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How Rocket Engines Work

by Marshall Brain

One of the most amazing endeavors man has ever undertaken is the exploration of space. A big part of the amazement is the complexity. Space exploration is complicated because there are so many problems to solve and obstacles to overcome. You have things like:

- The vacuum of space
- Heat management problems
- The difficulty of re-entry
- Orbital mechanics
- · Micrometeorites and space debris
- Cosmic and solar radiation
- The logistics of having restroom facilities in a weightless environment

But the biggest problem of all is harnessing enough energy simply to get a spaceship off the ground. That is where **rocket engines** come in.

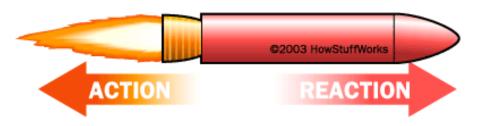
Rocket engines are, on the one hand, so simple that you can build and fly your own model rockets very inexpensively (see the links on the last page of the article for details). On the other hand, rocket engines (and their fuel systems) are so complicated that only three countries have actually ever put people in orbit. In this edition of <code>HowStuffWorks</code>, we will look at rocket engines to understand how

they work, as well as to understand some of the complexity surrounding them.

The Basics

When most people think about motors or engines, they think about rotation. For example, a reciprocating <u>gasoline engine</u> in a car produces rotational energy to drive the wheels. An <u>electric motor</u> produces rotational energy to drive a fan or spin a disk. A <u>steam</u> <u>engine</u> is used to do the same thing, as is a steam turbine and most gas turbines.

Rocket engines are fundamentally different. Rocket engines are **reaction** engines. The basic principle driving a rocket engine is the famous Newtonian principle that "to every action there is an equal and opposite reaction." A rocket engine is throwing mass in one direction and benefiting from the reaction that occurs in the other direction as a result.





This concept of "throwing mass and benefiting from the reaction" can be hard to grasp at first, because that does not seem to be what is happening. Rocket engines seem to be about flames and noise and pressure, not "throwing things." So let's look at a few examples to get a better picture of reality:

- If you have ever shot a **shotgun**, especially a big 12-gauge shot gun, then you know that it has a lot of "kick." That is, when you shoot the gun it "kicks" your shoulder back with a great deal of force. That kick is a reaction. A shotgun is shooting about an ounce of metal in one direction at about 700 miles per hour, and your shoulder gets hit with the reaction. If you were wearing roller skates or standing on a skateboard when you shot the gun, then the gun would be acting like a rocket engine and you would react by rolling in the opposite direction.
- If you have ever seen a big <u>fire hose</u> 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 backwards at great speed!

• When you blow up a **balloon** and let it go so that it flies all over the room before running out of air, you have created a rocket engine. In this case, what is being thrown is the air molecules inside the balloon. Many people believe that air molecules don't weigh anything, but they do (see the page on <u>helium</u> to get a better picture of the weight of air). When you throw them out the nozzle of a balloon, the rest of the balloon reacts in the opposite direction.

Imagine the following situation: You are wearing a <u>spacesuit</u> and you are floating in space beside the <u>space shuttle</u>; you happen to have a baseball in your hand.

If you throw the baseball, your body will react by moving in the opposite direction of the ball. The thing that controls the speed at which your body moves away is the **weight** of the baseball that you throw and the amount of **acceleration** that you apply to it. Mass multiplied by acceleration is force (f = m * a). Whatever force you apply to the baseball will be equalized by an identical reaction force applied to your body (m * a = m * a). So let's say that the baseball weighs 1 pound, and your body plus the space suit weighs 100 pounds. You throw the baseball away at a speed of 32 feet per second (21 mph). That is to say, you accelerate the 1-pound baseball with your arm so that it obtains a velocity of 21 mph. Your body reacts, but it weighs 100 times more than the baseball. Therefore, it moves away at one-hundredth the velocity of the baseball, or 0.32 feet per second (0.21 mph).

If you want to generate more **thrust** from your baseball, you have two options: increase the mass or increase the acceleration. You can throw a heavier baseball or throw a number of baseballs one after another (increasing the mass), or you can throw the baseball faster (increasing the acceleration on it). But that is all that you can do.



Photo courtesy NASA

A remote camera captures a close-up view of a Space Shuttle Main Engine during a test firing at the John C. Stennis Space Center in Hancock County, Mississippi.

A rocket engine is generally throwing mass in the form of a **high-pressure gas**. The engine throws the mass of gas out in one direction in order to get a reaction in the opposite direction. The mass comes from the weight of the fuel that the rocket engine burns. The burning process accelerates the mass of fuel so that it comes out of the rocket nozzle at high speed. The fact that the fuel turns from a solid or liquid into a gas when it burns does not change its mass. If you burn a pound of rocket fuel, a pound of exhaust comes out the nozzle in the form of a high-temperature, high-velocity gas. The form changes, but the mass does not. The burning process accelerates the mass.

Let's learn more about thrust.

Thrust

The "strength" of a rocket engine is called its **thrust**. Thrust is measured in "pounds of thrust" in the U.S. and in Newtons under the metric system (4.45 Newtons of thrust equals 1 pound of thrust). A pound of thrust is the amount of thrust it would take to keep a 1-pound object stationary against the force of gravity on Earth. So on Earth, the acceleration of gravity is 32 feet per second per second (21 mph per second). If you were floating in space with a bag of baseballs and you threw one baseball per second away from you at 21 mph, your baseballs would be generating the equivalent of 1 pound of thrust. If you were to throw the baseballs instead at 42 mph, then you would be generating 2 pounds of thrust. If you throw them at 2,100 mph (perhaps by shooting them out of some sort of baseball gun), then you are generating 100 pounds of thrust, and so on.

One of the funny problems rockets have is that the objects that the engine wants to throw actually weigh something, and the rocket has to carry that weight around. So let's say that you want to generate 100 pounds of thrust for an hour by throwing one baseball every second at a speed of 2,100 mph. That means that you have to start with 3,600 one pound baseballs (there are 3,600 seconds in an hour), or 3,600 pounds of baseballs. Since you only weigh 100 pounds in your spacesuit, you can see that the weight of your "fuel" dwarfs the weight of the payload (you). In fact, the fuel weights 36 times more than the payload. And that is very common. That is why you have to have a huge rocket to get a tiny person into space right now -- you have to carry a lot of fuel.

You can see this weight equation very clearly on the Space Shuttle. If you have ever seen the Space Shuttle launch, you know that there are three parts:

- The Orbiter
- The big external tank
- The two solid rocket boosters (SRBs)

The Orbiter weighs 165,000 pounds empty. The external tank weighs 78,100 pounds empty. The two solid rocket boosters weigh 185,000 pounds empty each. But then you have to load in the fuel. Each SRB holds 1.1 million pounds of fuel. The external tank holds 143,000 gallons of liquid oxygen (1,359,000 pounds) and 383,000 gallons of liquid hydrogen (226,000 pounds). The whole vehicle -- shuttle, external tank, solid rocket booster casings and all the fuel -- has a total weight of 4.4 million pounds at launch. 4.4 million pounds to get 165,000 pounds in orbit is a pretty big difference! To be fair, the orbiter can also carry a 65,000 pound payload (up to 15 x 60 feet in size), but it is still a big difference. The fuel weighs almost 20 times more than the Orbiter.

[Reference: The Space Shuttle Operator's Manual]

All of that fuel is being thrown out the back of the Space Shuttle at a speed of perhaps 6,000 mph (typical rocket exhaust velocities for chemical rockets range between 5,000 and 10,000 mph). The SRBs burn for about two minutes and generate about 3.3 million pounds of thrust each at launch (2.65 million pounds average over the burn). The three main engines (which use the fuel in the external tank) burn for about eight minutes, generating 375,000 pounds of thrust each during the burn.

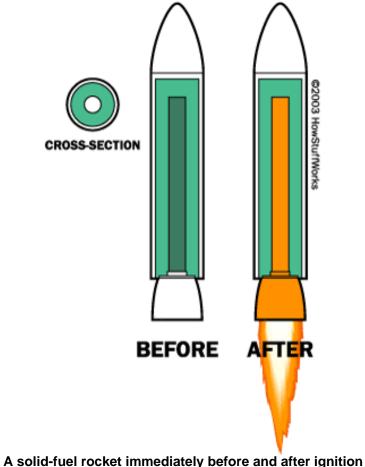
Solid-Fuel Rockets

Solid-fuel rocket engines were the first engines created by man. They were invented hundreds of years ago in China and have been used widely since then. The line about "the rocket's red glare" in the National Anthem (written in the early 1800's) is talking about small military solid-fuel rockets used to deliver bombs or incendiary devices. So you can see that rockets have been in use quite awhile.

The idea behind a simple solid-fuel rocket is straightforward. What you want to do is create something that burns very quickly but does not explode. As you are probably aware, gunpowder explodes. Gunpowder is made up 75% nitrate, 15% carbon and 10% sulfur. In a rocket engine you don't want an explosion -- you would like the power

released more evenly over a period of time. Therefore you might change the mix to 72% nitrate, 24% carbon and 4% sulfur. In this case, instead of gunpowder, you get a simple rocket fuel. This sort of mix will burn very rapidly, but it does not explode if loaded properly. Here's a typical cross section:





On the left you see the rocket before ignition. The solid fuel is shown in green. It is cylindrical, with a tube drilled down the middle. When you light the fuel, it burns along the wall of the tube. As it burns, it burns outward toward the casing until all the fuel has burned. In a small model rocket engine or in a tiny bottle rocket the burn might last a second or less. In a Space Shuttle SRB containing over a million pounds of fuel, the burn lasts about two minutes.

When you read about advanced solid-fuel rockets like the Shuttle's solid rocket boosters, you often read things like:

The propellant mixture in each SRB motor consists of an ammonium perchlorate (oxidizer, 69.6 percent by weight), aluminum (fuel, 16 percent), iron oxide (a catalyst, 0.4 percent), a polymer (a binder that holds the mixture together, 12.04 percent), and an epoxy curing agent (1.96 percent). The propellant is an 11-point starshaped perforation in the forward motor segment and a double- truncated- cone perforation in each of the aft segments and aft closure. This configuration provides high thrust at ignition and then reduces the thrust by

approximately a third 50 seconds after lift-off to prevent overstressing the vehicle during maximum dynamic pressure.

This paragraph discusses not only the fuel mixture but also the configuration of the channel drilled in the center of the fuel. An "11-point star-shaped perforation" might look like this:



The idea is to increase the surface area of the channel, thereby increasing the burn area and therefore the thrust. As the fuel burns the shape evens out into a circle. In the case of the SRBs, it gives the engine high initial thrust and lower thrust in the middle of the flight.

Solid-fuel rocket engines have three important advantages:

- Simplicity
- Low cost
- Safety

They also have two disadvantages:

- Thrust cannot be controlled.
- Once ignited, the engine cannot be stopped or restarted.

The disadvantages mean that solid-fuel rockets are useful for short-lifetime tasks (like missiles), or for booster systems. When you need to be able to control the engine, you must use a liquid propellant system.

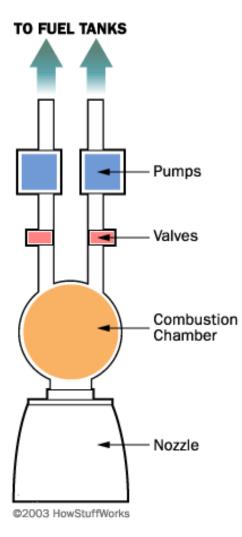
Liquid-Propellant Rockets

In 1926, Robert Goddard tested the first <u>liquid-propellant rocket engine</u>. His engine used <u>gasoline</u> and liquid oxygen. He also worked on and solved a number of fundamental problems in rocket engine design, including pumping mechanisms, cooling strategies and steering arrangements. These problems are what make liquid-propellant rockets so complicated.



Dr. Robert H. Goddard and his liquid oxygen-gasoline rocket in the frame from which it was fired on March 16, 1926, at Auburn, Mass. It flew for only 2.5 seconds, climbed 41 feet, and landed 184 feet away in a cabbage patch.

The basic idea is simple. In most liquid-propellant rocket engines, a fuel and an oxidizer (for example, gasoline and liquid oxygen) are pumped into a combustion chamber. There they burn to create a high-pressure and high-velocity stream of hot gases. These gases flow through a nozzle that accelerates them further (5,000 to 10,000 mph exit velocities being typical), and then they leave the engine. The following highly simplified diagram shows you the basic components.



This diagram does not show the actual complexities of a typical engine (see some of the links at the bottom of the page for good images and descriptions of real engines). For example, it is normal for either the fuel of the oxidizer to be a cold liquefied gas like liquid hydrogen or liquid oxygen. One of the big problems in a liquid propellant rocket engine is cooling the combustion chamber and nozzle, so the cryogenic liquids are first circulated around the super-heated parts to cool them. The pumps have to generate extremely high pressures in order to overcome the pressure that the burning fuel creates in the combustion chamber. The main engines in the Space Shuttle actually use two pumping stages and burn fuel to drive the second stage pumps. All of this pumping and cooling makes a typical liquid propellant engine look more like a plumbing project gone haywire than anything else -- look at the engines on this page to see what I mean.

All kinds of fuel combinations get used in liquid propellant rocket engines. For example:

- Liquid hydrogen and liquid oxygen used in the Space Shuttle main engines
- Gasoline and liquid oxygen used in Goddard's early rockets
- Kerosene and liquid oxygen used on the first stage of the large <u>Saturn V boosters</u> in the Apollo program
- Alcohol and liquid oxygen used in the German V2 rockets
- Nitrogen tetroxide/monomethyl hydrazine used in the Cassini engines

Other Possibilities

We are accustomed to seeing chemical rocket engines that burn their fuel to generate thrust. There are many other ways to generate thrust however. Any system that throws mass would do. If you could figure out a way to accelerate baseballs to extremely high speeds, you would have a viable rocket engine. The only problem with such an approach would be the baseball "exhaust" (high-speed baseballs at that...) left streaming through space. This small problem causes rocket engine designers to favor gases for the exhaust product.

Many rocket engines are very small. For example, attitude thrusters on <u>satellites</u> don't need to produce much thrust. One common engine design found on satellites uses no "fuel" at all -- **pressurized nitrogen thrusters** simply blow nitrogen gas from a tank through a nozzle. Thrusters like these kept Skylab in orbit, and are also used on the shuttle's manned maneuvering system.

New engine designs are trying to find ways to accelerate **ions** or **atomic particles** to extremely high speeds to create thrust more efficiently. NASA's Deep Space-1 spacecraft will be the first to use <u>ion engines</u> for propulsion. See <u>this page</u> for additional discussion of plasma and ion engines. <u>This article</u> discusses a number of other alternatives.

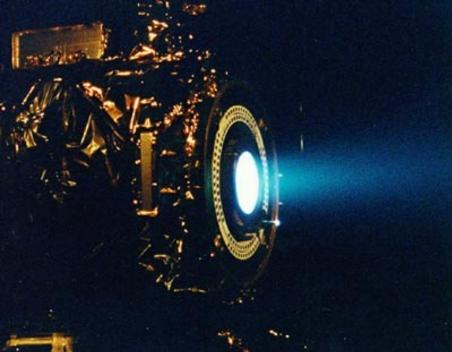


Photo courtesy NASA

This image of a xenon ion engine, photographed through a port of the vacuum chamber where it was being tested at NASA's Jet Propulsion Laboratory, shows the faint blue glow of charged atoms being emitted from the engine. The ion propulsion engine is the first non-chemical propulsion to be used as the primary means of propelling a spacecraft.

For more information, check out the links on the next page.

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