

Solid-fuel rocket

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A **solid rocket** or a **solid-fuel rocket** is a rocket with a motor that uses solid propellants (fuel/oxidizer). The earliest rockets were solid fueled and powered by gunpowder; they were used by the Chinese, Mongols and Arabs in warfare as early as the 13th century.^[1] All rockets used some form of solid or powdered propellant up until the 20th century, when liquid rockets and hybrid rockets offered more efficient and controllable alternatives. Solid rockets are still used today in model rockets and on larger applications for their simplicity and reliability. Since solid fuel rockets can remain in storage for long periods—and then reliably launch on short notice—they have been frequently used in military applications such as missiles. Solid fuel rockets are unusual as primary propulsion in modern space exploration, but are commonly used as booster rockets.

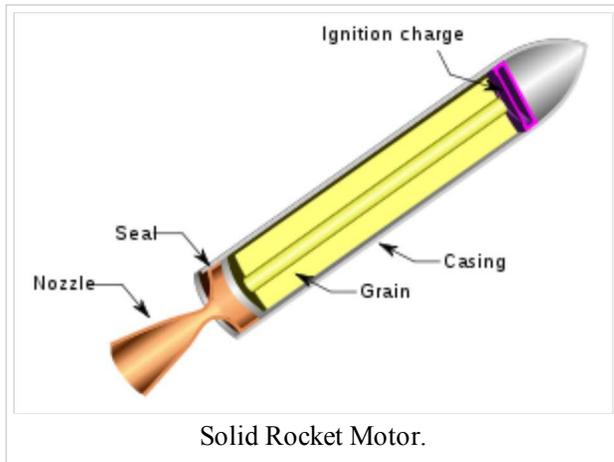


The Space Shuttle is launched with the help of two solid-fuel boosters known as SRBs

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Basic concepts



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

The grain behaves like a solid mass, burning in a predictable fashion and producing exhaust gases. 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 that they are burned in. More advanced solid rocket motors can not only be throttled but can be extinguished and then re-ignited by controlling the nozzle geometry or through the use of vent ports. Also,

pulsed rocket motors which burn in segments and which 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

Design begins with the total impulse required, this 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.
- The chamber pressure is determined by the nozzle orifice 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'.

The grain may be bonded to the casing, or not. Case-bonded motors are much more difficult to design, since the deformation, under operating conditions, of the case and the grain 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 and pressure, which may potentially induce rupture of the casing.

Another failure mode is casing seal design. 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.

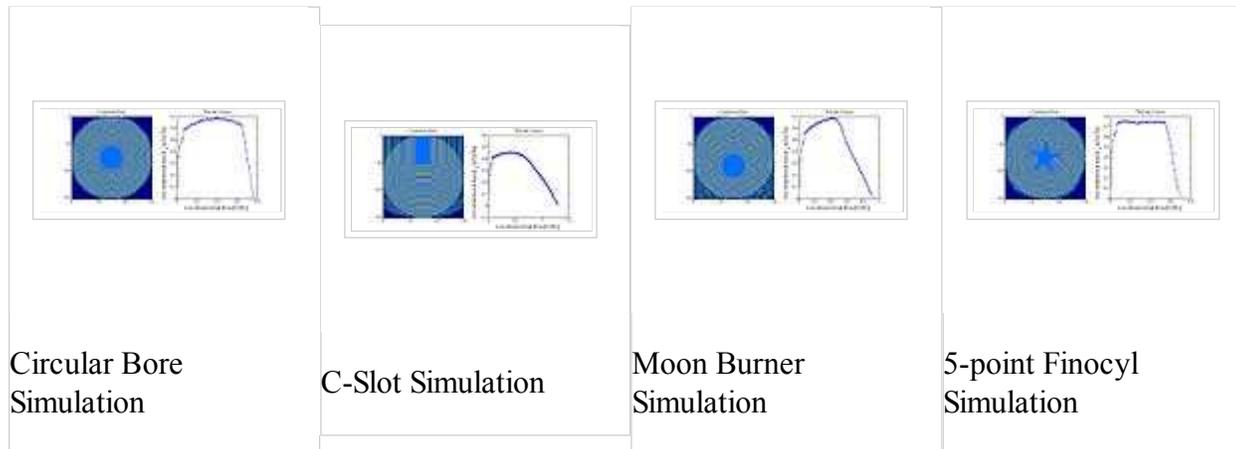
Grain geometry

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. The mass flux (kg/sec) [and therefore

pressure] of combustion gases generated is a function of the instantaneous surface area A_s , (m^2), and linear burn rate b_r (m/sec):

$$\dot{m} = \rho \cdot A_s \cdot b_r$$

Several geometric configurations are often used depending on the application and desired thrust curve:



- 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, 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

The casing may be constructed from a range of materials. Cardboard is used for small black powder model motors while aluminum is used for larger composite fuel hobby motors. Steel is 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

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 similar to those used in the V2 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 IIIC 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 ^[2].

Performance

A typical well-designed solid fuel (APCP) rocket motor may have a specific impulse (Isp) of 265 sec. This compares to ~330 seconds for kerosene/Lox and ~450 seconds for liquid hydrogen/Lox bipropellant engines ^[2].

Solid rockets can provide high thrust for relatively low cost. For this reason, solids have been used as initial stages in rockets (the classic example being the Space Shuttle), whilst reserving high specific impulse engines, especially less massive hydrogen fuelled 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 ^[3].

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

Propellant families

Black Powder (BP) Propellants

Composed of charcoal (fuel), potassium nitrate (oxidizer), and sulfur (additive), BP is one of the oldest pyrotechnic compositions with application to rocketry. Modernly, black powder finds use in low power model rockets (such as Estes and Quest rockets) 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. Due to its sensitivity to fracture (and therefore catastrophic failure upon ignition) and poor performance (specific impulse around 80 sec) BP does not typically find use in motors above 40 Ns.

Zinc-Sulfur (ZS) Propellants

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

"Candy" propellants

Candy propellants are generally 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 sec and thus are implemented primarily only with amateur and experimental rocketeers.

Double-Base (DB) Propellants

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. Typically, 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 sec) is required. The addition of metal fuels (such as aluminum) can increase the performance (around 250 sec) though metal oxide nucleation in the exhaust can turn the smoke opaque.

Composite propellants

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 aluminum as fuel and delivers medium performance (I_{sp} of about 210 sec) whereas Ammonium Perchlorate Composite Propellant often uses aluminum fuel and delivers high performance (I_{sp} of about 265 sec). 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.

In 2009, one has succeeded in creating a propellant of water and aluminum (ALICE).

High Energy Composite (HEC) propellants

HEC propellants typically 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. Although specific impulses around 275 sec have been achieved with HEC, implementation is limited due to the increased hazards of the high explosive additives.

Hobby and amateur rocketry

Solid fuel rocket motors can be bought for use in model rocketry; they are normally small cylinders of black powder fuel with an integral nozzle and sometimes a small charge that is set off when the propellant is exhausted after a time delay. This charge can be used to trigger a camera, or deploy a parachute. Without this charge and delay, the motor may ignite a second stage (black powder only).

In mid- and high power rocketry, commercially made APCP motors are widely used. They can be designed as either single use or reloadables. These motors are available in impulse ranges from "D" to "O", from several manufacturers. They are manufactured in standardized diameters, and varying lengths depending on required impulse. Standard motor diameters are 18, 24, 29, 38, 54, 75, 98, and 150 millimeters. Different propellant formulations are available to produce different thrust profiles, as well as "special effects" such as colored flames, smoke trails, or large quantities of sparks (produced by adding titanium sponge to the mix).

Designing solid rocket motors is particularly interesting to amateur rocketry enthusiasts. The design of a successful solid fuel motor requires application of continuum mechanics, combustion chemistry, materials science, fluid dynamics (including compressible flow), heat transfer, geometry (particle spectrum packing), and machining. The vast majority of amateur-built rocket motors utilize a composite propellant, most commonly APCP.^[*citation needed*]

Advanced research

- Environmentally sensitive fuel formulations such as ALICE (propellant)
- Ramjets with solid fuel
- Variable thrust designs based on variable nozzle geometry.
- hybrid rockets that use solid fuel and throttleable liquid or gaseous oxidizer

See also

- Spacecraft propulsion
- Liquid rocket
- Hybrid rocket
- Firework

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- Pyrotechnic composition
- Ammonium Perchlorate Composite Propellant

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- Intercontinental ballistic missile
- Jetex engine
- Space Shuttle Solid Rocket Booster
- Skyrocket

References

- ↑ chapters 1–2, *Blazing the trail: the early history of spacecraft and rocketry*, Mike Gruntman, AIAA, 2004, ISBN 156347705X.
- ↑ ^{*a*} ^{*b*} Sutton, George P. (2000). *Rocket Propulsion Elements; 7 edition*. Wiley-Interscience. ISBN 0-471-32642-9.
- ↑ Solid (<http://www.astronautix.com/props/solid.htm>)

External links

- Robert A. Braeunig rocket propulsion page (<http://www.braeunig.us/space/propuls.htm>)
- Astronautix Composite Solid Propellants (<http://www.astronautix.com/articles/complants.htm>)
- Ariane 5 SRB (http://www.esa.int/SPECIALS/Launchers_Access_to_Space/ASEDYQI4HNC_0.html)
- Amateur High Power Rocketry Association (<http://www.tripoli.org/>)
- Nakka-Rocketry (Design Calculations and Propellant Formulations) (<http://www.nakka-rocketry.net/>)
- 5 cent sugar rocket (<http://balloons.space.edu/ndra/nickle.html>)
- Practical Rocketry (<http://www.allstar.fiu.edu/aero/rocket2.htm>)
- NASA Practical Rocketry (<http://quest.nasa.gov/space/teachers/rockets/rocketry.html>)

- High Power Rocket Motor Basics (http://www.rockets4schools.org/education/HPR_Motor_Basics.pdf)

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Categories: Rocket engines | Spacecraft propulsion

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