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The Rocket: How It Works in Space

The rocket is a most remarkable device. Its early inventors could not have guessed that it would ultimately evolve into a machine capable of propelling robotic and human payloads through the vacuum of space. In fact, the rocket actually works better in a vacuum than in air! To understand rocket propulsion, we must first digress a bit into the physics of Isaac Newton.

NEWTONIAN MECHANICS AND ROCKET FUNDAMENTALS

A quirky and brilliant physicist, Isaac Newton framed, during the seventeenth century, the laws governing the motion of macroscopic objects moving at velocities, relative to the observer, well below the speed of light (almost 300,000 km/s). This discipline is called “kinematics” since it deals with motion in itself, not the causes of it. This type of physics, aptly called “Newtonian mechanics” works quite well at describing the behavior of almost all aspects common to everyday human experience, even space travel. It does not, however, accurately describe the motion of objects that are moving very fast.

To investigate kinematics of high-velocity objects moving at 20,000 km/s or faster, we need to apply the results of Einstein’s theory of special relativity. To consider the motion (and other properties) of microscopic objects—those much smaller than a pinhead or dust grain—we need to apply the principles of quantum mechanics. Both relativity and quantum mechanics were developed three centuries after Newton.

For macro-sized rockets moving at velocities measured in kilometers or tens of kilometers per second, Newtonian physics is quite adequate. The most relevant aspects of kinematics to rocket propulsion are inertia, velocity, acceleration, and linear momentum. We will consider each of these in turn.

INERTIA—OBJECTS RESIST CHANGES IN MOTION

Iron Age scholars such as Aristotle assumed that objects move the way they do because such motion is in their nature. Although not quantifiable, such a conclusion was an improvement over the earlier Bronze Age notion that a deity (or deities) controlled the motions of all objects.

G. Vulpetti et al., *Solar Sails,* Springer Praxis Books,
DOI 10.1007/978-1-4939-0941-4_2

Newton's first step in quantifying the concept of motion was to introduce the principle of inertia. All mass contains inertia—the greater the mass, the greater the inertia. Essentially, an object with mass or inertia tends to resist changes in its motion. The only way to alter the object's velocity is to act upon the object with a force. This principle is often referred to as Newton's first law; it has represented the birth of "dynamics:" namely, the description of a body's motion with the inclusion of the causes that determine it.

FORCE AND A MOST INFLUENTIAL EQUATION

As a point of fact, what really separated Newton from earlier kinematic researchers was his elegant and most successful mathematical representation of the force concept. No longer would forces be in the province of mysterious (and perhaps) unknowable essences or natures; no longer would gods or goddesses move things at their whim. Instead, an entire technological civilization would arise based on such simple, and easily verifiable equations as Newton's relationship among force (F), mass (M) and acceleration (A).

If we are working in the international units, force is measured in units of newtons (N), mass is in kilograms (kg), and acceleration—the rate at which velocity changes with time—is in meters per squared second (m/s^2). The famous force equation, which is called Newton's second law, is written as follows:

$$F = M\,A, \tag{2.1}$$

or Force = Mass times Acceleration.

Let's consider what this means in practice. If a 10 newton force acts on a 1 kg mass, Eq. (2.1) reveals that the force will accelerate the mass by 10 m/s^2. This force will just lift the object from the ground if it is directed upward, since Earth's gravitational acceleration (g) is 9.8 m/s^2. If the same force acts upon an object with a mass of 10 kg, the acceleration of the mass imparted by the force will be 1 m/s^2.

To apply Newton's second law successfully to any mode of propulsion, you must do two things: maximize the force and minimize the mass of the object you wish to accelerate.[1]

ACTIONS AND REACTIONS

Forces, velocities, and accelerations are representatives of a type of quantity called "vectors." Unlike "scalars," which only have magnitude, vector quantities have both magnitude and direction.

We unconsciously apply the concepts of scalars and vectors all the time. Let's say that we wish to fly between London and New York. We first book a flight on an Airbus or Boeing jetliner, since such a craft can cruise at speeds of around 1,000 km/h. But to minimize travel time between London and New York, we book a flight traveling in the direction of New York City—a jetliner traveling in the direction of Sydney, for example, would not do much to minimize our travel time.

[1] In space propulsion, this is a very difficult task indeed.

Now let's examine the case of a baseball or cricket player hitting a ball with a bat. The bat is swung to impart a force on the ball, which (if all goes well from the viewpoint of the batter or bowler) flies off in the desired direction at high speed. As high speed videotapes reveal, bats sometimes crack during the interaction. This is because a "reaction" force is imparted to the bat by the struck ball.

If you've ever fired a rifle or handgun, you've experienced action and reaction force pairs. An explosion accelerates the low mass bullet out the gun muzzle at high speed. This is the action force. The recoil of the weapon against your shoulder—which can be painful and surprising if you are not properly braced against it—is the reaction force.

Newton's third law considers action–reaction force pairs. For every action, Newton states, there is an equal-in-magnitude and opposite-in-direction reaction, always.

Jets and rockets are representative "action–reaction" propulsion systems. In a jet or chemical rocket, a controlled and contained explosion accelerates fuel to a high velocity. The ejection of this fuel from the engine nozzle is the action member of the force pair. The reaction is an equal force accelerating the engine (and structures connected to it) in the direction opposite the exhaust.

The trick with a successful jet or rocket is to minimize structural mass (and payload) and maximize fuel exhaust velocity.

LINEAR MOMENTUM: A CONSERVED QUANTITY

As first-year college physics students learn, Newton's third law can be used to demonstrate that linear momentum (P) is conserved in any physical system. Linear momentum is a vector quantity, which is defined as the product of mass (M) and velocity (V) and is written $P=MV$. If the chemical reaction in the rocket's combustion chamber increases the expelled fuel's momentum by P_f, conservation of linear momentum requires that the rocket's momentum changes by an equal amount as that of the expelled fuel, and that this change is oppositely directed to the change in fuel momentum.

In this text, the word *fuel* is used in a general context for simplicity. Actually, in most *chemical* rocket engines, there is some substance (the proper *fuel* that has to be burned, and some other substance (the *oxidizer*) that must be present to burn the fuel. Oxidizers contain oxygen, which is required for something to burn, hence its name. (Such substances altogether are named a *propellant*, in general.) This chemical reaction is called the *combustion.* Most of the energy released by such a reaction is found as kinetic energy of the reaction products (which are different from the propellant's molecules). They flow through a nozzle in gaseous form and achieve a final supersonic speed (the exhaust or ejection speed) with which they are exhausted away. Considered as a whole, this gas represents the reaction mass generating thrust. In solid rocket engines, fuel and oxidizer are appropriately mixed together and stored in the combustion chamber. In liquid rocket engines, fuel and oxidizer are kept separated in their tanks; they are channeled into the combustion chamber where they burn, producing the rocket's exhaust

Propellant and rocket are considered as an isolated system, which is only strictly true in the depths of space. Closer to home, atmospheric air resistance tends to decrease rocket efficiency, since linear momentum of air molecules encountered by the rocket changes during the interaction. Here, the atmosphere must be considered as part of the system, which includes rocket and propellant.

Close to a gravitating body, like near Earth's surface, a component of the total force must always be directed upward, so the rocket can remain in flight. Even in interplanetary space, the gravitational fields of Earth, Moon and Sun must be taken into account for estimating rocket performance.

THE ROCKET EQUATION

If one applies elementary calculus to propellant-rocket linear momentum conservation and sets up the problem correctly, it is easy to derive the classic equation of rocket performance. We will not derive this important equation here, but will instead consider its application.

First some definitions: the mass ratio (MR) is the quotient of the total rocket mass at ignition (including fuel) to the mass of the vehicle when the propellant gauge is on Empty. Let's say, for example, that a particular rocket has a mass at ignition of 1 million kg. When the propellant has all been exhausted, the rocket's mass is 100,000 kg; hence, this vehicle has a mass ratio of 1 million/100,000, which is exactly 10, or MR = 10.

Another significant quantity is the exhaust velocity of the rocket engine as measured by a sensor traveling with the vehicle, V_e. The final quantity expressed in the rocket equation is ΔV, which is total change of the rocket's velocity or velocity increment, measured just as all the propellant has been exhausted. All of these symbols are combined in the rocket equation as follows:

$$MR = \mathrm{e}^{\Delta V / V_e} \tag{2.2}$$

where e is approximately equal to 2.718 and is a universal constant called the "base of natural logarithms."

It is not necessary to be a rocket scientist or calculus whiz to appreciate this result. Let's say that the designers of a rocket wish the velocity increment to exactly equal the exhaust velocity. In this case, MR is 2.718 raised to the first power, or simply 2.718. For every kilogram of unfueled vehicle (payload, engines, structure, etc.), 1.718 kg of propellant are required.

This doesn't seem so bad, but let's examine what happens if we desire a velocity increment exactly twice the exhaust velocity. Now, MR is approximately equal to the square of 2.718, or about 7.4. For every kilogram of unfueled vehicle, 6.4 kg of propellant are required.

As a final illustration, consider what happens when the velocity increment is exactly three times the exhaust velocity. Now, MR becomes about 20, which means that approximately 19 kg of propellant are required for every kilogram of unfueled rocket.

This rapid, nonlinear increase of propellant requirement with velocity increment is called an “exponential” increase. This exponential increase demonstrates the impracticality of constructing a rocket to achieve much more than two or three times the exhaust velocity, particularly if the vehicle must overcome Earth’s gravity to reach a destination in outer space.

One of the most energetic chemical combinations known is the liquid hydrogen/liquid oxygen combusted aboard both the American Space Shuttle and the European Ariane launchers. The highest exhaust velocity for engines of this type is about 4.5 km/s.

If we desire to place a payload in low Earth orbit (LEO), say a few hundred kilometers above Earth’s surface, the spacecraft must be accelerated to about 8 km/s. If atmospheric drag during the early part of the rocket’s climb reduces effective exhaust velocity to about 4 km/s, $\Delta V/V_e$ is equal to 2. From the rocket equation, 6.4 kg of rocket fuel is required for every kilogram of unfueled vehicle (engines, structure, and payload). In reality, things are worse because a launcher, increasing its speed, undergoes atmospheric drag. (This drag is nothing more than friction between the rocket and the atmosphere.) The rocket’s total ΔV is higher by roughly 20–25 %, depending on the specific launcher design and the final orbit of payload into which it is injected.

To achieve LEO with a single-stage rocket would require advances in materials science. Strong, low mass structures would be required for vehicle components that must withstand the high accelerations of ascent to orbit. To date, the best that has been accomplished along these lines is the American Atlas missile and space launcher of the 1960s. The Atlas had an extraordinarily thin skin. If it weren’t for the pressure of the onboard fuel, the Atlas would have collapsed on the launch pad under the influence of Earth’s gravity. But even using this extreme measure, the Atlas was not quite a single-stage-to-orbit launcher. External boosters were used during the initial ascent phase and discarded when emptied.

If we desire a single-stage-to-orbit shuttle that is also reusable, the problem becomes even more daunting. Because of the equipment necessary to ensure reentry, the payload fraction of such craft would likely be very small, even accounting for great advances in materials and structures.

STAGED ROCKETS

To squeeze efficiencies out of our space launchers, many of the world’s space ports are located near the equator. For a west-to-east launch direction, Earth’s rotation provides about 0.46 km/s to the rocket, which eases the problem a bit. But geography can do little to alleviate the basic economics problem of space travel—the exhaust velocities of existing and feasible chemical launchers are simply too low!

One way around this, albeit an expensive one, is to utilize rocket stages. Basically, a big rocket lifts off from Earth’s surface. Its payload consists of a smaller rocket. At burnout, the big rocket falls away and the small rocket takes over.

This approach allows us to utilize chemical rockets to achieve LEO, to escape Earth (which requires a velocity increment of about 11 km/s), and to fly even faster. But there is a penalty—the payload fraction decreases dramatically as the number of stages increases and reliability issues become more pressing.

Let's consider a simple example of a 2-stage rocket. Assume that each stage has a rocket with an exhaust velocity of 4 km/s and that the mass ratio of each stage is an identical 7.4. This means that at first-stage burnout, the vehicle is moving at 4 km/s. At second-stage burnout, the vehicle's velocity is up to 8 km/s, more than enough to achieve Earth orbit.

Next assume that the mass of the first stage is 100,000 kg, not including fuel, and that 20 % of this mass is payload—the second stage in this case. The fuel required for the first stage is 620,000 kg.

At first-stage burnout, the second stage ignites. At ignition, this stage has a mass that is 20 % of 100,000 kg, or 20,000 kg. But to achieve the required burnout velocity, the mass ratio of the second stage is 7.4, identical to that of the first stage. At its burnout, the second stage therefore has a mass of about 2,700 kg. If the payload fraction of the second stage is 0.2, identical to that of the first stage, about 540 kg of useful payload achieves Earth orbit.

Remember that the total mass of the spacecraft on the launch pad was 720,000 kg including fuel. Less than 0.1 % of the on-pad vehicle mass is useful payload.

Real rockets do somewhat better, fortunately, than this simple example. The on-pad mass of Europe's Ariane 5 is about 740,000 kg. This launcher can inject about 10,000 kg into low-Earth orbit and send a bit more than half that mass toward geosynchronous orbit. But the economics are staggering—a commercial communications satellite might mass about 1 % of the vehicle complex that propels it toward geosynchronous Earth orbit.

Very recently, another European launcher named VEGA finished its test flights and is beginning its operational phase, at least 10 launches (within 2015) to LEOs with scientific satellites as payload. The VEGA program,[2] to which Italy is the major contributor in terms of design, technical management and manufacturing, is a four-stage launcher. The first three stages are thrusted by solid-propellant rockets, whereas the fourth one is a rocket with liquid (but not cryogenic) bipropellant engine. Its total mass at liftoff amounts to 137 metric tons, and is capable of delivering scientific spacecraft weighing from 1.1 to 2.3 tonnes to LEOs—from 300 to 1,500 km in altitude, and from 5 to 90° in orbital inclination over the Earth equator. The orbital altitude and inclination, chosen by the (institutional or private) customer, determines the maximum weight of the satellite (similarly to other launchers). Thus, the maximum payload fraction takes on $2.3/137 = 0.0168$, or 1.68 %. This is a high value indeed for non-cryogenic chemical engines, the exhaust velocities of which range from 2.75 to 3.09 km/s, approximately. This payload performance is mainly due to the high-tech materials of its structures (very light). Using non-cryogenic engines with advanced structural materials for putting scientific payloads into operational LEOs reduces the launch costs remarkably.

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[2] The reader is suggested visiting:

(1) http://www.elv.it/en/and its pages,
(2) http://www.russianspaceweb.com/vega_lv.html
(3) http://www.esa.int/Our_Activities/Launchers/Launch_vehicles/Vega

for broad information on the VEGA launch vehicle.

CHEMICAL ROCKETS AND THEIR ALTERNATIVES

The basic components of a typical chemical rocket are shown schematically in Fig. 2.1. In the chemical rockets, the payload is usually attached above the fuel and oxidizer tanks. A mixture of fuel and oxidizer is delivered to the combustion chamber and then ignited in what can only be called a "controlled explosion." The product of this high-energy (exothermic) chemical reaction is squirted out the nozzle at the base of the combustion chamber as exhaust. In a reaction to the exhaust's explosive release, the rocket accelerates in the opposite direction.

In the most energetic chemical rockets, the reactants are hydrogen (H_2) fuel and oxygen (O_2), which serves as the oxidizer. For those readers a bit rusty in chemistry, the subscript "2" means that each oxygen or hydrogen molecule contains two oxygen and hydrogen atoms, respectively.

In many fuel/oxidizer mixtures, a device much like an auto's spark plug is required to ignite the reactants. Hydrogen and oxygen react spontaneously, however. The product of this reaction is ordinary water (H_2O) and the reaction can be expressed as follows:

$$2H_2 + O_2 \rightarrow 2H_2O \tag{2.3}$$

In this balanced chemical reaction, two hydrogen molecules combine with one oxygen molecule to produce two molecules of water vapor.

Some rockets use liquid fuels, such as the mixture just considered. Others, such as the space shuttle's solid boosters, burn solid fuels. There are advantages and disadvantages to both approaches.

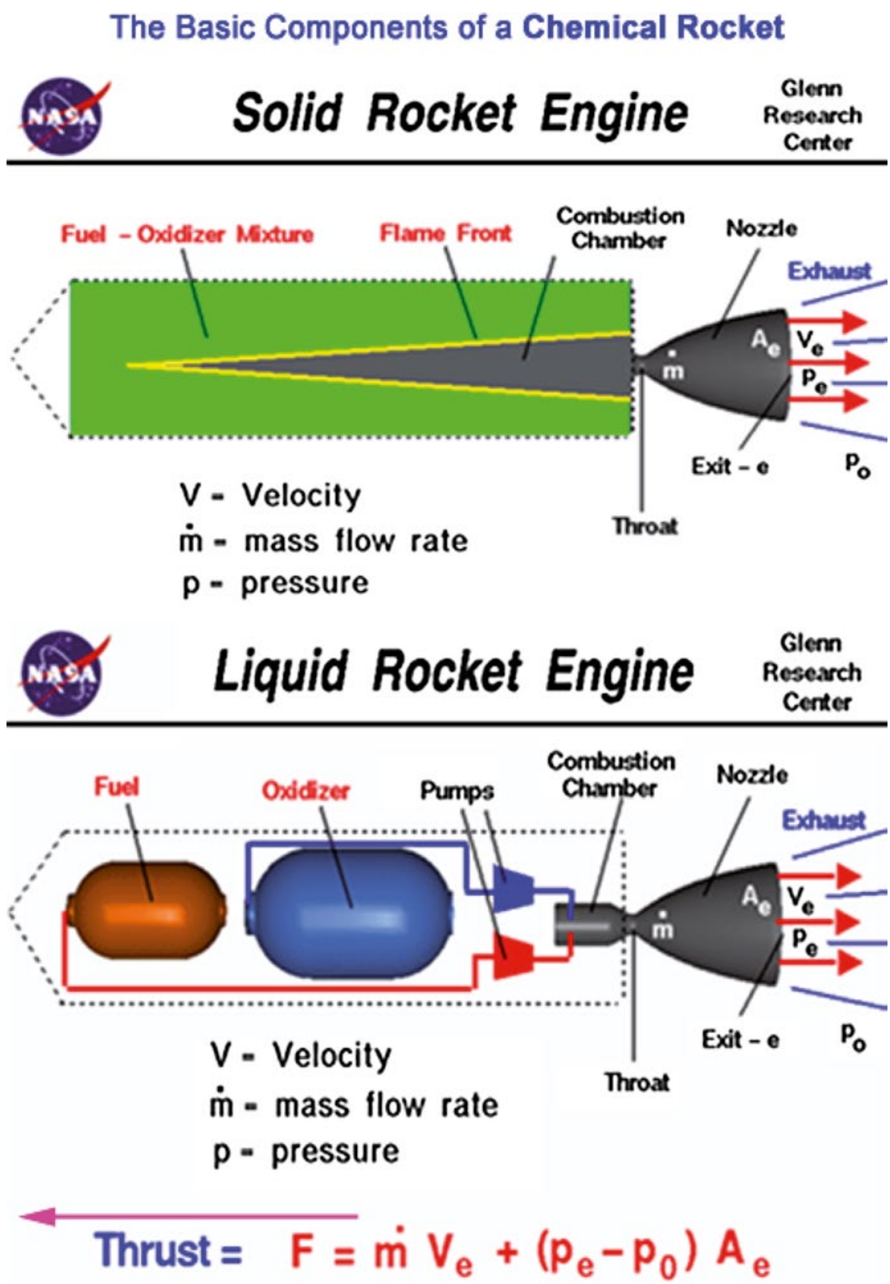
In general, liquid fuel combinations are more energetic. But they are more difficult to store, both on Earth and in space. Many liquid rockets can be stopped and restarted. Like a skyrocket, a solid rocket once ignited burns until all fuel is exhausted.

Lots of engineering effort goes into optimizing the components shown in Fig. 2.1, not to mention the complex plumbing connecting them. Engineers try to reduce the mass and the complexity of the payload faring that protects payloads as the rocket ascends through the atmosphere. Fuel tank mass is also minimized—as mentioned earlier, some fuel tanks (like those of the American Atlas boosters that orbited the Mercury astronauts) are supported by the pressure of the on-board fuel.

Combustion chambers must be low in mass, temperature resistant, and able to withstand the pressures of the expanding, ignited fuel mixtures. Millions of euros, dollars, and rubles have been expended on nozzle optimization, in an effort to squeeze the last few meters per second out of a rocket's exhaust velocity.

To overcome some of the limitations of the chemical rocket, various nonchemical rockets have been experimented with. If you don't mind a certain amount of radioactive fallout in your environment, you might consider the nuclear-thermal rocket. Ground tested by the US during the 1960s, these rockets heat a working fluid (usually water or hydrogen) to an exhaust velocity as much as twice that of the best chemical rocket. Reusable, single-stage-to-orbit nuclear-thermal shuttles are a possibility.

If you can't abide the idea of nuclear rockets streaking through the atmosphere, some of the nuclear thermal rocket's technology is applicable in the solar-thermal rocket. In this



2.1 Main components of chemical engines (Courtesy of NASA) low-thrust device suited for in-space, but not ground-to-orbit, application, sunlight is focused on the working fluid, which then squirts through a nozzle at an exhaust velocity comparable to that of the nuclear-thermal rocket. (Thrust, the "action" force of the rocket, is measured in newtons and is defined as the product of the fuel flow rate in kilograms per second and the exhaust velocity in meters per second. A rocket must have a thrust greater than the rocket's weight in order to rise from the ground.)

Another low-thrust possibility is to use collected solar energy or an on-board nuclear reactor to ionize and accelerate fuel to exhaust velocities in excess of 30 km/s. Several versions of these solar-electric or ion drives have seen application in robotic lunar and interplanetary missions.

From the point of view of exhaust velocity, the ultimate rocket is the nuclear-pulse drive. Nuclear-pulse rockets, which work well on paper, would be most dramatic to watch in flight since their fuel consists of nuclear charges (i.e., nuclear bombs) ignited a distance behind the craft. Fusion charges (hydrogen bombs) and even matter/antimatter combinations could conceivably propel such craft. The next chapter considers the potential and limitations of various chemical and nonchemical applications of the rocket principle.

FURTHER READING

Many details of chemical, electric and nuclear rocket propulsion are reviewed in monographs such as:

1. Martin J. L. Turner, *Rocket and Spacecraft Propulsion,* 2nd ed., Springer-Praxis, Chichester, UK, 2005.
2. T. W. Lee, *Aerospace Propulsion*, John Wiley & Sons, Ltd., 2014.

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