



# Fundamentals of Rocket Motors

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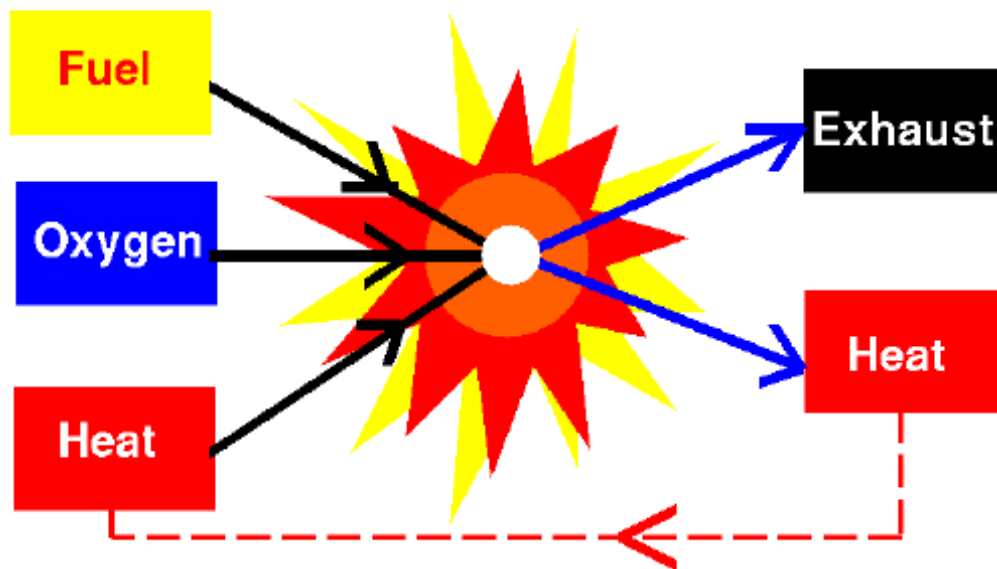
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# Combustion

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To move an airplane or a model rocket through the air, we must use a propulsion system to generate thrust. Different types of aircraft use different types of propulsion devices, but all aircraft rely on some type of engine to generate power. Rocket engines, internal combustion, or piston engines, and jet engines all depend on the burning of fuel to produce power. Burning a fuel is called **combustion**, a chemical process that we study in middle or high school.

Because combustion is so important for aircraft and rocket propulsion, we will review the fundamentals. **Combustion** is a chemical process in which a substance reacts rapidly with oxygen and gives off heat. The original substance is called the **fuel**, and the source of oxygen is called the **oxidizer**. The fuel can be a solid, liquid, or gas, although for airplane propulsion the fuel is usually a liquid. The oxidizer, likewise, could be a solid, liquid, or gas, but is usually a gas (air) for airplanes. For model rockets, a solid fuel and oxidizer is used.

During combustion, new chemical substances are created from the fuel and the oxidizer. These substances are called **exhaust**. Most of the exhaust comes from chemical combinations of the fuel and oxygen. When a hydrogen-carbon-based fuel (like gasoline) burns, the exhaust includes water (hydrogen + oxygen) and carbon dioxide (carbon + oxygen). But the exhaust could also include chemical combinations from the oxidizer alone. If the gasoline were burned in air, which contains 21% oxygen and 78% nitrogen, the exhaust could also include nitrous oxides (NOX, nitrogen + oxygen). Exhaust usually occurs as a gas; the temperature of the exhaust is high because of the heat released. (**Example: Soot** is a form of solid exhaust that occurs in some combustion processes.)

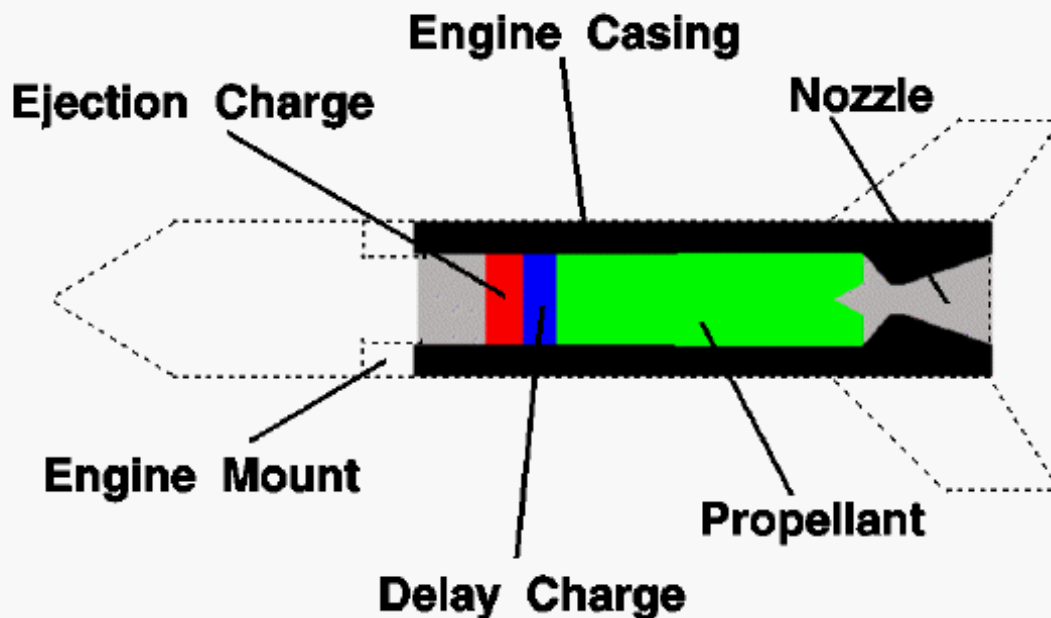
During the combustion process, as the fuel and oxidizer are turned into exhaust products, heat is generated. Interestingly, some source of heat is also necessary to start combustion. (Gasoline and air are both present in your automobile fuel tank; but combustion does not occur because there is no source of heat.) Since heat is both required to start combustion and is itself a product of combustion, we can see why combustion takes place very rapidly. Also, once combustion gets started, we don't have to provide a heat source because the heat of combustion will keep things going. (**Example: We don't have to keep lighting a campfire.**)

To summarize, for combustion to occur three things must be present: a fuel to be burned, a source of oxygen, and a source of heat. As a result of combustion, exhausts are created and heat is released. You can control or stop the combustion process by controlling the amount of the fuel available, the amount of oxygen available, or the source of heat.



## Model Solid Rocket Engine

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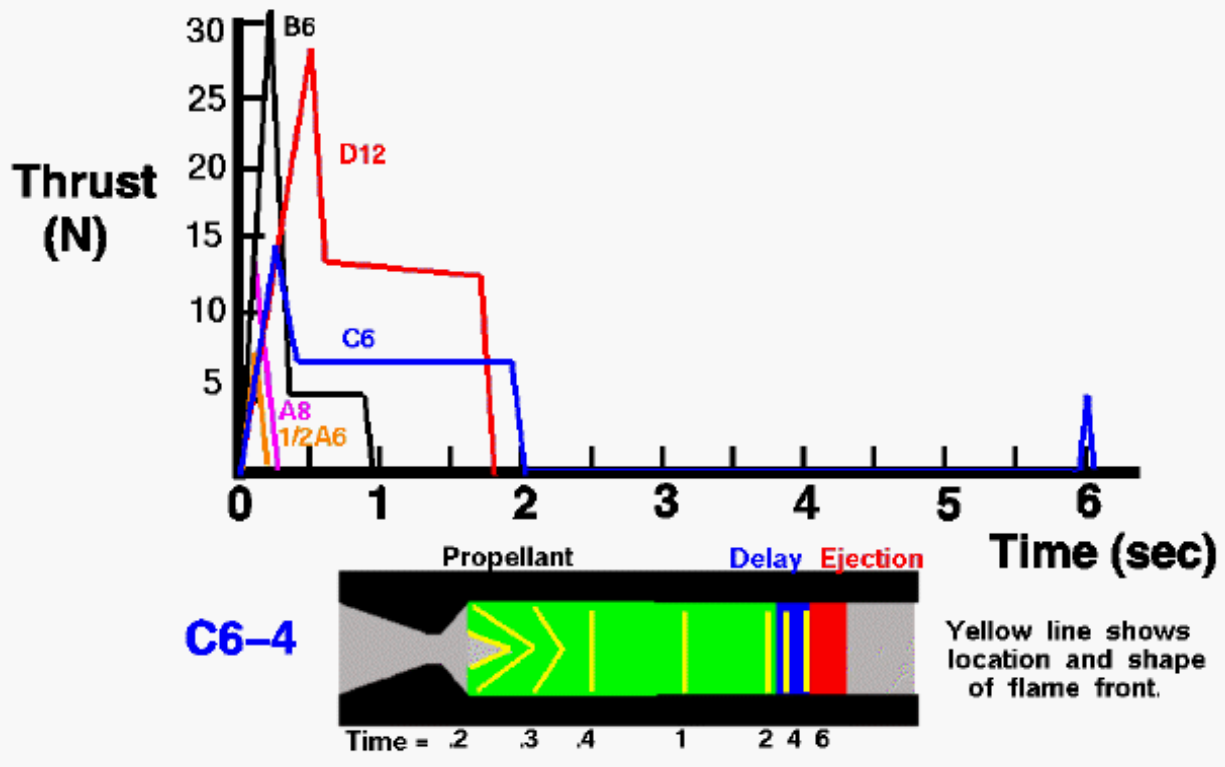
There are two main categories of rocket engines; liquid rockets and solid rockets. In a liquid rocket, the fuel and the source of oxygen (oxidizer) necessary for combustion are stored separately and pumped into the combustion chamber of the nozzle where burning occurs. In a solid rocket, the fuel and oxidizer are mixed together and packed into a solid cylinder. Under normal temperature conditions, the fuel and oxidizer will not burn; but they will burn when exposed to a source of heat. Some type of igniter is used to initiate the burning of a solid rocket motor at the end of the propellant facing the nozzle. Once the fuel starts to burn, hot exhaust gas is produced, which is used to propel the rocket, and a "flame front" is produced which moves into the propellant. Once the burning starts, it will proceed until all the propellant is burned. With a liquid rocket, you can stop the thrust by turning off the flow of fuel; but with a solid rocket, you would have to destroy the casing to stop the engine. Liquid rockets tend to be heavier and more complex because of the pumps, and you usually put the fuel in the rocket just before launch. A solid rocket is much easier to handle and can sit for years before firing.

On this slide we show a drawing of the parts of a model rocket engine so that you can learn how it works. We have laid the engine on its side, and "cut" the engine in half so that we can see what is inside. (Never disturb, cut, or modify a real model rocket engine. The propellant can ignite at any time if there is a source of heat.) The engine is installed in a rocket shown by the dashed lines on the figure. The **engine casing** is a cylinder made of heavy cardboard which contains the nozzle, propellants, and other explosive charges. At the right side of the engine is the nozzle, a relatively simple device used to accelerate hot gases and produce thrust. Model rocket nozzles are usually made of clays or ceramics because of the high temperature of the exhaust. The hot gases for a model rocket are produced by the solid **propellant**, shown in green. An electric igniter is used to launch a model rocket engine. As the flame burns through the propellant, the rocket experiences powered flight. When the flame front reaches the far left of the propellant, thrust goes to zero, and a **delay charge**, colored blue, begins to burn. During the delay, no thrust is produced and the rocket coasts up to its maximum altitude. The length of the delay varies between engines from 2 to 8 seconds and the amount of the delay is listed on the engine casing. When the delay charge is completely burned through, the **ejection charge**, shown in red, is ignited. This produces a small explosion which ejects hot gas out the front of the engine, through the **engine mount**, ejects the nose cone, and deploys the parachute for a safe recovery.



# Rocket Engine Performance

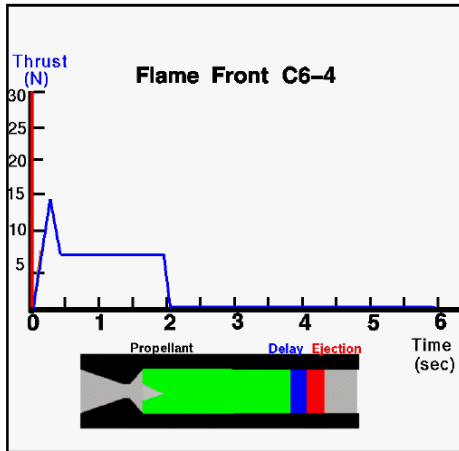
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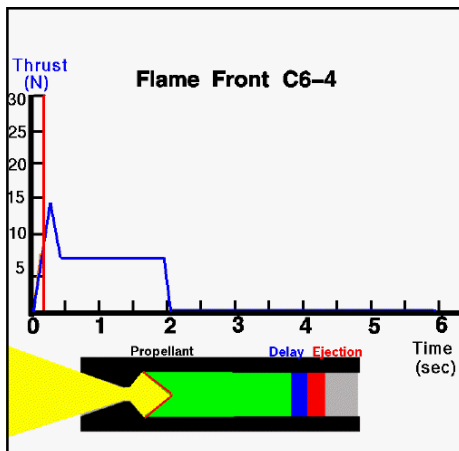
Model rocket performance (how far, how high, how fast) depends a great deal on the rocket engine performance. But there are several different ways to characterize rocket engine performance. Model rocket engines come in a variety of sizes, a variety of weights, with different amounts of propellant, with different burn patterns which effects the thrust profile, and with different values of the delay charge which sets the amount of time for the coasting phase of the flight. On this page, we discuss all of the engine performance factors that affect the flight of a model rocket.

At the top of the page we show typical performance curves for several different rocket engines. We are plotting the thrust of the engine versus the time following ignition for each engine. You will notice that when comparing engines, there is a great difference between the levels and shapes of the plots. And for any single engine, the thrust changes from time to time. At the bottom of the page, we show a typical engine schematic which we will use to explain why the thrust changes so much for a given engine. The thrust of any engine depends on how fast and how much hot gas exhaust passes through the nozzle. Solid rocket fuel only burns on the surface and the surface burns away as it turns into a gas. You can then imagine the flaming surface moving with time through the propellant. The flaming surface is called the **flame front**. At any time and at any location the amount of hot gas being produced depends on the area of the flame front. The greater the area, the greater the thrust. As the propellant burns away the shape and the area can change.

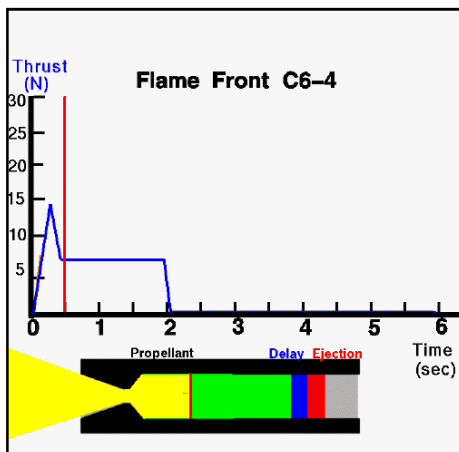
## Rocket Motor Burn Sequence



In this sequence, we show the shape and location of the flame front for a C6-4 engine. (We will explain the engine designations later on this page). The schematic is two dimensional while the real engine is three dimensional. So a three dimensional cone surface will appear as a two dimensional angle on the schematic. The flame front is shown as a red line and it moves through the propellant as the engine burns. The hot exhaust is shown in yellow. The time is noted on the plot by a moving red line.

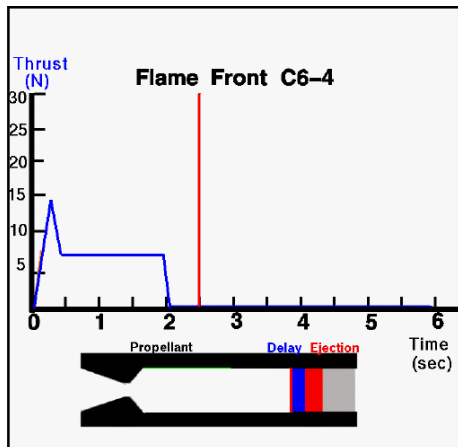


On a typical model rocket engine, a small cone is formed in the propellant on the nozzle end of the engine. As the fuel burns, the size of the cone increases until it hits the engine casing (about time = .2 on this engine).

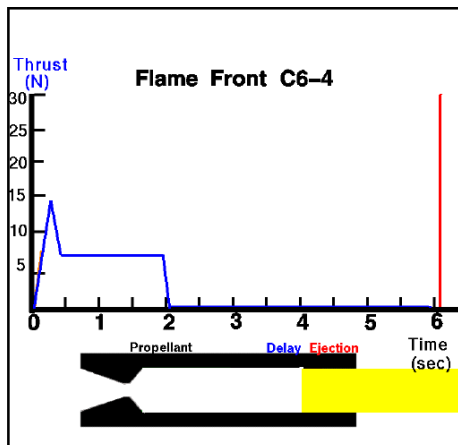


Between time = .2 and .5, the shape of the cone flattens out and the area and thrust decreases because the burn rate also depends on the curvature of the surface. By time = .5, the cone has become a flat flame front which proceeds on down the engine until the propellant is used up at time = 2. Between .5 and 2, the thrust is constant;

## Rocket Motor Burn Sequence



At time = 2, the thrust goes to zero and the delay charge begins to burn. Even though the delay charge is shorter (smaller) than the propellant, it burns longer because it is made of a different material. For this engine we have a 4 second delay (the "4" of C6-4 denotes the delay time)



At time = 6, the ejection charge is reached and ignited and blows out the front of the engine.

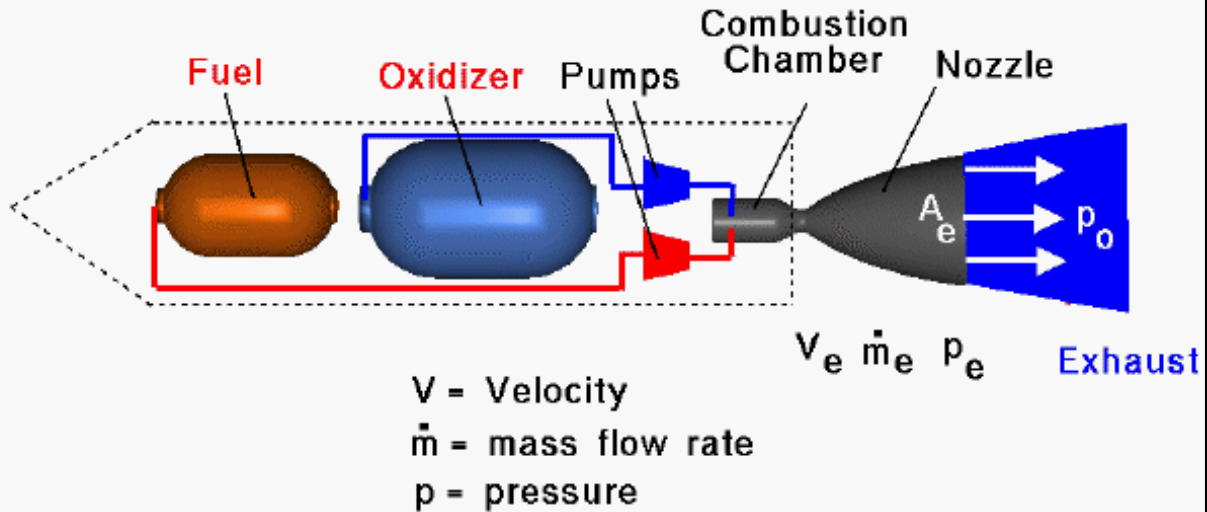
Considering the various engine plots, we see a burn pattern similar to the previously discussed C6-4, but with some variations in the amount of thrust. We have seen that the shape of the thrust curve is affected by the shape of the flame front. Designers of solid rockets can produce the given thrust curves by changing the total amount of propellant placed in the engine, by varying the angle of the cone in the propellant, and by varying the diameter of the propellant (and casing). Considering a single engine plot, the thrust varies greatly with time. We can specify a time-averaged thrust of the engine by adding up the product of the thrust over some small time increment times the amount of the time increment and then dividing by the total time. The number designation of an engine indicates the average thrust in Newtons. A C6-4 has an average thrust of 6 Newtons. The average thrust times the length of the engine burn in time is called the **total impulse** of the engine. The letter designation of an engine tells the maximum total impulse of that class of engine. An "A" engine has a maximum impulse of 2.5 Newton-seconds, a "1/2A" has 1.25 N-sec, a "B" has 5.0 N-sec, a "C" has 10.0 N-sec, and a "D" has 20.0 N-sec. If we compare the curves for B6 and the C6, we find that both engines have the same average thrust (6 Newtons), but the "C" engine burns almost twice as long for double the total impulse.

As mentioned above, the engine designer can affect the thrust and the total impulse of an engine by changing the diameter of the propellant (and casing). Typical "1/2A" engines are 13 mm in diameter, typical "A", "B" and "C" engines are 18 mm in diameter, and typical "D" engines are 24 mm in diameter. This is important to remember because a model rocket designed for a "B" engine will not accept a "1/2A" or a "D". The engines will not fit into the fixed engine mount of the rocket.



# Rocket Thrust

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$$\text{Thrust} = F = \dot{m}_e V_e + (p_e - p_0) A_e$$

On this slide, we show a schematic of a liquid rocket engine. Rocket engines were used on several high speed aircraft following World War II. In a **rocket**, stored fuel and stored oxidizer are pumped into a combustion chamber where they are mixed and exploded. The hot exhaust is then passed through a nozzle, which accelerates the flow. The exit velocity is determined by the shape of the rocket nozzle and is supersonic. The exit pressure is set by the nozzle shape as well and will only be equal to free stream pressure at some design condition. We must, therefore, use the longer version of the thrust equation to describe the thrust of the system. If the mass flow is denoted by "m dot", the exit velocity by  $V_e$ , the pressure at the exit by  $p_e$ , the free stream pressure by  $p_0$ , and the nozzle exit area by  $A_e$ , the thrust ( $F$ ) is given by:

$$F = \dot{m} * V_e + (p_e - p_0) * A_e$$

This thrust equation works for both liquid and solid rocket engines. The mass flow rate through the propulsion system is determined by the nozzle design. You can explore the design and operation of a rocket nozzle with our interactive nozzle simulator program which runs on your browser. Notice that there is no free stream mass times free stream velocity term in the thrust equation because no external air is brought on board. Since the oxidizer is carried on board the rocket, rockets can generate thrust in a vacuum where there is no other source of oxygen. That's why a rocket will work in space, where there is no surrounding air, and a gas turbine or propeller will not work. Jets and propellers rely on the atmosphere to provide the oxygen.