hand, DSTOs have many advantages over SSTOs. As the first stage components get detached after the propellant is burnt, the total mass carried to the orbitals includes mainly the payload mass and no dead mass (the mass of the empty propellant tank as in SSTOs). Thus the high payload ratio of DSTO's indicates that we can send a large amount of payload with a small amount of propellant. Plotting a graph between the total initial mass of the rocket and structural coefficient shows that SSTO's require smaller structural coefficients than DSTOs when launched with the same payload mass and same propellant to achieve the same delta-v. However, currently, a structural coefficient of less than 0.1 is not attainable, limiting the structural efficiency of SSTOs.

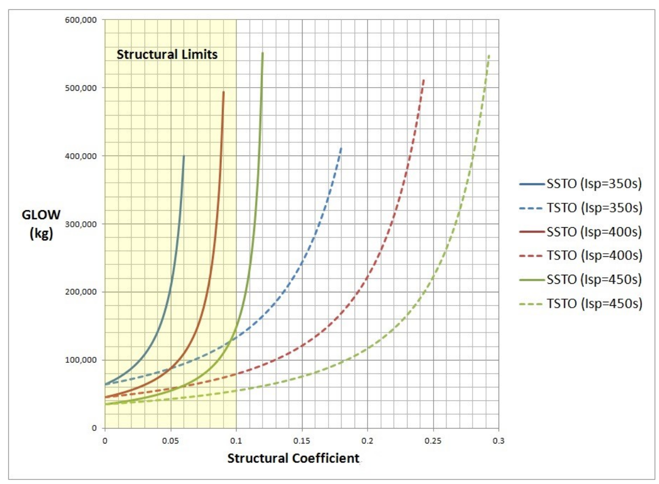



Fig-3: GLOW vs Structural Coefficient

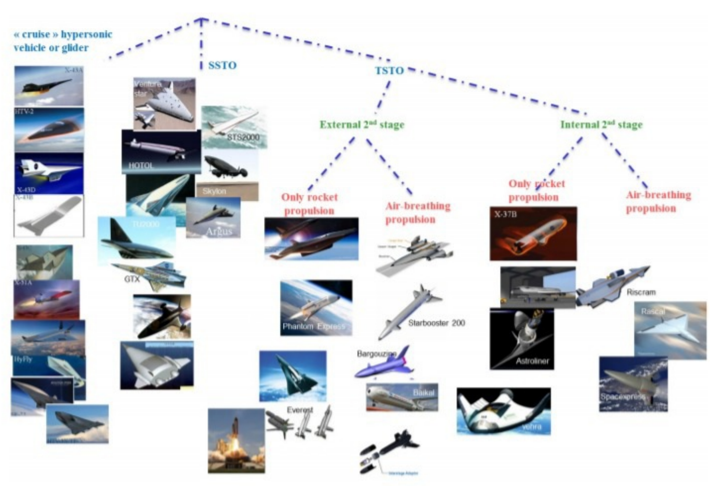



Figure 12: Complete review of SSTO and DSTO Rockets

# Structural

## 22 Basic Structure

Structural system is one of the four major components of a full-scale rocket. The structural system of a rocket includes all of the parts which make up the frame of the rocket; the cylindrical body, the fairings, and any control fins. It transmits the load from the forces generated during the flight and provides low aerodynamic drag for the flight.

## 23 Dynamic Pressure

Dynamic pressure depends upon the velocity of the rocket and density of air.As the rocket rises, the velocity increases, thus the dynamic pressure increases to some maximum point called Max Q. It is given by $q=(v^2)/2$, where q is the dynamic pressure  is the air density and v is the velocity of the rocket. After this point the air density decreases due to which the dynamic pressure decreases.It is an important property that helps structural engineers to design rockets and to determine the minimum aerodynamic strength of the rocket so as to avoid buckling.

## 24 Buckling

Buckling is the sudden deformation in structural components due to excess load. It can cause complete collapse of that component. Structures can be internally pressurized to keep the walls from buckling. The net stretching force due to internal pressure is made is made greater than the compressional force due to flight loads so the walls experience no compression and buckling can be avoided. Sometimes thin skin panels are used to continue carrying load even in the buckled state.

## 25 Materials Used

1. The frame, is made up of strong, but lightweight materials such as aluminum or titanium as the performance of the rocket depends directly on the weight of the structure.
2. These are high density materials which can be stretched into thin sheets while maintaining their strength. They are also resilient to high temperatures.
3. The fins are attached to the bottom for stability during the flight.
4. It is also coated with a thermal protection system, to keep out heat of air friction during the flight.

## 26 Future Advancements

1. New advancements in making the frame of the rocket by using materials such as beryllium and composite materials using high strength filaments.
2. The best current high-temperature metals, e. g., nickel and ferrous alloys, may soon be replaced by molybdenum.
3. Ceramics such as carbides have very high melting points and show much promise for high-temperature use.

Relatively brief encounters with a hot environment can be survived by the protection method, as in the insulation of rocket nozzles and reentry nose cones.

# Kerbal Space Program

## 27 What is Kerbal Space Program(KSP)?

It is a ***spaceflight simulation game*** based on a planet named **Kerbin**(Analogous to Earth) and other heavenly bodies in the solar system. It has a realistic physics engine and hence serves as a great medium to get a feel of space technology, orbital manoeuvres, Space Vehicles like rockets, aircraft, space planes, rovers etc. The game is very well suited to plan a full-fledged Space Mission and is very detailed in terms of features in control systems, specifications and performance of parts used in making the vehicles.

Figure 3:

Even NASA embraced this game as the authentic simulations would help inspire a generation of interstellar explorers. This is why we have used it to simulate the concepts we learned during the lectures conducted.

## 28 Limitations of KSP:

Being a game to simulate real-life space exploration experience, it does have a few shortcomings in itself, which brings some deviation from reality:

- Kerbin, being quite smaller in radius than Earth(Nearly 600 km only), but nearly the same gravity as Earth, makes it denser than Earth.
- The specific impulse $I_{sp}$ remains constant throughout, but in real life, it is dependent on mach number and varies constantly.
- The planetary distances are also lesser than the actual ones.

# 29 Mission Planning in KSP - Going to the Mun:

The mission given to us as a part of our project was to design a space mission that carried Kerbals to the mun, make a soft landing on the mun and bring the spaceship back safely to Kerbin. So we created a 3 stage rocket for this purpose. The full mission can be illustrated in the following steps:

- The pair of solid boosters provided the initial thrust, ensuring that we did not run out of fuel in the later stages. Around 2 minutes and 12 seconds after lift-off, the solid rocket boosters were separated as they ran out of fuel and will act as dead weight if we carry them any further.
- The rocket was tilted to achieve the required horizontal velocity to orbit around Kerbin. At around 3 minutes and 33 seconds, the rocket altitude was 70,000 m which is the height required for the low Kerbin orbit.
- The protective fairing was then separated safely as there is no more atmospheric drag that could damage the delicate instruments.
- When the rocket neared its apoapsis, a pro-grade burn was performed to achieve an orbit around Kerbin, and we finally reached the orbit at around 5 minutes and 41 seconds after liftoff.
- Then a trans-mun injection orbit manoeuvre was designed, which was later established. After the manoeuvres were demonstrated, we did a pro-grade burn at the required time and got it into a trans-mun injection orbit.
- After this, the rocket went from the Kerbin's sphere of influence to the mun's sphere of influence. ON reaching the periapsis of the mun, a retrograde burn was performed to slow down and get a stable orbit around the mun.
- Further retrograde burns were done to get a trajectory intersecting with its surface.
- Then the landing struts were extended to land safely on the mun's surface.
- We waited for the altitude respective to mun to decrease and performed retrograde burns at the appropriate time to slow down the velocity and make a soft landing.
- After landing successfully, the ladders were deployed to get the Kerbals down safely on the surface of mun. After some time, they boarded back on the spacecraft, and it was time to return to Kerbin.
- And we lifted off from the mun and achieved an orbit around the mun.

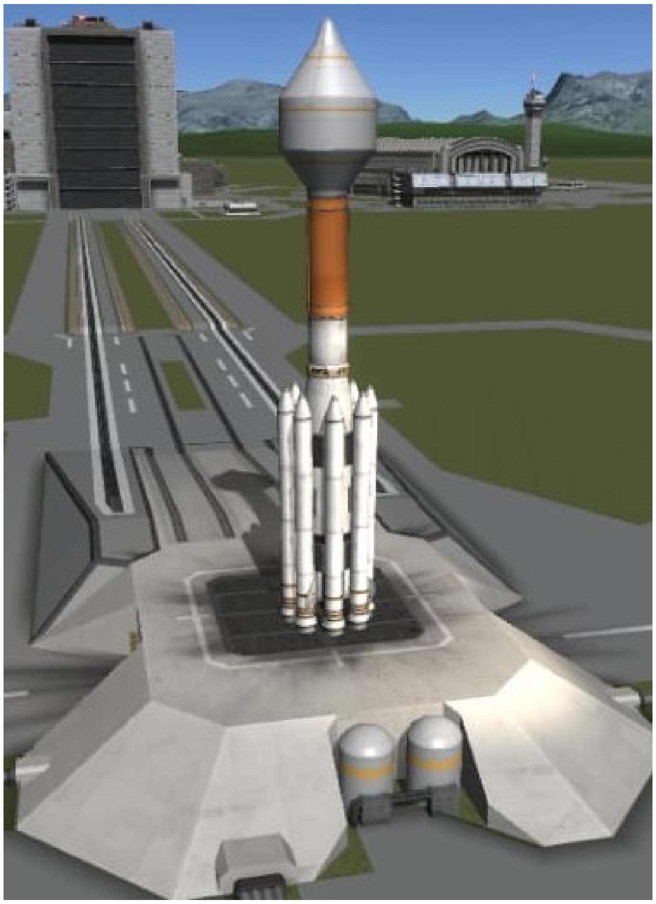


Figure 5: Before Launch

## 30 Components of the rocket used:

Mk1-2 Command Pod, Mk16-XL Parachute, AE-FF2 Airstream Protective Shell (2.5 m), Heat Shield (2.5 m), Rockomax Brand Decoupler(x2), Advanced Reaction Wheel Module(Large), Z-4K Rechargeable Battery Bank, Rockomax X200-16 Fuel Tank, Rockomax X200-8 Fuel Tank, TR-XL Stack Separator, Mk-55 “Thud” Liquid Fuel Engine (x3), LT-2 Landing Strut (x3), OX-STAT Photovoltaic Panels (x3), RE-L10 “Poodle” Liquid Fuel Engine, Double-C Seismic Accelerometer, 2HOT Thermometer, Rockomax Jumbo-64 Fuel Tank, RE-M3 “Mainsail” Liquid Fuel Engine, Mk3 to 2.5 m Adapter, Mk3 Rocket Fuel Fuselage, Mk3 Rocket Fuel Fuselage Short, S3 KS-25x4 “Mammoth” Liquid Fuel Engine, Hydraulic Detachment Manifold (x8), S1 SRB-KD25k ”Kickback” Solid Fuel Booster (x8).

## 31 Future Goals

Further, we would like to increase the efficiency of the missions we take up. Also, the next spot we will be aiming is to Kerbol(Analogous to Mars).

# Trajectory Optimization

## 32 Trajectory Optimization

Have you ever wondered about why rockets follow a parabolic path rather than going vertically ? Well if you want to launch a rocket vertically and just keep it going then it will reach desired altitude but after fuel gets over it will fall back due to earth’s gravity,so we need a tangential component of velocity to stay in orbit.Rockets are launched vertically to get out of the thick lower atmosphere as quickly as possible. Then they perform a **pitch-over maneuver** and gain some forward velocity. It could save fuel.

Rockets are defined by many variables and constraints, and ultimately deliver a payload to orbit at some cost. These characteristics provide the basis for an optimization problem

**Maximize J1 = Payload Mass (metric tons) Minimize J2 = Cost** ($ ) The trajectory subsystem takes in several inputs and calculates the fuel usage and final altitude via the shooting method. It uses the ODE with a state vector composed of radial position, radial velocity,longitude, angular velocity, and mass. The model calculates the changes in velocity using the thrust, gravity, and drag applied at the correct angles.

So, in overall define **state vector** being :

$$\mathbf{X} = [\ \mathbf{r}\ \theta\ \mathbf{v}\ r\ \mathbf{v}\ t\ \mathbf{m}\ ]$$

where, **r** = geocentric distance $\theta$ = right ascension ( Angular Displacement from launch pads initial position ) **v** $r$ and **v** $t$ being radial and transverse velocity components. For position vector, we define (**ECI**) $earth - centredinertial$ coordinate system while velocity vector being in (**LVLH**) $Local - Vertical - Local - Horizontal$ frame.

The resulting equations of motion $\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{u}, t)$ are:

$$\dot{r} = v_r$$

$$\dot{\theta} = \frac{v_t}{r}$$

$$\dot{v}_r = \frac{v_t^2}{r} - \frac{\mu}{r^2} + \frac{T_a}{m}\hat{T}_r + \frac{T_b - D}{m}\frac{v_r}{v_{rel}}$$

$$\dot{v}_t = -\frac{v_r v_t}{r} + \frac{T_a}{m}\hat{T}_t + \frac{T_b - D}{m}\frac{v_t - \omega_E r}{v_{rel}}$$

$$\dot{m} = -\frac{T_{vac}}{c}$$

Trajectory optimization, which uses gravity as the driving force to steer the rocket into a particular trajectory.

During the gravity turn phase of the ascent trajectory the thrust direction is forced to be parallel to the relative velocity. In order to maintain the same equations of motion across all phases, the thrust magnitude T is fictitiously split into two attributes,Ta and Tb . Ta represents the optimally controlled thrust contribution, while Tb is always parallel to the relative velocity. It can be noticed that Ta and Tb are alternatively null: during the zero-lift arcs Ta is zero, while Tb is equal to the real thrust magnitude; conversely,Ta=T and Tb=0 during the other propelled arcs.

It offers two main advantages over a trajectory controlled solely through the vehicle's own thrust. First, the thrust is not used to change the spacecraft's direction, so more of it is used to accelerate the vehicle into orbit. Second, during the initial ascent phase the vehicle can maintain low or even **zero angle of attack**. This **minimizes transverse aerodynamic stress on the launch vehicle**, allowing for a lighter launch vehicle

### Optimization method (using MOGA model)

In order to populate a Pareto front, a multi-objective genetic algorithm (MOGA) was used.This heuristic technique was chosen because discrete design variables such as material type and propellant type were used, and genetic algorithms handle discrete variables well. The two objectives were to **maximize J1 (payload mass)** and **minimize J2 (cost).**

## References

[1] https://bit.ly/3c0awqk