Rocketry

Revision 1.00

Chapters

1. Introduction
2. Applications of Rockets
3. Principles of Rocket Motors
4. Types of Rocket Motor
5. Rocket Structures and Systems
6. Launch Vehicles
7. Model Rockets

Chapter 1
Introduction

Early History

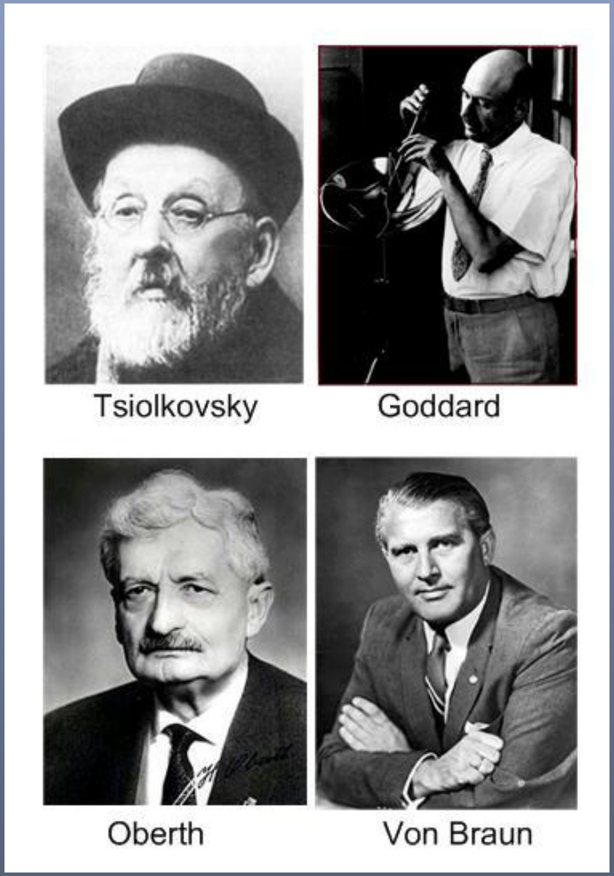
- 9^{th} Century
  - Chinese use gunpowder motors to extend the range of arrows
- Mongols bring rocket weapons to the west
- Rockets used at siege of Constantinople in 1453
- Congreve’s rockets bombard Copenhagen in 1807

- Royal Navy fires Congreve’s rockets at Fort McHenry, Baltimore
  - The “rockets’ red glare” in the American National Anthem
- William Hale improves accuracy by spinning rocket in 1844
  - rockets remain less accurate than artillery

20^{th} Century

- The control and guidance of rockets improved by new technologies:
  - Liquid and gaseous propellants
  - Gyroscopic guidance
- Liquid & gaseous propellants allowed control over the thrust of a rocket
- Gyroscopic guidance greatly improved the accuracy of rockets

The dawn of modern rocketry



The 4 founders of modern Rocketry:

- Konstantin Tsiolkovsky
- Robert Goddard
- Hermann Oberth
- Wernher von Braun

The Dawn of Modern Rocketry

- **Konstantin Tsiolkovsky** established the principles for high powered, multi staged, rockets in Russia
- **Robert Goddard** built and launched the first liquid fuelled rockets and developed many of the ideas used in modern rocketry
- **Hermann Oberth** developed the basic mathematics of rocket propulsion
- **Wernher von Braun** developed the basic technologies for practical rocket propulsion in Germany
- **Robert Esnault-Pelterie** researches rocket technology in France and champions

Robert Goddard's 1926 Rocket

- This is the first liquid fuelled rocket with its creator, Robert Goddard.
- A few minutes after this picture was taken the rocket was successfully launched, leading ultimately to the space age.

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World War 2

- Von Braun developed the V2 rocket for the Germans
- The V2 was a German weapon which was used to attack London from the safety of Northern Europe.
- This was the first mass produced rocket.

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The Space Race

- After WW2 Russia and America developed **Intercontinental Ballistic Missiles (ICBM)** to deliver nuclear weapons into each other's territory.
- In October 1957 Russian scientist called **Sergei Korolyov** used one of his *R-7* ballistic missiles to launch the first satellite, Sputnik.
- On 12th April 1961 a Russian pilot, **Yuri Gagarin**, became the first man to travel in space. He was launched to orbit on a modified *R-7* ICBM.

The Space Race

- On 25th May 1961 The American president, John F Kennedy, committed America to land a man on the Moon
- A new and larger rocket was needed, and Von Braun developed the largest rocket ever built: the **Saturn V**
- on 20th July 1969 when **Neil Armstrong** and **Buzz Aldrin** walked on the moon

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Saturn V

- The Saturn 5 is the biggest rocket ever made:
  - over 110 meters tall
  - weight over 3 million kilogrammes
  - over 6 million components
- The world's largest building had to be built in order to assemble a Saturn V.
- The building was so large that Wembley Stadium would fit on its roof.

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Exploration of Space

- Spaceflight has many scientific and technical applications:
  - international communications
  - the Global Positioning System (GPS)
  - astronomy
  - better weather forecasting
  - earth observation

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Exploration of Space

- Manned spaceflight supporting space stations:
  - **Skylab** (America)
  - **Salyut** (Russia)
  - **Mir** (Russia)
  - **International Space Station** (ISS – many nations)

Exploration of Space

- Larger rockets built to launch increasingly large spacecraft:

Atlas (America) **Ariane**(Europe).
Delta (America) **Zenit** (Russia)
Titan (America) **Cosmos** (Russia)
Long March (China) **Proton** (Russia)
H-2 (Japan) **GSLV** (India)

Chapter 2
Applications of Rockets

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Applications of Rockets

- Rockets are vehicles, and like all vehicles they exist to move things, for example:
  - Move a scientific instrument from the ground into the upper atmosphere
  - Take astronauts to space (and back)
  - Fire a rescue line between two ships
  - Place a weapon onto a target
  - Eject a pilot from a damaged aircraft

Applications of Rockets

- An object carried by a rocket for peaceful purposes is called the **payload**
- An object carried for military purposes is called a **warhead**

Uses of rockets

- Military rockets and missiles
- Rocket cars
- Rocket Planes
- Flares
- Space flight
- Rescue
- Entertainment
- Hobby and amateur rockets
- Transportation

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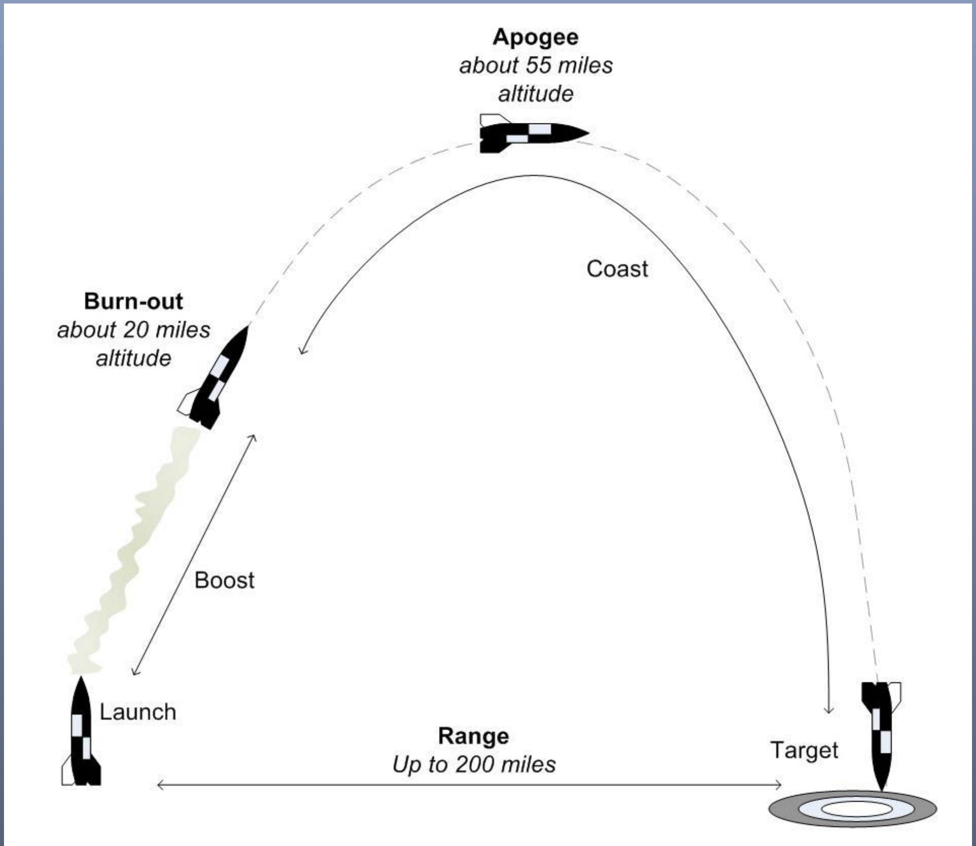
Military Rockets and Missiles

- Military rockets are **unguided** weapons
  - they have no ability to steer themselves towards a target
  - Suitable for static or slow moving targets

Military Rockets and Missiles

- Missiles are **guided** weapons
  - they have the ability to change direction
  - they follow instructions to help them to hit the target
  - Radar, TV, heat sensors are used to locate and home onto targets

Military Rockets and Missiles



- The German V2 was the first rocket to be used as a long range weapon
- It carried a 1 ton warhead for up to 200 miles
- Rocket motor accelerated the V2 to 3000 mph
- It coasted to 55 miles altitude
- The V2 fell ballistically onto its target

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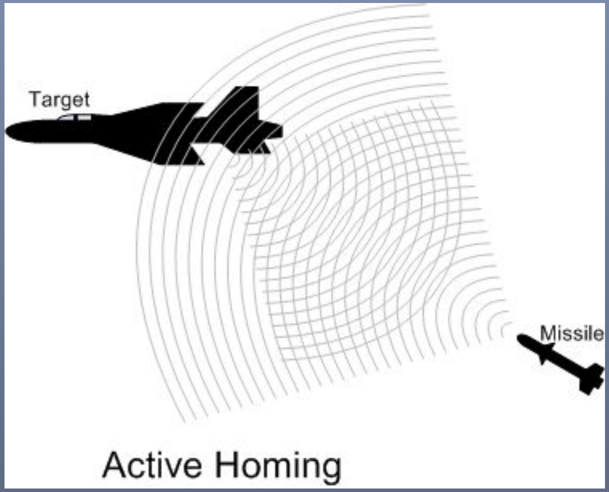
Active Homing



- In an active homing system the missile uses its own radar transmitter and receiver to find and track the target, sending commands to the flight system to steer the missile towards the target.

- A missile with active homing can steer itself onto the target without external assistance

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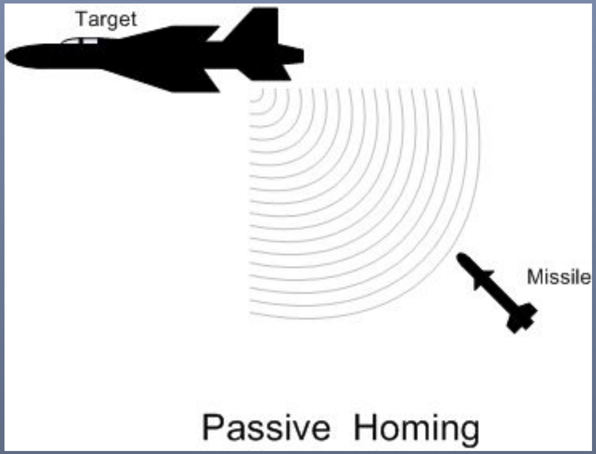
Passive Homing



- In a passive homing system the missile does not transmit, but looks for a signal to indicate where the target is.
- This could be a radio or heat signal from the target itself, radar reflections from another radar, or target illumination.

Military Rockets and Missiles

- **Surface to Air Missile** (SAM). Launched from the ground or ships to attack aircraft.
- **Air to Surface Missile** (ASM). Launched from aircraft to attack targets on the ground.
- **Surface to Surface Missile** (SSM). Launched from the ground to attack targets on the ground.
- **Air to Air Missile** (AAM). Launched from aircraft to attack other aircraft.

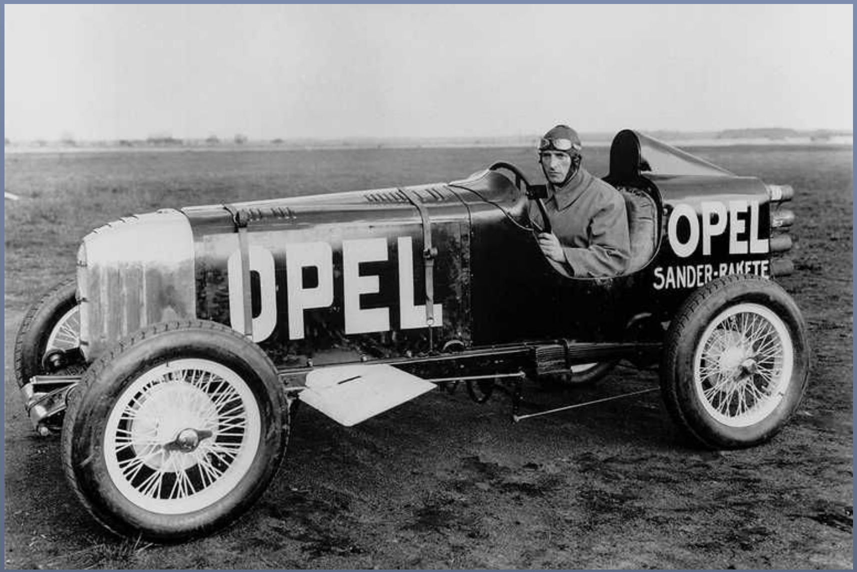
Military Rockets and Missiles

- **Anti Tank Missile**.   Launched from the surface with a warhead specifically designed to penetrate the armour of tanks.
- **Anti Shipping Missile**. launched from the surface, ships or aircraft to attack ships.
- **Ballistic Missile**. Launched from the surface to carry nuclear or conventional warheads to surface targets. ballistic missiles capable of travelling great distances are called **Intercontinental Ballistic Missiles** (ICBM)

Military Rockets and Missiles

- **Anti Shipping Missile**. launched from the surface, ships or aircraft to attack ships.
- **Ballistic Missile**. Launched from the surface to carry nuclear or conventional warheads to surface targets. ballistic missiles capable of travelling great distances are called **Intercontinental Ballistic Missiles** (ICBM)
- **Anti Ballistic Missile**. Surface launched missiles designed to destroy incoming ballistic missiles.

Rocket Cars



- The first recorded rocket car was the RAK-1 made by Fritz Opel in 1928 as a publicity stunt. The car achieved a top speed of 47 mph.
- The fastest rocket car was the Blue Flame which achieved a speed of 622.407 mph at the Bonneville Salt Flats on 23 Oct 1970.

Rocket Sleds

- Rocket sleds are similar to rocket trains as they both run along a track.
- They're used for testing:
  - experimental equipment on the ground
  - ejector seats
  - rocket systems
  - munitions
- The fastest recorded speed by a rocket sled is 6416 mph

Rocket Planes

- Rocket planes offer very high speed but are much less efficient than jet aircraft.
- The Messerschmitt ME 163 is the only mass produced rocket plane
- It was designed to be a rocket powered fighter aircraft.
- It saw service in 1944.

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Rocket Planes

- The X-15 was the first aircraft to fly into space
- Only three X-15 aircraft were made, and one was lost in a crash
- It was used as a test vehicle for many of the ideas which were incorporated into manned spacecraft

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Rocket Planes

- Rocket planes are used at experimental test vehicles.
- The US Government has built a succession of experimental rocket powered aircraft called the “X Planes”
- The first aircraft to break the sound barrier was the rocket propelled **Bell X-1**, piloted by **Chuck Yeager**
- Note the Mach diamonds in the picture

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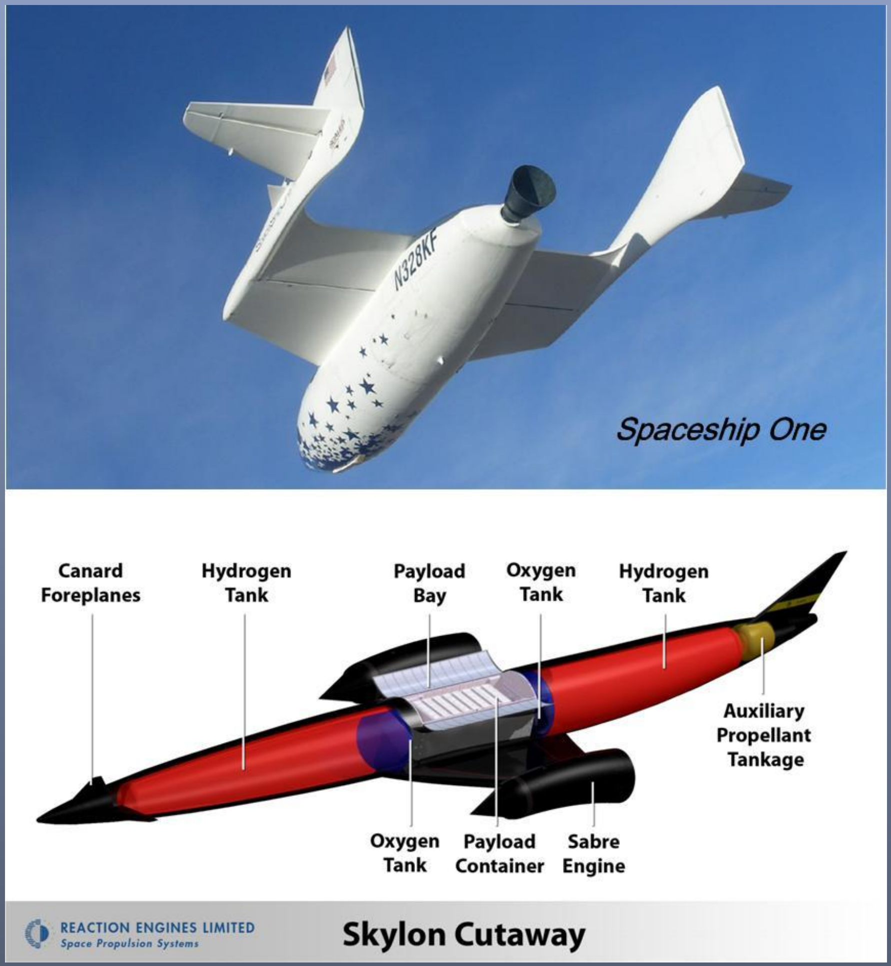
Flares

- Rocket powered flares have may uses:
  - A red flare launched from a ship or small boat is an internationally recognised distress signal
  - Trip flares are used by the military to provide early warning of enemy approaches
- The flare is boosted by a rocket motor and desc ends slowly by parachute

Rocket Planes



- “Spaceship One” was the first privately made rocket plane to fly to space.
- “Spaceship Two”, a larger version of Spaceship One, is designed to offer space tourists for Virgin Galactic
- “Skylon” is being designed in the UK to offer space flight from conventional runways.

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Escape Systems

- **Ejector seats** are installed in many in military aircraft to rapidly remove the pilot from danger.
- Once fired, the seat's operation is automatic, giving an unconscious or injured pilot a good chance of survival

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Escape

- It is impractical to install individual ejector seats into space capsules, so an alternative system is used for manned space missions.
- To prevent setting fire to the capsule the escape system has 3 nozzles so the hot exhaust plume is deflected around the side of the capsule

Spaceflight

- Space begins at the **Karman Line** at an altitude of 100 km (62.1 miles) above sea level.
- At this altitude there is no useable atmosphere so:
  - Air breathing propulsion such as jets and internal combustion engines will not work
  - Aircraft have no atmosphere to develop lift from their wings
  - Balloons have no atmosphere to provide buoyancy
- The only type of propulsion that will get objects into space is a rocket motor.

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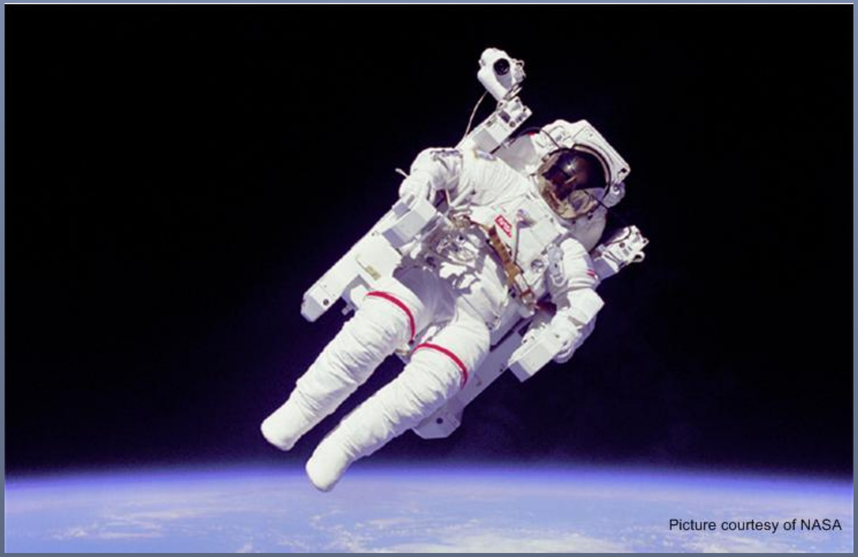
Spaceflight

- Rockets have been used for every type of space mission:
  - launching satellites
  - manned space flight
  - sending probes to other planets
  - exploration of the upper atmosphere
- Rockets that are used to propel objects to orbits outside the atmosphere are called **launch vehicles**.

Rocket Belts



- **Rocket belts** are a type of personal flying machine.
- The limitation of rocket belts is that the pilot can only carry a small amount of propellant, typically enough for only 10 to 30 seconds flight
- Rocket belts have found a practical use in the weightlessness of space. NASA's Man Manouvering Unit (MMU) is a practical rocket belt that has seen extensive use on space shuttle missions.

Chapter 3
Principles of Rocket Motors

Newton's Third Law

- Rocket motors are an example of Newton's third law in practice:
  - *"To every action there is an equal and opposite reaction"*
- For example: stand on a skateboard and throw a ball.
  - The ball goes in one direction (the action)
  - You go in the other direction (the reaction)

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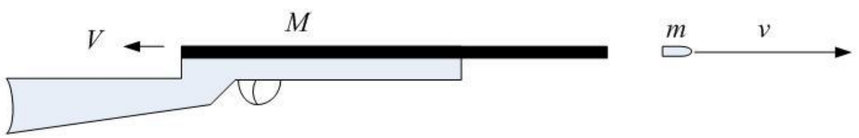
Action and Reaction



Action and Reaction

Action: The bullet travels in one direction

Reaction: The rifle recoils in the opposite direction

- The rifle has a mass M kg and recoils at a velocity V m/s the bullet has a mass m kg and leaves the rifle at a velocity v m/s.
- It can be shown from Newton's laws that:

$$MV = -mv$$

- The minus sign shows that the bullet and rifle travel in opposite directions

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Action and Reaction

- The mass of the bullet multiplied by its velocity is called the momentum of the bullet.
- This equation tells us that the momentum of the rifle is the same as the momentum of the bullet, but in the opposite direction.
- The action (the bullet with momentum mv) has an equal and opposite reaction (the recoil of the rifle with momentum MV in the opposite direction to the bullet)

Action and Reaction

- So what has this to do with rockets?
- Imagine that a rocket motors ejects a mass of *m* of gas every second at a velocity *v*
- The rocket which has a mass *M* will travel in the opposite direction at a velocity *V*

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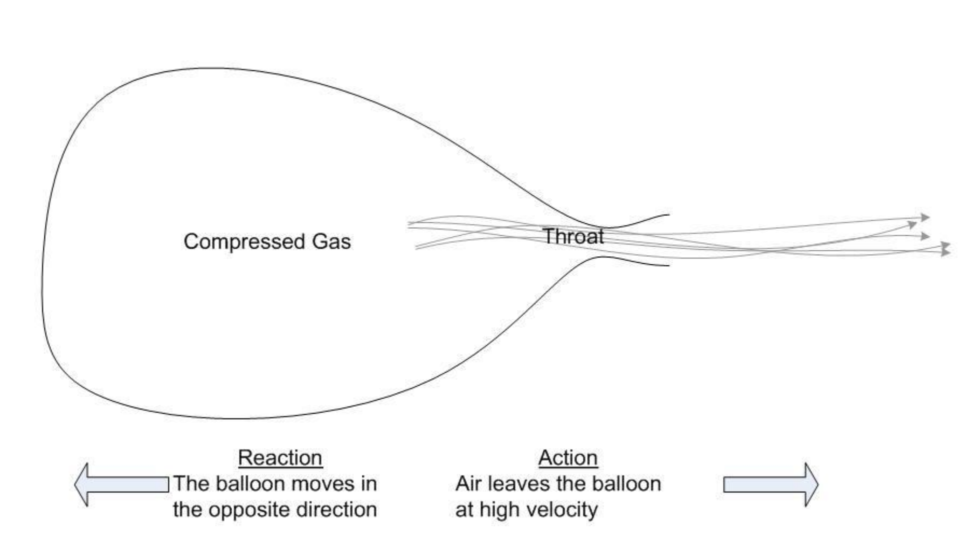
A Balloon "Rocket"



- The gas in a balloon is under pressure and can onbly escape in one direction: through the neck of the balloon (rocket scientists call it the "throat")
- The escaping gas produces an "action"
- The balloon moves in the opposite direction as a "reaction"

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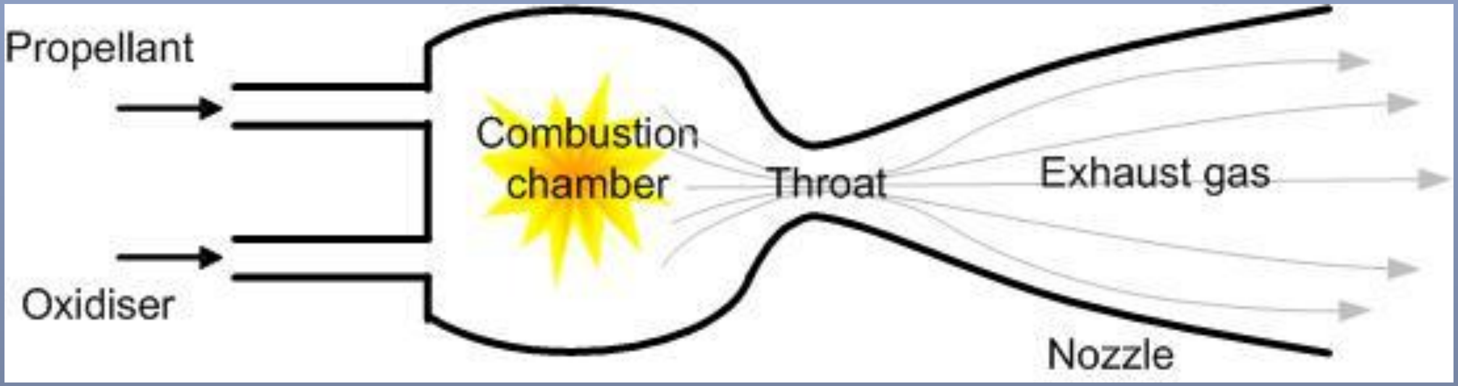
Motor Principles

- Balloons are very inefficient as rocket motors
  - They run out of gas very quickly
  - They don't provide much "action" (called "thrust" by rocket scientists)
- We can improve performance by:
  - Having a continuous supply of gas to provide thrust for a longer time
  - Heating the gas to raise its pressure
  - Make it leave the throat at the highest possible speed to increase the thrust

Motor Principles

- We can create hot gas inside the rocket motor by burning two chemicals:
  - a fuel, called a "propellant"
  - an "oxidiser"
- We burn them inside a "combustion chamber" to produce gas at very high pressure
- The hot gas that results from this combustion escapes through the throat, where it is squeezed to accelerate it to a very high velocity

Motor Principles



- Propellant and oxidiser are pumped into the combustion chamber in the correct ratio.
- The propellant burns in the combustion chamber using oxygen obtained from the oxidiser
- The hot exhaust gas expands through the throat where it accelerates
- The exhaust gas expands in the nozzle

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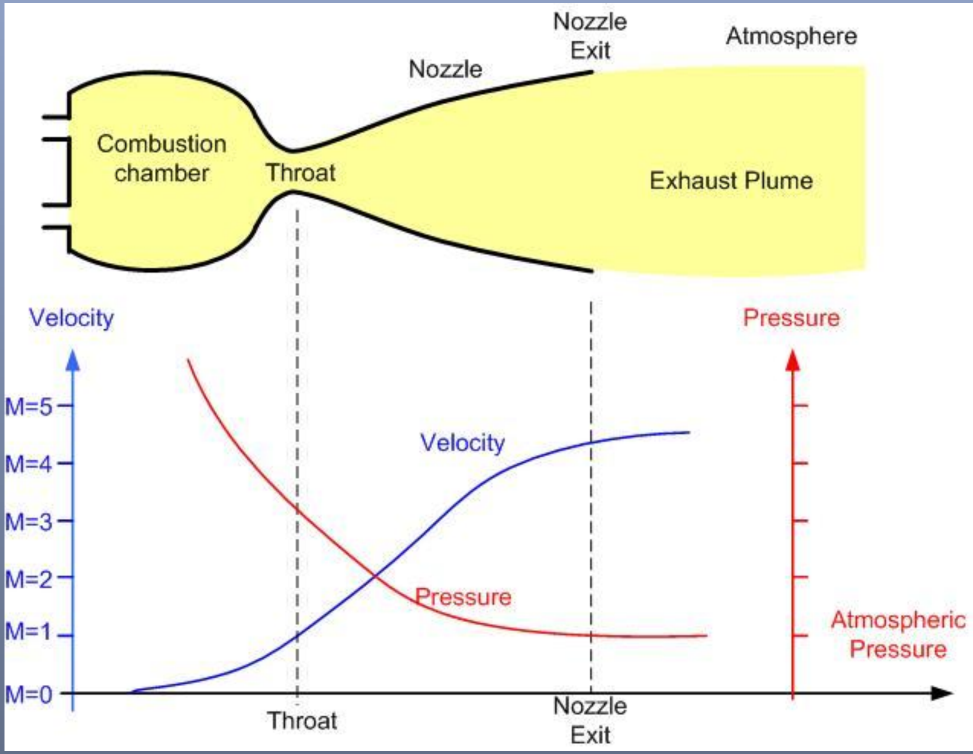
Motor Principles

- **Gustav de Laval**'s nozzle
  - discovered by de Laval in 1897 in Sweden
- Gas can be accelerated to high velocities if:
  - the gas travels at exactly Mach 1 through the throat
  - A bell shaped nozzle allows the gas to expand in a controlled manner
  - The gas pressure at the exit of the nozzle is the same as atmospheric pressure
- Modern rocket motors use the De Laval nozzle to greatly improve performance

Motor Principles



- As the exhaust gas expands through the de Laval nozzle:
  - The pressure of the gas decreases
  - The velocity of the gas increases

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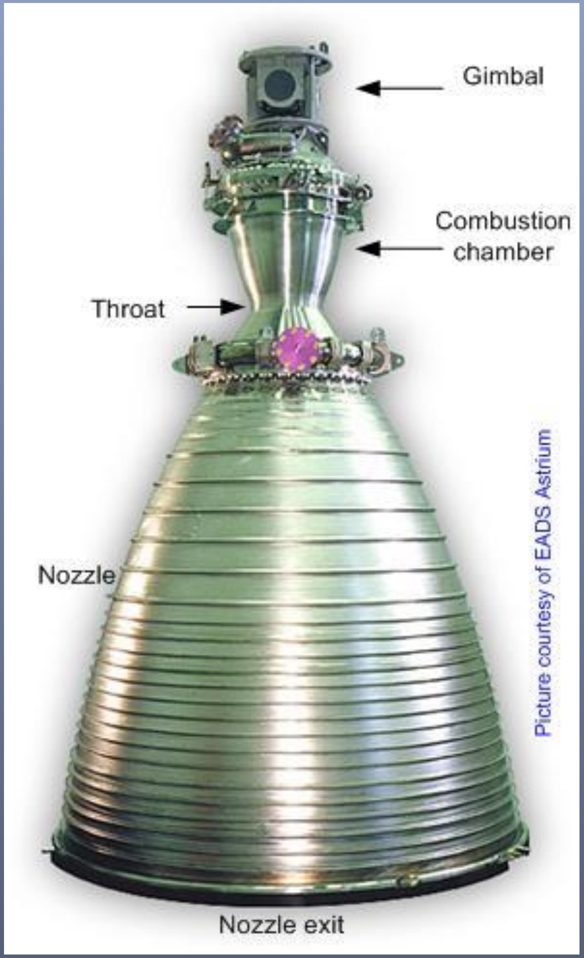
A Real Rocket Motor

- The "gimbal" attaches the motor to the rocket
- The "combustion chamber" is where the propellant and oxidiser are burned
- The "throat" squeeezes the gas and makes it move faster
- The "nozzle" helps to accelerate the gas.
- The picture shows a "Vulcain" motor made by EADS



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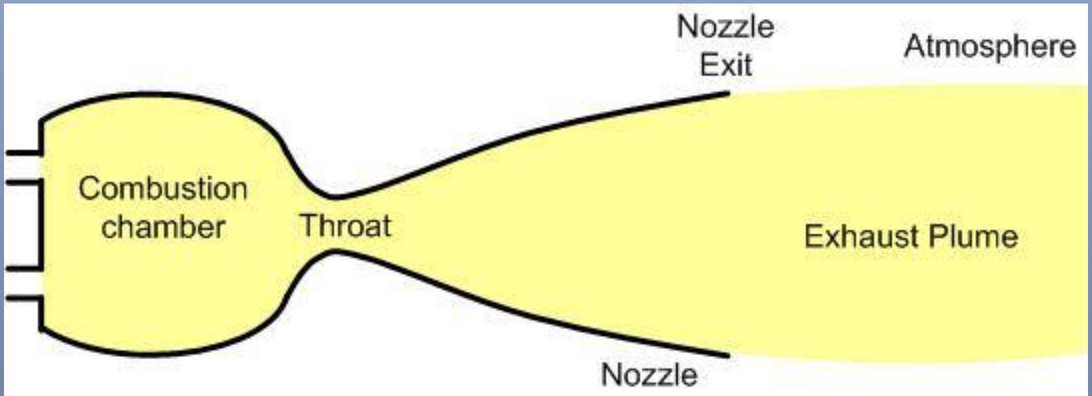
Motor Principles



- In an ideal motor the hot gas leaving the nozzle (called the “exhaust plume”) is at atmospheric pressure.
- Some rocket motors, for example launch vehicles, are required to operate from sea level to the vacuum of space.
- The atmospheric pressure changes throughout the flight, and the efficiency of the motor is affected by this change.

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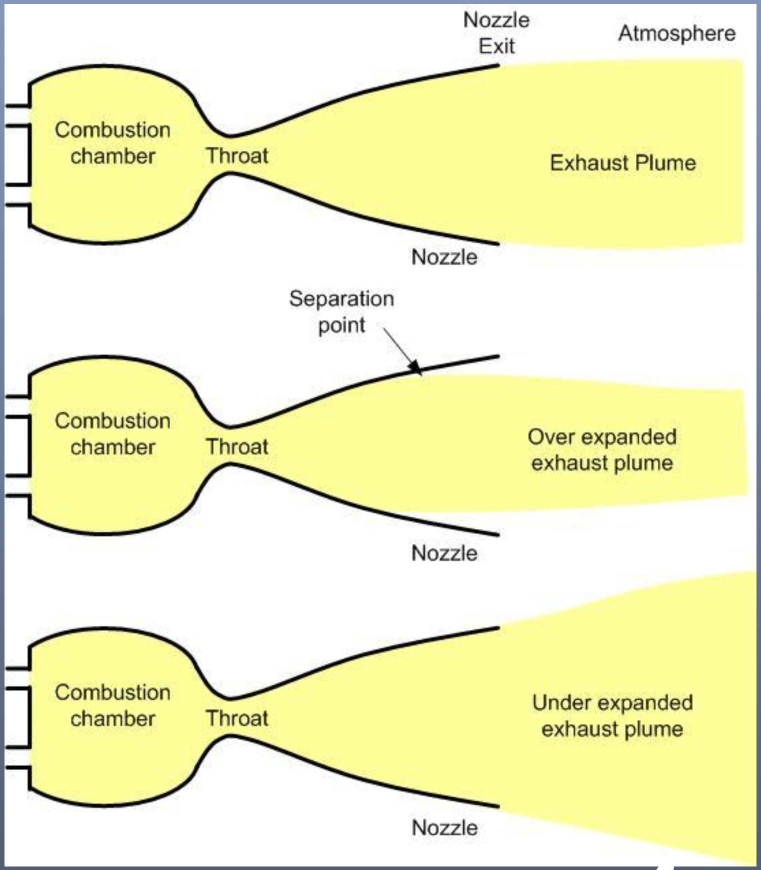
Motor Principles

- A rocket motor is designed to operate efficiently at a particular altitude at which the nozzle exit pressure is the same as the atmospheric pressure.

Ideal conditions:
Nozzle pressure = Atmospheric pressure
(Correctly expanded)

Low altitude:
Nozzle pressure > Atmospheric pressure
(over expanded)

High altitude:
Nozzle pressure < Atmospheric pressure
(under expanded)



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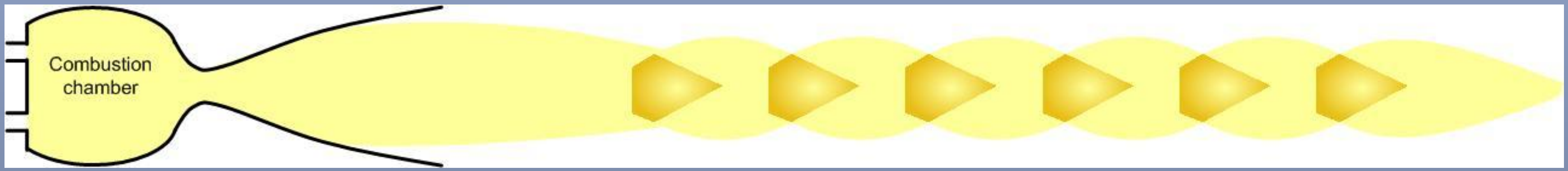
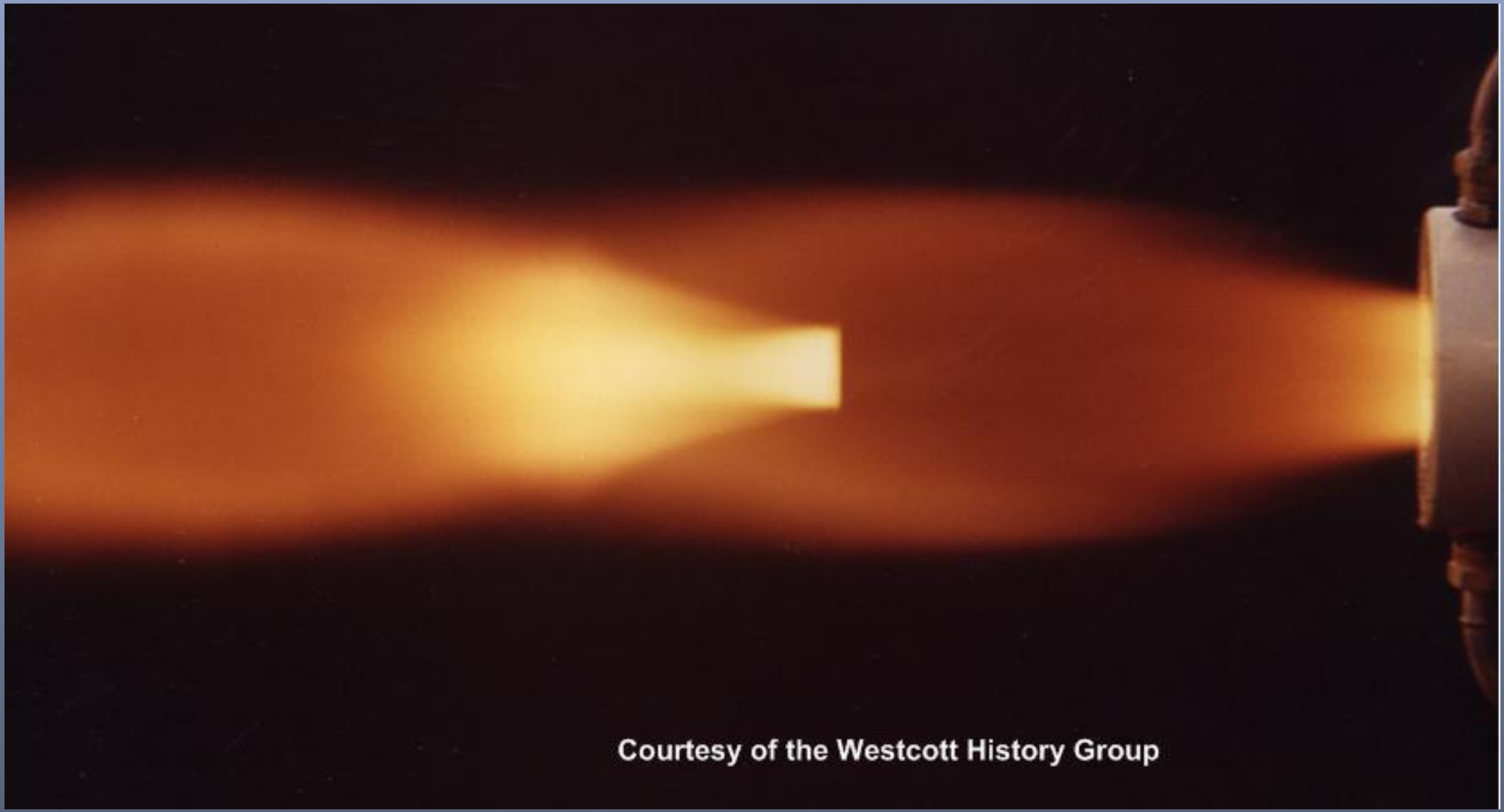
Motor Principles



- The exhaust plume of an over expanded flow often contains “Mach diamonds”.
- Mach diamonds are regions of brightness caused by shock waves in the exhaust plume

Mach Diamonds



Mach Diamonds

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Mach Diamonds

Click here to show movie!

A static test of a rocket motor

Rocket Motor Performance

The amount of “push” produced by a rocket motor is called its “thrust”.

Thrust is a force, and it can be calculated from the equation:

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

F is the thrust (in Newtons)

$\dot{m}$ (pronounced “m dot”) is the mass flow rate in kg/sec. It is the amount of exhaust gas which leaves the motor every second

v_e is the velocity at which the gas leaves the rocket motor in m/sec

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Rocket Motor Performance

- It can be seen that thrust can be increased by changing two parameters:

- Increase the mass flow rate:
  - burn more propellant and oxidiser in the combustion chamber every second

- Increase the exhaust velocity by
  - increasing combustion pressure by burning the propellant at a higher temperature
  - improving nozzle design

Rocket Motor Performance

- We can improve the efficiency of a rocket motor by using different propellants
- We can compare the performance of a rocket by determining how much thrust can be obtained in 1 second by burning 1 kg of propellant
- We call this measure of performance the “**specific impulse”** of the propellant, and define it as

$$\text{Specific impulse} = \frac{\text{Thrust x duration of burn}}{\text{Weight of propellant burned}}$$

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Rocket Motor Performance

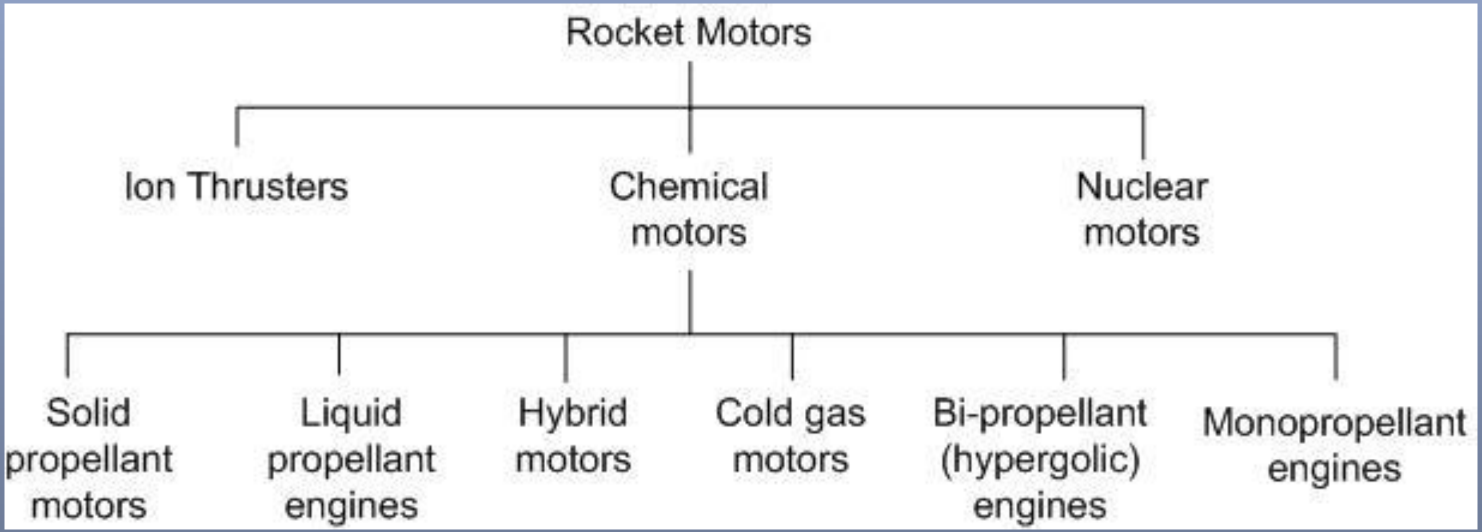
- Some common propellants and their specific impulse:

Propellant	Specific Impulse	Comments
Black Powder (BP)	40 s	Used in model rocket motors and fireworks
Ammonium percholorate composite propellant (APCP)	150 s	Used in solid rocket boosters and high power model rocket motors
Hydrazine (monopropellant)	220 s	
RP-1 and Liquid Oxygen (LOX)	370 s	Very widely used in launch vehicles. RP-1 is a form of pure kerosene.

- It can be seen that RP-1 and LOX are nearly ten times as efficient as black powder

Chapter 4
Types of Rocket Motor

Types of Rocket Motor



- Rocket motors can be classified into many types.
- Rocket propulsion systems that have moving parts, for example pumps and turbines, are called engines.
- Propulsion systems without moving parts are called motors.

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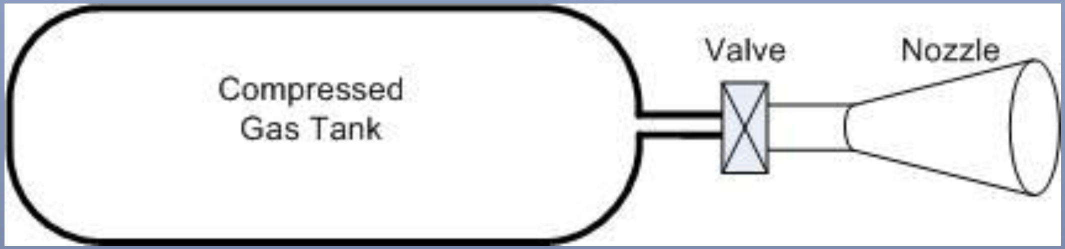
Cold Gas



- The cold gas motor is the simplest form of rocket propulsion
- When thrust is needed a valve is opened.
- The gas escapes through a nozzle where it is accelerated.
- Cold gas motors are used in NASA's Man Manoeuvring Unit (MMU)

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Cold Gas

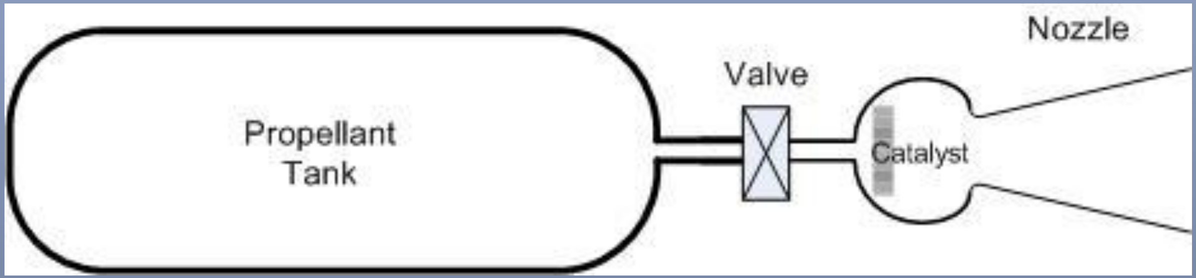
Advantages

- Cheap
- Simple
- Safe
- Useful where small amounts of thrust are needed for short periods of time.

Disadvantages

- Low thrust
- Very inefficient.

Monopropellant



- Monopropellant engines use a single chemical that spontaneously ignites in the presence of a catalyst.
- Some monopropellants can reach full operating temperature and pressure in 1/100 of a second or less, which makes them useful in applications where a short burst of thrust is required.

Monopropellant

- **Hydrogen peroxide** and **hydrazine** are two common monopropellants.
- Very pure hydrogen peroxide, sometimes referred to as **high test peroxide** (HTP), is very unstable. When it comes into contact with a platinum catalyst it spontaneously decomposes to water and oxygen, releasing a lot of heat and creating superheated steam and oxygen.
- Hydrazine decomposes into ammonia, nitrogen and hydrogen at about 800ºC when it comes into contact with a platinum catalyst

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Monopropellant

Advantages

- Simplicity
- Relatively high specific impulse
- Quick response
- Easy to control

Disadvantages

- Chemical can be very dangerous to manufacture, transport and store.

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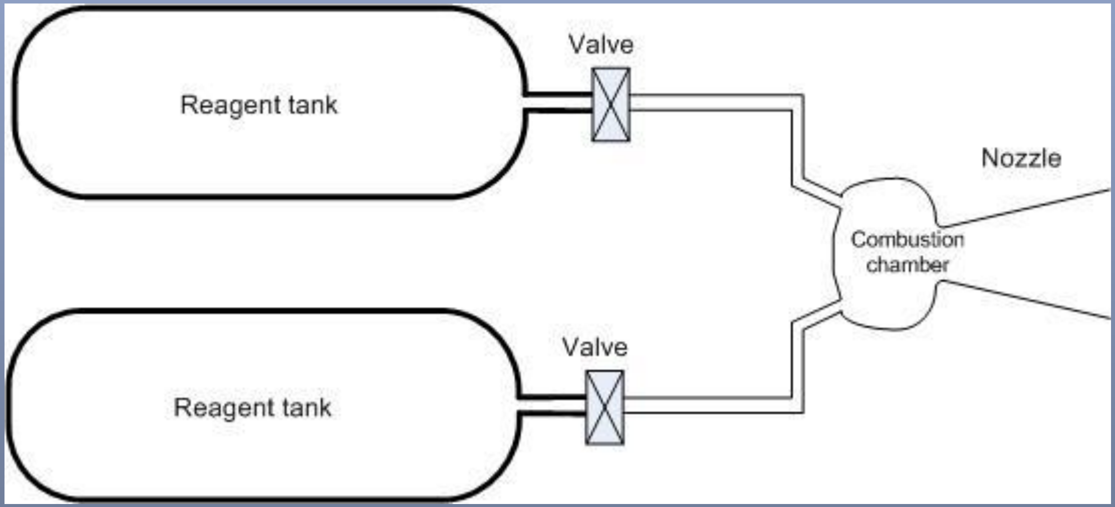
Bipropellant



- Bi-propellant engines are a form of liquid propellant engine which require no ignition system.
- They use two chemical reagents which spontaneously ignite as soon as they come into contact with each other and release a lot of heat.
- Chemical reactions which spontaneously ignite are called hypergolic.

Bipropellant

- Nitrogen tetroxide and hydrazine are useful reagents in bi-propellant engines.
- They can be stored for long periods, are relatively light liquids, and react strongly.
- Bi-propellant engines based on these two chemicals are commonly used in satellites and deep space probes.

Bipropellant

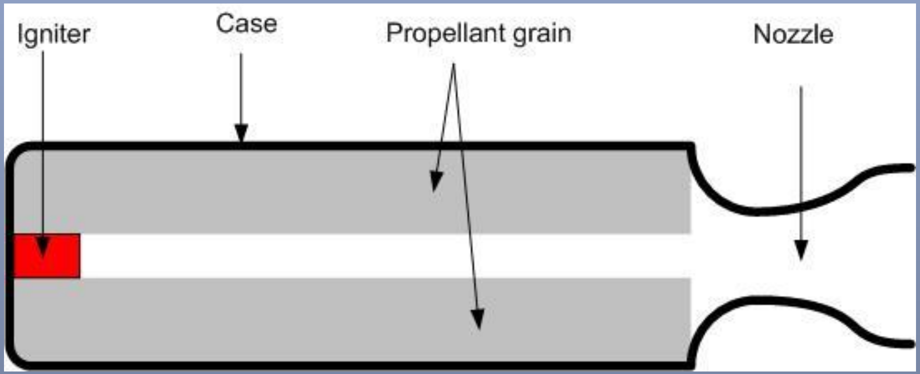
Advantages

- Simple
- Reliable
- Well proven technology

Disadvantages

- The chemicals can be very dangerous to manufacture, transport and store.

Solid Motors



- Solid propellant motors are the most common type of rocket motor
- When the igniter fires it sets fire to the surface of the propellant. The hot gas from this combustion fills the hollow core of the motor and rushes out through the throat and nozzle.
- The propellant burns outwards from the core to the case until it has all been consumed, often referred to as burn out.

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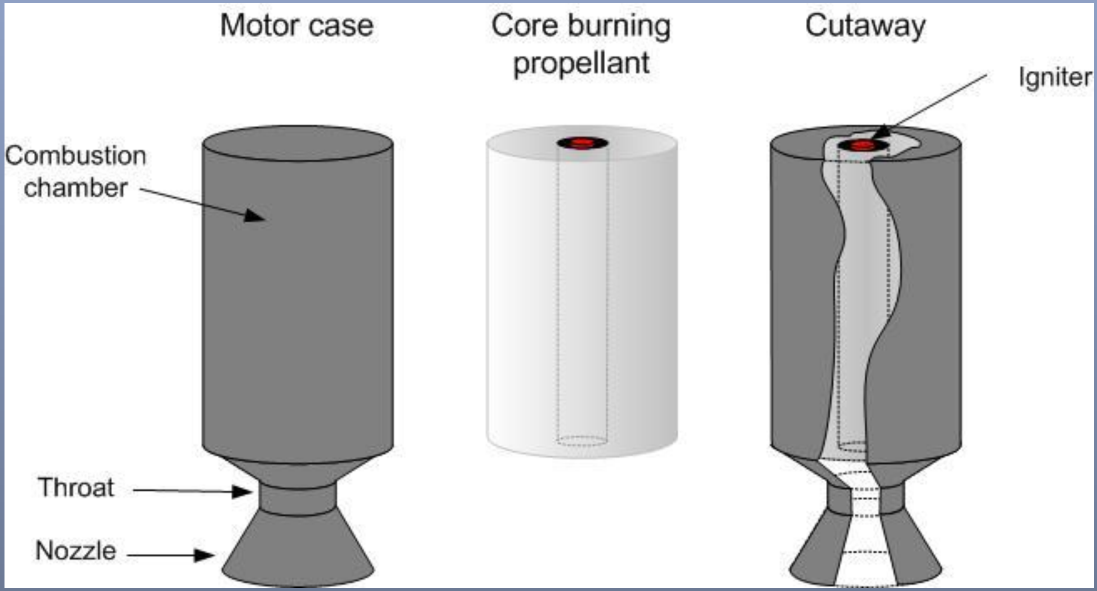
Solid Motors

- Solid propellant rocket motors are ideal for applications which require a predictable thrust for a fixed period of time.
- Some common applications are:
  - missiles
  - launch vehicles
  - model rockets
  - safety systems
  - ejector seats
  - flares
  - fireworks

Solid Motors



- The propellant fills a metal case which serves as a combustion chamber.
- This motor is called a core burning motor as, after ignition, the hollow core of the motor burns outwards towards the walls of the case

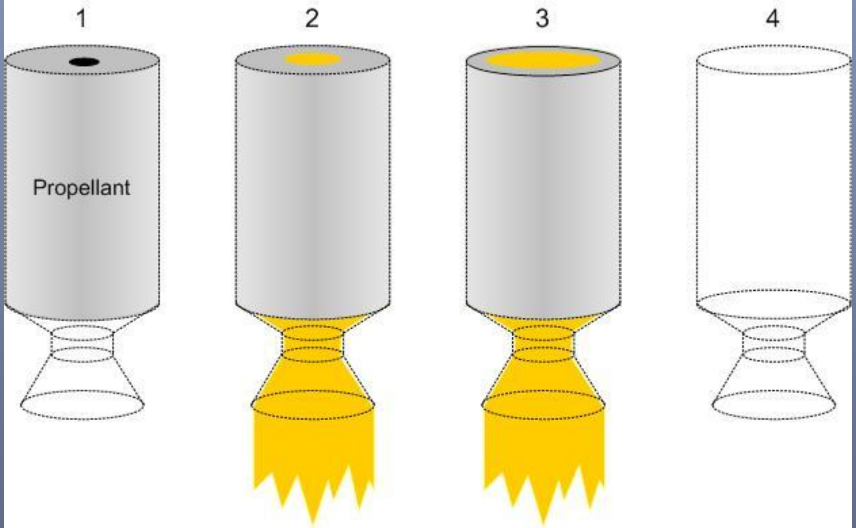
Solid Motors

- Solid propellants must contain both the propellant and the oxidiser

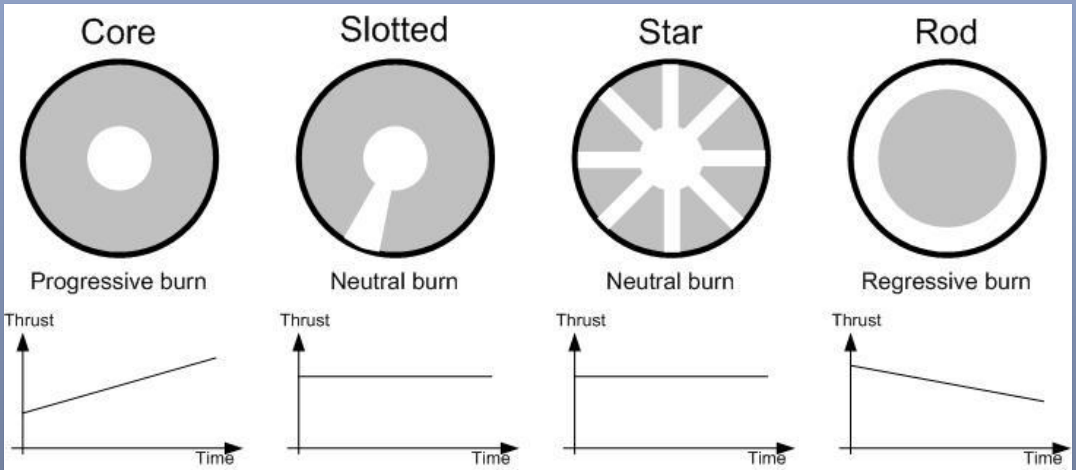
- Common propellants are
  - Black powder
  - Ammonium perchlorate composite propellant (APCP)

Solid Motors

- If we had a transparent case we would see the propellant burn from the core outwards
- As the propellant burns from the core outwards, the burning surface area increases. The motor thus produces more gas per second.
- As more gas is produced the mass flow rate increases, so the thrust increases with time.
- This is called a progressive burn as thrust increases with time.



Solid Motors



- Rocket motor designers design the shape of the propellant to give specific thrust profiles.
- By changing the shape of the propellant inside the case it is possible to create motors with thrust profiles that
  - increase with time (progressive)
  - remain constant with time (neutral)
  - decrease with time (regressive).

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Solid Motors

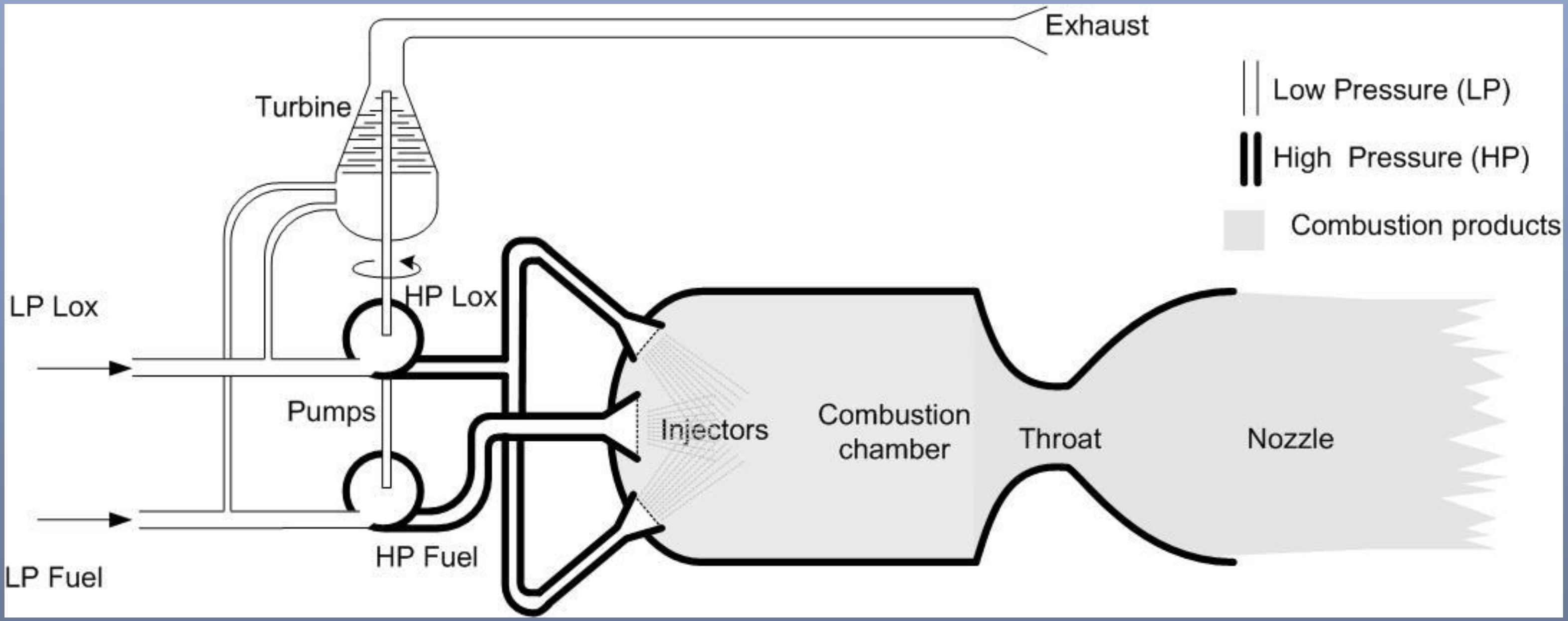
Advantages

- Easy to manufacture
- Simple to use
- Propellant is relatively safe to store and transport

Disadvantages

- Once ignited the propellant cannot be controlled or extinguished.

Liquid & Gas Engines



- Liquid & gas rocket engines are very complex.
- Fuel and an oxidiser, usually liquid oxygen (LOX) are burned in a combustion chamber to generate very high temperature exhaust gases.

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Liquid & Gas Engines

- Engines which use liquid or gaseous fuels are very common in large rockets
- They can be very efficient and have specific impulse up to 400 seconds.
- They can have very high thrust.

Liquid & Gas Engines

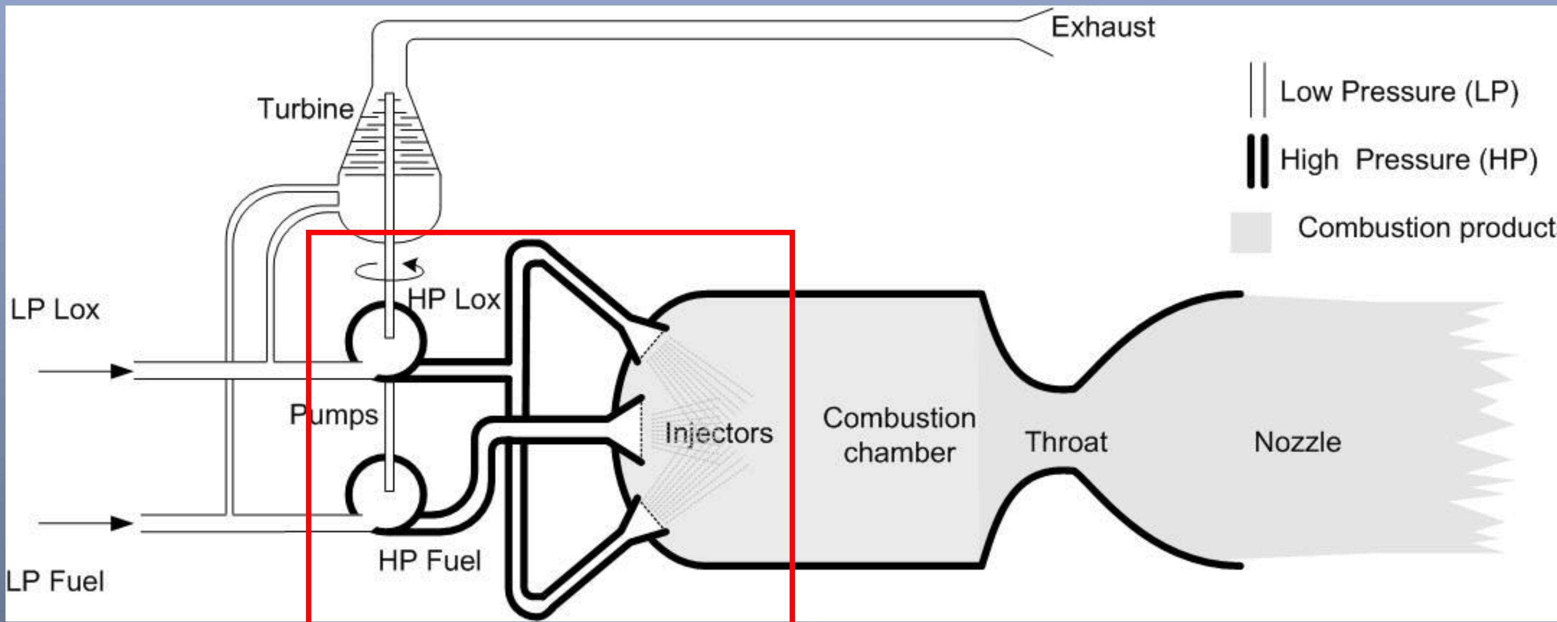
Advantages

- High thrust is possible
- Very efficient

Disadvantages

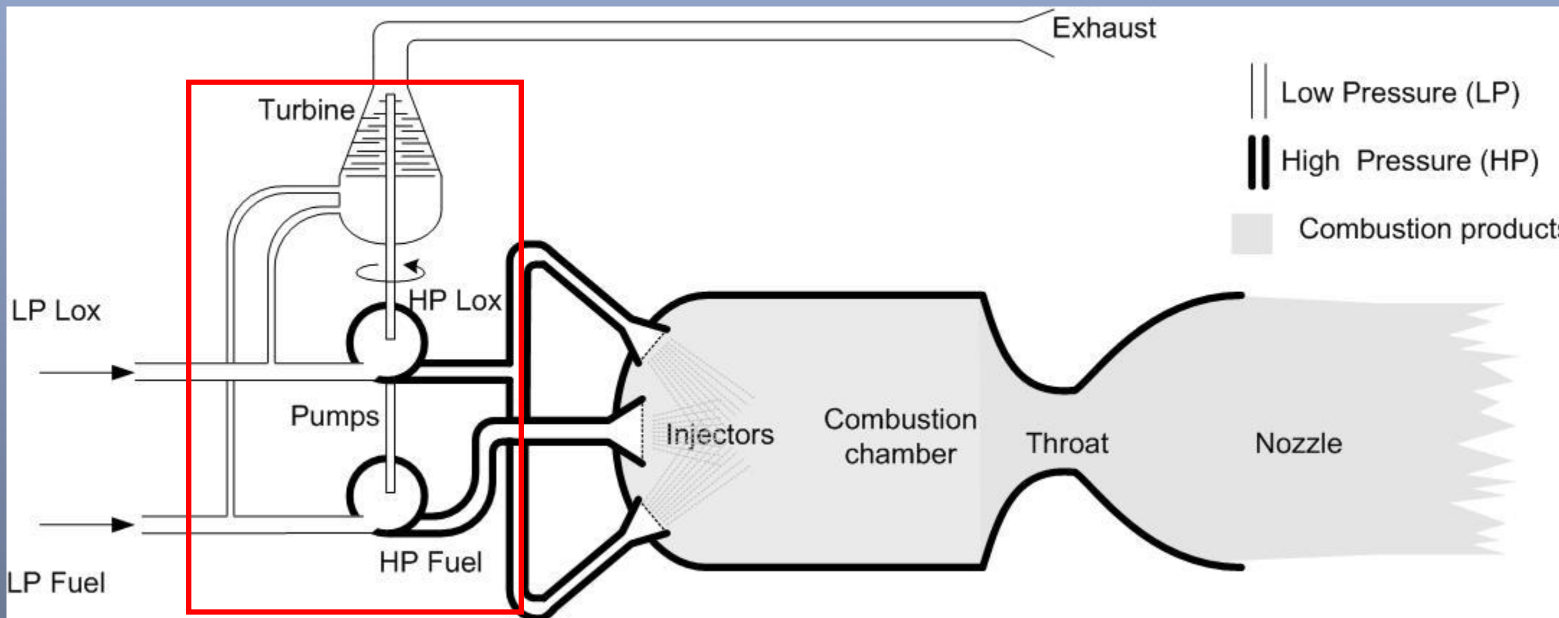
- Extremely complex
- Difficult to design
- expensive to design and manufacture

Liquid & Gas Engines



- Fuel and LOX are pumped into the combustion chamber at high pressure.
- Specially designed injectors mix the fuel and LOX to ensure that all the fuel is burned

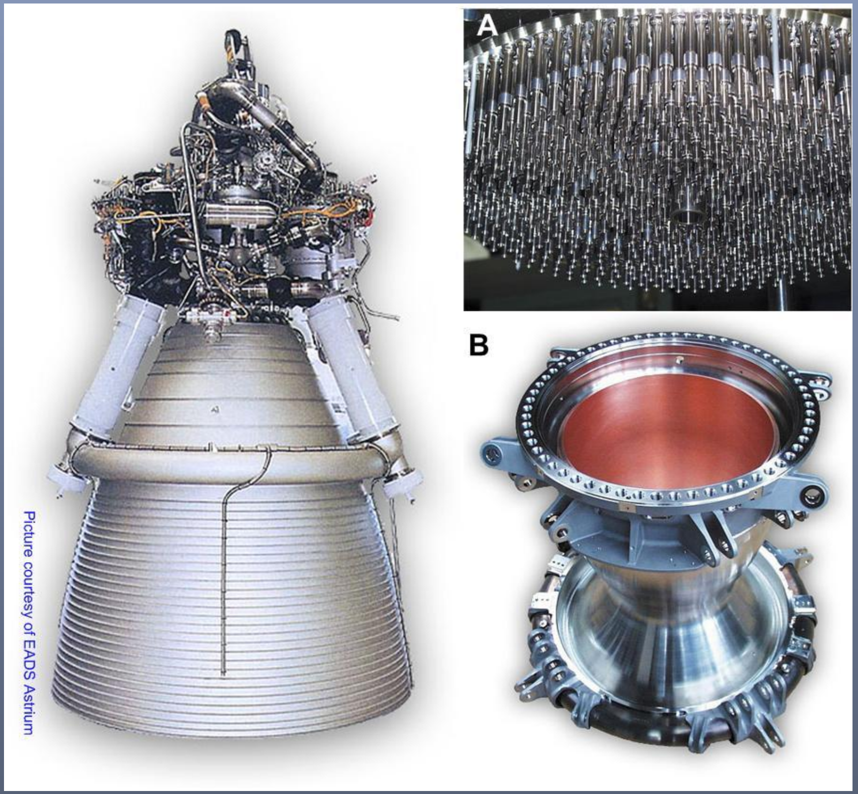
Liquid & Gas Engines



- Some of the fuel and LOX are used to power a turbine which drives the pumps.
- The waste gases from the turbine are at low temperature and are not used for propulsion.

Liquid & Gas Engines

- Vulcain rocket engine from EADS
- The injector assembly (A) sprays the fuels and LOX into the chamber to ensure that it is thoroughly mixed before combustion
- The bottom of the combustion chamber and throat (B) are very precisely manufactured to ensure the smooth flow of gas through the throat
- The combustion chamber is surrounded by the pumps, turbine and valves for feeding fuel and LOX to the injectors.



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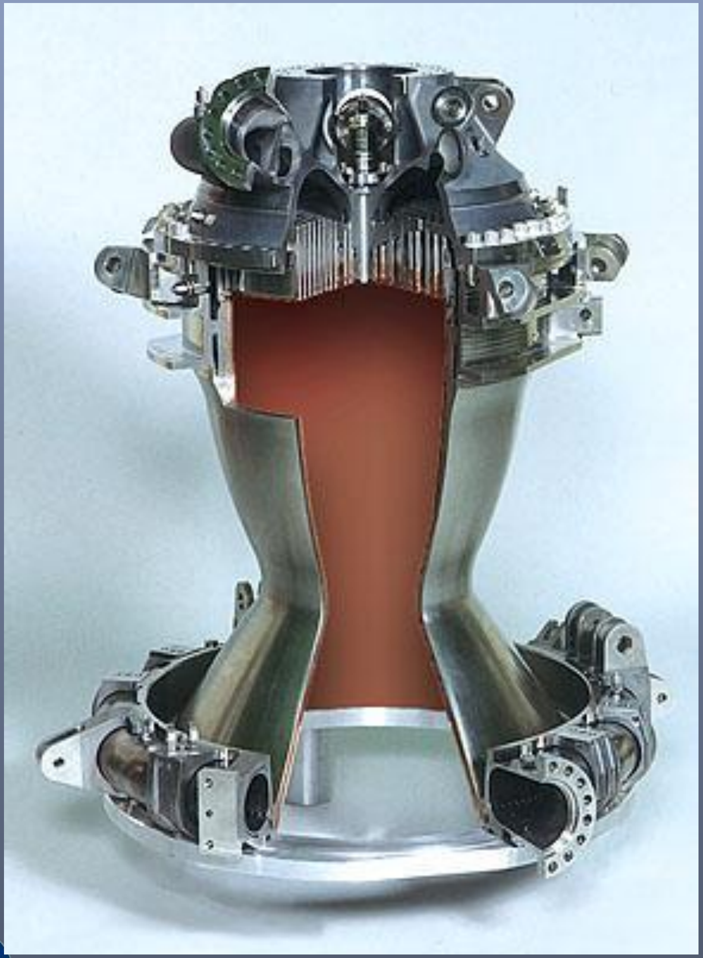
Liquid & Gas Engines



- Vulcain rocket engine from EADS
- This shows the injector at the top, combustion chamber and throat.

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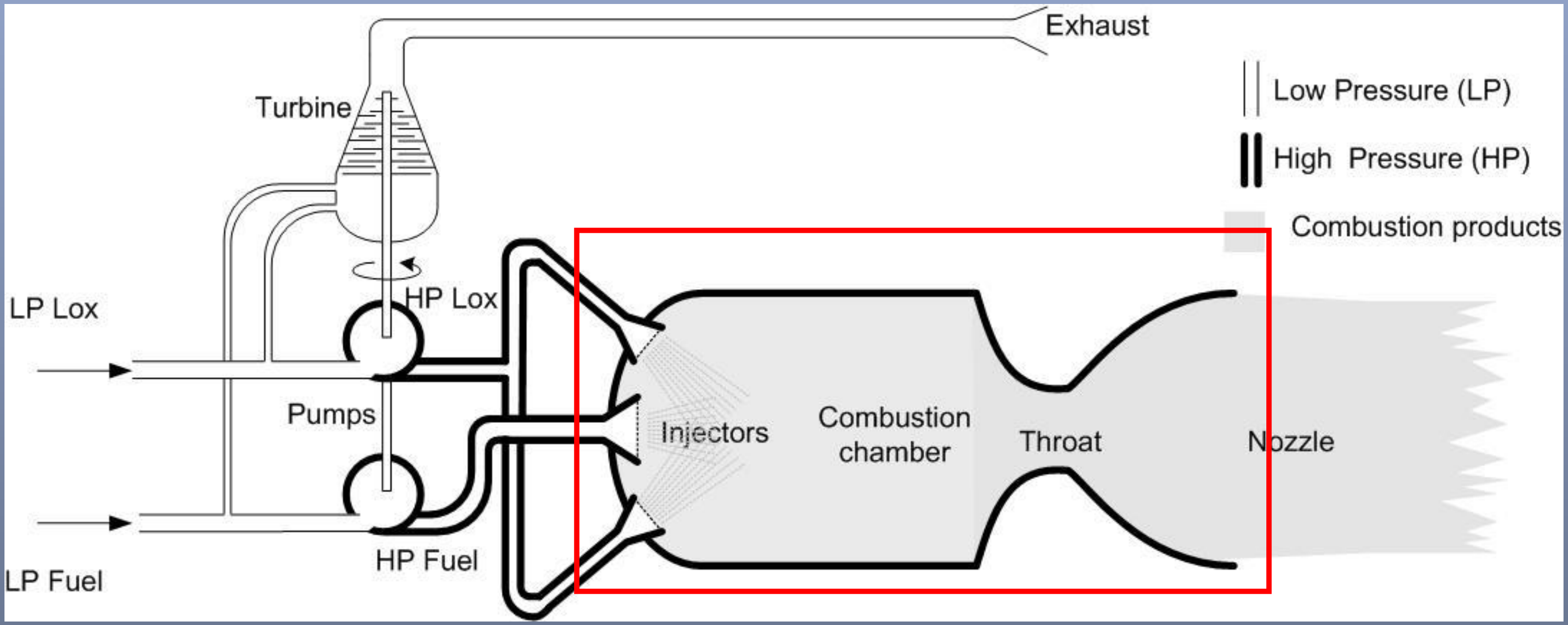
Liquid & Gas Engines



- The exhaust gases in the combustion chamber, throat and nozzle achieve temperatures of over 2000°C.
- This is hot enough to melt the steel from which the walls of the engine are made.
- The walls of the injector and combustion chamber are cooled by spraying a thin film of cool fuel on the walls of the chamber.

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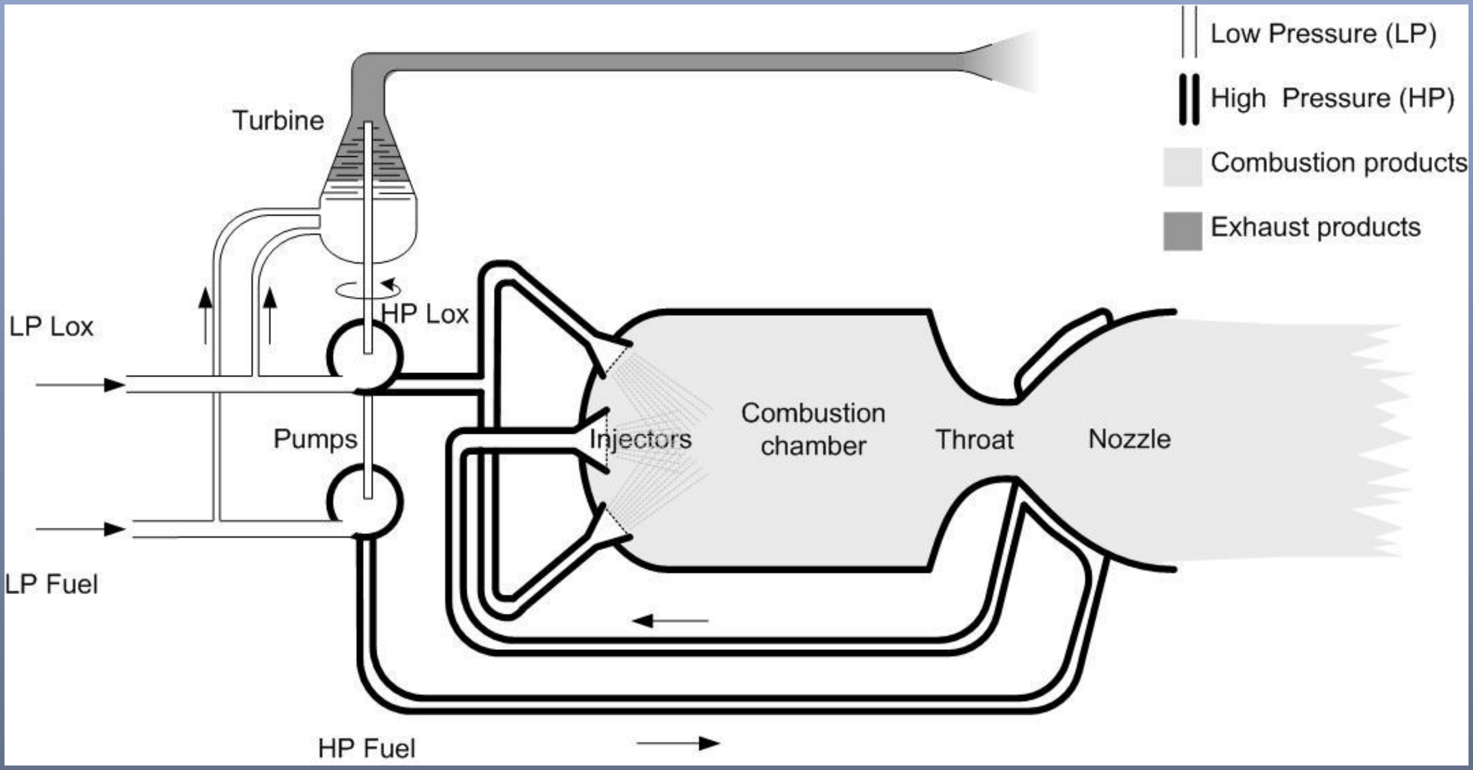
Liquid & Gas Engines



- To prevent the throat and nozzle from melting cold, high pressure, fuel is pumped through narrow pipes to cool the steel.
- This is called "regenerative cooling"

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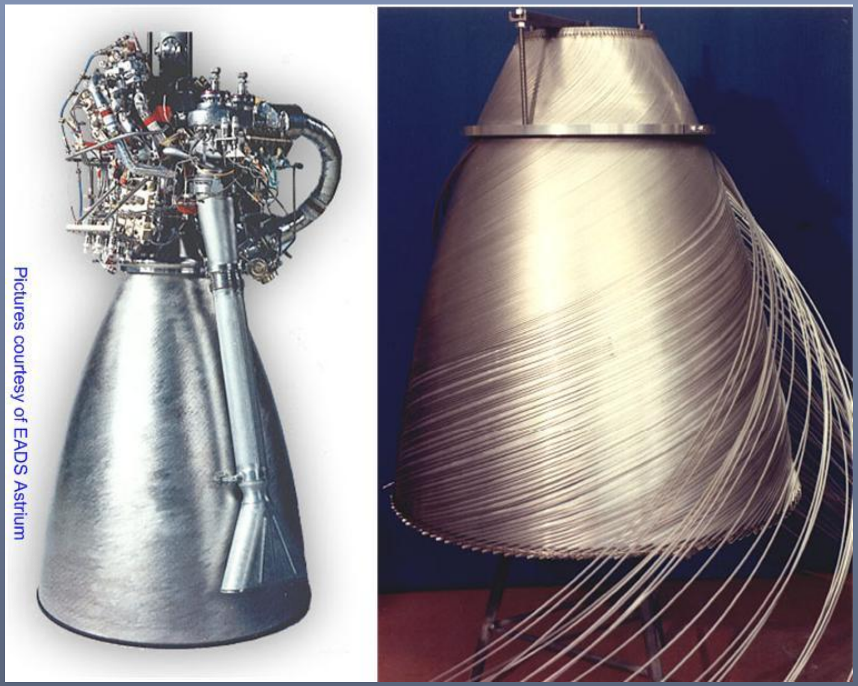
Liquid & Gas Engines

- HM7 engine made by EADS
- The picture on the left shows the motor assemble, including the exhaust from the turbine.
- The picture on the right shows the fine mesh of cooling tubes for regenerative cooling of a nozzle.
- Each tube has to be accurately positioned and perfectly welded to prevent a catastrophic leak of hot fuel.



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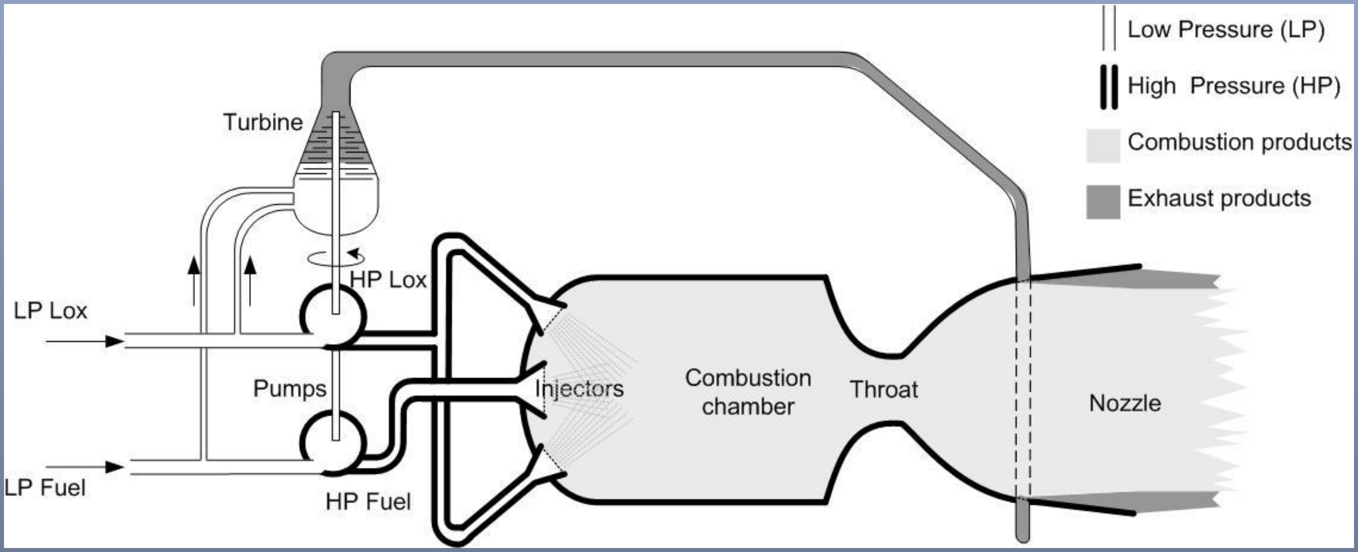
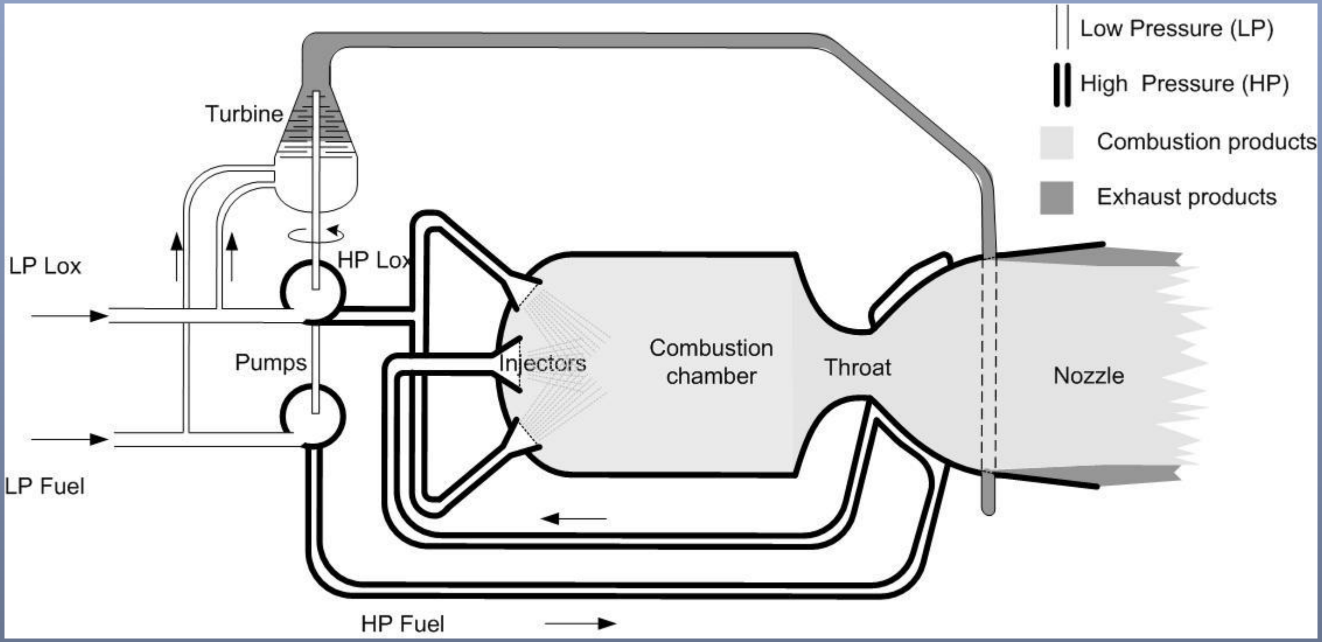
Liquid & Gas Engines



- Another technique for cooling the nozzle is to inject the used gases from the turbine.
- These form a thin film of (relatively) cool gas between the nozzle walls and the exhaust gas, preventing the nozzle wall from melting.
- This is called “film cooling”, sometimes called “curtain cooling”.

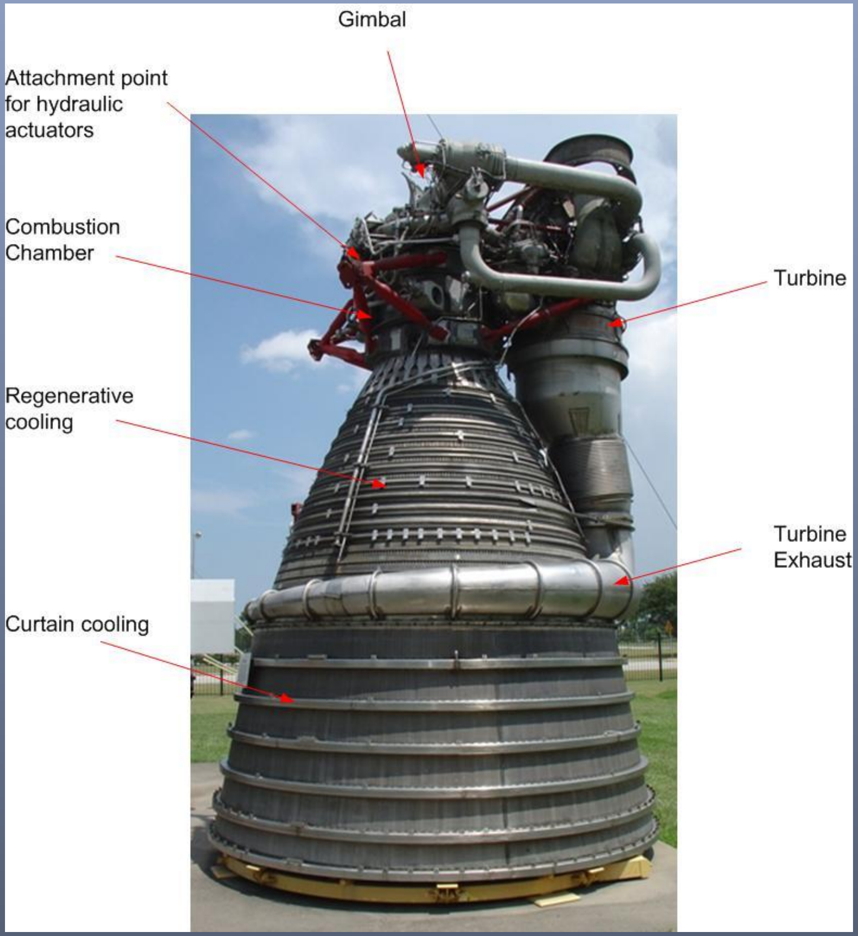
Liquid & Gas Engines



- Some rocket engines use both regenerative cooling and curtain cooling.
- The F-1 engine, used on the Saturn 5 rocket, used both regenerative and curtain cooling to protect its very long nozzle.

Liquid & Gas Engines

- The F-1 rocket engine is the most powerful rocket engine ever built.
- It was cooled using regenerative cooling in the upper nozzle and curtain cooling in the lower nozzle.
- The regenerative cooling used a grid of pipes which surrounded the upper nozzle.
- The gases for curtain cooling were introduced from the turbine exhaust, which was wrapped around the lower nozzle.



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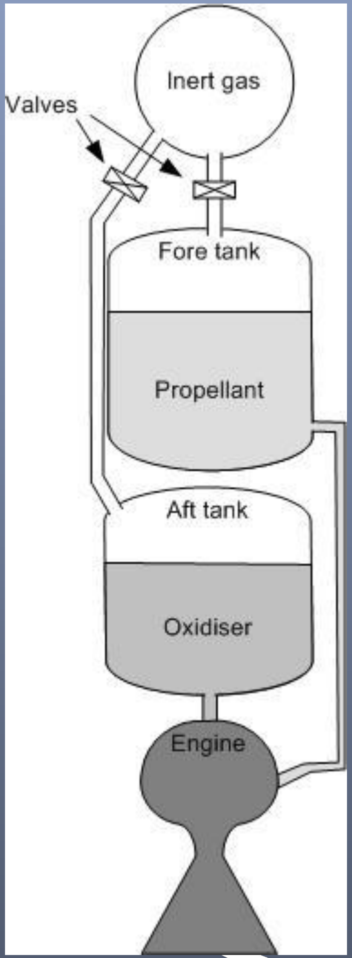
Liquid & Gas Engines

- The fuel and oxidizer are stored in tanks inside the rocket body.
- Tanks are pressurized with an inert gas to force the fuel and oxidizer towards the engine.
- This arrangement is called a "blowdown" system.
- "Inert" means that the gas will not chemically react with the fuel or oxidiser.
- Helium is often used as the inert gas.



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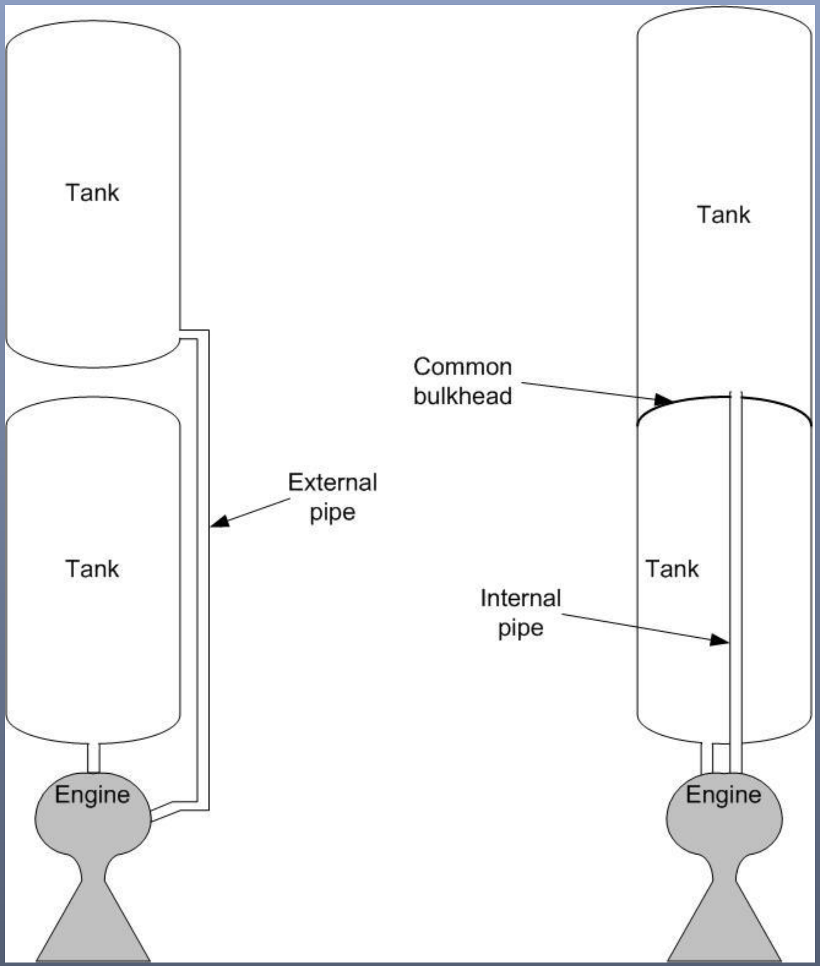
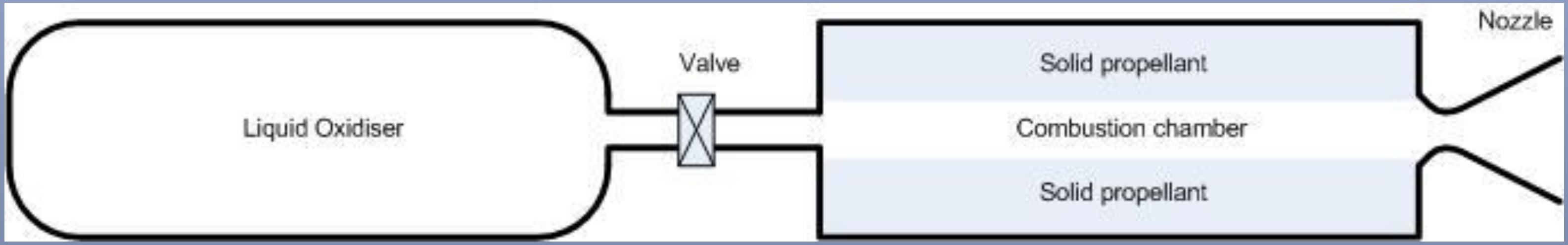
Liquid & Gas Engines



- The fuel and propellant tanks are normally stacked one above the other.
- The chemical from the upper tank needs to be fed to the motor. In some rockets the pipe it external to the rocket.
- To save weight some rockets use one large tank which is divided by a bulkhead. The pipe from the upper tank is routed through the lower tank.

Hybrid Motors



- Hybrid motors burn a solid propellant in a gaseous oxidiser. They are this a hybrid of a solid motor and a liquid/gas motor.
- The valve lets the oxidiser into the combustion chamber where it is ignited.
- The solid propellant will burn while the gas is flowing, but will stop when the valve closes.

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Hybrid Motors

- A hybrid motor uses a pressurised oxidiser in liquid or gaseous form and forces it through a solid propellant.
- The propellant can be a conventional solid propellant, or any material that can burn at a high temperature and produce gas.
- Plastics are commonly used as the propellant as they are intrinsically safe to manufacture and store.
- LOX or Nitrous Oxide are commonly used as the gaseous oxidiser.

Hybrid Motors

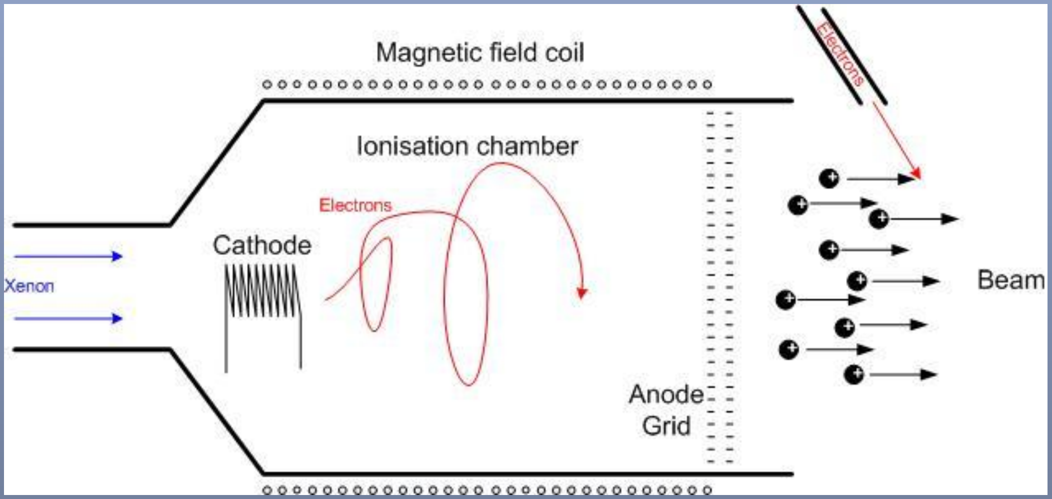
Advantages

- Relatively simple construction
- Low cost to build and operate
- Materials are safe to manufacture and transport
- Higher specific impulse than some solid propellant motors

Disadvantages

- Some residual propellant is usually left
- Difficult to relight

Electric Propulsion



- Ion thrusters use electric and magnetic fields to accelerate gas ions to very high velocity, typically 30 km per second
- The momentum of the gas ions provides the thrust

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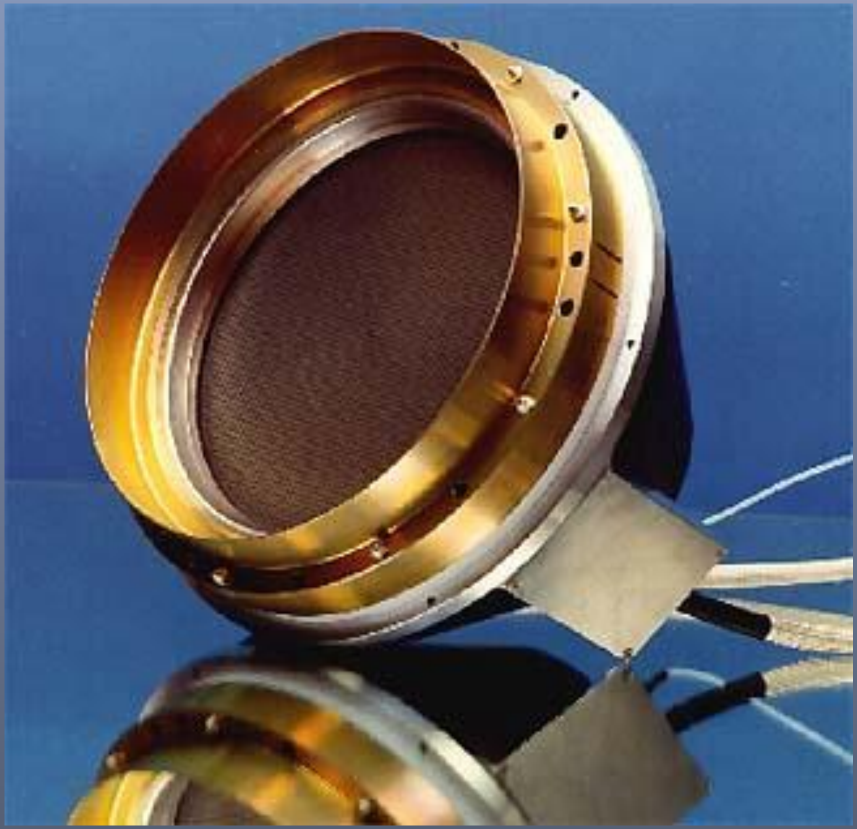
Electric Propulsion

- They are ideal as manoeuvring thrusters for satellites where low thrust and high efficiency are important.
- Ion thrusters have a very low mass flow rate (m-dot) but the gas has a very high velocity (30 km/s).
- Ion thrusters can only work in the vacuum of space. They do not work inside the atmosphere.

Electric Propulsion



- RIT XT Ion Thruster made by EADS
- This small thruster provides about 0.1 Newtons of thrust. It is designed to be used as a manoeuvring thruster for satellites.
- It has a specific impulse better than 3000 seconds.
- The thruster is about 20cm across

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Electric Propulsion

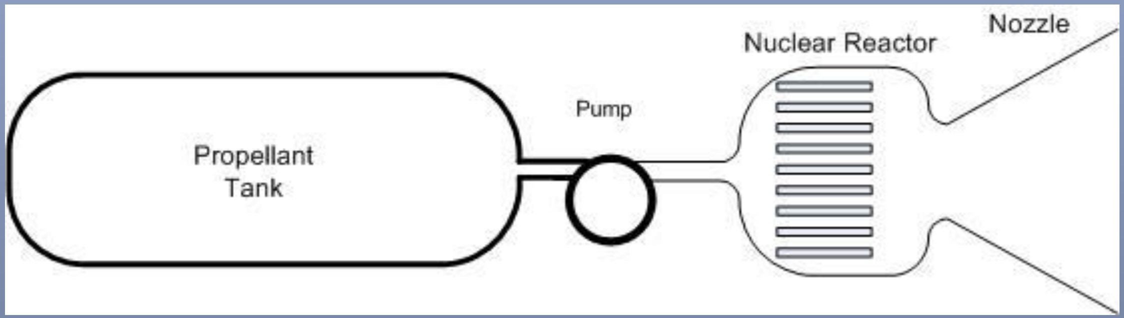
Advantages

- Simple
- Very high specific impulse
- Light weight.

Disadvantages

- Low thrust
- Need a lot of electrical power
- Cannot work inside the atmosphere

Nuclear Thermal



- A light gas, ideally hydrogen, is pumped from a storage tank through a nuclear reactor.
- The reactor heats the gas to a very high temperature, and it expands through a de-Laval nozzle.

Nuclear Thermal

- Nuclear thermal engines have the potential to offer both high thrust and a specific impulse of over 1000.
- There have been experiments to make nuclear thermal engines, starting with the NERVA programme in 1947, but these engines have yet to be used in a rocket.
- The difficulties are not technical but political; no nation wants nuclear reactors flying over it's territory.

Nuclear Thermal

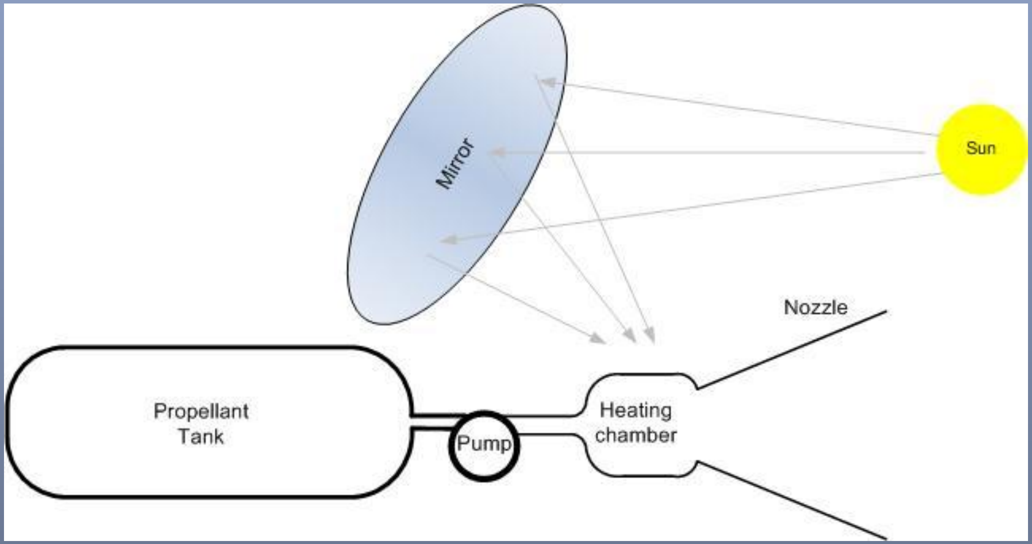
Advantages

- High thrust
- High specific impulse.

Disadvantages

- Unproven technology
- Political issues of launching nuclear reactors.

Solar Thermal



- Solar thermal propulsion focuses the sun's rays on a small chamber through which gas is being pumped.
- The gas is heated to a temperature of 2000ºC, which causes it to expand through a nozzle.

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Solar Thermal

- Solar thermal propulsion is a novel proposal for generating small thrusts for long durations with high efficiency.
- It is suitable to gradually accelerate small objects in space.
- The technology is currently unproven

Solar Thermal

Advantages

- Simple
- Availability of limitless energy from the sun.

Disadvantages

- Power decreases as the motor gets further from the Sun
- The need for accurate pointing of the mirror
- This technology has yet to be tried in space.

Comparison

Type	Thrust range	Specific Impulse (seconds)	Comments
Cold gas	0.1 N to 250 N	70 s	
Solid propellant	1 N to 12,500,000 N	80 s to 250 s	
Liquid propellant	100 N to 6,600,000 N	200 s to 450 s	
Bi-propellant	5 N to 400 N	250 s to 400 s	
Monopropellant	0.5 N to 500 N	150 s to 300 s	
Hybrid	10 N to 60,000 N	200 s to 400 s	Higher thrust hybrids are being developed.
Ion thruster	0.02 N to 10 N	2500-10000 s	
Nuclear Thermal	1,000,000 N	1000 s	Unproven technology
Solar Thermal	<20N	800 s	Unproven technology

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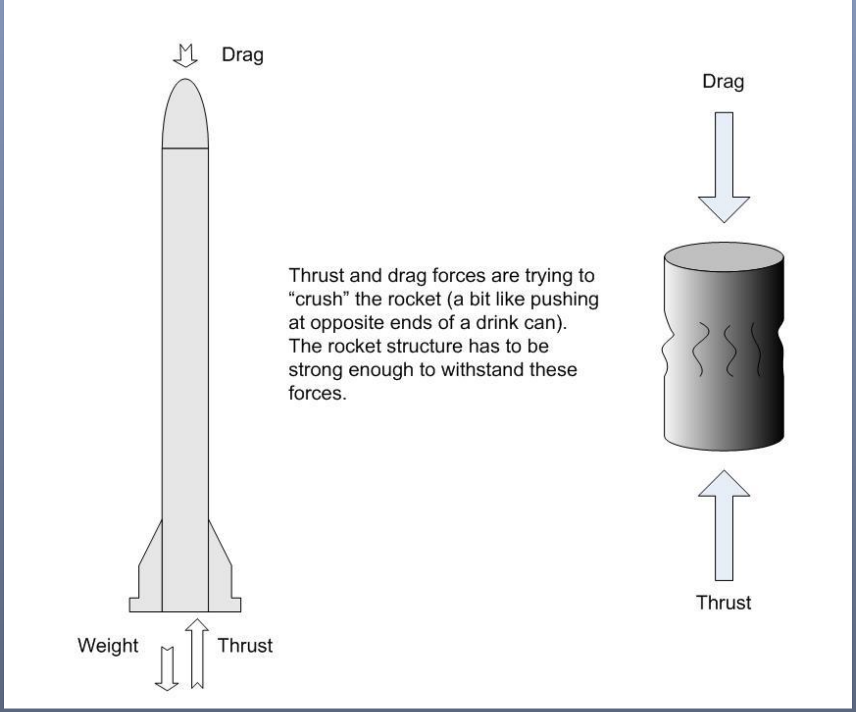
Chapter 5
Rocket Structures and Systems

Forces on a Rocket

- When a rocket lifts off there are three main forces acting on it.
- **Thrust** from the motor, at the bottom of the rocket trying to push it upwards.
- The **weight** of the rocket, propellant and payload, trying to hold the rocket on the ground.
- Aerodynamic **drag**, pushing on the nose and trying to slow the rocket down.



Forces on a Rocket

- Thrust
  - Depends on the amount of propellant and oxidiser that is being burned in the combustion chamber.
- Weight
  - The weight of the empty rocket is called its **dry mass**
  - The total weight is the dry mass plus the weight of the payload and fuels.
- Drag
  - Depends on the aerodynamic shape of the rocket and its velocity
  - As velocity increase the amount of drag increases.

Forces on a Rocket

- At **lift off** the rocket is stationary
  - Thrust must be greater than the weight to lift the rocket
  - Thrust to weight ratio is about 1.2 to 1.6 for a launch vehicle
  - Drag is zero because the rocket isn't moving
- Once the rocket is moving
  - Thrust must be greater than drag plus weight
  - Weight decreases as propellant is burned
  - Drag increases as the rocket gains speed.
- The thrust and drag try to "crush" the rocket
  - At "**max Q**" these forces are at their greatest

Rocket Performance

- Rockets must be light and strong to perform well
- Two standard ratios that are used to asess the strength and weight of a rocket
  - **mass ratio**. This is defined as the ratio of the rocket with propellant (the **wet mass**) to the ratio of the rocket without propellant (the **dry mass**)
  - **propellant mass fraction**. This is defined as the ratio of the mass of propellant to the wet mass of the rocket. The propellant mass fraction shows how much of the lift-off mass is propellant.

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Rocket Performance

If m_0 is the initial total mass, including propellant, m_f is the final total mass, and m_p is the mass of propellant, then:

$$\text{Mass ratio} = \frac{m_f}{m_0}$$

$$\text{Propellant mass fraction} = \frac{m_p}{m_0}$$

A propellant mass fraction above 0.8 is regarded as good, and some modern rockets have propellant mass fractions of over 0.85.

The propellant mass fraction of the Space Shuttle is about 0.82.

Rocket Performance

- The table shows the mass ratio of some rockets. The newest (Ariane 5) is at the top, and the oldest (V2) is at the bottom.
- The continuing improvement in rocket design is very clear from this table.

Vehicle	Mass ratio
Ariane 5	39.9
Space Shuttle	15.4
Saturn V	23.1
X-15	2.3
V2	3.8

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Rocket Structures

- Rockets need to be as light as possible to increase the thrust to weight ratio
- Rockets need to retain their strength and stiffness throughout launch and flight
- How do you make a rocket light and strong?
  - use lightweight materials
  - thicken the outer skin
  - add struts and other structural parts
- BUT every kg of metal that is added to the rocket a kg of payload or fuel has to be removed
  - This reduces the usefulness of the rocket

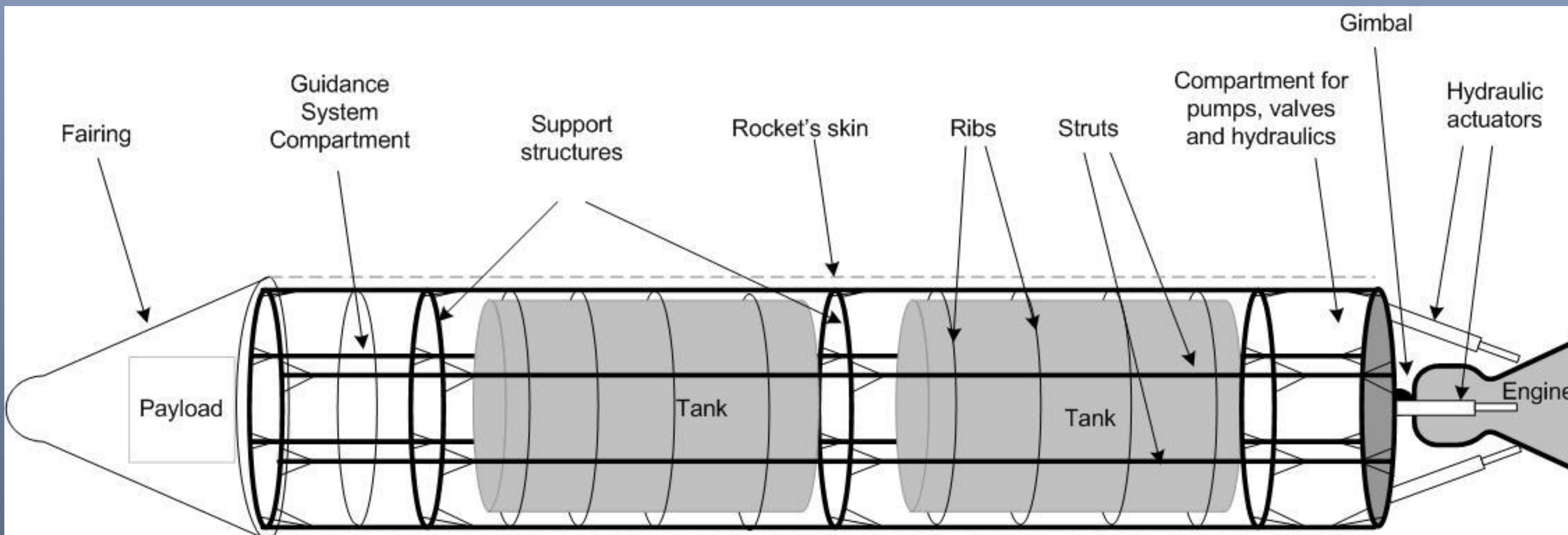
Rocket Structures

- The rocket structure
  - Transmits the thrust through the rocket to the payload
  - Supports internal components, for example fuel tanks and electronics
- Structures need to be light
  - The motor lifts as little surplus weight as possible
  - Allows the rocket to carry the maximum payload and fuel
- Structures need to be strong
  - The rocket must not bend or crumple in flight

Rocket Structures

- One common structure attaches all components to a tubular frame
- The frame comprises
  - struts which run the length of the rocket body
  - ribs which run around the body
- Motor, tanks and guidance systems are attached to the frame using support structures
- A lightweight skin is attached to the frame
  - panels allow access for maintenance and testing

Rocket Structures



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Rocket Structures

- An alternative structure uses no frame, just a skin
  - Called a **monocoque** structure
  - The rocket is pressurised to make the skin stretch and stiffen the rocket
- The propellant tanks use the skin of the rocket as their outer wall
  - Helium is pumped into the tank to maintain pressure as fuel and oxidiser are consumed.
  - This also provides a blowdown system for propellant
- This structure is relatively light

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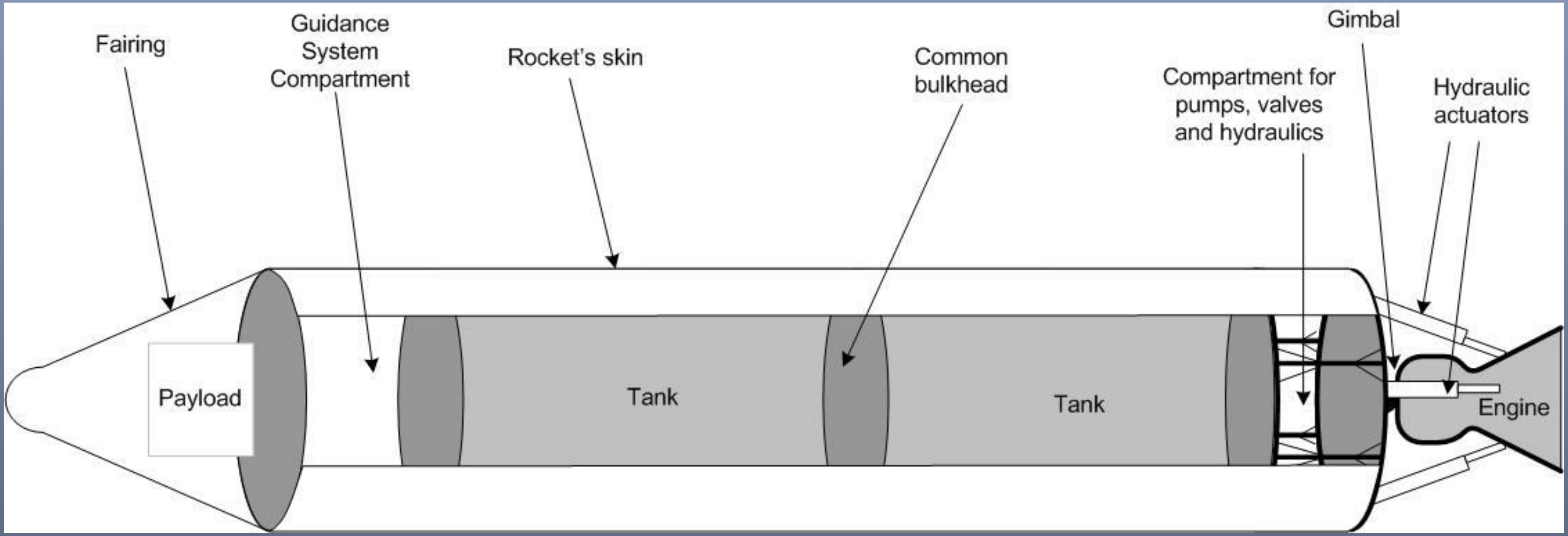
Rocket Structures



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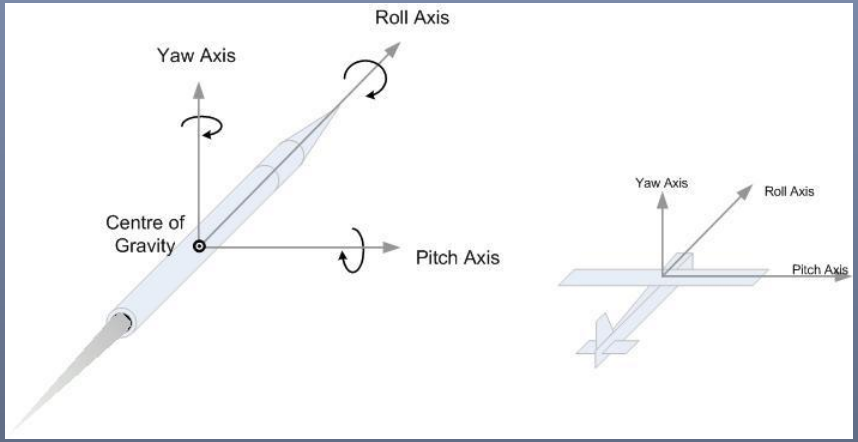
Guidance

- Like aircraft, rockets can spin or **roll**, the nose can **pitch** up and down, and the rocket can **yaw** from side to side.
- Aeronautical engineers define roll, pitch and yaw as rotations around imaginary lines (called axes) which pass through the centre of gravity of a rocket.



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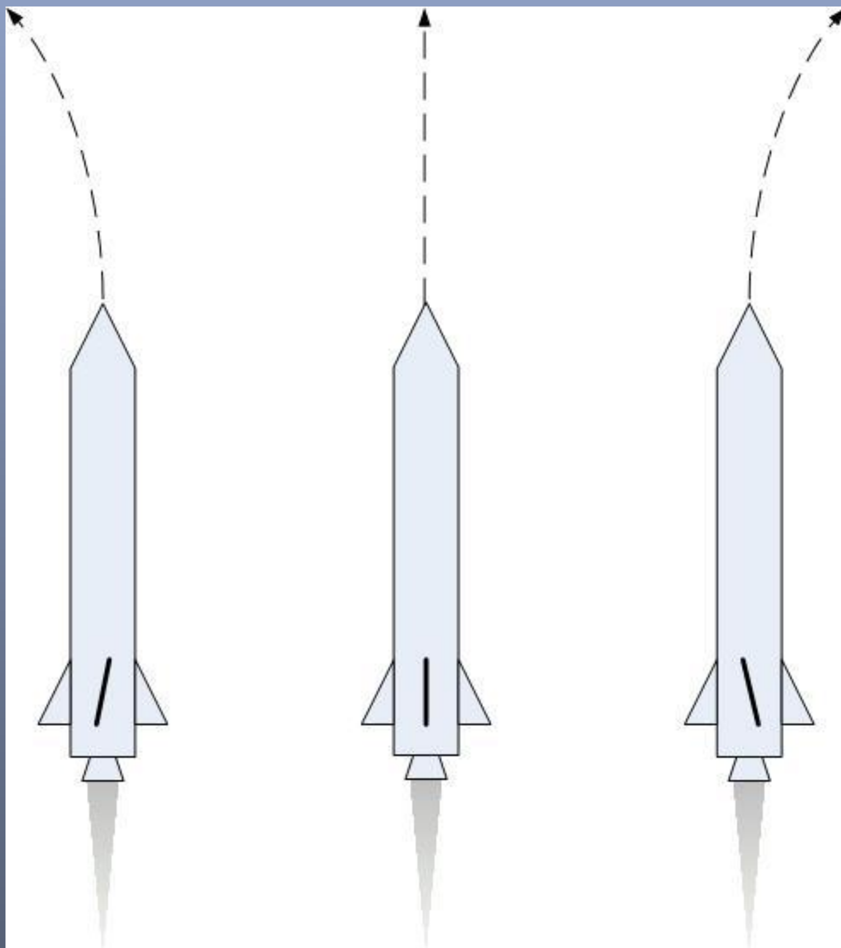
Guidance

- In a rocket the roll axis is about the direction of travel, just like an aircraft.
- It is difficult to define pitch and yaw axes in a round bodied rocket or missile.
- Rocket and missile engineers choose these directions arbitrarily, usually aligning the axes with the direction of fins or the orientation of any gyroscopes inside the rocket.

Guidance



- The control surfaces of an aircraft interact with the air to generate forces, and these forces are used to turn the aircraft.
- Missiles usually operate inside the atmosphere so they often use control surfaces to “fly” in a similar manner to an aircraft.
- These control surfaces, called **fins**, are used to aligned with the yaw and pitch axes, and are deflected to produce aerodynamic forces.

Guidance

- The AIM-9 Sidewinder used two sets of fins to steer the missile.
- The forward fins controlled pitch and yaw, and worked in pairs to steer the missile.
- The aft fins controlled roll using an ingenious gyroscope system powered by the airflow over the fins.

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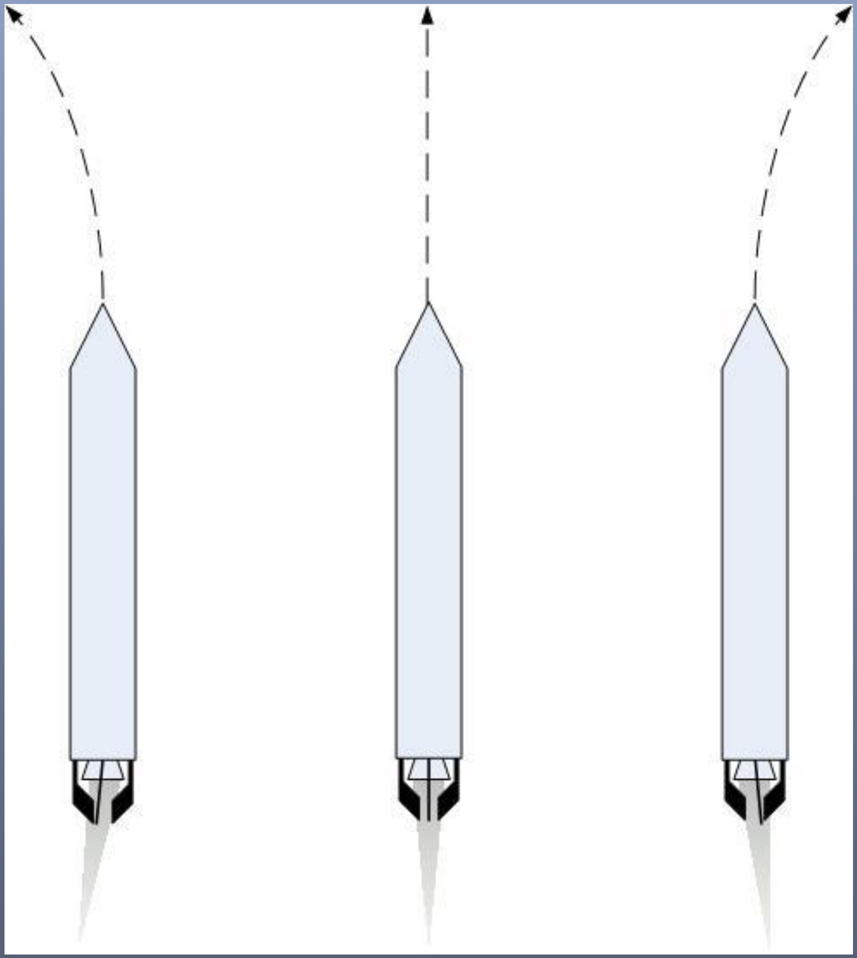
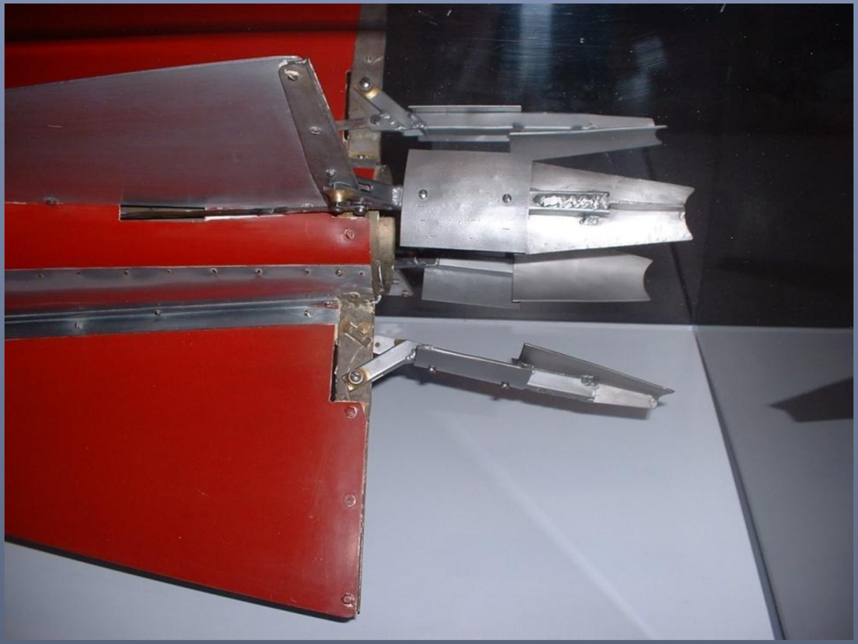
Guidance



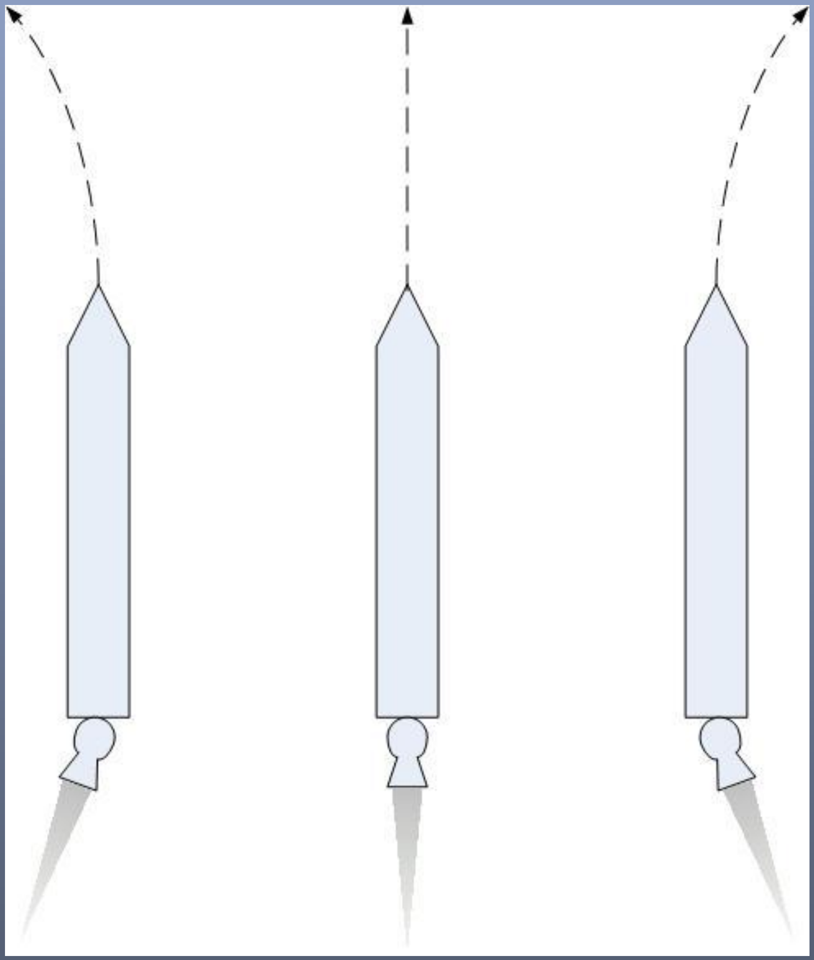
- Many of Robert Goddard's more successful rockets guided the rocket by inserting vanes into the exhaust plume.
- Inserting a vane deflected the flow changed the direction of the thrust.
- A set of four vanes allowed the rocket to be steered in both pitch and yaw. Rigid fins controlled the roll of the rocket.
- This system was later used by Wernher von Braun in the V2

Guidance



- This picture shows the vanes on the back of a Robert Goddard rocket from 1935.
- Goddard made his vanes from metal. Because his rockets were experimental the engine only burned for a few seconds.
- The metal vanes did not have time to melt in the hot exhaust plume during such short flights.

Guidance



- Engineers realised that it was easy to mount the engine on gimbals and tilt the whole motor using hydraulics.
- Tilting the motor changed the direction of the thrust, which caused the rocket to pitch or yaw.
- This technique is still commonly used in modern rockets and missiles.

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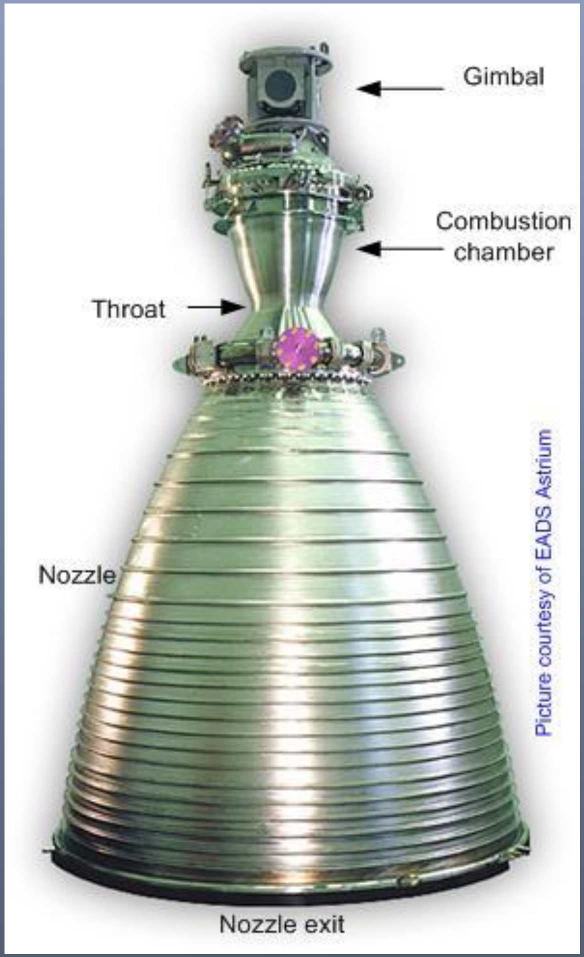
Guidance



- This picture shows the Vulcain engine, made by EADS and used on the Ariane 5 launch vehicle.
- The gimbal can be seen at the top the combustion chamber.

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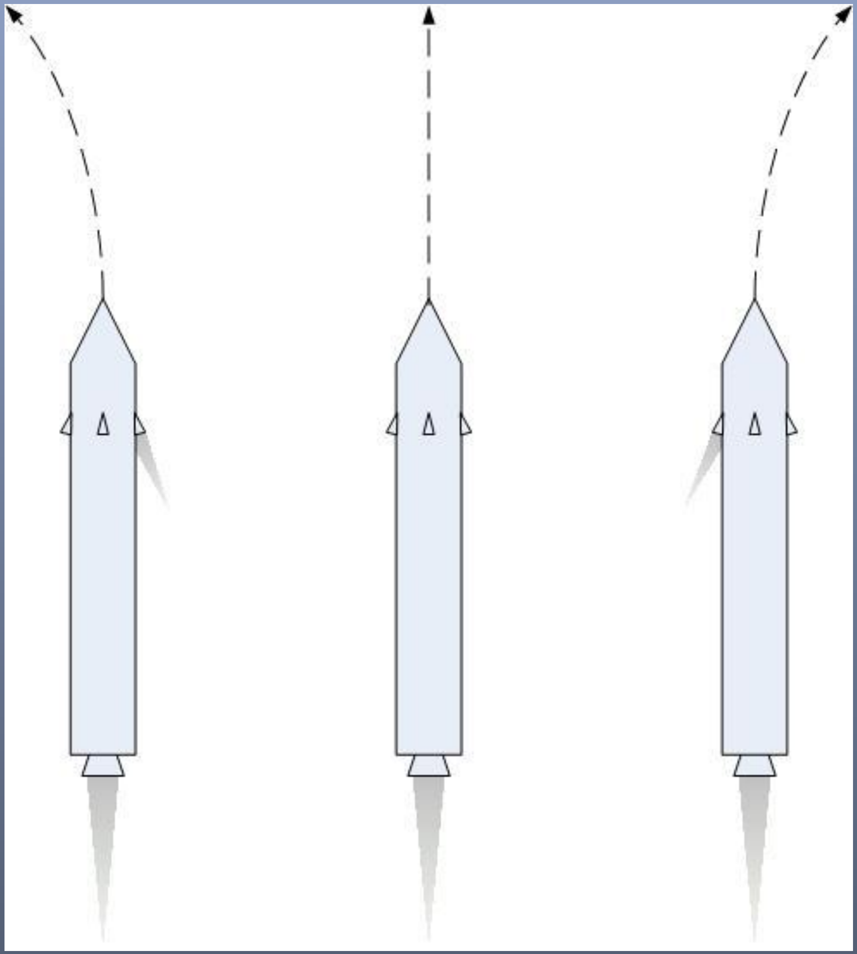
Guidance



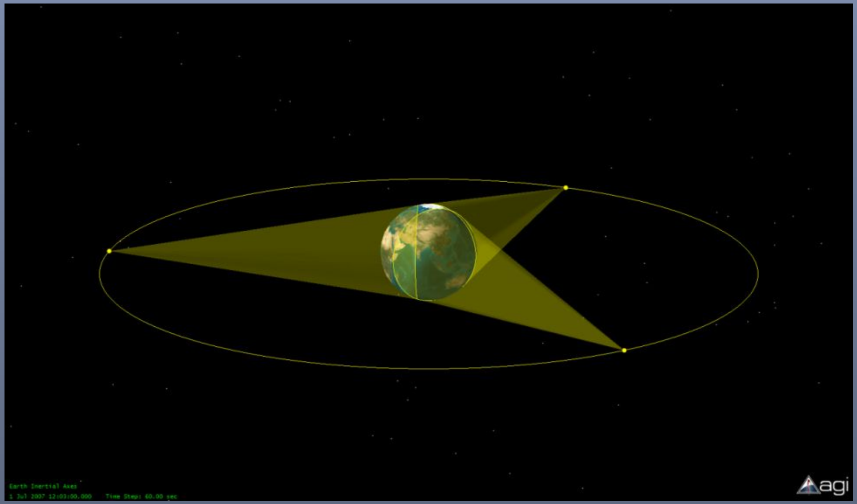
- Another technique, used on larger rockets and in space, is to have small thrusters on the rocket.
- These are mounted to give a sideways thrust.
- When it is necessary to steer the rocket one or more of these thrusters is fired, nudging the rocket in pitch or yaw.

Chapter 6
Launch Vehicles

Launch Vehicles

- Satellites have revolutionised our lives:
  - Television and news broadcast
  - Telephone
  - Internet access
  - Military communications
  - Weather
  - Disaster monitoring

Launch Vehicles



- Many of these satellites need to maintain a constant position above the earth.
- If a satellite is launched to a point 36000 km above the equator it will orbit the earth once every 24 hours and appear to be stationary to an observer on the ground.
- This orbit is known as a geostationary orbit

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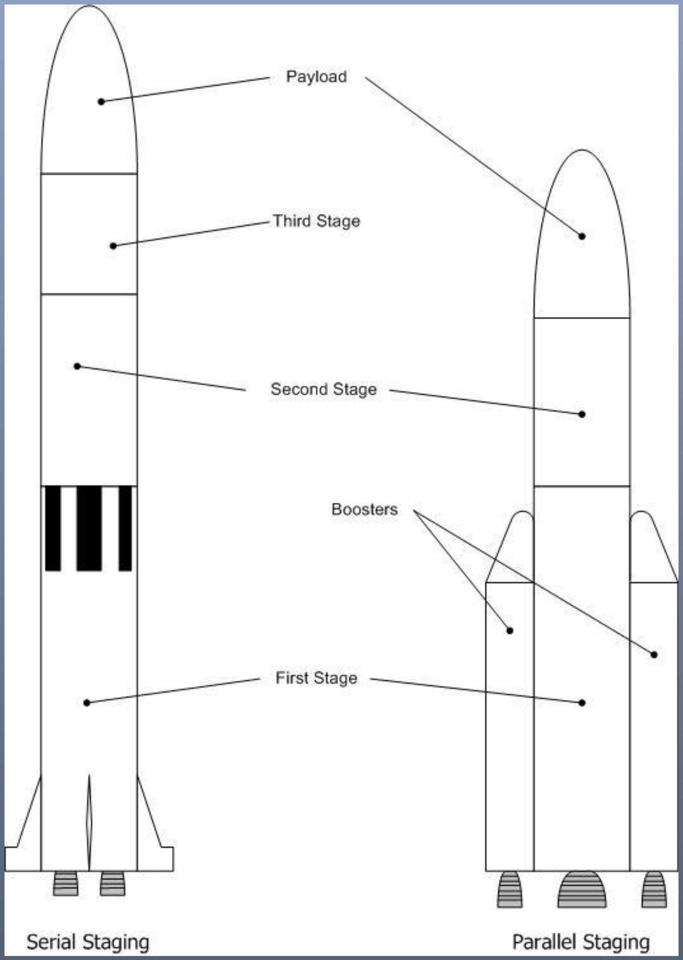
Launch Vehicles

- Some of these satellites weigh over 10 tonnes.
- It takes a very large rocket to lift a 10 tonne satellite to 36000 km
- These large rockets are called **launch vehicles**

Launch Vehicles



- The performance of a launch vehicle can be improved by getting rid of bits of the structure that are no longer needed during the flight.
- This technique, called **staging**, is used in all current launch vehicles.
- There are two standard forms of staging: **serial staging** and **parallel staging**.
- In serial staging the stages are stacked vertically in the rocket and are fired one after another.
- Parallel staging uses stages strapped alongside each other which are fired simultaneously.
- Most launch vehicle use both serial and parallel staging

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Launch Vehicles

- The Ariane 5 is Europe’s main launch vehicle.
- It can lift over 10 tonnes to geostationary orbit.
- The picture shows an Ariane 5 launching from its site at Kourou in French Guiana in 2008.
- The picture is used with the kind permission of Arianespace, the company which operates the Ariane 5.

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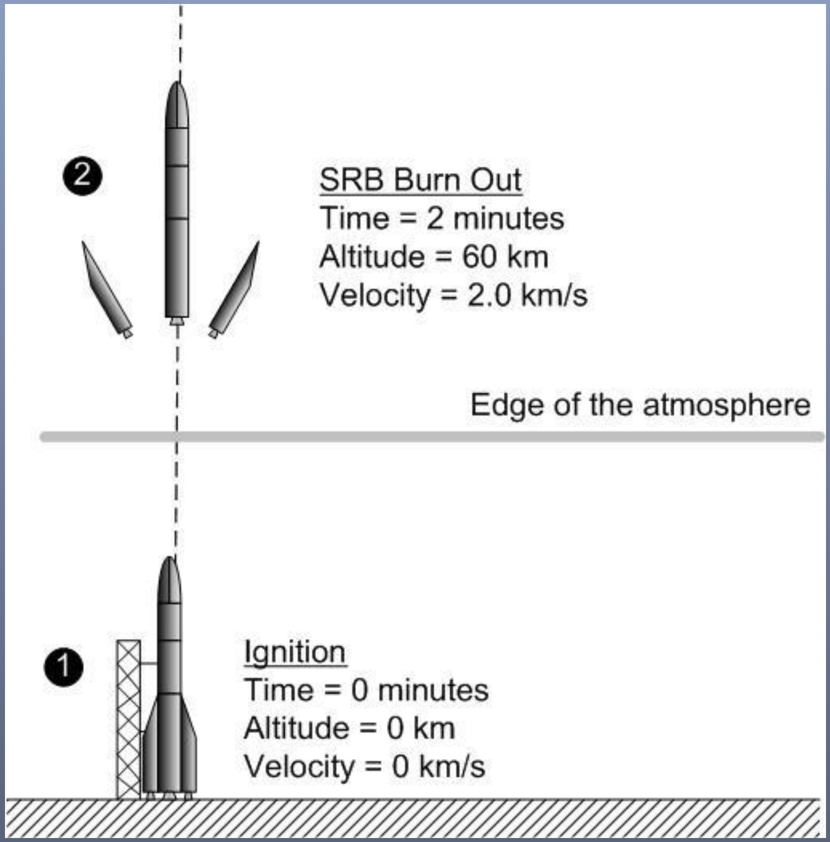
Launch to Geostationary Orbit



- It is normal for launch vehicles like Ariane 5 to have 3 stages, and for each stage to be dropped as its propellant is consumed.
- The first stage uses a single powerful engine, the Vulcain for Ariane 5
- Heavy lift rockets like the Ariane 5 have two or more solid rocket boosters (SRB) to help the launcher to lift heavier satellites
- Bothe the main engine and SRB are ignited at lift off➊
- The SRB are jettisoned about 2 minutes into the flight when their fuel is spent ➋

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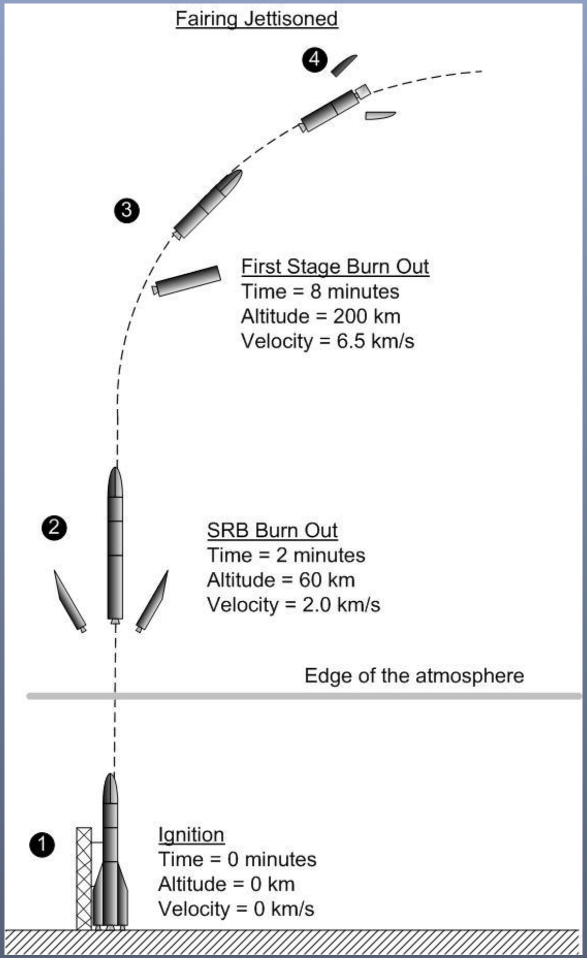
Launch to Geostationary Orbit



- About 8 minutes into the flight the first stage has consumed all its fuel.
- The first stage is jettisoned and the second stage engine ignites ❸
- The payload is protected by an aerodynamic fairing inside the atmosphere. This is not needed when the rocket is in space so it is jettisoned ❹

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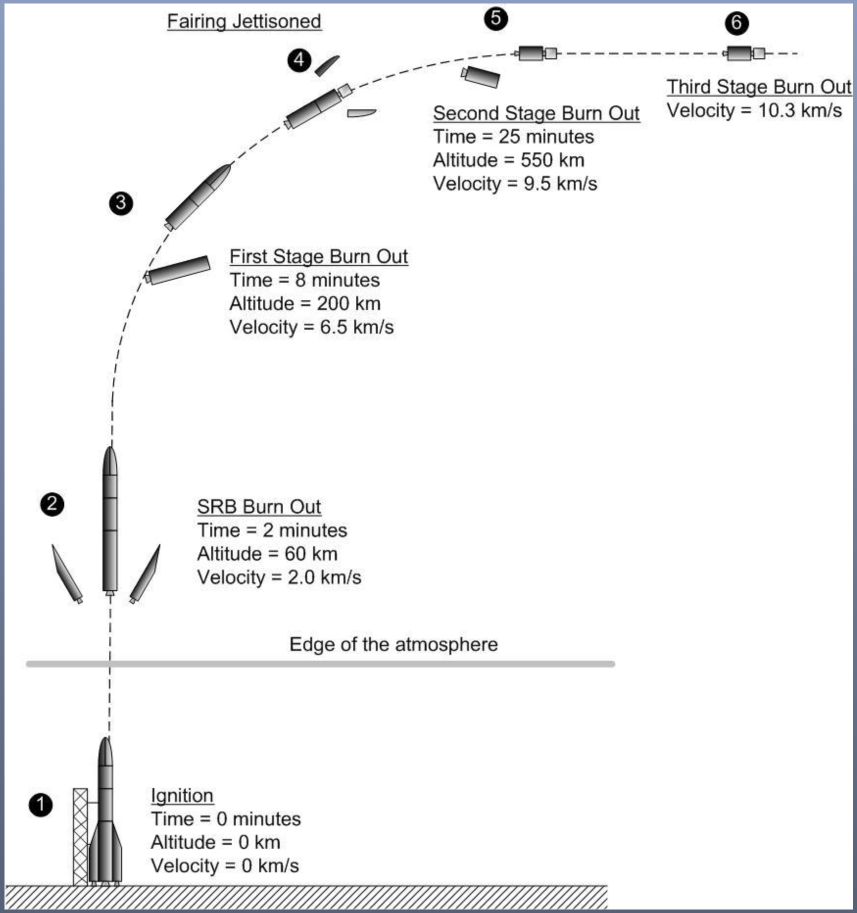
Launch to Geostationary Orbit



- About 25 minutes into the flight the seond stage has consumed all its fuel and is jetissoned ❺
- The third stage is ignited. and burns until the correct velocity has been achieved. At this time it is shut down ❻
- The satellite has enough speed to coast to 36000 km altitude, the highest point of the flight.
- This highest point is called the **apogee**

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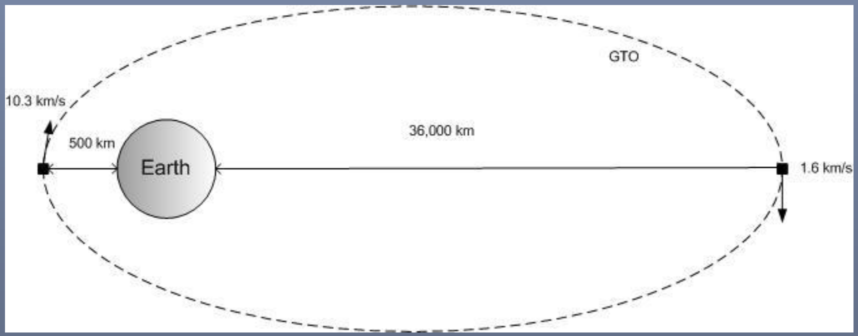
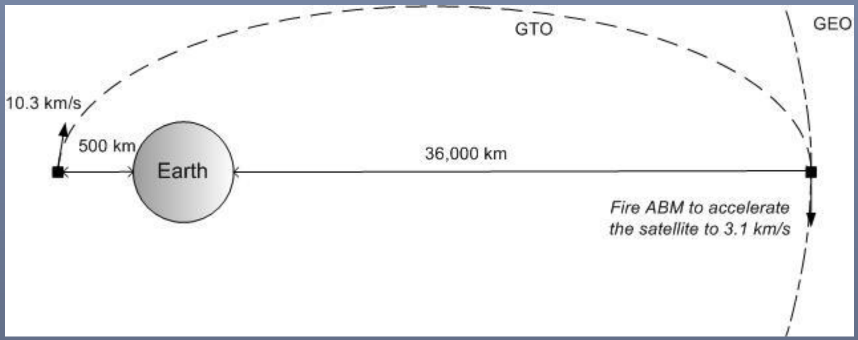
Launch to Geostationary Orbit



- The launch vehicle needs to accelerate the satellite to a horizontal velocity of 10.3 km/s at an altitude of about 500km.
- This puts the satellite in an elliptical geostationary transfer orbit (GTO)
- In this orbit the satellite will coast up to the geostationary orbit at 36,000 km altitude
- Gravity slows the satellite until, at 36000 km, it is only travelling at 1.6 km/s

Launch to Geostationary Orbit



- The satellite completes several orbits of the GTO while its electronic systems are powered up.
- AT the highest point, called apogee, the satellite fires its own rocket motor, called the apogee boost motor ABM)
- The ABM accelerates the satellite from 1.6 km/s to 3.1 km/s, putting the satellite into a circular orbit at 36000 km altitude. It is now in the geostationary orbit.

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Current Launch Vehicles

The table shows the payload capability of some current launch vehicles.

Operator	Launcher name	Payload to GTO (tonnes)	Launch sites
USA	Atlas 5	13.0	Cape Canaveral, USA
USA	Delta 4	12.9	Cape Canaveral, USA
Russia	Proton	6.0	Baikonur, Russia
Europe	Ariane 5	10.5	Kourou, French Guiana
Japan	H2	6.0	Tanegashima, Japan
China	Long March	4.5	Xichang, China
USA/Russia	Sea Launch	5.9	Offshore platform

Chapter 7
Model Rockets

Model Rockets

- Model Rockets are a run and inexpensive way of learning about rocketry
- Model rockets are not toys but are real rockets
- The specialist body for all model rocketry in the UK is the United Kingdom Rocketry Association (UKRA)

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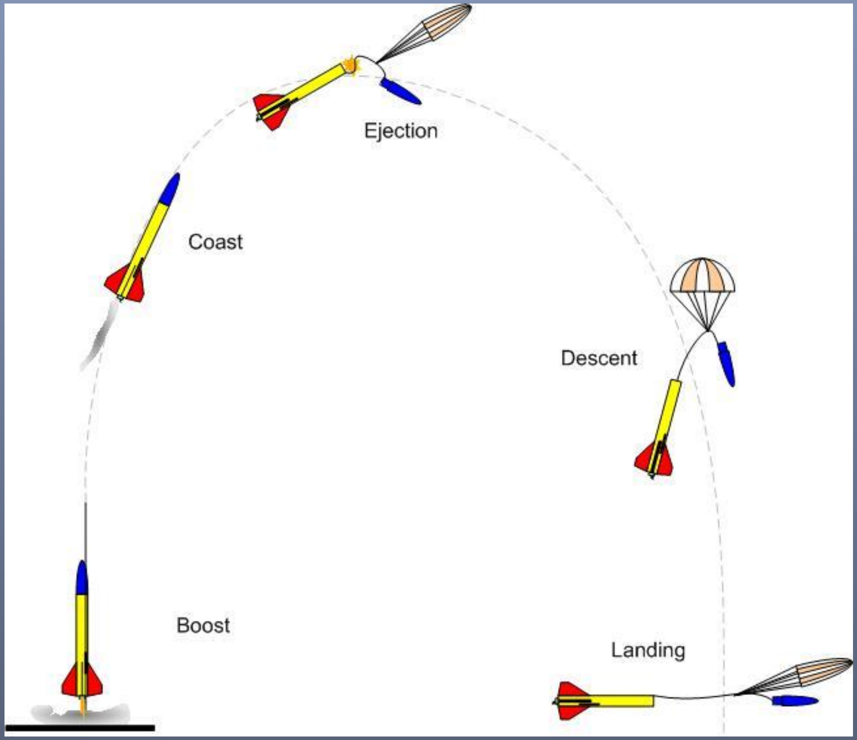
Model Rockets

- Model rockets are real rockets in miniature:
  - They are launched from a launch pad
  - The pad supports the rocket while it accelerates
  - The motors are ignited electrically from a safe distance
  - The rocket deploys a parachute
  - Rockets can be flown many times.

Model Rockets



- The five phases of a model rocket flight are called
  - boost
  - coast
  - ejection
  - descent
  - landing.

Model Rockets

- Boost phase: The motor propels the rocket to its highest speed.
- Coast: After the motor has burned all its propellant the rocket continues to move. It coasts upwards, slowing down due to its weight and drag.
- Ejection: At the highest point of the flight (called the apogee) a small charge ejects the parachute.
- Descent: The rocket drifts back to earth under its parachute.
- Landing: The rocket returns safely to earth, ready to be prepared for another flight.

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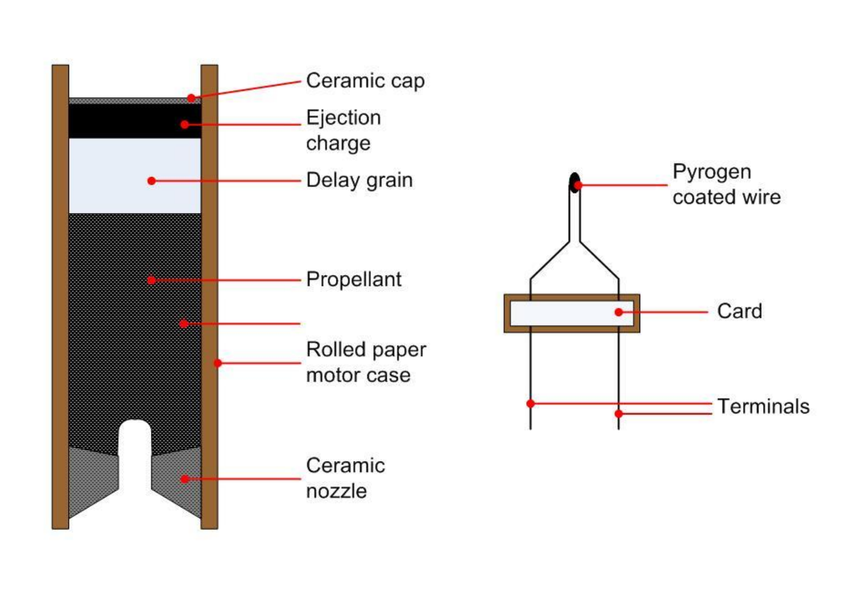
Model Rocket Motors

- Model rocket motors are similar to real solid rocket motors
- The cardboard motor case contains the propellant while it burns
- A ceramic nozzle accelerates the exhaust gas
- The motor is ignited by passing an electrical current through the igniter
  - the current heats the wire
  - this ignites the pyrogen which fires the motor.



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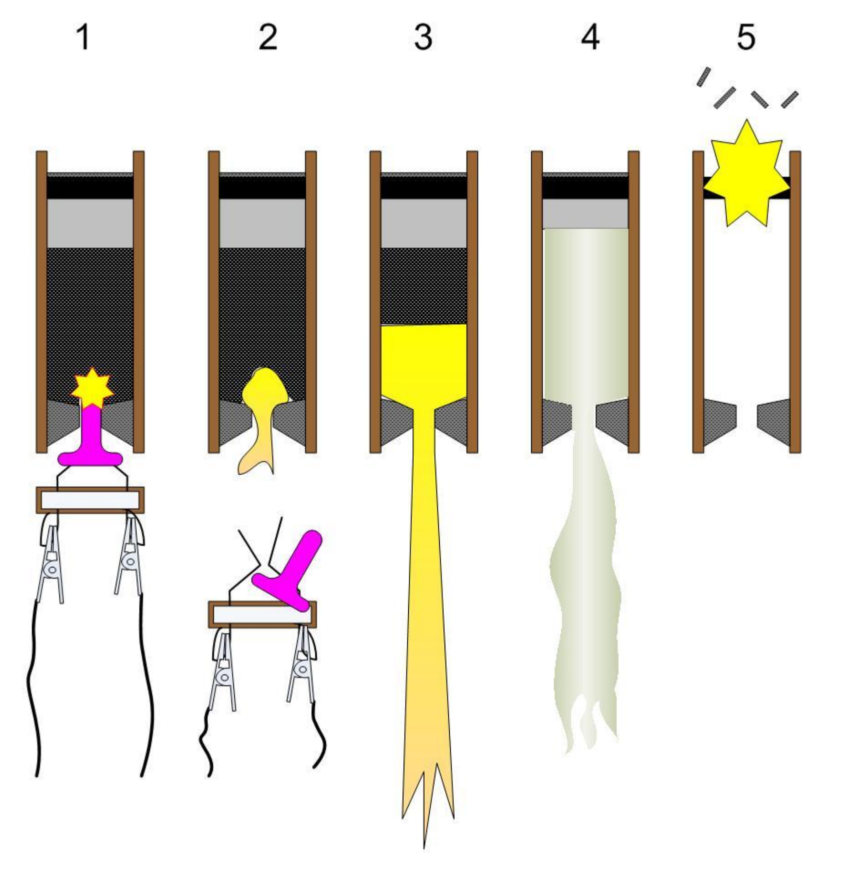
Model Rocket Motors

- 1. The igniter, held in place by a plastic plug, causes a flash of heat which ignites the propellant.
- 2. The gas from the burning propellant pushes the igniter and plug out the nozzle.
- 3. Hot exhaust gas propels the rocket until the propellant is all consumed.
- A delay grain creates tracking smoke while the rocket coasts to apogee.
- A small explosive charge fires which ejects the parachute.



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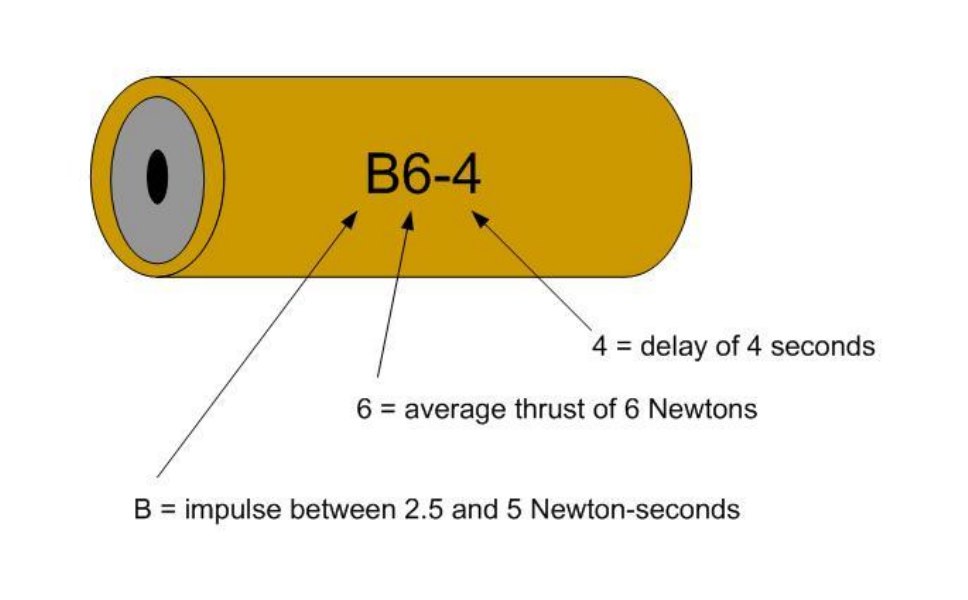
Model Rocket Motors

- Model rocket motors are classified by their impulse
- Impulse is the amount of thrust a motor gives (Newtons) multipled by the time for which the motor provides that thrust (seconds)
  - Impulse = thrust x time
- Impulse is measured in Newton-seconds (Ns)
- Motors are given a letter which reflect their impulse range

Impulse Class	Impulse	Propellant
A	1.26-2.50 Ns	BP
B	2.51-5.00 Ns	BP
C	5.01-10.00 Ns	BP
D	10.01-20.00 Ns	BP or AP
E	20.01-40.00	BP or AP
F	40.01-80.00	AP
G	80.01-160.00	AP

Model Rocket Motors



- A model rocket motor is specified with a simple code:
  - A letter which denotes the impulse range
  - A number which is the average thrust provided by the motor (Newtons)
  - A second number which is the coasting delay (seconds) before the ejection charge is fired

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Model Rocket Types

- They are classified by the overall impulse provided by the motor
  - Low power rockets (Impulse A to D)
  - Medium power rockets (Impulse E to G)
  - High power rockets (Impulse H and above)

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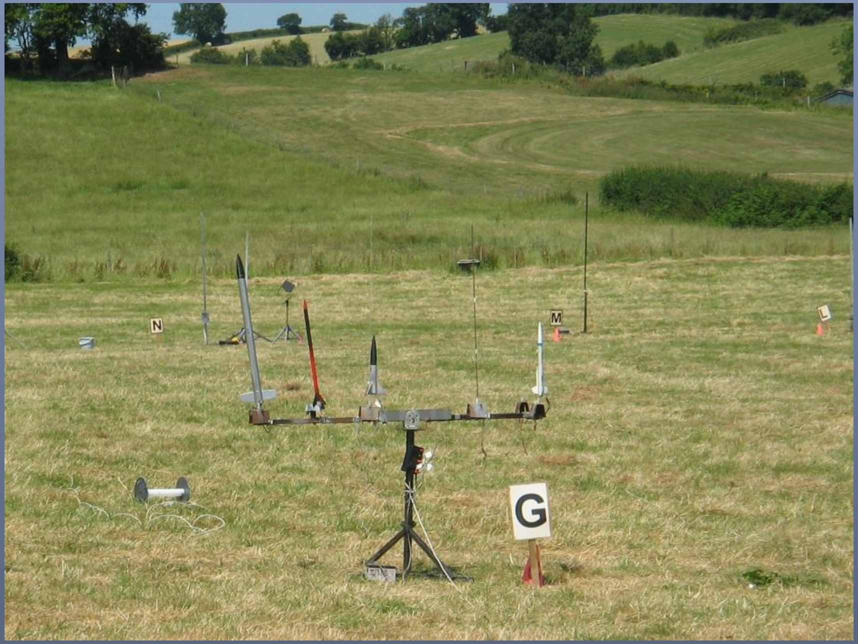
Model Rocket Types



- Low power rockets can fly to altitudes many hundreds of feet.
- Motors use solid propellant motors with black powder as the propellant
- The picture shows a launch pad with several low power rockets

Model Rocket Types

- Medium power rockets can fly up to 3000 ft
- Motors use solid propellant motors powered by ammonium perchlorate composite propellant (APCP)
- The picture shows medium powered rocket (scale model of an AMRAAM missile)

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Model Rocket Types

- High power rockets use large and powerful motors
- Solid propellant motors using APCP are common.
- Hybrid motors are also used
- Rockets can fly to altitudes of over 10,000 ft
- Supersonic flights are common
- The picture shows a high power rocket, over 2m tall, lifting off for a flight to over 5000 ft

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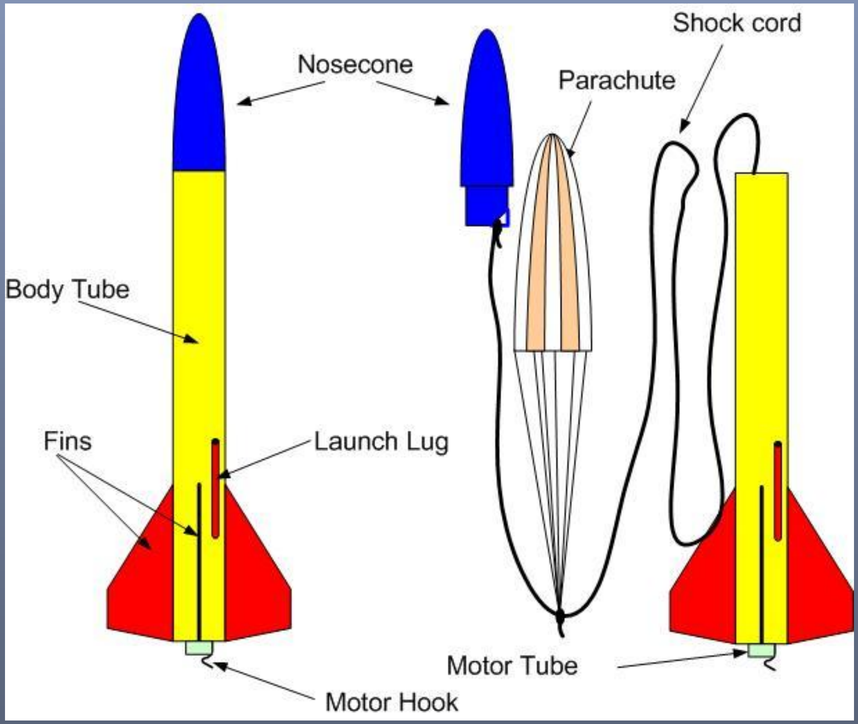
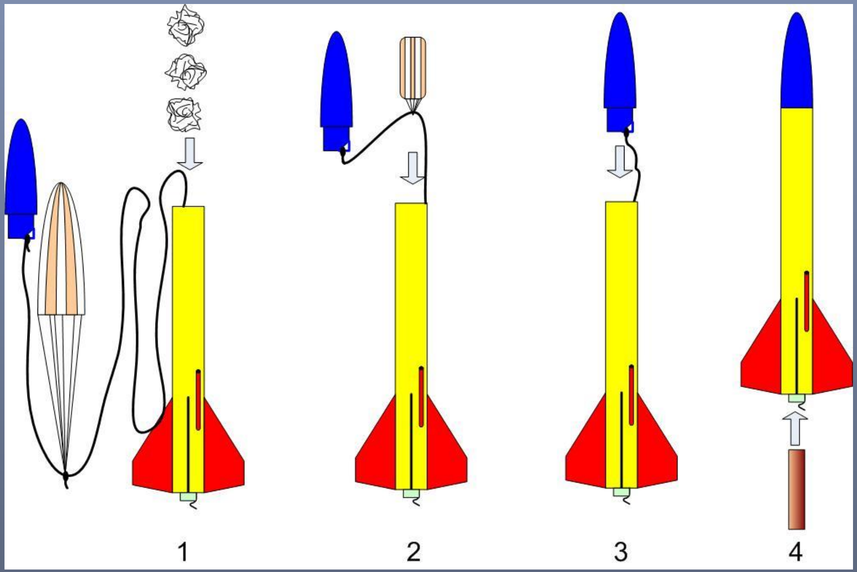
Model Rocket Design

- The nosecone is the aerodynamic front part of the rocket
- The body tube is a strong structure which contains the motor and parachute
- Fins ensure that the rocket flies straight
- The motor hook keeps the motor in place
- The launch lug is used to hold the rocket to the launch rod.
- The shock cord holds the nosecone, parachute and body together during descent



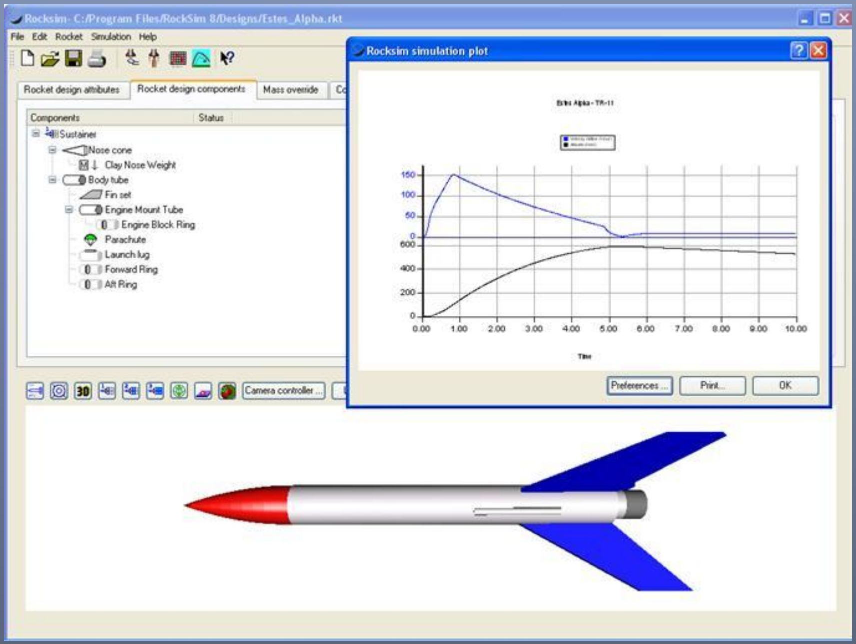
Model Rocket Design



- To prepare a rocket for flight:
  - insert some flameproof wadding in the tube. This protects the parachute from the ejection charge.
  - Fold the parachute and pack it into the tube
  - Place the nosecone into the body tube to hold the parachute in place

Model Rocket Design

- It's possible to design your own rockets using specialist software.
- The software allows you to
  - choose materials,
  - design the shape of the rocket
  - flight test the rocket with different motors
- The software produces graphs and charts to tell you how the rocket performs
- Some common software packages are Rocksim, SpaceCad and OpenRocket



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Getting started

- Squadrons can have their own rocketry programme
- Squadrons that want to fly model rockets should read ACP 20 ACTI 75
- An inexpensive starter kit can be obtained from your local model shop
- You local rocketry club would be happy to help you make your first launch a success

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