

Solid-propellant rocket

A **solid-propellant rocket** or **solid rocket** is a **rocket** with a **rocket engine** that uses **solid propellants** (**fuel/oxidizer**). The earliest rockets were solid-fuel rockets powered by **gunpowder**; they were used in **warfare** by the **Chinese**, **Indians**, **Mongols** and **Persians**, as early as the 13th century.^[1]

All rockets used some form of solid or powdered **propellant** up until the 20th century, when **liquid-propellant rockets** offered more efficient and controllable alternatives. Solid rockets are still used today in military armaments worldwide, **model rockets**, **solid rocket boosters** and on larger applications for their simplicity and reliability.

Since solid-fuel rockets can remain in storage for a long time without much propellant degradation, and the fact that they almost always launch reliably, they have been frequently used in military applications such as **missiles**. The lower performance of solid propellants (as compared to liquids) does not favor their use as primary propulsion in modern medium-to-large launch vehicles customarily used to orbit commercial satellites and launch major space probes. Solids are, however, frequently used as strap-on boosters to increase payload capacity or as spin-stabilized add-on upper stages when higher-than-normal velocities are required. Solid rockets are used as light launch vehicles for **low Earth orbit** (LEO) payloads under 2 tons or escape payloads up to 500 kilograms (1,100 lb).^{[2][3]}

Basic concepts[edit]

A simplified diagram of a solid-fuel rocket.

1. A solid **fuel-oxidizer mixture** (propellant) is packed into the rocket, with a cylindrical hole in the middle.
2. An **igniter** combusts the surface of the propellant.
3. The cylindrical hole in the propellant acts as a **combustion chamber**.
4. The hot exhaust is choked at the throat, which, among other things, dictates the amount of thrust produced.
5. Exhaust exits the rocket.

A simple solid **rocket motor** consists of a casing, **nozzle**, grain (**propellant charge**), and **igniter**.

The solid grain mass **burns** in a predictable fashion to produce exhaust gases, the flow of which is described by **Taylor–Culick flow**. The **nozzle** dimensions are calculated to maintain a design **chamber** pressure, while producing **thrust** from the exhaust gases.

Once ignited, a simple solid rocket motor cannot be shut off, because it contains all the ingredients necessary for combustion within the chamber in which they are burned. More advanced solid rocket motors can not only be **throttled** but also be extinguished^[4] and then re-ignited by controlling the nozzle geometry or through the use of vent ports. Also, **pulsed rocket motors** that burn in segments and that can be ignited upon command are available.

Modern designs may also include a steerable nozzle for guidance, **avionics**, recovery hardware (**parachutes**), **self-destruct** mechanisms, **APUs**, controllable tactical motors, controllable divert and **attitude control** motors, and thermal management materials.

Design[[edit](#)]

Design begins with the total [impulse](#) required, which determines the [fuel](#) & [oxidizer](#) mass. Grain geometry and chemistry are then chosen to satisfy the required motor characteristics.

The following are chosen or solved simultaneously. The results are exact dimensions for grain, nozzle, and case geometries:

- The grain burns at a predictable rate, given its surface area and chamber pressure. [\[citation needed\]](#)
- The chamber pressure is determined by the nozzle throat diameter and grain burn rate.
- Allowable chamber pressure is a function of casing design.
- The length of burn time is determined by the grain "web thickness". [\[clarification needed\]](#)

The grain may or may not be bonded to the casing. Case-bonded motors are more difficult to design, since the deformation of the case and the grain under flight must be compatible.

Common modes of failure in solid rocket motors include fracture of the grain, failure of case bonding, and air pockets in the grain. All of these produce an instantaneous increase in burn surface area and a corresponding increase in exhaust gas production rate and pressure, which may rupture the casing.

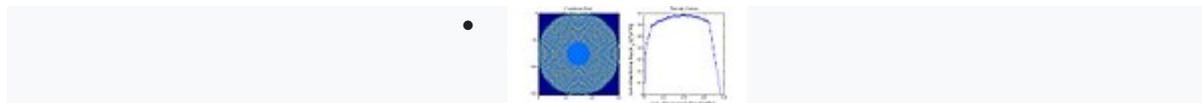
Another failure mode is casing [seal](#) failure. Seals are required in casings that have to be opened to load the grain. Once a seal fails, hot gas will erode the escape path and result in failure. This was the cause of the [Space Shuttle Challenger disaster](#).

Grain geometry[[edit](#)]

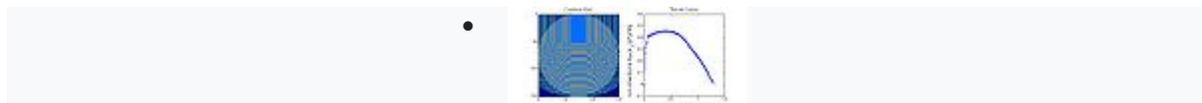
Solid rocket fuel [deflagrates](#) from the surface of exposed propellant in the combustion chamber. In this fashion, the geometry of the propellant inside the rocket motor plays an important role in the overall motor performance. As the surface of the propellant burns, the shape evolves (a subject of study in internal ballistics), most often changing the propellant surface area exposed to the combustion gases. Since the propellant volume is equal to the [cross sectional](#)

[area](#) times the fuel length, the [volumetric](#) propellant consumption rate is the cross section area times the linear burn rate, and the [instantaneous mass flow rate](#) of combustion gases generated is equal to the volumetric rate times the fuel density:

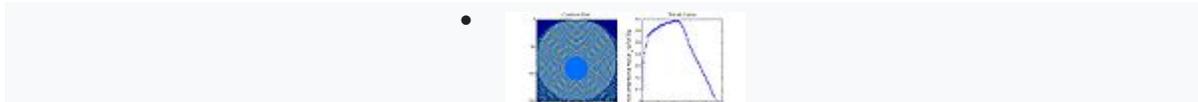
Several geometric configurations are often used depending on the application and desired [thrust curve](#):



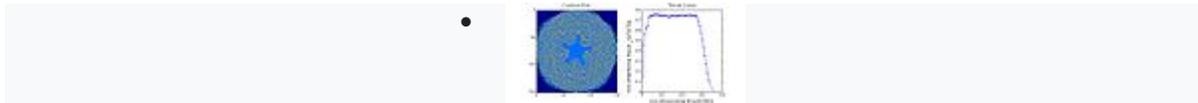
Circular bore simulation



C-slot simulation



Moon burner simulation



5-point finocyl simulation

- Circular bore: if in [BATES](#) configuration, produces progressive-regressive thrust curve.
- End burner: propellant burns from one axial end to other producing steady long burn, though has thermal difficulties, center of gravity (CG) shift.
- C-slot: propellant with large wedge cut out of side (along axial direction), producing fairly long regressive thrust, though has thermal difficulties and asymmetric CG characteristics.
- Moon burner: off-center circular bore produces progressive-regressive long burn, though has slight asymmetric CG characteristics
- Finocyl: usually a 5- or 6-legged star-like shape that can produce very level thrust, with a bit quicker burn than circular bore due to increased surface area.

Casing^[edit]

The casing may be constructed from a range of materials. Cardboard is used for small [black powder](#) model motors, whereas aluminium is used for larger composite-fuel hobby motors. Steel was used for the [space shuttle boosters](#). Filament-wound [graphite epoxy casings](#) are used for high-performance motors.

The casing must be designed to withstand the pressure and resulting stresses of the rocket motor, possibly at elevated temperature. For design, the casing is considered a [pressure vessel](#).

To protect the casing from corrosive hot gases, a sacrificial thermal liner on the inside of the casing is often implemented, which [ablates](#) to prolong the life of the motor casing.

Nozzle^[edit]

Main article: [Rocket engine nozzle](#)

A [convergent-divergent](#) design accelerates the exhaust gas out of the nozzle to produce thrust. The nozzle must be constructed from a material that can withstand the heat of the combustion gas flow. Often, heat-resistant carbon-based materials are used, such as amorphous [graphite](#) or [carbon-carbon](#).

Some designs include directional control of the exhaust. This can be accomplished by gimbaling the nozzle, as in the Space Shuttle SRBs, by the use of jet vanes in the exhaust as in the [V-2](#) rocket, or by liquid injection thrust vectoring (LITV).

An early [Minuteman](#) first stage used a single motor with four [gimballed](#) nozzles to provide pitch, yaw, and roll control.

LITV consists of injecting a liquid into the exhaust stream after the nozzle throat. The liquid then vaporizes, and in most cases chemically reacts, adding mass flow to one side of the exhaust stream and thus providing a control moment. For example, the [Titan III](#)C solid boosters injected [nitrogen tetroxide](#) for LITV; the tanks can be seen on the sides of the rocket between the main center stage and the boosters.^[10]

Performance^[edit]



An [exhaust](#) cloud engulfs [Launch Pad 39A](#) at [NASA's Kennedy Space Center](#) as the [Space Shuttle *Endeavour*](#) lifts off.

A typical, well-designed [ammonium perchlorate composite propellant](#) (APCP) first-stage motor may have a vacuum [specific impulse](#) (Isp) as high as 285.6 seconds (2.801 km/s) (Titan IVB SRMU).^[11] This compares to 339.3 s (3.327 km/s) for RP1/LOX (RD-180)^[12] and 452.3 s (4.436 km/s) for LH₂/LOX (Block II [RS-25](#))^[13] bipropellant engines. Upper stage specific impulses are somewhat greater: as much as 303.8 s (2.979 km/s) for APCP (Orbus 6E),^[14] 359 s (3.52 km/s) for RP1/LOX (RD-0124)^[15] and 465.5 s (4.565 km/s) for LH₂/LOX (RL10B-2).^[16] Propellant fractions are usually somewhat higher for (non-segmented) solid propellant first stages than for upper stages. The 53,000-kilogram (117,000 lb) Castor 120 first stage has a propellant mass fraction of 92.23% while the 14,000-kilogram (31,000 lb) Castor 30 upper stage developed for Orbital Science's Taurus II COTS(Commercial Off The Shelf) (International Space Station resupply) launch vehicle has a 91.3% propellant fraction with 2.9% graphite epoxy motor casing, 2.4% nozzle, igniter and thrust vector actuator, and 3.4% non-motor hardware including such things as payload mount, interstage adapter, cable raceway, instrumentation, etc. Castor 120 and Castor 30 are 2.36 and 2.34 meters (93 and 92 in) in diameter, respectively, and serve as stages on the Athena IC and IIC commercial launch vehicles. A four-stage Athena II using Castor 120s as both first and second stages became the first commercially developed launch vehicle to launch a lunar probe ([Lunar Prospector](#)) in 1998.

Solid rockets can provide high thrust for relatively low cost. For this reason, solids have been used as initial stages in rockets (for example the [Space Shuttle](#)), while reserving high specific impulse engines, especially less massive hydrogen-fueled engines, for higher stages. In addition, solid rockets have a long history as the final boost stage for satellites due to their simplicity, reliability, compactness and reasonably high [mass fraction](#).^[17] A spin-stabilized solid rocket motor is sometimes added when extra velocity is required, such as for a mission to a comet or the outer solar system, because a spinner does not require a guidance system (on the newly added stage). Thiokol's extensive family of mostly titanium-cased *Star* space motors has been widely used, especially on Delta launch vehicles and as spin-stabilized upper stages to launch satellites from the cargo bay of the Space Shuttle. *Star* motors have propellant fractions as high as 94.6% but add-on structures and equipment reduce the operating mass fraction by 2% or more.

Higher performing solid rocket propellants are used in large strategic missiles (as opposed to commercial launch vehicles). [HMX](#), C₄H₈N₄(NO₂)₄, a nitramine with greater energy than ammonium perchlorate, was used in the propellant of the Peacekeeper ICBM and is the main ingredient in NEPE-75 propellant used in the Trident II D-5 Fleet Ballistic Missile.^[18] It is because of explosive hazard that the higher energy military solid propellants containing HMX are not used in commercial launch vehicles except when the LV is an adapted ballistic missile already containing HMX propellant (Minotaur IV and V based on the retired Peacekeeper ICBMs).^[19] The Naval Air Weapons Station at China Lake, California, developed a new compound, C₆H₆N₆(NO₂)₆, called simply [CL-20](#) (China Lake compound #20). Compared to HMX, CL-20 has 14% more energy per mass, 20% more energy per volume, and a higher oxygen-to-fuel ratio.^[20] One of the motivations for development of these very high [energy density](#) military solid propellants is to achieve mid-course exo-atmospheric ABM capability from missiles small enough to fit in existing ship-based below-deck vertical launch tubes and air-mobile truck-mounted launch tubes. CL-20 propellant compliant with Congress' 2004 insensitive munitions (IM) law has been demonstrated and may, as its cost comes down, be suitable for use in commercial launch vehicles, with a very significant increase in performance compared with the currently favored APCP solid propellants. With a specific impulse of 309 s already demonstrated by Peacekeeper's second stage using HMX propellant, the higher energy of CL-20 propellant can be expected to increase specific impulse to around 320 s in similar ICBM or launch vehicle upper stage applications, without the explosive hazard of HMX.^[21]

An attractive attribute for military use is the ability for solid rocket propellant to remain loaded in the rocket for long durations and then be reliably launched at a moment's notice.

Propellant families[\[edit\]](#)

Black powder (gunpowder) propellant[\[edit\]](#)

Black powder (gunpowder) is composed of [charcoal](#) (fuel), [potassium nitrate](#) (oxidizer), and [sulfur](#) (fuel and catalyst). It is one of the oldest [pyrotechnic](#) compositions with application to rocketry. In modern times, black powder finds use in low-power model rockets (such as [Estes](#) and Quest rockets),^{[22][23]} as it is cheap and fairly easy to produce. The fuel grain is typically a mixture of pressed fine powder (into a solid, hard slug), with a burn rate that is highly dependent upon exact composition and operating conditions. The performance or [specific impulse](#) of black powder is low, around 80 seconds. The grain is sensitive to fracture and, therefore, catastrophic failure. Black powder does not typically find use in motors above 40 newtons (9.0 pounds-force).

Zinc–sulfur (ZS) propellants[\[edit\]](#)

Composed of powdered [zinc](#) metal and powdered sulfur (oxidizer), ZS or "micrograin" is another pressed propellant that does not find any practical application outside specialized amateur rocketry circles due to its poor performance (as most ZS burns outside the combustion chamber) and fast linear burn rates on the order of 2 m/s. ZS is most often employed as a novelty propellant as the rocket accelerates extremely quickly leaving a spectacular large orange fireball behind it.

"Candy" propellants[\[edit\]](#)

In general, [rocket candy](#) propellants are an oxidizer (typically potassium nitrate) and a sugar fuel (typically [dextrose](#), [sorbitol](#), or [sucrose](#)) that are cast into shape by gently melting the propellant constituents together and pouring or packing the [amorphous colloid](#) into a mold. Candy propellants generate a low-medium specific impulse of roughly 130 s and, thus, are used primarily by amateur and experimental rocketeers.

Double-base (DB) propellants[\[edit\]](#)

DB propellants are composed of two [monopropellant](#) fuel components where one typically acts as a high-energy (yet unstable) monopropellant and the other acts as a lower-energy stabilizing (and gelling) monopropellant. In typical circumstances, [nitroglycerin](#) is dissolved in a [nitrocellulose](#) gel and solidified with additives. DB propellants are implemented in applications where minimal smoke is required yet medium-high performance (I_{sp} of roughly 235 s) is required. The addition of metal fuels (such as [aluminium](#)) can increase the performance (around 250 s), though [metal oxide nucleation](#) in the exhaust can turn the smoke opaque.

Composite propellants[\[edit\]](#)

A powdered oxidizer and powdered metal fuel are intimately mixed and immobilized with a rubbery binder (that also acts as a fuel). Composite propellants are often either [ammonium nitrate](#)-based (ANCP) or [ammonium perchlorate](#)-based (APCP). Ammonium nitrate composite propellant often uses [magnesium](#) and/or [aluminium](#) as fuel and delivers medium performance (I_{sp} of about 210 s) whereas [ammonium perchlorate composite propellant](#) often uses aluminium fuel and delivers high performance (vacuum I_{sp} up to 296 s with a single piece nozzle or 304 s with a high area ratio telescoping nozzle).^[14] Aluminium is used as fuel because it has a reasonable specific energy density, a high volumetric energy density, and is difficult to ignite accidentally. Composite propellants are cast, and retain their shape after the rubber binder, such as [Hydroxyl-terminated polybutadiene](#) (HTPB), [cross-links](#) (solidifies) with the aid of a curative additive. Because of its high performance, moderate ease of manufacturing, and moderate cost, APCP finds widespread use in space rockets, military rockets, hobby and amateur rockets, whereas cheaper and less efficient ANCP finds use in amateur rocketry and [gas generators](#). [Ammonium dinitramide](#), $\text{NH}_4\text{N}(\text{NO}_2)_2$, is being considered as a 1-to-1 chlorine-free substitute for ammonium perchlorate in composite propellants. Unlike ammonium nitrate, ADN can be substituted for AP without a loss in motor performance.

Polyurethane-bound aluminium-APCP solid fuel was used in the submarine launched [Polaris missiles](#).^[24] APCP used in the space shuttle [Solid Rocket Boosters](#) consisted of ammonium perchlorate (oxidizer, 69.6% by weight), aluminium (fuel, 16%), iron oxide (a catalyst, 0.4%), polybutadiene acrylonitrile (PBAN) polymer (a non-urethane rubber binder that held the mixture together and acted as secondary fuel, 12.04%), and an epoxy [curing](#) agent (1.96%).^{[25][26]} It developed a specific impulse of 242 seconds (2.37 km/s) at sea level or 268 seconds (2.63 km/s) in a vacuum. The 2005-2009 [Constellation Program](#) was to use a similar PBAN-bound APCP.^[27]

In 2009, a group succeeded in creating a propellant of [water](#) and nanoaluminium ([ALICE](#)).

High-energy composite (HEC) propellants [\[edit\]](#)

Typical HEC propellants start with a standard composite propellant mixture (such as APCP) and add a high-energy explosive to the mix. This extra component usually is in the form of small crystals of [RDX](#) or [HMX](#), both of which have higher energy than ammonium perchlorate. Despite a modest increase in specific impulse, implementation is limited due to the increased hazards of the high-explosive additives.

Composite modified double base propellants [\[edit\]](#)

Composite modified double base propellants start with a nitrocellulose/nitroglycerin double base propellant as a binder and add solids (typically [ammonium perchlorate](#) (AP) and powdered [aluminium](#)) normally used in composite propellants. The ammonium perchlorate makes up the oxygen deficit introduced by using [nitrocellulose](#), improving the overall specific impulse. The aluminium improves specific impulse as well as combustion stability. High performing propellants such as [NEPE-75](#) used to fuel the [Trident II D-5](#), [SLBM](#) replace most of the AP with [polyethylene glycol](#)-bound [HMX](#), further increasing specific impulse. The mixing of composite and double base propellant ingredients has become so common as to blur the functional definition of double base propellants.

Minimum-signature (*smokeless*) propellants [\[edit\]](#)

One of the most active areas of solid propellant research is the development of high-energy, minimum-signature propellant using $C_6H_6N_6(NO_2)_6$ [CL-20 nitroamine](#) ([China Lake](#) compound #20), which has 14% higher energy per mass and 20% higher energy density than HMX. The new propellant has been successfully developed and tested in tactical rocket motors. The propellant is non-polluting: acid-free, solid particulates-free, and lead-free. It is also smokeless and has only a faint shock diamond pattern that is visible in the otherwise transparent exhaust. Without the bright flame and dense smoke trail produced by the burning of aluminized propellants, these smokeless propellants all but eliminate the risk of giving away the positions from which the missiles are fired. The new CL-20 propellant is shock-insensitive (hazard class 1.3) as opposed to current HMX smokeless propellants which are highly detonable (hazard class 1.1). CL-20 is considered a major breakthrough in solid rocket propellant technology but has yet to see widespread use because costs remain high.^[20]

Electric solid propellants [\[edit\]](#)

Electric solid propellants (ESPs) are a family of high performance [plastisol](#) solid propellants that can be ignited and throttled by the application of electric current. Unlike conventional rocket motor propellants that are difficult to control and extinguish, ESPs can be ignited reliably at precise intervals and durations. It requires no moving parts and the propellant is insensitive to flames or electrical sparks.^[20]