DEPARTMENT OF AEROSPACE ENGINEERING

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UNIT V - PERFORMANCE OF AEROSPACE VEHICLES

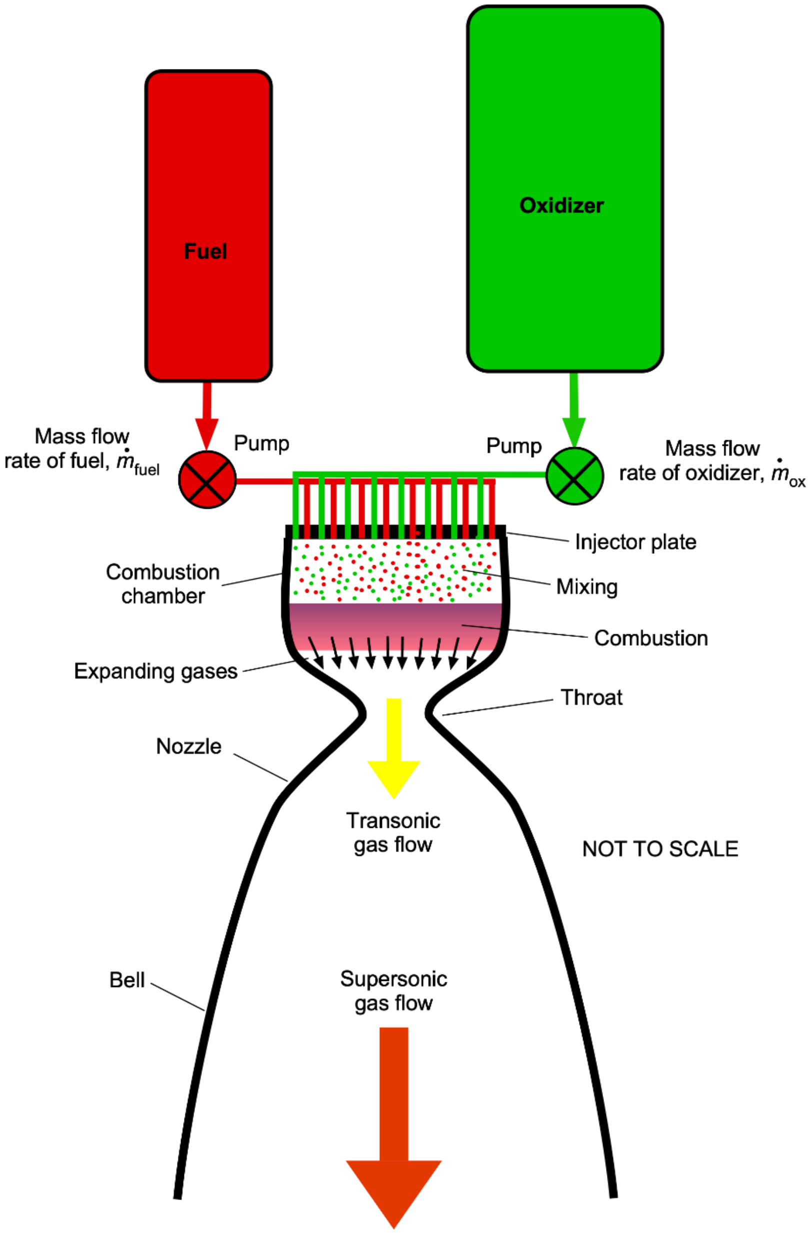
Analyze Nozzle and Propellant Types

Nozzle

The nozzle is designed to accelerate the high-pressure, high-temperature gases generated in the combustion chamber to a very high supersonic exit or jet velocity. As shown in the figure below, the nozzle typically has two sections: the convergent and divergent sections. The resulting shape is often referred to as a nozzle "bell." The convergent section narrows down the flow area, increasing the velocity of the gases as they pass through it and accelerating them to transonic and then supersonic conditions.

The convergent section then leads to the throat, the narrowest part of the nozzle. Beyond the throat, the divergent area widens, allowing the supersonic gases to expand and accelerate to their final velocity, V_j. Ideally, this expansion continues smoothly and progressively until the hot gases reach the exit area of the nozzle.

Therefore, the design of the nozzle, including the length and shape of the divergent section, is critical in achieving optimal thrust performance from the rocket engine. Generally, the nozzle must be long enough, and the exit area must be large enough to ensure that the pressure at the exit is close to the ambient pressure outside the nozzle. This feature is essential for maximizing the propulsion system's efficiency and achieving maximum thrust.

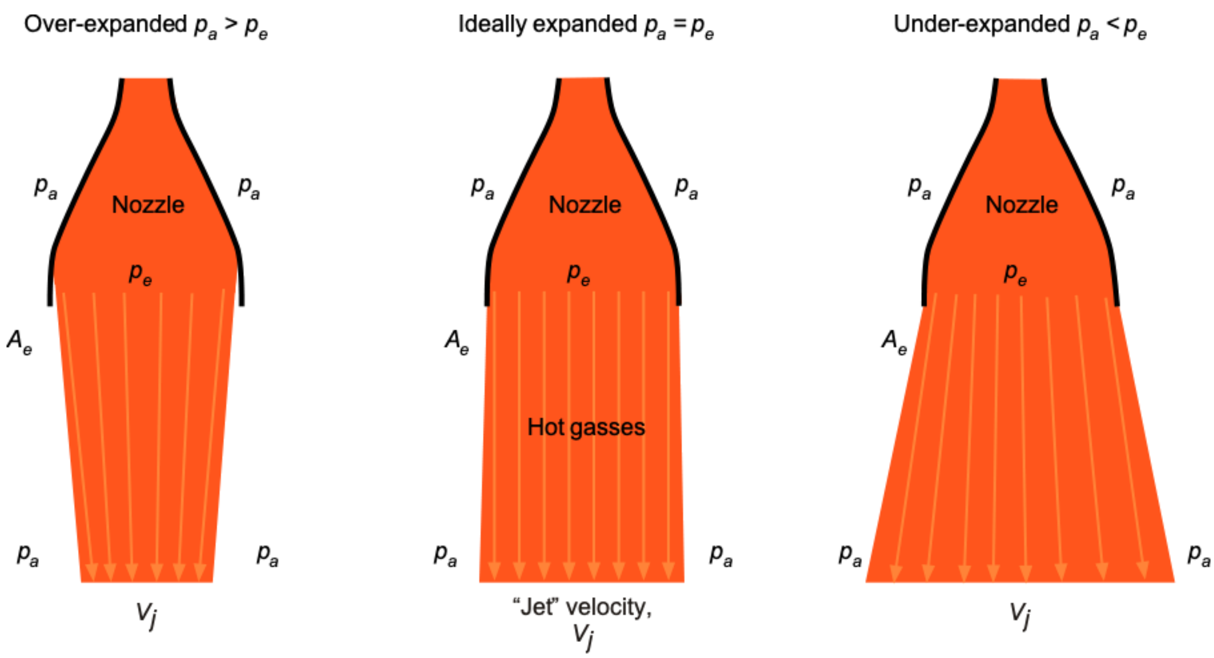


A rocket engine has a convergent/divergent nozzle designed to expand the exhaust gases to supersonic conditions.

Nozzle Efficiency

Designing rocket engines for launch vehicles that can operate efficiently across a wide range of in-atmosphere altitudes is a significant engineering challenge that requires careful consideration of many factors. These factors include the shape and size of the nozzle, the materials used for the nozzle, the propellant flow rate, the combustion characteristics of the fuel and oxidizer, and the cooling system(s). Designers aim to achieve the best possible performance of the rocket engine across the entire altitude range of a rocket's atmospheric flight trajectory to maximize its thrust and efficiency. Rocket engines must also be optimized for efficiency when they reach the vacuum of space.

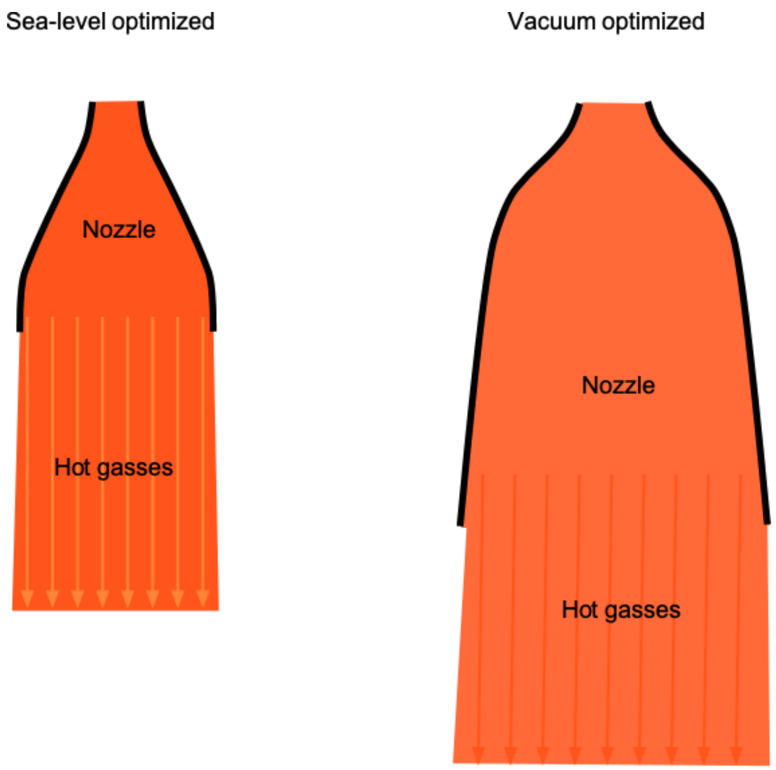
When the exhaust pressure at the exit of the nozzle matches the ambient pressure of the surrounding environment, it is known as *ideal* or *optimum* expansion, as shown in the figure below. In this ideal state, there is a zero pressure gradient, and all the exhaust gases are directed away from the engine, resulting in maximum thrust generation because nearly all of the momentum of the exhaust gas is converted into thrust. This operating condition gives rocket engines their highest possible performance in terms of thrust and efficiency. However, achieving optimal expansion requires careful design and optimization of the nozzle's shape, i.e., the shape of the bell.



Rocket engines' nozzles must be designed to balance thrust and efficiency over various ambient pressures. Under- or over-expansion of the gas flow will result in a loss of thrust and efficiency.

Over-expansion means that the external (atmospheric) pressure, P_a, is higher than the exit pressure, P_e. When an *over-expanded flow* passes through the nozzle, the higher external pressure at the exit produces a positive (or adverse) pressure gradient that slows the jet flow, and the jet flux subsequently converges as it exits the nozzle. The pressure difference may be high enough to cause the flow to separate from the nozzle's walls. Over-expansion of the gas flow reduces the thrust and efficiency of the engine. The solution, in this case, is to use a shorter bell.

The opposite situation, where the atmospheric pressure is lower than the exit pressure and gives an adverse pressure gradient, is called an *under-expanded flow*. In this case, the flow continues to develop and expand outward after it exits the nozzle, so this process also does not contribute to thrust production. The solution, in this case for thrust recovery, is a larger and longer bell. When designing rocket engines for launch vehicles that must fly in the atmosphere, the nozzle may be designed for a slight over-expansion at sea level, i.e., recognizing that the exhaust pressure at the exit of the nozzle will likely be lower than the ambient pressure of the surrounding air. This design approach can better optimize the rocket engine's performance during more of the launch profile, allowing the engine to balance, on average, its overall thrust and efficiency throughout the atmosphere.



Rocket engine nozzles are designed so that the pressure of the hot gases exiting the nozzle matches the external pressure at any given altitude or in the vacuum of space, providing maximum thrust and efficiency.

Many rocket engines, including the Merlin used in the Falcon 9, have a nozzle designed to work efficiently across a wide range of altitudes, from sea level to the stratosphere, where the pressure is very low. The RS-25 engines, first used for the Space Shuttle program, were optimized for sea-level operation during the initial phase of the launch and also when it transitioned to vacuum-optimized operation. To this end, the RS-25 engine has a movable nozzle extension to optimize its performance. When rocket engines operate at sea level, the nozzles are usually designed to give a slightly over-expanded condition, so they become more ideally expanded with increasing altitude in the atmosphere.

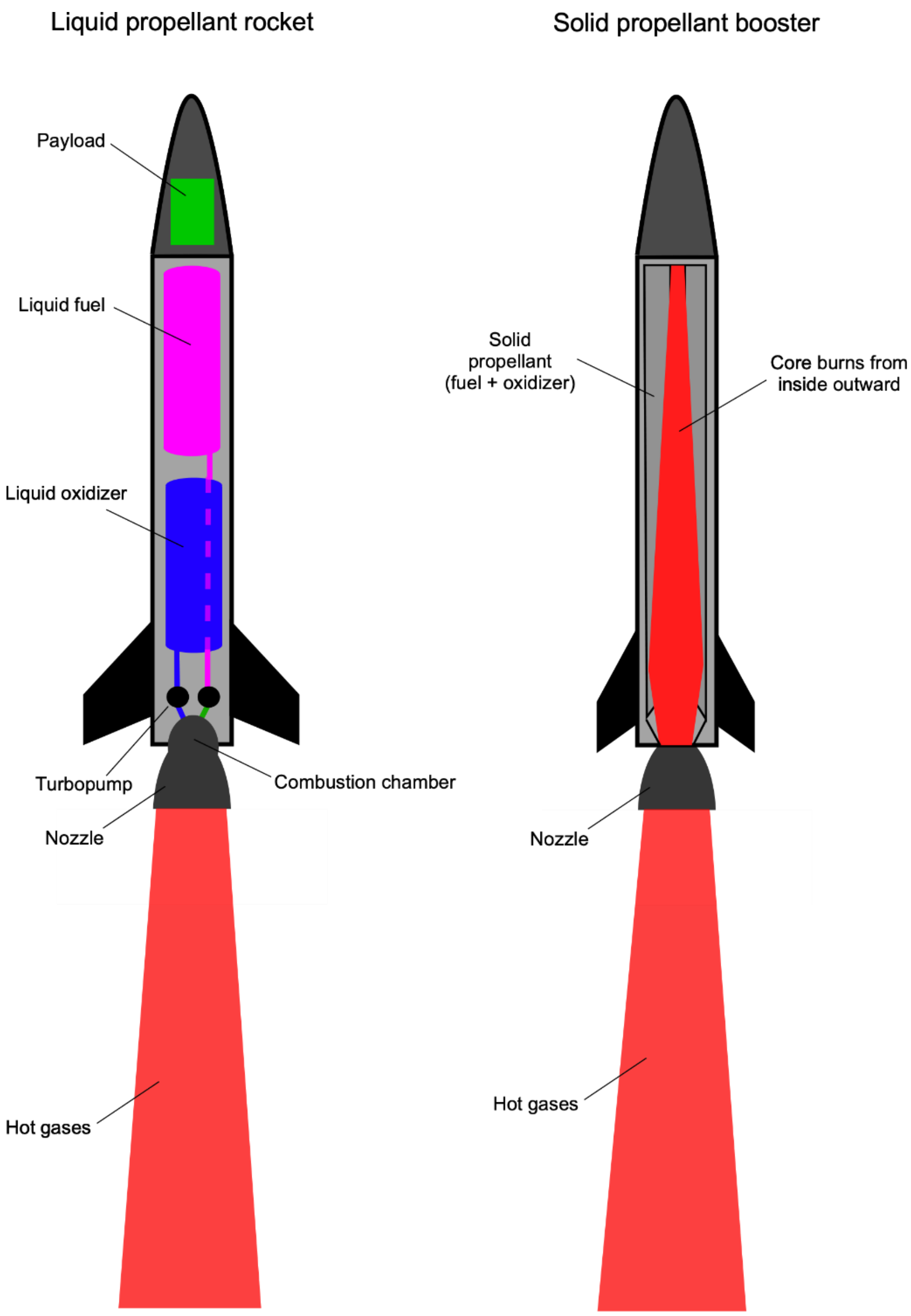
It will be noticed that second or upper-stage "vacuum-optimized" rocket engines have *much larger nozzles* than those used on sea-level (or atmospheric) optimized engines, as shown in the figure below. The Merlin second-stage engine is a good example. The second stage, "vacuum-optimized" Merlin, uses the biggest nozzle as practically possible to get an ideal expansion of the exhaust gases. The vacuum-optimized Merlin engine has a bigger exhaust section and a larger expansion nozzle ratio of 165:1, compared to the sea-level optimized version, which has a smaller 16:1 expansion ratio nozzle. The larger nozzle allows a more ideal and efficient expansion of the exhaust gases in the space vacuum, maximizing the propulsive thrust and efficiency.

Types of Rocket Engines

Like all propulsion systems, rocket engines are energy conversion devices. The kinetic energy of the expelled propellant (hence the eventual gain in kinetic energy of the vehicle) comes from:

1. Compressing the propellant into its tank.
2. Liberating the chemical potential energy of a fuel and an oxidizer.
3. An electrical or thermal power supply.
4. Some combination of these latter methods.

Rocket engines can be broadly categorized according to their thrust and thrust-producing efficiency. Rocket propulsion systems are selected according to mission objectives. Generally, there is no "one-size-fits-all" solution, and several rocket propulsion systems could be used for a given space mission. As shown in the figure below, there are two primary types: a liquid propellant rocket and a solid propellant rocket. The latter type is often used as a secondary booster. Another type, the hybrid rocket engine, is considered later.



The two primary types of rockets are liquid-propellant rockets and solid-propellant rockets. Each has relative advantages.

High-Thrust Propulsion Systems

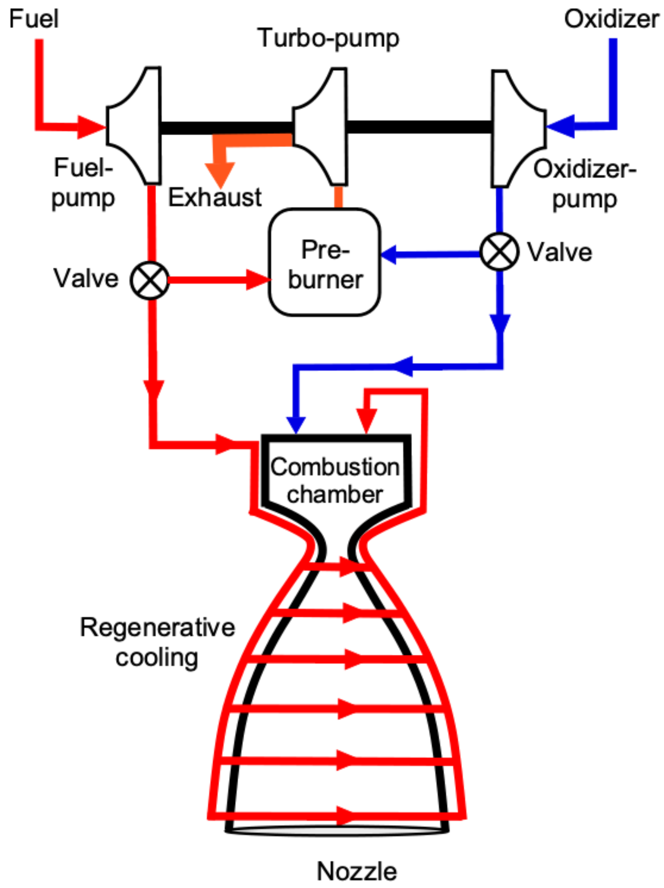
High-thrust systems are used to overcome gravity, such as in a planetary launch vehicle, or to quickly accelerate a vehicle already in space, such as for an orbital ejection maneuver. These systems store energy in the propellant so that it can be converted at a high rate, roughly proportional to the propellant flow rate.

Bipropellant Systems

Bipropellant propulsion systems typically come to mind regarding rocket propulsion, i.e., one imagines flames and clouds of smoke, such as during a NASA Space Shuttle or SpaceX Falcon 9 launch. The propellant is the combustion product of a fuel and an oxidizer. Combustion is generally the fastest way to convert propellant energy. Bipropellant systems are further categorized as gas/liquid propellant systems, solid propellant systems, or hybrid solid fuel/oxidizer systems.

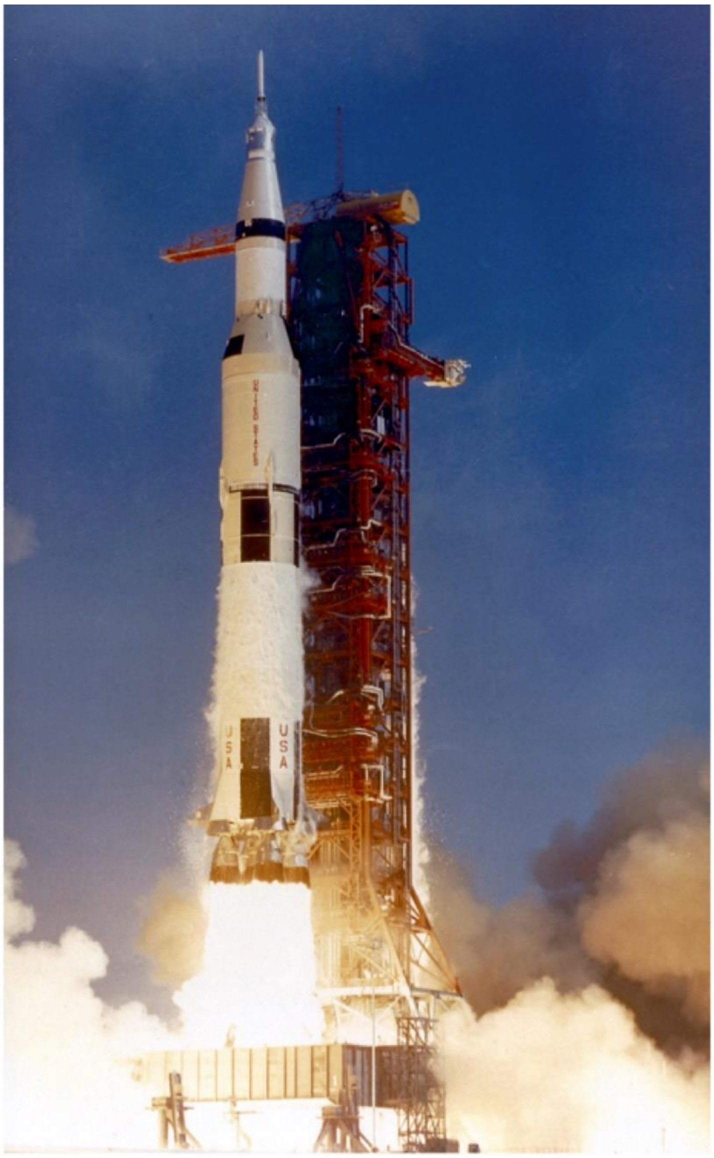
Gas/Liquid Systems

Examples of this type of propulsion system include the Space Shuttle main engine (SSME), which burned liquid hydrogen (LH_2) and liquid oxygen (LOX), and the Merlin engine used on the SpaceX Falcon 9, which burns Rocket Propellant-One or RP-1 (a densified kerosene) and LOX, the combination often being called Kerolox. The process of mixing the fuel and oxidizer in the engine is shown in the schematic below. The enormous volume flow rates require turbo-pumps, which are driven by burning a small quantity of fuel and oxidizer tapped off from a bypass circuit.



The internal flow paths of fuel and oxidizer inside a rocket motor have to flow through pipes at high volumetric rates created by turbo-pumps.

As shown in the photograph below, a Saturn V rocket launched Apollo 11, the first mission to land humans on the moon, and lifted off from Kennedy Space Center in July 1969. The first stage of the Saturn V rocket used five F-1 engines. These engines burned RP-1 fuel with LOX as the oxidizer. The F-1 engine was the most powerful single-nozzle liquid-fueled rocket engine ever flown. The second stage used five J-2 engines; the propellant for these engines comprised LH. And LOX. The J-2 engine was designed to provide efficient propulsion in the higher levels of the atmosphere and into space. The third stage of the Saturn V rocket used one J-2 engine, which was also used for the trans-lunar injection maneuver, which set the spacecraft in the direction of the Moon.



The Saturn V three-stage rocket. The first stage rotor motors burned RP-1 and LOX.
Liquid methane (CH) is gaining popularity for commercial rocket engines because of its availability, modest cost, and good performance. It is also far better for the environment than RP-1, which produces many toxic byproducts. One advantage of a gas/liquid system is that the engine can be throttled by regulating the fuel flow. However, this capability comes at a price, including the complexity and associated weight of pumps, valves, pipes, and cryogenic fuel tanks. Hypergolic propellants are those that combust spontaneously upon contact with one another. These propellants are used for in-space applications rather than launch vehicles, partly because their performance is much lower than that of hydrocarbon and LOX or RP-1 and LOX systems. Also, on the one hand, these chemicals tend to be highly toxic. On the other hand, their advantages are reliability, simplicity (no ignition system required), and ignition speed. For example, the Apollo lunar lander used hydrazine (N H) and nitrogen tetroxide (N O), as did the Space Shuttle reaction control system (RCS).

Solid Fuel Systems

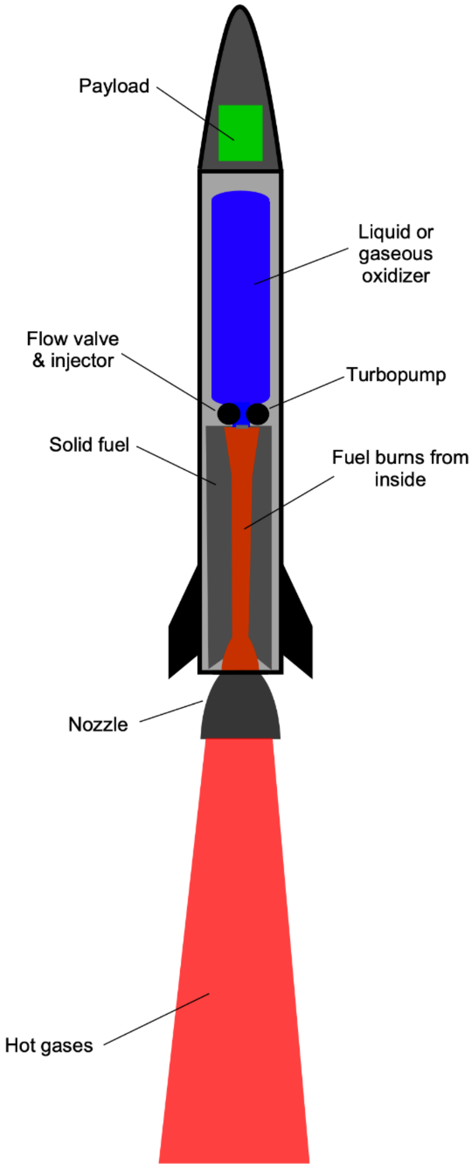
The Space Shuttle solid rocket booster (SRB) is one example of the use of solid propellant. Solid fuels are also favored for military applications, such as air-to-air missiles and intercontinental ballistic missiles (ICBMs) because they require little pre-launch processing. After ignition, the propellant burns until the target is reached or exhausted.

Solid fuel is usually powdered metal mixed with a binder. Aluminum (Al) is most commonly used, and magnesium (Mg) is sometimes used. Typical oxidizers are ammonium perchlorate (AP) and ammonium nitrate (AN). The fuel and oxidizer are mixed with a binder, usually some plastic or (more commonly) synthetic rubber, such as hydroxyl-terminated polybutadiene (HTPB) or polybutadiene acrylonitrile (PBAN). The Space Shuttle SRBs used Al and AN, with PBAN as a binder.

Most commercially available fuels for amateur rocket builders are based on Al and AP with HTPB because this combination is more thermally efficient and can be safely stored and processed. Unlike liquid-fueled rocket engines, solid-fuel rockets cannot be throttled. Once ignited, like a firework, they must burn until the propellant is exhausted.

Hybrid Systems

Hybrid systems use a solid fuel and a gaseous or liquid oxidizer, or rarely, the reverse, as shown in the figure below. Experimentalists, amateur rocket builders, and small rocket companies favor hybrids because they are relatively simple and inexpensive to construct. Unlike solid propellants, they can also be throttled and turned off and on again.



Hybrid rocket systems use a solid fuel with a separate oxidizer.

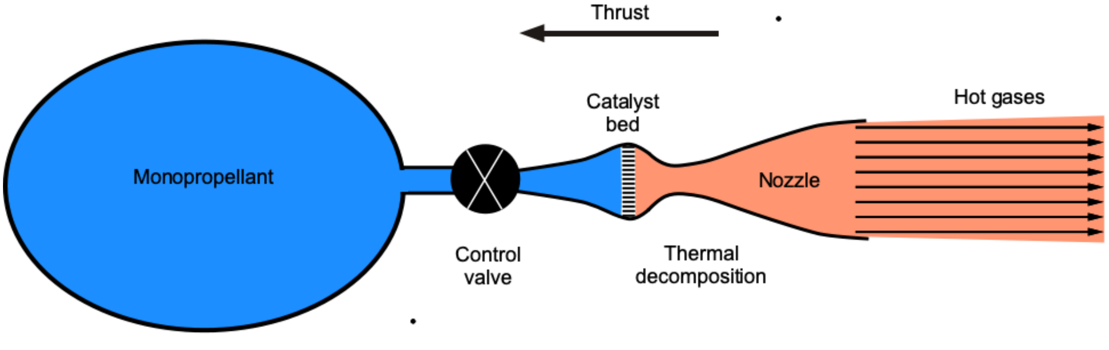
It is often argued that hybrid systems are safer than solid propellants or liquid systems. However, this is only partially correct because the propellant used in the rocket still comprises the same fuel and oxidizer. Nevertheless, solid fuel is more stable because it is not pre-mixed with an oxidizer, so it can be safely stored and has a longer shelf life. Typical oxidizers used in hybrid rockers are gaseous (compressed) oxygen (O_2), nitrous oxide (N_2O), and hydrogen peroxide H_2O .

Hybrid rocket motors, however, have not found many applications in commercial space applications because they have no performance advantage, i.e., they have relatively modest values in terms of thrust-producing efficiency, and designing for optimal performance is *tentative et error* (i.e., trial and error). A notable exception is SpaceShipOne, which by design uses HTPB and N_2O.

Experimentalists and amateur rocket builders often use polyvinyl chloride (PVC) or acrylonitrile butadiene styrene (ABS) as a solid fuel because these are readily available at low cost. Nitrous oxide (N_2O) or "Nitrous" can be used as an oxidizer with several different fuels, and it is popular for use in hybrid rockets. Nitrous oxide is readily available at a modest cost at automotive stores for use in high-performance race car engines, which allows the engine to burn more fuel and create more power by providing more oxygen during combustion. N_2O is also used for medical purposes as a mild anesthetic known as "laughing gas."

Monopropellant Systems

Monopropellants do not burn but decompose exothermally in contact with a catalyst. Monopropellant engines generate thrust from the propellant flowing through a valve into a catalytic decomposition chamber, where the propellant goes through a highly energetic decomposition process. The hot gases then accelerate through a nozzle, as shown in the figure below. These thrusters generally provide thrust levels up to about 3,000 N (674 lb).

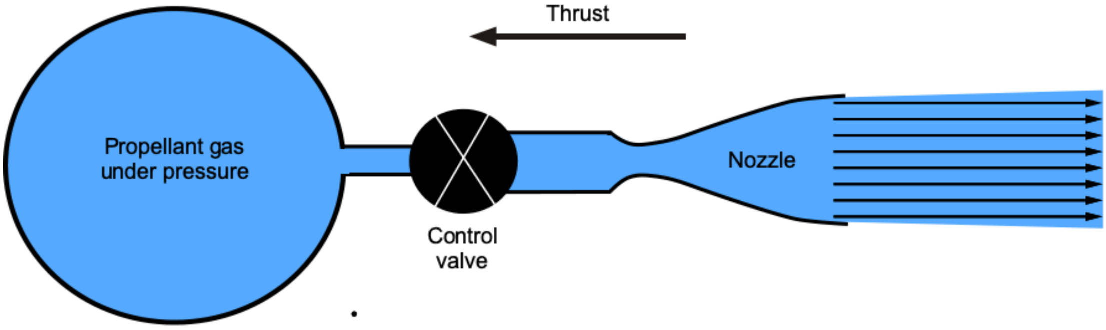


Monopropellant rocket engines are favored for small vehicles and reaction control systems because of their relative simplicity over bipropellants, although at the expense of reduced performance.

Hydrogen peroxide (H_2O_2) is often used for monopropellant engines because it decomposes into water and diatomic oxygen when it comes into contact with many metal oxides, especially silver oxide. An H_2O_2 system propelled the Apollo lunar lander trainer. Hydrazine has been used more extensively because of its higher performance and ease of reaction initiation. The rocket engine on the New Horizons spacecraft is an N_2H_4 monopropellant system.

Cold Gas Thrusters

Cold gas thrusters are rocket engines that use compressed gas, typically nitrogen or helium, as a propellant. They release the pressurized gas through a nozzle to generate thrust, as shown in the figure below. Because they do not involve any combustion, cold gas thrusters have a relatively low specific impulse, which means they provide less thrust per unit of propellant than other rocket engines. Their simplicity makes them less efficient and powerful than engines that use monopropellants or bipropellants.



Cold gas thrusters have a straightforward design, consisting only of a fuel tank, a regulating valve, a propelling nozzle, and some plumbing.

Cold gas thrusters are commonly used for small spacecraft or subsystems that require small, precise movements or adjustments. They are appropriate for CubeSats, nanosats, and small spacecraft attitude control. Any gas can be used as a propellant, but those with lower molecular weights, such as hydrogen (H2), nitrogen (N2), and helium (He), will perform better.

High-Efficiency Propulsion Systems

In high-efficiency systems, the energy is not stored in the propellant but is generated by an onboard system. Therefore, the energy conversion rate is not proportional to the propellant flow rate but is limited by the power supply system's capability. For example, solar panels or a nuclear source can generate electrical or thermal power. Considering the energy supply rate (power) to the propellant to be fixed, a lower propellant flow rate will give higher efficiency but at a lower thrust, which is insufficient for use as a launch vehicle. High-efficiency systems are then used for long-duration missions to deep space or to raise the orbits of satellites.

In each case, this propulsion system does not have to oppose gravity directly (that is, to “lift” the spacecraft). However, it increases its velocity gradually once the spacecraft is already in space. The most straightforward system heats the propellant gas, which expands rapidly through a nozzle. A solar thermal system collects and focuses the sun’s rays onto the propellant flow path. A thermal electric system heats the gas with a resistive element or an electric arc. In other systems, electrical power is used to ionize the propellant gas and produce an electric and/or magnetic field, after which the charged particles are accelerated. Several configurations exist for such systems, including ion thrusters, Hall effect thrusters, and magnetoplasmadynamic thrusters.

Electric rocket engines, such as ion thrusters or Hall effect thrusters, are becoming increasingly attractive for use on spacecraft. These engines cannot produce much thrust but are highly efficient and maintain thrust production for long periods, making them well-suited for deep space missions.