Rocket

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A **rocket** (from Italian *rocchetto* "bobbin")[nb 1][1] is a missile, spacecraft, aircraft or other vehicle that obtains thrust from a rocket engine. Rocket engine exhaust is formed entirely from propellant carried within the rocket before use.[2] Rocket engines work by action and reaction and push rockets forward simply by expelling their exhaust in the opposite direction at high speed, and can therefore work in the vacuum of space.

A Soyuz-U, at Baikonur cosmodrome's Site 1/5 in Kazakhstan

In fact, rockets work more efficiently in space than in an atmosphere. Multi-stage rockets are capable of attaining escape velocity from Earth and therefore can achieve unlimited maximum altitude. Compared with airbreathing engines, rockets are lightweight and powerful and capable of generating large accelerations. To control their flight, rockets rely on momentum, airfoils, auxiliary reaction engines, gimballed thrust, momentum wheels, deflection of the exhaust stream, propellant flow, spin, and/or gravity.

Rockets for military and recreational uses date back to at least 13th century China.[3] Significant scientific, interplanetary and industrial use did not occur until the 20th century, when rocketry was the enabling technology for the Space Age, including setting foot on the moon. Rockets are now used for fireworks, weaponry, ejection seats, launch vehicles for artificial satellites, human spaceflight, and space exploration.

Chemical rockets are the most common type of high power rocket, typically creating a high speed exhaust by the combustion of fuel with an oxidizer. The stored propellant can be a simple pressurized gas or a single liquid fuel that disassociates in the presence of a catalyst (monopropellants), two liquids that spontaneously react on contact (hypergolic propellants), two liquids that must be ignited to react, a solid combination of fuel with oxidizer (solid fuel), or solid fuel with liquid oxidizer (hybrid propellant system). Chemical rockets store a large amount of energy in an easily released form, and can be very dangerous. However, careful design, testing, construction and use minimizes risks.

Contents

History

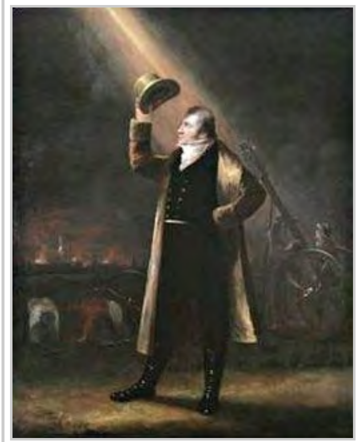
The first gunpowder-powered rockets were developed in Song China, by the 13th century. The Chinese rocket technology was adopted by the Mongols and the invention was spread via the Mongol invasions to the Near East and Europe in the mid 13th century.[4] Medieval and early modern rockets were used militarily as incendiary weapons in sieges.

An early Chinese text to mention the use of rockets was the *Huolongjing*, written by the Chinese artillery officer Jiao Yu in the mid-14th century. Between 1270 and 1280, Hasan al-Rammah wrote *al-furusiyyah wa al-manasib al-harbiyya* (*The Book of Military Horsemanship and Ingenious War Devices*), which included 107 gunpowder recipes, 22 of which are for rockets.[5][6] In Europe, Konrad Kyeser described rockets in his military treatise *Bellifortis* around 1405.[7]

Drawing of a Chinese soldier lighting a rocket's fuse (1890)

Depiction of a rocket (1405)

The name *Rocket* comes from the Italian *rocchetta*, meaning "bobbin" or "little spindle", given due to the similarity in shape to the bobbin or spool used to hold the thread to be fed to a spinning wheel. The Italian term was adopted into German in the mid 16th century by Leonhard Fronsperger and Conrad Haas, and by the early 17th century into English.[1] *Artis Magnae Artilleriae pars prima*, an important early modern work on rocket artillery, by Kazimierz Siemienowicz, was first printed in Amsterdam in 1650.



William Congreve at the bombardment of Copenhagen (1807)

The first iron-cased rockets were developed in the late 18th century in the Kingdom of Mysore, adopted and improved as the Congreve rocket and used in the Napoleonic Wars. The first mathematical treatment of the dynamics of rocket propulsion is due to William Moore (1813). In 1815, Alexander Dmitrievich Zasyadko constructed rocket-launching platforms, which allowed rockets to be fired in salvos (6 rockets at a time), and gun-laying devices. William Hale in 1844 greatly increased the accuracy of rocket artillery. The Congreve rocket was further improved by Edward Mounier Boxer in 1865.

Konstantin Tsiolkovsky (1903) first speculated on the possibility of manned spaceflight with rocket technology. Robert Goddard in 1920 published proposed improvements to rocket technology in *A Method of Reaching Extreme Altitudes*. In 1923, Hermann Oberth (1894–1989) published *Die Rakete zu den Planetenräumen* ("The Rocket into Planetary Space")

Modern rockets originated when Goddard attached a supersonic (de Laval) nozzle to the combustion chamber of a liquid-fueled rocket engine. These nozzles turn the hot gas from the combustion chamber into a cooler, hypersonic, highly directed jet of gas, more than doubling the thrust and raising the engine efficiency from 2% to 64%. Use of liquid propellants instead of gunpowder greatly improved the effectiveness of rocket artillery in World War II, and opened up the possibility of manned spaceflight after 1945.

In 1943, production of the V-2 rocket began in Germany. In parallel with the guided missile programme, rockets were also used on aircraft, either for assisting horizontal take-off (RATO), vertical take-off (Bachem Ba 349 "Natter") or for powering them (Me 163, see list of World War II guided missiles of Germany). The Allies' rocket programs were less sophisticated, relying mostly on unguided missiles like the Soviet Katyusha rocket. The Americans captured a large number of German rocket scientists, including Wernher von Braun, and brought them to the United States as part of Operation Paperclip. After the war, rockets were used to study high-altitude conditions, by radio telemetry of temperature and pressure of the atmosphere, detection of cosmic rays, and further research; notably the Bell X-1, the first manned vehicle to break the sound barrier. Independently, in the Soviet Union's space program research continued under the leadership of the chief


Goddard with a liquid oxygen-gasoline rocket (1926)

designer Sergei Korolev.

During the Cold War, rockets became extremely important militarily as modern intercontinental ballistic missiles (ICBMs). The 1960s became the decade of rapid development of rocket technology particularly in the Soviet Union (Vostok, Soyuz, Proton) and in the United States (e.g. the X-15). Rockets were now used for space exploration, with the American manned programs Project Mercury, Project Gemini and later the Apollo programme culminated in 1969 with the first manned landing on the moon via the Saturn V.

Types

Vehicle configurations


Saturn V is the biggest rocket to have successfully flown.

Rocket vehicles are often constructed in the archetypal tall thin "rocket" shape that takes off vertically, but there are actually many different types of rockets including:[8][9]

- tiny models such as balloon rockets, water rockets, skyrockets or small solid rockets that can be purchased at a hobby store
- missiles
- space rockets such as the enormous Saturn V used for the Apollo program
- rocket cars
- rocket bike[10]
- rocket-powered aircraft (including rocket assisted takeoff of conventional aircraft- RATO)
- rocket sleds
- rocket trains
- rocket torpedoes[11][12]
- rocket-powered jet packs[13]
- rapid escape systems such as ejection seats and launch escape systems
- space probes


Launch of *Apollo 15* Saturn V rocket: $T - 30$ s through $T + 40$ s

Design

A rocket design can be as simple as a cardboard tube filled with black powder, but to make an efficient, accurate rocket or missile involves overcoming a number of difficult problems. The main difficulties include cooling the combustion chamber, pumping the fuel (in the case of a liquid fuel), and controlling and correcting the direction of motion.[14]

Components

Rockets consist of a propellant, a place to put propellant (such as a propellant tank), and a nozzle. They may also have one or more rocket engines, directional stabilization device(s) (such as fins, vernier engines or engine gimbals for thrust vectoring, gyroscopes) and a structure (typically monocoque) to hold these components together. Rockets intended for high speed atmospheric use also have an aerodynamic fairing such as a nose cone, which usually holds the payload.[15]

As well as these components, rockets can have any number of other components, such as wings (rocketplanes), parachutes, wheels (rocket cars), even, in a sense, a person (rocket belt). Vehicles frequently possess navigation systems and guidance systems that typically use satellite navigation and inertial navigation systems.

Engines

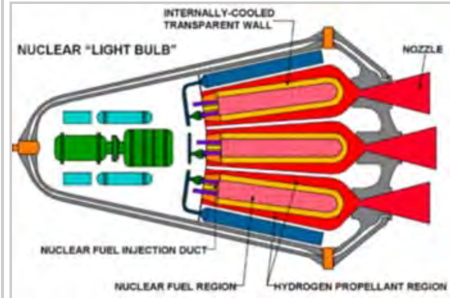

Viking 5C rocket engine

Rocket engines employ the principle of jet propulsion.[2] The rocket engines powering rockets come in a great variety of different types; a comprehensive list can be found in rocket engine. Most current rockets are chemically powered rockets (usually internal combustion engines,[16] but some employ a decomposing monopropellant) that emit a hot exhaust gas. A rocket engine can use gas propellants, solid propellant, liquid propellant, or a hybrid mixture of both solid and liquid. Some rockets use heat or pressure that is supplied from a source other than the chemical reaction of propellant(s), such as steam rockets, solar thermal rockets, nuclear thermal rocket engines or simple pressurized rockets such as water rocket or cold gas thrusters. With combustive propellants a chemical reaction is initiated between the fuel and the oxidizer in the combustion chamber, and the resultant hot gases accelerate out of a rocket engine nozzle (or nozzles) at the rearward-facing end of the rocket. The acceleration of these gases through the engine exerts force ("thrust") on the combustion chamber and nozzle, propelling the vehicle (according to Newton's Third Law). This actually happens because the force (pressure times area) on the combustion chamber wall is unbalanced by the nozzle opening; this is not the case in any other direction. The shape of the nozzle also generates force by directing the exhaust gas along the axis of the rocket.[2]

Propellant

Rocket propellant is mass that is stored, usually in some form of propellant tank or casing, prior to being used as the propulsive mass that is ejected from a rocket engine in the form of a fluid jet to produce thrust.[2] For chemical rockets often the propellants are a fuel such as liquid hydrogen or kerosene burned with an oxidizer such as liquid oxygen or nitric acid to produce large volumes of very hot gas. The oxidiser is either kept separate and mixed in the combustion chamber, or comes premixed, as with solid rockets.

Sometimes the propellant is not burned but still undergoes a chemical reaction, and can be a 'monopropellant' such as hydrazine, nitrous oxide or hydrogen peroxide that can be catalytically decomposed to hot gas.



Gas Core light bulb

Alternatively, an inert propellant can be used that can be externally heated, such as in steam rocket, solar thermal rocket or nuclear thermal rockets.[2]

For smaller, low performance rockets such as attitude control thrusters where high performance is less necessary, a pressurised fluid is used as propellant that simply escapes the spacecraft through a propelling nozzle.[2]

Uses

Rockets or other similar reaction devices carrying their own propellant must be used when there is no other substance (land, water, or air) or force (gravity, magnetism, light) that a vehicle may usefully employ for propulsion, such as in space. In these circumstances, it is necessary to carry all the propellant to be used.

However, they are also useful in other situations:

Military


A Trident II missile launched from sea.

Some military weapons use rockets to propel warheads to their targets. A rocket and its payload together are generally referred to as a *missile* when the weapon has a guidance system (not all missiles use rocket engines, some use other engines such as jets) or as a *rocket* if it is unguided. Anti-tank and anti-aircraft missiles use rocket engines to engage targets at high speed at a range of several miles, while intercontinental ballistic missiles can be used to deliver multiple nuclear warheads from thousands of miles, and anti-ballistic missiles try to stop them. Rockets have also been tested for reconnaissance, such as the Ping-Pong rocket, which was launched to surveil enemy targets, however, recon rockets have never come into wide use in the military.

Science and research

Sounding rockets are commonly used to carry instruments that take readings from 50 kilometers (31 mi) to 1,500 kilometers (930 mi) above the surface of the Earth.[17]

Rocket engines are also used to propel rocket sleds along a rail at extremely high speed. The world record for this is Mach 8.5.[18]

Spaceflight

Larger rockets are normally launched from a launch pad that provides stable support until a few seconds after ignition. Due to their high exhaust velocity—2,500 to 4,500 m/s (9,000 to 16,200 km/h; 5,600 to 10,100 mph)—rockets are particularly useful when very high speeds are required, such as orbital speed at approximately 7,800 m/s (28,000 km/h; 17,000 mph). Spacecraft delivered into orbital trajectories become artificial satellites, which are used for many commercial purposes. Indeed, rockets remain the only way to launch spacecraft into orbit and beyond.[19] They are also used to rapidly accelerate spacecraft when they change orbits or de-orbit for landing. Also, a rocket may be used to soften a hard parachute landing immediately before touchdown (see retrorocket).

A Bumper sounding rocket

Rescue

Apollo LES pad abort test with boilerplate crew module.

Rockets were used to propel a line to a stricken ship so that a Breeches buoy can be used to rescue those on board. Rockets are also used to launch emergency flares.

Some crewed rockets, notably the Saturn V[20] and Soyuz[21] have launch escape systems. This is a small, usually solid rocket that is capable of pulling the crewed capsule away from the main vehicle towards safety at a moments notice. These types of systems have been operated several times, both in testing and in flight, and operated correctly each time.

This was the case when the Safety Assurance System (Soviet nomenclature) successfully pulled away the L3 capsule during three of the four failed launches of the Soviet moon rocket, N1 vehicles 3L, 5L and 7L. In all three cases the capsule, albeit unmanned, was saved from destruction. It should be noted that only the three aforementioned N1 rockets had functional Safety Assurance Systems. The outstanding vehicle, 6L, had dummy upper stages and therefore no escape system giving the N1 booster a 100% success rate for egress from a failed launch.[22][23][24][25]

A successful escape of a manned capsule occurred when Soyuz T-10, on a mission to the Salyut 7 space station, exploded on the pad.[26]

Solid rocket propelled ejection seats are used in many military aircraft to propel crew away to safety from a vehicle when flight control is lost.[27]

Hobby, sport, and entertainment

Hobbyists build and fly a wide variety of model rockets. Many companies produce model rocket kits and parts but due to their inherent simplicity some hobbyists have been known to make rockets out of almost anything. Rockets are also used in some types of consumer and professional fireworks. A Water Powered Rocket is a type of model rocket using water as its reaction mass. The pressure vessel (the engine of the rocket) is usually a used plastic soft drink bottle. The water is forced out by a pressurized gas, typically compressed air. It is an example of Newton's third law of motion.

The scale of amateur rocketry can range from a small rocket launched in your own backyard to a rocket that reached space.[28] Amateur rocketry is split into three categories: low power, mid power, and high power.

Australia, Austria, Canada, Germany, New Zealand, Switzerland, the United Kingdom, and the United States have high power rocket associations which provide certifications to its members to fly different rocket motor sizes. While joining these organizations is not a requirement, they often provide insurance and flight waivers for their members.

Hydrogen peroxide rockets are used to power jet packs,[29] and have been used to power cars and a rocket car holds the all time (albeit unofficial) drag racing record.[30]

Corpulent Stump is the most powerful non commercial rocket ever launched on an Aerotech engine in the United Kingdom.

Noise

Rocket exhaust generates a significant amount of acoustic energy. As the supersonic exhaust collides with the ambient air, shock waves are formed. The sound intensity from these shock waves depends on the size of the rocket as well as the exhaust velocity. The sound intensity of large, high performance rockets could potentially kill at close range.[31]

Workers and media witness the Water Sound Suppression System test at Launch Pad 39A.

The Space Shuttle generates 180 dB of noise around its base.[32] To combat this, NASA developed a sound suppression system which can flow water at rates up to 900,000 gallons per minute (57 m^3/s) onto the launch pad. The water reduces the noise level from 180 dB down to 142 dB (the design requirement is 145 dB).[33] Without the sound suppression system, acoustic waves reflect off of the launch pad towards the rocket, vibrating the sensitive payload and crew. These acoustic waves can be so severe that they can destroy the rocket.

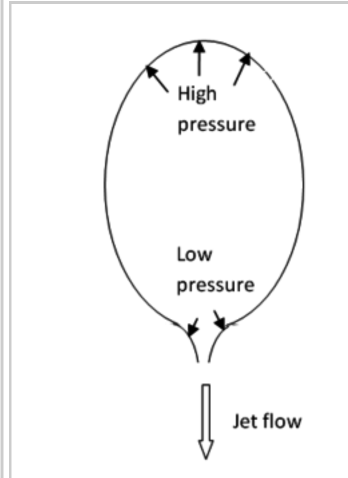
A Saturn V launch was detectable on seismometers a considerable distance from the launch site.

Noise is generally most intense when a rocket is close to the ground, since the noise from the engines radiates up away from the jet, as well as reflecting off the ground. This noise can be reduced somewhat by flame trenches with roofs, by water injection around the jet and by deflecting the jet at an angle.[31]

For crewed rockets various methods are used to reduce the sound intensity for the passengers, and typically the placement of the astronauts far away from the rocket engines helps significantly. For the passengers and crew, when a vehicle goes supersonic the sound cuts off as the sound waves are no longer able to keep up with the vehicle.[31]

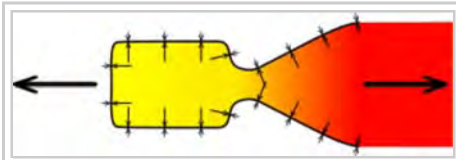
Physics

Operation



A balloon with a tapering nozzle. In this case, the nozzle itself does not push the balloon but is pulled by it. A convergent/divergent nozzle would be better.

The effect of the combustion of propellant in the rocket engine is to increase the velocity of the resulting gases to very high speeds, hence producing a thrust. Initially, the gases of combustion are sent in every direction, but only those that produce a net thrust have any effect. The ideal direction of motion of the exhaust is in the direction so as to cause thrust. At the top end of the combustion chamber the hot, energetic gas fluid cannot move forward, and so, it pushes upward against the top of the rocket engine's combustion chamber. As the combustion gases approach the exit of the combustion chamber, they increase in speed. The effect of the convergent part of the rocket engine nozzle on the high pressure fluid of combustion gases, is to cause the gases to accelerate to high speed. The higher the speed of the gases, the lower the pressure of the gas (Bernoulli's principle or conservation of energy) acting on that part of the combustion chamber. In a properly designed engine, the flow will reach Mach 1 at the throat of the nozzle. At which point the speed of the flow increases. Beyond the throat of the nozzle, a bell shaped expansion part of the engine allows the gases that are expanding to push against that part of the rocket engine. Thus, the bell part of the nozzle gives additional thrust. Simply expressed, for every action there is an equal and opposite reaction, according to Newton's third law with the result that the exiting gases produce the reaction of a force on the rocket causing it to accelerate the rocket.[34][nb 2]



Rocket thrust is caused by pressures acting on both the combustion chamber and nozzle

In a closed chamber, the pressures are equal in each direction and no acceleration occurs. If an opening is provided in the bottom of the chamber then the pressure is no longer acting on the missing section. This opening permits the exhaust to escape. The remaining pressures give a resultant thrust on the side opposite the opening, and these pressures are what push the rocket along.

The shape of the nozzle is important. Consider a balloon propelled by air coming out of a tapering nozzle. In such a case the combination of air pressure and viscous friction is such that the nozzle does not push the balloon but is *pulled* by it.[35] Using a convergent/divergent nozzle gives more force since the exhaust also presses on it as it expands outwards, roughly doubling the total force. If propellant gas is continuously added to the chamber then these pressures can be maintained for as long as propellant remains. Note that in the case of liquid propellant engines, the pumps moving the propellant into the combustion chamber must maintain a pressure larger than the combustion chamber -typically on the order of 100 atmospheres.[2]

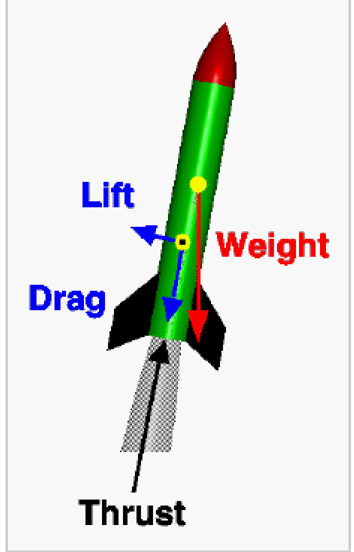
As a side effect, these pressures on the rocket also act on the exhaust in the opposite direction and accelerate this exhaust to very high speeds (according to Newton's Third Law).[2] From the principle of conservation of momentum the speed of the exhaust of a rocket determines how much momentum increase is created for a given amount of propellant. This is called the rocket's *specific impulse*.[2] Because a rocket, propellant and exhaust in flight, without any external perturbations, may be considered as a closed system, the total momentum is always constant. Therefore, the faster the net speed of the exhaust in one direction, the greater the speed of the rocket can achieve in the opposite direction. This is especially true since the rocket body's mass is typically far lower than the final total exhaust mass.

Forces on a rocket in flight

The general study of the forces on a rocket is part of the field of ballistics. Spacecraft are further studied in the subfield of astrodynamics.

Flying rockets are primarily affected by the following:[36]

- Thrust from the engine(s)
- Gravity from celestial bodies
- Drag if moving in atmosphere
- Lift; usually relatively small effect except for rocket-powered aircraft



Forces on a rocket in flight

Rockets that must travel through the air are usually tall and thin as this shape gives a high ballistic coefficient and minimizes drag losses.

In addition, the inertia and centrifugal pseudo-force can be significant due to the path of the rocket around the center of a celestial body; when high enough speeds in the right direction and altitude are achieved a stable orbit or escape velocity is obtained.

These forces, with a stabilizing tail (the *empennage*) present will, unless deliberate control efforts are made, naturally cause the vehicle to follow a roughly parabolic trajectory termed a gravity turn, and this trajectory is often used at least during the initial part of a launch. (This is true even if the rocket engine is mounted at the nose.) Vehicles can thus maintain low or even zero angle of attack, which minimizes transverse stress on the launch vehicle, permitting a weaker, and hence lighter, launch vehicle.[37][38]

Drag

Drag is a force opposite to the direction of the rocket's motion. This decreases acceleration of the vehicle and produces structural loads. Deceleration force for fast-moving rockets are calculated using the drag equation.

Drag can be minimised by an aerodynamic nose cone and by using a shape with a high ballistic coefficient (the "classic" rocket shape—long and thin), and by keeping the rocket's angle of attack as low as possible.

During a rocket launch, as the vehicle speed increases, and the atmosphere thins, there is a point of maximum aerodynamic drag called Max Q. This determines the minimum aerodynamic strength of the vehicle, as the rocket must avoid buckling under these forces.[39]

Net thrust

A typical rocket engine can handle a significant fraction of its own mass in propellant each second, with the propellant leaving the nozzle at several kilometres per second. This means that the thrust-to-weight ratio of a rocket engine, and often the entire vehicle can be very high, in extreme cases over 100. This compares with other jet propulsion engines that can exceed 5 for some of the better[40] engines.[41]

It can be shown that the net thrust of a rocket is:

$$F_n = \dot{m}\, v_e$$ [2]:2–14

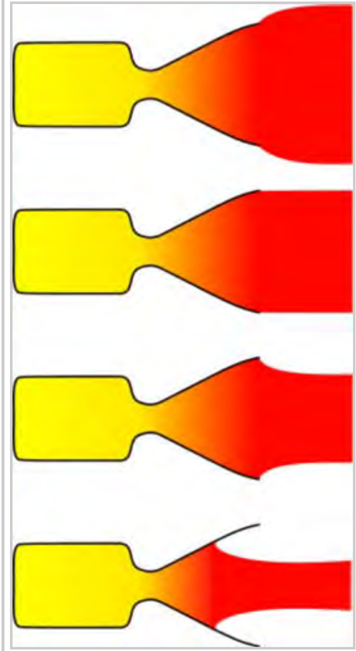
where:

$\dot{m} =$ propellant flow (kg/s or lb/s)

v_e = the effective exhaust velocity (m/s or ft/s)

The effective exhaust velocity v_e is more or less the speed the exhaust leaves the vehicle, and in the vacuum of space, the effective exhaust velocity is often equal to the actual average exhaust speed along the thrust axis. However, the effective exhaust velocity allows for various losses, and notably, is reduced when operated within an atmosphere.

The rate of propellant flow through a rocket engine is often deliberately varied over a flight, to provide a way to control the thrust and thus the airspeed of the vehicle. This, for example, allows minimization of aerodynamic losses[39] and can limit the increase of *g*-forces due to the reduction in propellant load.



A rocket jet shape varies based on external air pressure. From top to bottom: Underexpanded
Ideally Expanded
Overexpanded
Grossly overexpanded

Total impulse

Impulse is defined as a force acting on an object over time, which in the absence of opposing forces (gravity and aerodynamic drag), changes the momentum (integral of mass and velocity) of the object. As such, it is the best performance class (payload mass and terminal velocity capability) indicator of a rocket, rather than takeoff thrust, mass, or "power". The total impulse of a rocket (stage) burning its propellant is:[2]:27

$$I = \int F dt$$

When there is fixed thrust, this is simply:

$$I = Ft$$

The total impulse of a multi-stage rocket is the sum of the impulses of the individual stages.

Specific impulse

As can be seen from the thrust equation, the effective speed of the exhaust controls the amount of thrust produced from a particular quantity of fuel burnt per second.

An equivalent measure, the net impulse per weight unit of propellant expelled, is called specific Impulse, I_{sp}, and this is one of the most important figures that describes a rocket's performance. It is defined such that it is related to the effective exhaust velocity by:

$$v_e = I_{sp} \cdot g_0$$ [2]:29

where:

I_{sp} has units of seconds

g_0 is the acceleration at the surface of the Earth

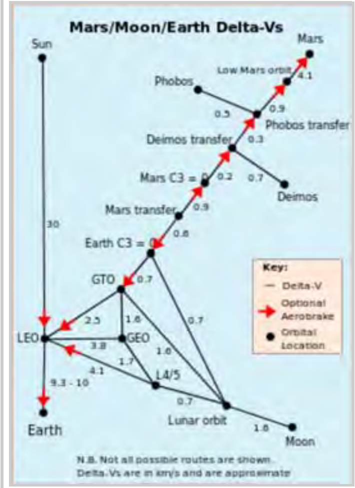
I_{sp} in vacuum of various rockets

Rocket	Propellants	I_{sp}, vacuum (s)
Space shuttle liquid engines	LOX/LH_2	453[42]
Space shuttle solid motors	APCP	268[42]
Space shuttle OMS	NTO/MMH	313[42]
Saturn V stage 1	LOX/RP-1	304[42]

Thus, the greater the specific impulse, the greater the net thrust and performance of the engine. I_{sp} is determined by measurement while testing the engine. In practice the effective exhaust velocities of rockets varies but can be extremely high, ~4500 m/s, about 15 times the sea level speed of sound in air.

Delta-v (rocket equation)

The delta-v capacity of a rocket is the theoretical total change in velocity that a rocket can achieve without any external interference (without air drag or gravity or other forces).



A map of approximate Delta-v's around the solar system between Earth and Mars[43][44]

When v_e is constant, the delta-v that a rocket vehicle can provide can be calculated from the Tsiolkovsky rocket equation:[45]

$$\Delta v = v_e \ln \frac{m_0}{m_1}$$

where:

- m_0 is the initial total mass, including propellant, in kg (or lb)
- m_1 is the final total mass in kg (or lb)
- v_e is the effective exhaust velocity in m/s (or ft/s)
- Δv is the delta-v in m/s (or ft/s)

When launched from the Earth practical delta-v's for a single rockets carrying payloads can be a few km/s. Some theoretical designs have rockets with delta-v's over 9 km/s.

The required delta-v can also be calculated for a particular manoeuvre; for example the delta-v to launch from the surface of the Earth to Low earth orbit is about 9.7 km/s, which leaves the vehicle with a sideways speed of about 7.8 km/s at an altitude of around 200 km. In this manoeuvre about 1.9 km/s is lost in air drag, gravity drag and gaining altitude.

The ratio $\frac{m_0}{m_1}$ is sometimes called the *mass ratio*.

Mass ratios

Almost all of a launch vehicle's mass consists of propellant.[46] Mass ratio is, for any 'burn', the ratio between the rocket's initial mass and its final mass.[47] Everything else being equal, a high mass ratio is desirable for good performance, since it indicates that the rocket is lightweight and hence performs better, for essentially the same reasons that low weight is desirable in sports cars.

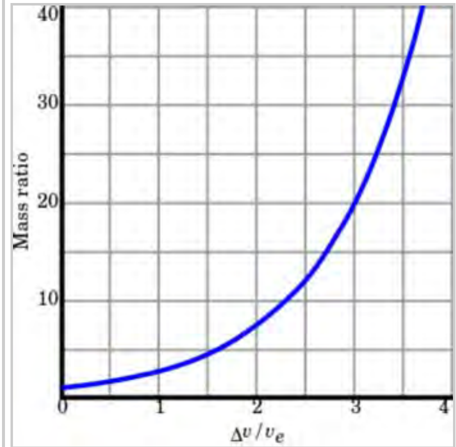
Rockets as a group have the highest thrust-to-weight ratio of any type of engine; and this helps vehicles achieve high mass ratios, which improves the performance of flights. The higher the ratio, the less engine mass is needed to be carried. This permits the carrying of even more propellant, enormously improving the delta-v. Alternatively, some rockets such as for rescue scenarios or racing carry relatively little propellant and payload and thus need only a lightweight structure and instead achieve high accelerations. For example, the Soyuz escape system can produce 20g.[21]

Achievable mass ratios are highly dependent on many factors such as propellant type, the design of engine the vehicle uses, structural safety margins and construction techniques.

The highest mass ratios are generally achieved with liquid rockets, and these types are usually used for orbital launch vehicles, a situation which calls for a high delta-v. Liquid propellants generally have densities similar to water (with the notable exceptions of liquid hydrogen and liquid methane), and these types are able to use lightweight, low pressure tanks and typically run high-performance turbopumps to force the propellant into the combustion chamber.

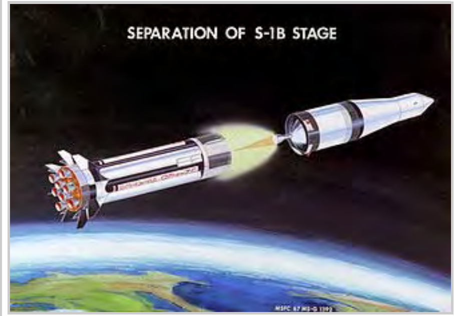
Some notable mass fractions are found in the following table (some aircraft are included for comparison purposes):

Vehicle	Takeoff Mass	Final Mass	Mass ratio	Mass fraction
Ariane 5 (vehicle + payload)	746,000 kg [48] (~1,645,000 lb)	2,700 kg + 16,000 kg[48] (~6,000 lb + ~35,300 lb)	39.9	0.975
Titan 23G first stage	117,020 kg (258,000 lb)	4,760 kg (10,500 lb)	24.6	0.959
Saturn V	3,038,500 kg[49] (~6,700,000 lb)	13,300 kg + 118,000 kg[49] (~29,320 lb + ~260,150 lb)	23.1	0.957
Space Shuttle (vehicle + payload)	2,040,000 kg (~4,500,000 lb)	104,000 kg + 28,800 kg (~230,000 lb + ~63,500 lb)	15.4	0.935
Saturn 1B (stage only)	448,648 kg[50] (989,100 lb)	41,594 kg[50] (91,700 lb)	10.7	0.907
Virgin Atlantic GlobalFlyer	10,024.39 kg (22,100 lb)	1,678.3 kg (3,700 lb)	6.0	0.83
V-2	13,000 kg (~28,660 lb) (12.8 ton)		3.85	0.74 [51]
X-15	15,420 kg (34,000 lb)	6,620 kg (14,600 lb)	2.3	0.57[52]
Concorde	~181,000 kg (400,000 lb [52])		2	0.5[52]
Boeing 747	~363,000 kg (800,000 lb[52])		2	0.5[52]



The Tsiolkovsky rocket equation gives a relationship between the mass ratio and the final velocity in multiples of the exhaust speed

Staging



Spacecraft staging involves dropping off unnecessary parts of the rocket to reduce mass.


Apollo 6 while dropping the interstage ring

Thus far, the required velocity (delta-v) to achieve orbit has been unattainable by any single rocket because the propellant, tankage, structure, guidance, valves and engines and so on, take a particular minimum percentage of take-off mass that is too great for the propellant it carries to achieve that delta-v. Since Single-stage-to-orbit has so far not been achievable, orbital rockets always have more than one stage.

For example, the first stage of the Saturn V, carrying the weight of the upper stages, was able to achieve a mass ratio of about 10, and achieved a specific impulse of 263 seconds. This gives a delta-v of around 5.9 km/s whereas around 9.4 km/s delta-v is needed to achieve orbit with all losses allowed for.

This problem is frequently solved by staging — the rocket sheds excess weight (usually empty tankage and associated engines) during launch. Staging is either *serial* where the rockets light after the previous stage has fallen away, or *parallel*, where rockets are burning together and then detach when they burn out.[53]

The maximum speeds that can be achieved with staging is theoretically limited only by the speed of light. However the payload that can be carried goes down geometrically with each extra stage needed, while the additional delta-v for each stage is simply additive.

Acceleration and thrust-to-weight ratio

From Newton's second law, the acceleration, a, of a vehicle is simply:

$$a = \frac{F_n}{m}$$

Where m is the instantaneous mass of the vehicle and F_n is the net force acting on the rocket (mostly thrust but air drag and other forces can play a part.)

As the remaining propellant decreases, rocket vehicles become lighter and their acceleration tends to increase until the propellant is exhausted. This means that much of the speed change occurs towards the end of the burn when the vehicle is much lighter.[2] However, the thrust can be throttled to offset or vary this if needed. Discontinuities in acceleration also occur when stages burn out, often starting at a lower acceleration with each new stage firing.

Peak accelerations can be increased by designing the vehicle with a reduced mass, usually achieved by a reduction in the fuel load and tankage and associated structures, but obviously this reduces range, delta-v and burn time. Still, for some applications that rockets are used for, a high peak acceleration applied for just a short time is highly desirable.

The minimal mass of vehicle consists of a rocket engine with minimal fuel and structure to carry it. In that case the thrust-to-weight ratio[nb 3] of the rocket engine limits the maximum acceleration that can be designed. It turns out that rocket engines generally have truly excellent thrust to weight ratios (137 for the NK-33 engine,[54] some solid rockets are over 1000[2]:442), and nearly all really high-g vehicles employ or have employed rockets.

The high accelerations that rockets naturally possess means that rocket vehicles are often capable of vertical takeoff, and in some cases, with suitable guidance and control of the engines, also vertical landing. For these operations to be done it is necessary for a vehicle's engines to provide more than the local gravitational acceleration.

Energy

Energy efficiency


Space Shuttle *Atlantis* during launch phase

Rocket launch vehicles take-off with a great deal of flames, noise and drama, and it might seem obvious that they are grievously inefficient. However, while they are far from perfect, their energy efficiency is not as bad as might be supposed.

The energy density of a typical rocket propellant is often around one-third that of conventional hydrocarbon fuels; the bulk of the mass is (often relatively inexpensive) oxidizer. Nevertheless, at take-off the rocket has a great deal of energy in the fuel and oxidizer stored within the vehicle. It is of course desirable that as much of the energy of the propellant end up as kinetic or potential energy of the body of the rocket as possible.

Energy from the fuel is lost in air drag and gravity drag and is used for the rocket to gain altitude and speed. However, much of the lost energy ends up in the exhaust.[2]:37–38

In a chemical propulsion device, the engine efficiency is simply the ratio of the kinetic power of the exhaust gases and the power available from the chemical reaction:[2]:37–38

$$\eta_c = \frac{\frac{1}{2}\dot{m}v_e^2}{\eta_{combustion}P_{chem}}$$

100% efficiency within the engine (engine efficiency $\eta_c = 100\%$) would mean that all the heat energy of the combustion products is converted into kinetic energy of the jet. This is not possible, but the near-adiabatic high expansion ratio nozzles that can be used with rockets come surprisingly close: when the nozzle expands the gas, the gas is cooled and accelerated, and an energy efficiency of up to 70% can be achieved. Most of the rest is heat energy in the exhaust that is not recovered.[2]:37–38 The high efficiency is a consequence of the fact that rocket combustion can be performed at very high temperatures and the gas is finally released at much lower temperatures, and so giving good Carnot efficiency.

However, engine efficiency is not the whole story. In common with the other jet-based engines, but particularly in rockets due to their high and typically fixed exhaust speeds, rocket vehicles are extremely inefficient at low speeds irrespective of the engine efficiency. The problem is that at low speeds, the exhaust carries away a huge amount of kinetic energy rearward. This phenomenon is termed propulsive efficiency (η_p).[2]:37–38

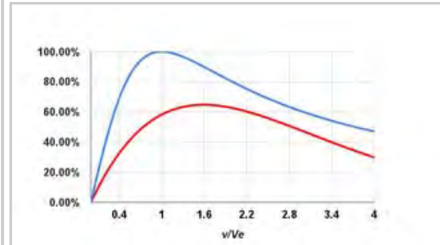
However, as speeds rise, the resultant exhaust speed goes down, and the overall vehicle energetic efficiency rises, reaching a peak of around 100% of the engine efficiency when the vehicle is travelling exactly at the same speed that the exhaust is emitted. In this case the exhaust would ideally stop dead in space behind the moving vehicle, taking away zero energy, and from conservation of energy, all the energy would end up in the vehicle. The efficiency then drops off again at even higher speeds as the exhaust ends up travelling forwards- trailing behind the vehicle.

From these principles it can be shown that the propulsive efficiency η_p for a rocket moving at speed u with an exhaust velocity c is:

$$\eta_p = \frac{2\frac{u}{c}}{1+(\frac{u}{c})^2}$$ [2]:37–38

And the overall (instantaneous) energy efficiency η is:

$$\eta = \eta_p \eta_c$$



Plot of instantaneous propulsive efficiency (blue) and overall efficiency for a rocket accelerating from rest (red) as percentages of the engine efficiency

For example, from the equation, with an η_c of 0.7, a rocket flying at Mach 0.85 (which most aircraft cruise at) with an exhaust velocity of Mach 10, would have a predicted overall energy efficiency of 5.9%, whereas a conventional, modern, air-breathing jet engine achieves closer to 35% efficiency. Thus a rocket would need about 6x more energy; and allowing for the specific energy of rocket propellant being around one third that of conventional air fuel, roughly 18x more mass of propellant would need to be carried for the same journey. This is why rockets are rarely if ever used for general aviation.

Since the energy ultimately comes from fuel, these considerations mean that rockets are mainly useful when a very high speed is required, such as ICBMs or orbital launch. For example, NASA's space shuttle fires its engines for around 8.5 minutes, consuming 1,000 tonnes of solid propellant (containing 16% aluminium) and an additional 2,000,000 litres of liquid propellant (106,261 kg of liquid hydrogen fuel) to lift the 100,000 kg vehicle (including the 25,000 kg payload) to an altitude of 111 km and an orbital velocity of 30,000 km/h. At this altitude and velocity, the vehicle has a kinetic energy of about 3 TJ and a potential energy of roughly 200 GJ. Given the initial energy of 20 TJ,[nb 4] the Space Shuttle is about 16% energy efficient at launching the orbiter.

Thus jet engines, with a better match between speed and jet exhaust speed (such as turbofans—in spite of their worse η_c)—dominate for subsonic and supersonic atmospheric use, while rockets work best at hypersonic speeds. On the other hand, rockets serve in many short-range *relatively* low speed military applications where their low-speed inefficiency is outweighed by their extremely high thrust and hence high accelerations.

Oberth effect

One subtle feature of rockets relates to energy. A rocket stage, while carrying a given load, is capable of giving a particular delta-v. This delta-v means that the speed increases (or decreases) by a particular amount, independent of the initial speed. However, because kinetic energy is a square law on speed, this means that the faster the rocket is travelling before the burn the more orbital energy it gains or loses.

This fact is used in interplanetary travel. It means that the amount of delta-v to reach other planets, over and above that to reach escape velocity can be much less if the delta-v is applied when the rocket is travelling at high speeds, close to the Earth or other planetary surface; whereas waiting until the rocket has slowed at altitude multiplies up the effort required to achieve the desired trajectory.

Safety, reliability and accidents

Space Shuttle Challenger was torn apart T+73 seconds after hot gases escaped the SRBs, causing the breakup of the Shuttle stack

The reliability of rockets, as for all physical systems, is dependent on the quality of engineering design and construction.

Because of the enormous chemical energy in rocket propellants (greater energy by weight than explosives, but lower than gasoline), consequences of accidents can be severe. Most space missions have some problems.[55] In 1986, following the Space Shuttle Challenger disaster, American physicist Richard Feynman, having served on the Rogers Commission estimated that the chance of an unsafe condition for a launch of the Shuttle was very roughly 1%;[56] more recently the historical per person-flight risk in orbital spaceflight has been calculated to be around 2%[57] or 4%.[58]

Costs and economics

The costs of rockets can be roughly divided into propellant costs, the costs of obtaining and/or producing the 'dry mass' of the rocket, and the costs of any required support equipment and facilities.[59]

Most of the takeoff mass of a rocket is normally propellant. However propellant is seldom more than a few times more expensive than gasoline per kilogram (as of 2009 gasoline was about $1/kg [$0.45/lb] or less), and although substantial amounts are needed, for all but the very cheapest rockets, it turns out that the propellant costs are usually comparatively small, although not completely negligible.[59] With liquid oxygen costing $0.15 per kilogram ($0.068/lb) and liquid hydrogen $2.20/kg ($1.00/lb), the Space Shuttle in 2009 had a liquid propellant expense of approximately $1.4 million for each launch that cost $450 million from other expenses (with 40% of the mass of propellants used by it being liquids in the external fuel tank, 60% solids in the SRBs).[60][61][62]

Even though a rocket's non-propellant, dry mass is often only between 5-20% of total mass,[63] nevertheless this cost dominates. For hardware with the performance used in orbital launch vehicles, expenses of $2000–$10,000+ per kilogram of dry weight are common, primarily from engineering, fabrication, and testing; raw materials amount to typically around 2% of total expense.[64][65] For most rockets except reusable ones (shuttle engines) the engines need not function more than a few minutes, which simplifies design.

Extreme performance requirements for rockets reaching orbit correlate with high cost, including intensive quality control to ensure reliability despite the limited safety factors allowable for weight reasons.[65] Components produced in small numbers if not individually machined can prevent amortization of R&D and facility costs over mass production to the degree seen in more pedestrian manufacturing.[65] Amongst liquid-fueled rockets, complexity can be influenced by how much hardware must be lightweight, like pressure-fed engines can have two orders of magnitude lesser part count than pump-fed engines but lead to more weight by needing greater tank pressure, most often used in just small maneuvering thrusters as a consequence.[65]

To change the preceding factors for orbital launch vehicles, proposed methods have included mass-producing simple rockets in large quantities or on large scale,[59] or developing reusable rockets meant to fly very frequently to amortize their up-front expense over many payloads, or reducing rocket performance requirements by constructing a hypothetical non-rocket spacelaunch system for part of the velocity to orbit (or all of it but with most methods involving some rocket use).

The costs of support equipment, range costs and launch pads generally scale up with the size of the rocket, but vary less with launch rate, and so may be considered to be approximately a fixed cost.[59]

Rockets in applications other than launch to orbit (such as military rockets and rocket-assisted take off), commonly not needing comparable performance and sometimes mass-produced, are often relatively inexpensive.

See also

Lists

- Chronology of Pakistan's rocket tests
- List of rockets
- Timeline of rocket and missile technology
- Timeline of spaceflight

General Rocketry

- Astrodynamics—the study of spaceflight trajectories
- Gantry
- Pendulum rocket fallacy—an instability of rockets
- Rocket garden—a place for viewing unlaunched rockets
- Rocket launch
- Rocket launch site
- Variable-mass system—the form of Newton's second law used for describing rocket motion

Propulsion and Propellant

- Ammonium Perchlorate Composite Propellant—Most common solid rocket propellant
- Bipropellant rocket—two-part liquid or gaseous fuelled rocket
- Hot Water rocket—powered by boiling water
- Pulsed Rocket Motors—solid rocket that burns in segments
- Spacecraft propulsion—describes many different propulsion systems for spacecraft
- Tripropellant rocket—variable propellant mixes can improve performance

Recreational Rockets

- High-powered rocket
- National Association of Rocketry
- Tripoli Rocketry Association

Recreational Pyrotechnic Rocketry

- Bottle rocket—small firework type rocket often launched from bottles
- Skyrocket—fireworks that typically explode at apogee

Weaponry

- Air-to-ground rockets
- Fire Arrow—one of the earliest types of rocket
- Katyusha rocket launcher—rack mounted rocket
- Rocket-propelled grenade—military use of rockets
- Shin Ki Chon—Korean variation of the Chinese fire arrow
- VA-111 Shkval—Russian rocket-propelled supercavitation torpedo

Rockets for Research

- Rocket plane—winged aircraft powered by rockets
- Rocket sled—used for high speeds along ground
- Sounding rocket—suborbital rocket used for atmospheric and other research

Misc

- Aircraft

- Equivalence principle—Einstein was able to show that the effects of gravity were completely equivalent to a rocket's acceleration in any small region of space
- Rocket Festival—Tradition bamboo rockets of Laos and Northeastern Thailand
- Rocket mail—the delivery of mail by rocket or missile.

Notes

1. English *rocket*, first attested in 1566 (OED), adopted from the Italian term, given due to the similarity in shape to the bobbin or spool used to hold the thread to be fed to a spinning wheel. The modern Italian term is *razzo*.
2. The confusion is illustrated in http://science.howstuffworks.com/rocket.htm; "If you have ever seen a big fire hose spraying water, you may have noticed that it takes a lot of strength to hold the hose (sometimes you will see two or three firefighters holding the hose). The hose is acting like a rocket engine. The hose is throwing water in one direction, and the firefighters are using their strength and weight to counteract the reaction. If they were to let go of the hose, it would thrash around with tremendous force. If the firefighters were all standing on skateboards, the hose would propel them backward at great speed!"
3. "thrust-to-weight ratio F/W_g is a dimensionless parameter that is identical to the acceleration of the rocket propulsion system (expressed in multiples of g_0) ... in a gravity-free vacuum"[2]:442
4. The energy density is 31MJ per kg for aluminum and 143 MJ/kg for liquid hydrogen, this means that the vehicle consumes around 5 TJ of solid propellant and 15 TJ of hydrogen fuel.

1. Bernhard, Jim (1 January 2007). *Porcupine, Picayune, & Post: How Newspapers Get Their Names*. University of Missouri Press. p. 126. ISBN 9780826266019. Retrieved 28 May 2016.
2. Sutton, George P.; Biblarz, Oscar (2001). *Rocket Propulsion Elements*. John Wiley & Sons. ISBN 9780471326427. Retrieved 28 May 2016.
3. MSFC History Office. "Rockets in Ancient Times (100 B.C. to 17th Century)". *A Timeline of Rocket History*. NASA. Retrieved 2009-06-28.
4. "Rockets appear in Arab literature in 1258 A.D., describing Mongol invaders' use of them on February 15 to capture the city of Baghdad." "A brief history of rocketry". *NASA Spacelink*. Retrieved 2006-08-19.
5. Hassan, Ahmad Y. "Gunpowder Composition for Rockets and Cannon in Arabic Military Treatises In Thirteenth and Fourteenth Centuries". *History of Science and Technology in Islam*. Archived from the original on February 26, 2008. Retrieved March 29, 2008.
6. Hassan, Ahmad Y. "Transfer Of Islamic Technology To The West, Part III: Technology Transfer in the Chemical Industries". *History of Science and Technology in Islam*. Archived from the original on March 9, 2008. Retrieved 2008-03-29.
7. Riper, A. Bowdoin Van (2004). *Rockets and missiles : the life story of a technology*. Westport: Greenwood Press. p. 10. ISBN 978-0-313-32795-7.
8. "NASA History: Rocket vehicles". Hq.nasa.gov. Retrieved 2012-12-10.
9. "OPEL Rocket vehicles". Strangevehicles.greyfalcon.us. Retrieved 2012-12-10.
10. "Rocket bicycle sets 207mph speed record By Leo Kelion". BBC News. 2013-11-11. Retrieved 2014-11-11.
11. Polmar, Norman; Moore, Kenneth J. (2004). *Cold War submarines : the design and construction of U.S. and Soviet submarines*. Washington, DC: Brassey's. p. 304. ISBN 978-1-57488-594-1.
12. III, compiled by A.D. Baker (2000). *The Naval Institute guide to combat fleets of the world 2000-2001 : their ships, aircraft, and systems*. Annapolis, Md.: Naval Institute Press. p. 581. ISBN 978-1-55750-197-4.
13. "The Rocketman". The Rocketman. Retrieved 2012-12-10.
14. Richard B. Dow (1958), *Fundamentals of Advanced Missiles*, Washington (DC): John Wiley & Sons, loc 58-13458
15. United States Congress. House Select Committee on Astronautics and Space Exploration (1959), "4. Rocket Vehicles", *Space handbook: Astronautics and its applications : Staff report of the Select Committee on Astronautics and Space Exploration*, House document / 86th Congress, 1st session, no. 86, Washington (DC): U.S. G.P.O., OCLC 52368435
16. Charles Lafayette Proctor II. "internal combustion engines". Concise Britannica. Retrieved 2012-12-10.

17. Marconi:KSC, Elaine. "NASA - What is a Sounding Rocket?". *www.nasa.gov*. Retrieved 28 May 2016.
18. "Test sets world land speed record". www.af.mil. Archived from the original on June 1, 2013. Retrieved 2008-03-18.
19. "Spaceflight Now-worldwide launch schedule". Spaceflightnow.com. Retrieved 2012-12-10.
20. "Apollo launch escape subsystem". ApolloSaturn. Retrieved 2012-12-10.
21. "Soyuz T-10-1 "Launch vehicle blew up on pad at Tyuratam; crew saved by abort system" ". Astronautix.com. Retrieved 2012-12-10.
22. Wade, Mark. "N1 Manned Lunar Launch Vehicle". *astronautix.com*. Encyclopedia Astronautica. Retrieved 24 June 2014.
23. Wade, Mark. "N1 5L launch - 1969.07.03". *astronautix.com*. Encyclopedia Astronautica. Retrieved 24 June 2014.
24. Harvey, Brian (2007). *Soviet and Russian lunar exploration*. Berlin: Springer. p. 226. ISBN 9780387739762. Retrieved 2 July 2014.
25. "N1 (vehicle 5L) moon rocket Test - launch abort system activated". *YouTube.com*. 2015 YouTube, LLC. Retrieved 12 January 2015.
26. Wade, Mark. "Soyuz T-10-1". *astronautix.com*. Encyclopedia Astronautica. Retrieved 24 June 2014.
27. Bonsor, Kevin (2001-06-27). "Howstuff works ejection seats". Science.howstuffworks.com. Retrieved 2012-12-10.
28. "CSXT GO FAST! Rocket Confirms Multiple World Records". Colorado Space News. 4 September 2014.
29. "jetbelt". Transchool.eustis.army.mil. 1961-10-12. Retrieved 2010-02-08.
30. "Sammy Miller". Eurodragster.com. Retrieved 2012-12-10.
31. Potter, R.C; Crocker, M.J (1966), *Acoustic Prediction Methods for Rocket Engines, Including the Effects of Clustered Engines and Deflected Exhaust Flow, CR-566* (PDF), Washington, D.C.: NASA, OCLC 37049198
32. "Launch Pad Vibroacoustics Research at NASA/KSC" (http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20020094348.pdf), Retrieved on 30 April 2016.
33. "Sound Suppression System" (http://www.nasa.gov/mission_pages/shuttle/launch/sound-suppression-system.html), Retrieved on 30 April 2016.
34. Warren, J. W. (1979). *Understanding force : an account of some aspects of teaching the idea of force in school, college and university courses in engineering, mathematics and science*. London: Murray. pp. 37–38. ISBN 9780719535642.
35. Warren, J. W. (1979). *Understanding force : an account of some aspects of teaching the idea of force in school, college and university courses in engineering, mathematics and science*. London: Murray. p. 28. ISBN 9780719535642.
36. "NASA- Four forces on a model rocket". Grc.nasa.gov. 2000-09-19. Retrieved 2012-12-10.
37. Glasstone, Samuel (1 January 1965). *Sourcebook on the Space Sciences*. D. Van Nostrand Co. p. 209. OCLC 232378. Retrieved 28 May 2016.
38. Callaway, David W. (March 2004). "Coplanar Air Launch with Gravity-Turn Launch Trajectories" (PDF). *Masters Thesis*: 2. Archived from the original (PDF) on November 28, 2007.
39. "Space Shuttle Max-Q". Aerospaceweb. 2001-05-06. Retrieved 2012-12-10.
40. "General Electric J85". Geae.com. 2012-09-07. Retrieved 2012-12-10.
41. "Mach 1 Club". Thrust SSC. Retrieved 2016-05-28.
42. http://www.braeunig.us/space/propel.htm
43. "table of cislunar/mars delta-vs". Archived from the original on 2007-07-01.
44. "cislunar delta-vs". Strout.net. Retrieved 2012-12-10.
45. "Choose Your Engine". Projectrho.com. 2012-06-01. Retrieved 2012-12-10.
46. "The Evolution of Rockets". Istp.gsfc.nasa.gov. Retrieved 2012-12-10.
47. "Rocket Mass Ratios". Exploration.grc.nasa.gov. Retrieved 2012-12-10.
48. Astronautix- Ariane 5g (http://astronautix.com/lvs/ariane5g.htm)
49. Astronautix - Saturn V (http://astronautix.com/lvs/saturnv.htm)
50. Astronautix- Saturn IB (http://astronautix.com/lvs/saturnib.htm)
51. Astronautix-V-2 (http://www.astronautix.com/lvs/v2.htm)
52. AIAA2001-4619 RLVs (http://mae.ucdavis.edu/faculty/sarigul/aiaa2001-4619.pdf)
53. NASA (2006). "Rocket staging". *Beginner's Guide to Rockets*. NASA. Retrieved 2016-05-28.
54. "Astronautix NK-33 entry". Astronautix.com. 2006-11-08. Retrieved 2012-12-10.
55. "A brief history of space accidents". Jane's Civil Aerospace. 2003-02-03. Archived from the original on 2003-02-04. Retrieved 2010-04-24.
56. "Rogers commission Appendix F". Retrieved 2012-12-10.

57. "Going Private: The Promise and Danger of Space Travel By Tariq Malik". Space.com. 2004-09-30. Retrieved 2012-12-10.
58. "Weighing the risks of human spaceflight". The Space Review. 21 July 2003. Retrieved 1 December 2010.
59. "A Rocket a Day Keeps the High Costs Away" (http://www.fourmilab.ch/documents/rocketaday.html) by John Walker. September 27, 1993.
60. "Space Shuttle Use of Propellants and Fluids" (PDF). Nasa.gov. Archived from the original (PDF) on October 17, 2011. Retrieved 2011-04-30.
61. "NASA Launch Vehicles and Facilities". Nasa.gov. Retrieved 2011-04-30.
62. "NASA - Space Shuttle and International Space Station". Nasa.gov. Retrieved 2011-04-30.
63. "Mass Fraction". Andrews Space and Technology (original figure source). Retrieved 2011-04-30.
64. Regis, Ed (1990),*Great Mambo Chicken And The Transhuman Condition: Science Slightly Over The Edge*, Basic Books, ISBN 0-201-56751-2. Excerpt online (http://groups.google.com/group/sci.space/browse_thread/thread/dcc29174a504c200/7e68102f0a014325?hl=en&ie=UTF-8&oe=utf-8&q)
65. U.S. Air Force Research Report No. AU-ARI-93-8: LEO On The Cheap. Retrieved April 29, 2011.

External links

Governing agencies

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- National Association of Rocketry (USA) (http://www.nar.org/)
- Tripoli Rocketry Association (http://www.tripoli.org/)
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- Rocketdyne Technical Articles (https://web.archive.org/web/20070521025308/http://www.pwrengineering.com/data.htm)
- Relativity Calculator - Learn Tsiolkovsky's rocket equations (https://web.archive.org/web/20080820201246/http://www.relativitycalculator.com/rocket_equations.shtml)
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