Rockets and Launch Vehicles

4.2.1

In This Chapter You'll Learn to...

- ☛ Explain some of the basic principles of rocket science
- ☛ Discuss the various types of rocket systems and their operating principles
- ☛ Describe launch-vehicle subsystems and their key design issues
- ☛ Discuss the principles of rocket staging and how to determine the velocity change from a staged launch vehicle

Outline

Rockets take spacecraft where they need to go in space. Rockets form the core of the propulsion subsystems found on everything from fireworks to Space Shuttles to the Star Ship *Enterprise*. Propulsion subsystems

- Get spacecraft into space
- Move them around after they get there
- Change their attitude (the direction they're pointing)

Figure 4.2.1-1 characterizes these propulsion-system functions.

A launch vehicle needs a large velocity change, ΔV, to get from Earth's surface into orbit. Launch vehicles rely on their propulsion subsystems to produce this huge velocity change. After a spacecraft gets into space, its propulsion subsystem provides the necessary ΔV to take it to its final mission orbit and then provides orbital corrections and other maneuvers throughout the mission lifetime.

Space Mission Architecture. This chapter deals with the Launch Vehicles segment of the Space Mission Architecture.

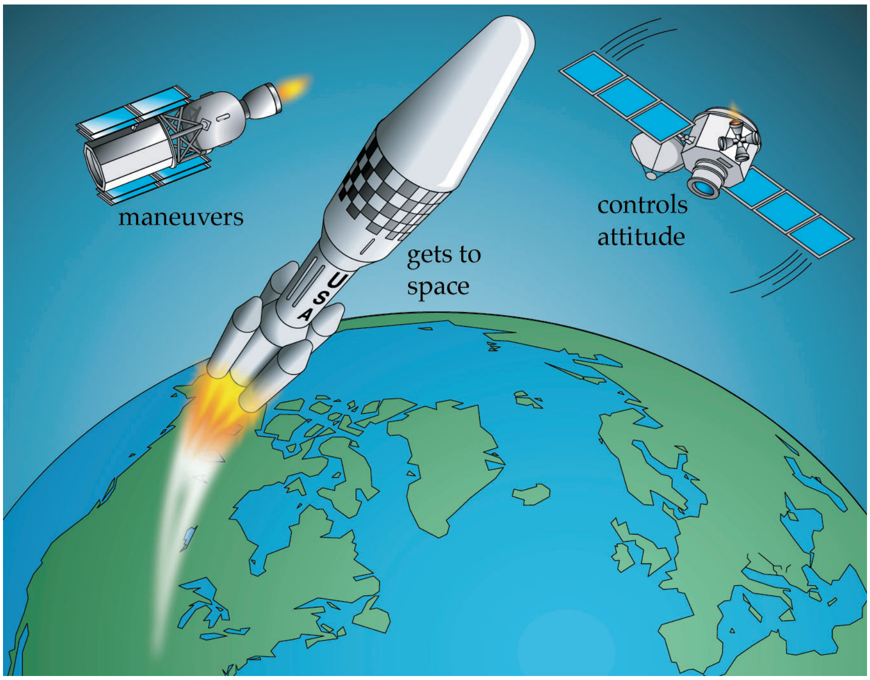

Figure 4.2.1-1. Rocket Functions. Rockets take spacecraft into orbit, move them around in space, and help control their attitude.

Propulsion is also essential for controlling the attitude of a spacecraft, which way it is pointed. One easy way of doing this is using small rockets called thrusters. In this chapter we peel back the mysteries of rocket science to see how rockets work and how rocket scientists put together propulsion subsystems for spacecraft and launch vehicles.

4.2.1.1 Rocket Science

In This Section You'll Learn to...

- Explain the basic operating principles of rockets
- Define and determine important parameters describing rocket performance—thrust, specific impulse, density specific impulse, and velocity change
- Explain how rockets convert stored energy into thrust
- Explain basic trade-offs in rocket design

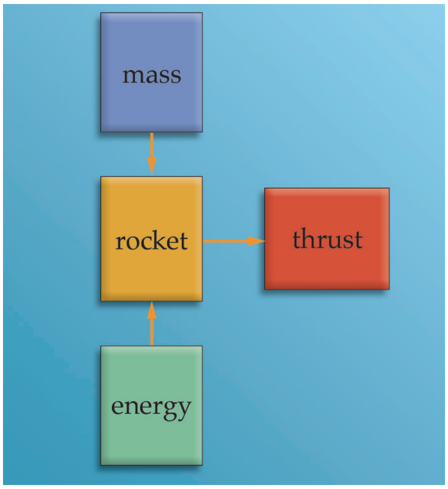

Figure 4.2.1-2. The Simplest Version of a Rocket System. The rocket's basic function is to take mass, add energy, and convert them into thrust, a force large enough to move a vehicle.

You can't be a real rocket scientist until you can explain how a rocket works. In this section, we'll dissect rockets to see how all that noise, smoke, and fire can hurtle a spacecraft into space. Let's start with the big picture. A rocket is basically a system that takes mass plus energy and converts them into a force to move a vehicle. The input mass for a rocket is usually called *propellant*. The force a rocket produces is *thrust*. Figure 4.2.1-2 shows the block diagram for this simplified version of a rocket system.

Our examination of rocket systems begins by looking at the output—thrust. This approach requires us to dust off Newton's Laws to see how high-speed exhaust going in one direction pushes a vehicle in another. Next we'll see how this thrust, over time, produces a velocity change for the vehicle. Most important for mission planning, we'll also see how to calculate this effect and ensure we have enough propellant to get our vehicle where we want it to go. We'll then turn our attention to the process at the heart of a rocket: how it converts stored energy plus some mass into the high-speed exhaust. We'll tie all these concepts together by looking at the simplest example of a rocket—cold-gas thrusters—to see how varying some of the inputs and design variables changes the thrust and the system's overall efficiency.

Thrust

A rocket ejects mass at high speed in one direction so a vehicle can go in the other. The simplest example of this is a balloon. Most people have blown up a toy balloon and let go of the stem to watch it fly wildly around the room, as shown in Figure 4.2.1-3. What makes the balloon go? Recall from Chapter 4 Newton's Third Law:

For every action there is an equal but opposite reaction.

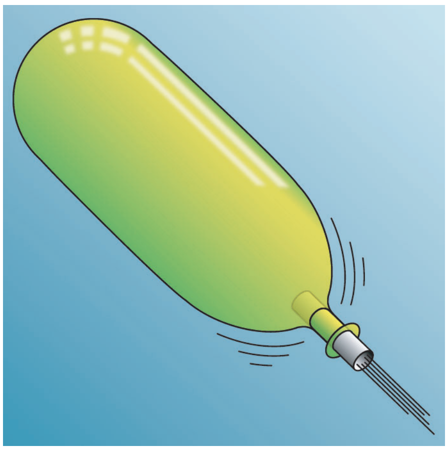
Figure 4.2.1-3. An Inflatable Rocket. A toy balloon is a simple example of a rocket. When we let go of the stem, "rocket propulsion" causes it to fly wildly around the room.

When you blow into a balloon, you force air into it, making the rubber skin tighten, increasing the internal air pressure, and storing energy like a spring. When you let go of the stem, the air pressure has an escape route, so the skin releases, forcing the air out under pressure. Following Newton's Third Law, as the air, which has mass, is forced out in one direction (the action), an equal force pushes the balloon in the opposite direction (the reaction).

Let's look at this action/reaction situation in a bit more detail to see where the force comes from. Consider a rocket scientist perched in a wagon armed with a load of rocks, as shown in Figure 4.2.1-4. If he's initially at rest and begins to throw the rocks in one direction, because of Newton's Third Law, an equal but opposite force will move him (and the wagon load of rocks) in the opposite direction.

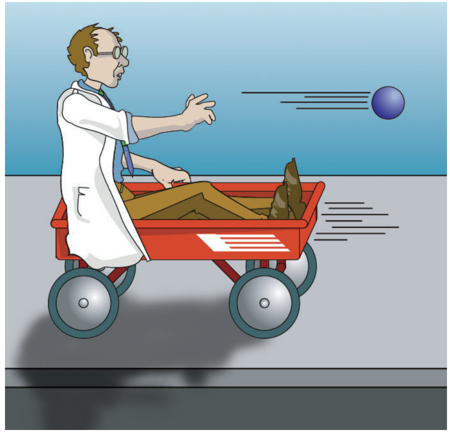

Figure 4.2.1-4. A One-person Rocket. A person throwing rocks out the back of a wagon illustrates the basic principles of a rocket. Muscles apply force to the rock, accelerating it in one direction, causing an equal but opposite force on the person and the wagon, and pushing them in the opposite direction.

To throw the rocks, the scientist has to apply a force to them. This force is identical in magnitude, but opposite in direction, to the force applied to the scientist and thus, the wagon. However, remember the concept of conservation of linear momentum we discussed in Chapter 4. It tells us the change in speed of the rock (because it has less mass) will be greater than the change in speed of the wagon.

The rock's mass leaves at a rate we call the *mass flow rate*, represented by "mdot" and measured in kilograms per second. Recall from Chapter 4 that linear momentum is always conserved! So as the momentum of the ejected mass (rocks) goes in one direction, the momentum of the rocket (or wagon in this case) goes in the other direction, as shown in Figure 4.2.1-4. This basic principle produces rocket thrust. A rocket expends energy to eject mass out one end at high velocity, pushing it (and the attached vehicle) in the opposite direction.

Momentum change has the same units as force—the force on the rocket we defined to be thrust. We also define a comprehensive term called *effective exhaust velocity, C*, that tells us how fast the propellant (the rocks) is leaving the rocket. newton's Third Law then leads us to an

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Important Concept

The thrust a rocket produces depends only on the velocity of the propellant ejected (effective exhaust velocity) and how much mass is ejected in a given time (mass flow rate, or mdot).

Equation (4.2.1-1) summarizes this relationship.

$$F_{thrust} = mdotC \qquad (4.2.1\text{-}1)$$

where

F_{thrust} = rocket's total thrust (N)

C = effective exhaust velocity (m/s)

mdot = mass flow rate (kg/s)

This relationship should make sense from our wagon example. The scientist can increase the thrust on the wagon by either increasing the rate at which he throws the rocks (higher mdot) or by throwing the rocks faster (higher C). Or he could do both. For example, if he threw bowling balls, he could produce a high mdot but with lower velocity than if he were throwing small pebbles.

Of course, exhaust velocities for typical rockets are much, much higher than anyone can achieve by throwing rocks. For typical chemical rockets similar to the Space Shuttle's, the exhaust velocity can be as high as 3 km/s. Because these high velocities are hard to visualize, it's useful to think about the raw power involved in a rocket engine. We define *power* as energy expended per unit time. At lift-off, the Space Shuttle's three main engines plus its solid-rocket boosters produce 26.6 billion watts of power. That is equivalent to 13 Hoover Dams! We'll see the effect of all that power next.

The Rocket Equation

To better understand how we use the thrust produced by rockets to get a vehicle where we want it to go, we first need to introduce a new concept—impulse. Impulse will help us understand the total velocity change rockets deliver.

Impulse

So a rocket produces thrust that pushes on a vehicle. Then what happens? If you push on a door, it opens. If you hit a ball with a bat, it flies to the outfield. Returning to our scientist in the wagon, note that to give the rocks their velocity, he has to apply a force to them over some length of time. Force applied to an object over time produces an *impulse*. When your bat hits that fast ball speeding over home plate, the impact seems instantaneous, but the bat actually contacts the ball for a fraction of a second, applying its force to the ball during that time.

To change momentum, we can apply a large force acting over a short time (like a bat hitting a ball) or a smaller force acting over a longer time (like an ant moving a bread crumb). We define *total impulse, I*, to be the result of applying a large force on an object for some length of time. This result is the same as the object's change in momentum. Again, think about the bat hitting the ball. The muscles in your arms produce a force. You apply this force on the ball for a short time, which produces a total impulse on the ball, changes its momentum, and drives it out over the fence.

Impulse works the same way for rockets as it does for baseballs. We want to change our rocket's velocity and hence its momentum, so we must apply some impulse. This impulse comes from the thrust acting over a time interval. But as we showed, we can produce the same impulse for a rocket by applying a small thrust over a long time or a large thrust over a short time.

Although total impulse is useful for telling us the total effect of rocket thrust, it doesn't give us much insight into the rocket's efficiency. To compare the performance of different types of rockets, we need something new: specific impulse—one of the most useful terms in rocket science. *Specific impulse, I_{sp}*, tells us the cost, in terms of the propellant mass, needed to produce a given thrust on a rocket. In other words, specific impulse tells us "bang for the buck" for a given rocket. The higher the better in terms of a rocket's overall efficiency.

Important Concept

Specific impulse tells us the thrust produced by a given weight flow rate of propellant.

Equation (4.2.1-2) summarizes this relationship.

$$I_{sp} = \frac{F_{thrust}}{\text{mdot } g_o} \quad (4.2.1\text{-}2)$$

where

I_{sp} = specific impulse (s)

F_{thrust} = force of thrust (N)

mdot = propellant's mass flow rate (kg/s)

g_o = gravitational acceleration constant = 9.81 m/s^2

I_{sp} represents rocket efficiency, the ratio of what we get (momentum change) to what we spend (propellant). So the higher the I_{sp}, the more efficient the rocket.

Earlier, we found the force of thrust in terms of the mass flow rate and the effective exhaust velocity. By substituting Equation (4.2.1-1) into Equation (4.2.1-2), we get another useful expression for I_{sp}.

$$I_{sp} = \frac{C}{g_o} \quad (4.2.1\text{-}3)$$

where

C = effective exhaust velocity (m/s)

Notice g_o is a constant value representing the acceleration due to gravity at sea level, which we use to calibrate the equation. This means *no matter where we go in the universe, we humans will use the same value of g_o to measure rocket performance*.

As a measure of rocket performance, I_{sp} is like the miles per gallon (m.p.g.) rating given for cars. The higher the I_{sp} is for a rocket, the more ΔV it will deliver for a given weight of propellant. Another way to think about I_{sp} is that the faster a rocket can expel propellant, the more efficient it is.

Velocity Change

When you take a long trip in your car, you have to make sure you'll have enough gas in the tank to get there. This concern is even more important for a trip into space where no gas stations sit along the way. But how do you determine how much "gas," or propellant, you need for a given mission?

Naturally, some rockets are more efficient than others. For example, one rocket may need 100 kg of propellant to change velocity by 100 m/s while another needs only 50 kg. To figure how much propellant we need for a given trip, we must have a relationship between the velocity change and the amount of propellant used. We call this relationship the *ideal rocket equation*. It tells us how much ΔV we get for a certain amount of propellant used.

Specific impulse, I_{sp}, is defined as thrust produced by a given weight flow rate of propellant. We measure mass in kg, weight in Newtons. To convert mass to weight multiply by the acceleration due to gravity.

Important Concept

The velocity change (ΔV) delivered by a rocket depends on its effective exhaust velocity (C) and the ratio of initial to final mass of the rocket. The higher the effective exhaust velocity, the more ΔV delivered for a given mass of propellant used.

Equation (4.2.1-4) summarizes this concept.

$$\Delta V = C \ln\left(\frac{m_{initial}}{m_{final}}\right) \tag{4.2.1-4}$$

where

ΔV = velocity change (m/s)

C = effective exhaust velocity (m/s)

ln = natural logarithm of the quantity in the parentheses

$m_{initial}$ = vehicle's initial mass, before firing the rocket (kg)

m_{final} = vehicle's final mass, after firing the rocket (kg)

Equation (4.2.1-4) is one of the most useful relationships of rocket propulsion. Armed with this equation, we can determine how much propellant we need to do almost anything, from stopping the spin of a spacecraft in orbit, to launching a satellite to another solar system. Notice that we're taking the natural logarithm of the ratio of initial to final mass. *The difference between initial and final mass represents the amount of propellant used*. ΔV is also a function of the effective exhaust velocity. This relationship should make sense because, as the propellant moves out of the nozzle faster, momentum changes more, and the rocket goes faster.

We can substitute the definition of I_{sp} into the rocket Equation (4.2.1-4) to compute the ΔV for a rocket, if we know the I_{sp} and the rocket's initial and final mass.

$$\Delta V = I_{sp} g_o \ln\left(\frac{m_{initial}}{m_{final}}\right) \tag{4.2.1-5}$$

where

ΔV = vehicle's velocity change (m/s)

I_{sp} = propellant's specific impulse (s)

g_o = gravitational acceleration at sea level (9.81 m/s^2)

ln = natural logarithm of the quantity in the parentheses

$m_{initial}$ = vehicle's initial mass, before firing the rocket (kg)

m_{final} = vehicle's final mass, after firing the rocket (kg)

Rockets

Now that we've seen what rockets do—expel high-speed exhaust in one direction so a space vehicle can go in the other—let's look closer at how they do it. Figure 4.2.1-5 shows a simplified view of a rocket system.

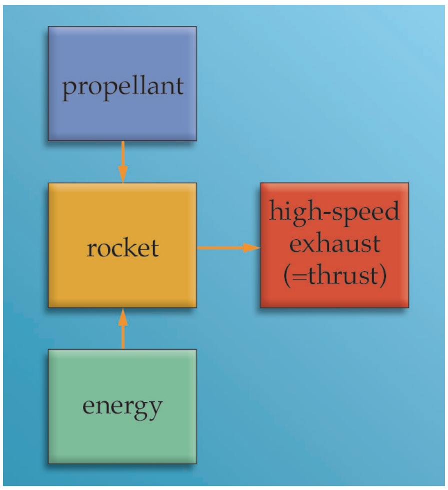

Figure 4.2.1-5. A Simplified Rocket System. Rockets take in propellant and energy to produce a high speed exhaust. Conservation of momentum between the exhaust and the rocket produces thrust.

For discussion, we can break this process into two steps. First, energy must *transfer* to the propellant in some form. Second, the energized propellant must *convert* into high-speed exhaust. Figure 4.2.1-6 shows this expanded view of a rocket system.

Two basic types of rockets are in use. Their classification depends on the form of energy transferred to the propellant and converted to high-speed exhaust. The types are

- Thermodynamic rockets—rely on thermodynamic energy (heat and pressure)
- Electrodynamic rockets—rely on electrodynamic energy (electric charge and electric and magnetic fields)

Thermodynamic energy is in the form of heat and pressure—something we're all familiar with. A covered pot of water on the stove reaches high temperature and produces high-pressure steam. Most of us have seen how the thermodynamic energy in steam drives trains or produces electricity in power plants.

In a *thermodynamic rocket*, thermodynamic energy transfers to the propellant in the form of heat and pressure. A propellant can produce heat through a chemical reaction or from external sources such as electrical, solar, or nuclear energy. Gaseous or liquid propellants are delivered to the rocket under pressure, supplying additional thermodynamic energy. However, for now, the result is the most important thing. Once energy transfers to the propellant, we have a high-temperature, high-pressure gas—a gas with lots of thermodynamic energy. Air in a toy balloon or high-pressure gases from burning liquid hydrogen and liquid oxygen inside the Shuttle's main engines are two extreme examples.

Later in this section, we'll look at the simplest type of rocket, a cold-gas thruster, that relies on gas under pressure as its only source of thermodynamic energy. In Section 4.2.1.2 we'll look at other, more complex and efficient types of thermodynamic rockets.

Electrodynamic rockets rely on *electrodynamic energy*, which relates to the energy available from charged particles moving in electric and magnetic fields. This is the energy that makes our hair stand on end when we get a shock and makes magnets stick to some metals.

Recall, *charge* is a basic property of matter, like mass, and can be either positive or negative. Like charges repel each other and opposite charges attract. Typically, a molecule of propellant has the same number of protons and electrons, making it electrically neutral. But if one or more electrons can be "stripped off," the resulting molecule will have a net positive charge, making it an *ion*, as illustrated in Figure 4.2.1-7. To create the ion, the electrical-power subsystem (EPS) must supply electrodynamic energy. Unlike a thermodynamic rocket, in which the inherent energy of the energized propellant is quite high, an ion's inherent energy is relatively low. However, once a particle is charged, additional electrodynamic

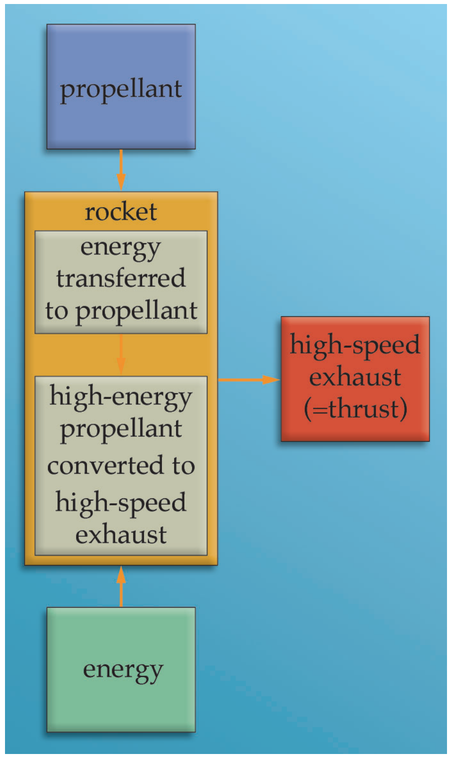

Figure 4.2.1-6. More Detailed View of Rockets. Energy first transfers to the incoming mass. This high-energy mass then converts to high-speed mass, producing thrust.

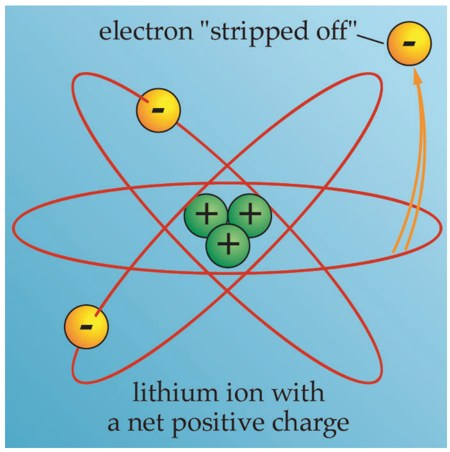

Figure 4.2.1-7. An Ion. We create an ion when we "strip off" outer-shell electrons from a neutral atom or molecule, leaving a net positive charge. Electric or magnetic fields can then accelerate this ion.

energy can easily accelerate it to very high velocities. Later in this section, we'll look at how we do this inside an electrodynamic rocket.

The form of energy transferred to the propellant determines how it converts to high-speed exhaust. Two ways of doing this are

- Thermodynamic expansion—using nozzles
- Electrodynamic acceleration—using electric and magnetic fields

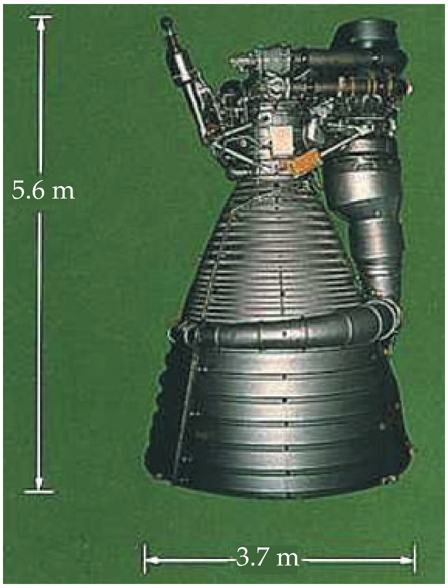

Figure 4.2.1-8. Saturn V Nozzles. Most rockets rely on nozzles to convert thermal energy into kinetic energy through thermodynamic expansion. We show the huge nozzles for the Saturn V F-1 engines here. *(Courtesy of NASA/Marshall Space Flight Center)*

Thermodynamic Expansion—Nozzles

By far, the most commonly used types of rockets rely on nozzles. *Nozzles* convert the thermal energy produced by chemical, nuclear, or electrical sources into kinetic energy through thermodynamic expansion. In Figure 4.2.1-8, we show the huge nozzles used by the Saturn V F-1 engines that propelled astronauts to the Moon. Figure 4.2.1-9 shows a simplified cut-away view of a rocket's combustion chamber and nozzle. Hot gasses produced from burning propellants in the combustion chamber channel into a narrow section called the *throat*. Past the throat, the exhaust expands until it exits the nozzle. Nozzles can convert the thermal energy of the hot gasses in the combustion chamber into the kinetic energy of the exhaust. How? By following the *Bernoulli Principle*, named after its discoverer, Italian mathematician, Daniel Bernoulli (1700–1782).

The Bernoulli Principle is one of the most important concepts in science. It helps us explain the dynamics of weather and how birds and planes fly. This principle tells us that as low-velocity gasses channel into the nozzle's converging section, called the throat, they go faster and faster until they reach the speed of sound at the narrowest part of the throat. As they expand past the throat, and the nozzle area increases, the velocity keeps increasing to supersonic speeds. The more we expand gas through the nozzle, the higher the exit velocity.

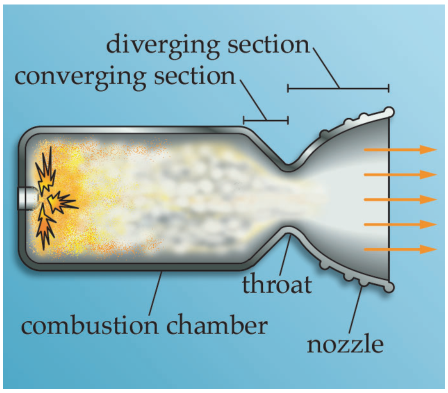

Figure 4.2.1-9. Standard Combustion Chamber and Nozzle Configuration. A standard thermodynamic rocket has two main parts—a combustion chamber (where energy transfers to a propellant) and the nozzle (where high energy combustion products convert to high-velocity exhaust). The Bernoulli Principle tells us low-velocity gasses channel into the nozzle's converging section, called the throat. They go faster and faster until they reach the speed of sound at the narrowest part of the throat. As they expand past the throat, and the nozzle's area increases, the velocity keeps increasing to supersonic speeds. The high- speed exhaust produces thrust.

Not all nozzles are created equal. In the ideal case, we'd like the pressure of the exhaust coming out of the nozzle to equal the pressure of the atmosphere outside. But what happens when $P_{exit} \neq P_{atmosphere}$? When this happens, we have a rocket that's not as efficient as it could be. We can consider two possible situations

- *Over-expansion:* $P_{exit} < P_{atmosphere}$. This is often the case for a rocket at lift-off. Because many launch pads are near sea level, the atmospheric pressure is at a maximum. This atmospheric pressure can cause shock waves to form at the nozzle's lip. These shock waves represent areas where kinetic energy turns back into enthalpy (heat and pressure). In other words, they rob kinetic energy from the flow, lowering the exhaust velocity and thus decreasing the overall thrust.
- *Under-expansion:* $P_{exit} > P_{atmosphere}$. In this case, the exhaust gasses have not expanded as much as they could have within the nozzle, so there's a "loss" in the sense that we've not converted all the enthalpy we could have into velocity. This is the normal case for a rocket operating in a vacuum, because P_{exit} is always higher than $P_{atmosphere}$

($P_{atmosphere}$ = 0 in vacuum). Unfortunately, we'd need an infinitely long nozzle to expand the flow to zero pressure, so in practice we must accept some loss in efficiency.

Figure 4.2.1-10 illustrates all cases of expansion. In Section 4.2.1.3, we'll see how to deal with this problem for launch-vehicle rocket engines.

The total expansion in the nozzle depends, of course, on its design. We define the nozzle's *expansion ratio, ε*, as the ratio between the nozzle's exit area, A_e, and the throat area, A_t

$$\varepsilon = \frac{A_e}{A_t} \tag{4.2.1-6}$$

where
ε = nozzle's expansion ratio (unitless)
A_e = nozzle's exit area (m^2)
A_t = engine's throat area (m^2)

It turns out that a thermodynamic rocket's efficiency depends on only two things: the temperature in the combustion chamber and the molecular mass of the propellants. *Molecular mass* is a measure of the mass per molecule of propellant. Thus, to improve I_{sp} for thermodynamic rockets, we try to produce the highest combustion temperature while minimizing the propellant's molecular mass.

Important Concept

The efficiency measured by specific impulse, of a thermodynamic rocket goes up as the combustion temperature goes up or as the molecular mass of propellant goes down.

We can express this relationship more compactly as

$$I_{sp} \propto \sqrt{\frac{T_{combustion}}{M}} \tag{4.2.1-7}$$

where
I_{sp} = specific impulse (s)
$T_{combustion}$ = combustion temperature (K)
M = molecular mass (kg/mole)
[*Note:* The symbol "∝" means proportional to]

As a result, the most efficient thermodynamic systems operate at the highest temperature with the propellants having the lowest molecular mass. Molecular mass can be found by looking at a periodic table of the elements. Hydrogen, the lowest, is at one end, and uranium is at the other end. For this reason, hydrogen is often the fuel of choice because it has the lowest possible molecular mass and achieves high temperatures in combustion.

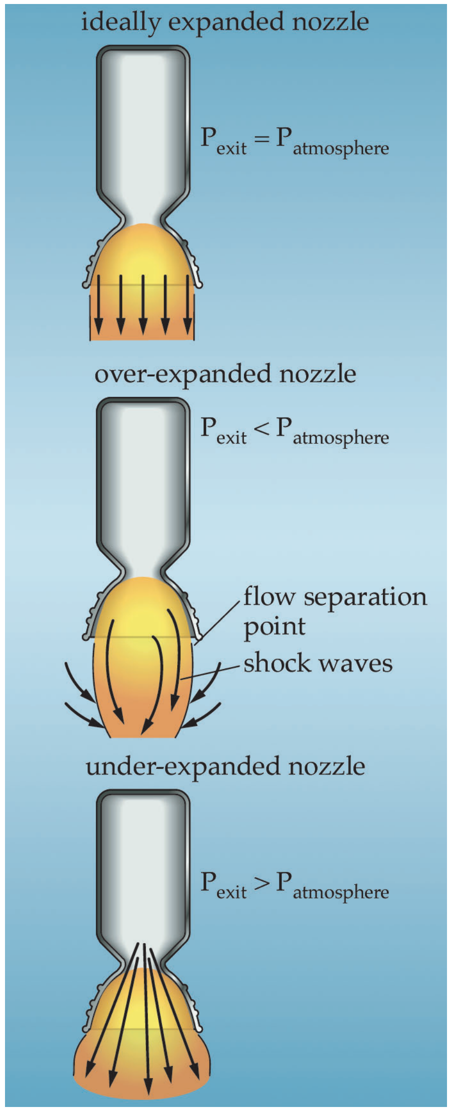

Figure 4.2.1-10. Nozzle Expansion. To effectively convert all the enthalpy (heat and pressure) available in the combustion products to high-velocity flow, we need the nozzle's exit pressure (P_{exit}) to equal the outside atmospheric pressure ($P_{atmosphere}$). When $P_{exit} < P_{atmosphere}$, the flow is overexpanded, causing shock waves that decrease flow velocity. When $P_{exit} > P_{atmosphere}$, the flow is underexpanded, meaning not all available enthalpy converts to velocity. Here, we show all three expansion cases. In practice, we need an infinitely long nozzle to achieve perfect expansion in a vacuum.

Summary. Let's review what we've discussed about thermodynamic rockets. Figure 4.2.1-11 further expands our systems view of a thermodynamic rocket and summarizes important performance parameters. Recall, rocket propulsion has two important steps: energy transfer and acceleration. These two steps take place in the combustion chamber and nozzle, respectively. The most important output is the thrust that moves a vehicle from point A to point B.

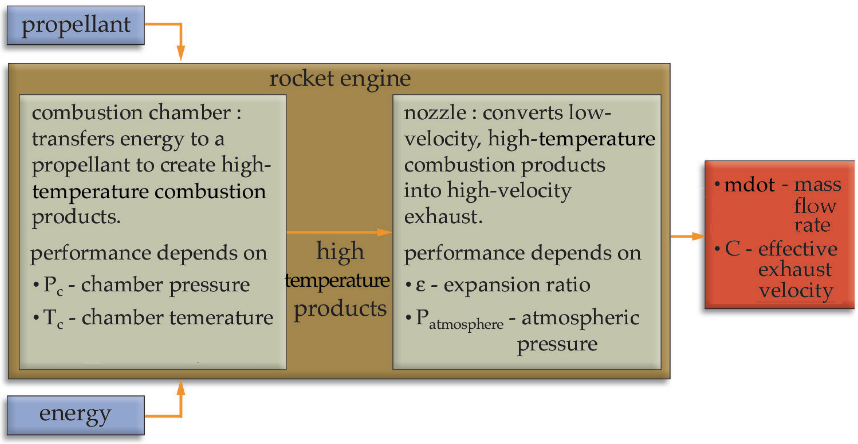

Figure 4.2.1-11. Expanded Systems View of a Thermodynamic Rocket. In this expanded view of a thermodynamic rocket system, we can see the various inputs, processes, and outputs. Propellant and energy combine in the combustion chamber to produce high-temperature products. The performance of this process depends on the chamber pressure (P_c), the chamber temperature (T_c), and the molecular mass of the propellants (M). The nozzle converts these high-temperature products to high-velocity flow. The nozzle performance depends on its expansion ratio, ε, and the outside atmospheric pressure (P_a). The final output is high-speed flow that produces thrust. Total thrust depends on the mass flow rate (mdot), and the exhaust velocity (C).

Now that we've filled your head with the behavior of gasses (or blown a lot of hot air, depending on how you look at it), let's put all these principles together by looking at an example of the simplest type of thermodynamic rocket in use: a cold-gas rocket.

Cold-gas Rockets. A *cold-gas rocket* uses thermodynamic energy in the form of pressurized propellant as its energy source, similar to the toy balloon example we talked about at the beginning of the chapter. Although spacecraft designers don't send balloons into orbit, the basic principles of cold-gas rockets aren't that different. A coiled spring stores mechanical energy that can be converted to work, such as running an old-fashioned, wind-up watch. Similarly, any fluid under pressure has stored mechanical energy that can be used to do work. Any rocket system containing fluids under pressure (and virtually all do) uses this mechanical energy in some way. As we'll see, usually this energy is a minor contribution to the overall energy of the propellant. But for cold-gas rockets, this is the propellant's main energy.

Table 4.2.1-1 summarizes basic principles and propellants used by cold-gas rockets, and Figure 4.2.1-12 shows a diagram of a simple cold-gas system.

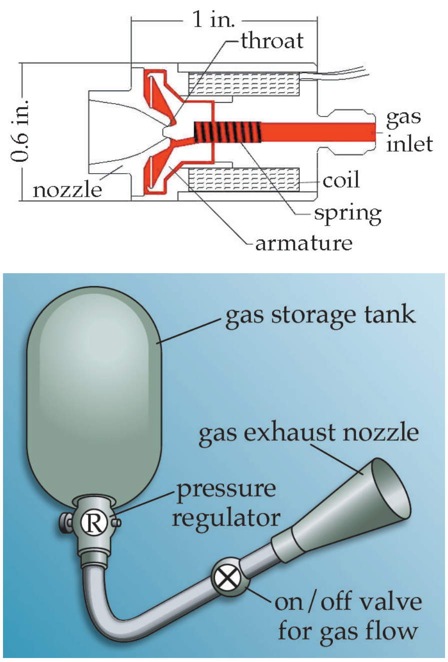

Figure 4.2.1-12. A Cold-gas Thruster. A cold-gas thruster is perhaps the simplest example of a rocket. In a typical thruster, shown in the cross-sectional drawing (upper), a gas enters from the right and stays behind the solenoid seal until it opens on command, releasing the gas through the nozzle. *(Courtesy of Polyflex Aerospace, Ltd., U.K.)*

Table 4.2.1-1. Summary of Cold-gas Rockets.

Operating Principle	Uses the thermodynamic energy contained in a compressed gas and expands the gas through a nozzle, producing high-velocity exhaust
Propellants	Helium (He), Nitrogen (N_2), Carbon dioxide (CO_2), or virtually any compressed gas
Advantages	• Extremely simple • Reliable • Safe, low-temperature operation • Short impulse bit (thrust pulses)
Disadvantages	Low I_{sp} and I_{dsp} compared to other types of rockets
Example	UoSAT-12 Cold-gas thrusters Propellant = N_2, P_c = 4 bar, Thrust = 0.1 N, I_{sp} = 65 s

Figure 4.2.1-13. Manned Maneuvering Unit (MMU). The MMU relies on small nitrogen cold-gas rockets to move astronauts around in space. *(Courtesy of NASA/Johnson Space Center)*

Cold-gas rockets are very reliable and can be turned on and off repeatedly, producing very small, finely controlled thrust pulses (also called *impulse bits*)—a desirable characteristic for attitude control. A good example of them is on the manned maneuvering unit (MMU) that Shuttle astronauts used. The MMU, shown in Figure 4.2.1-13, uses compressed nitrogen and many small thrusters to give astronauts complete freedom to maneuver.

Unfortunately, because cold-gas systems have relatively low thrust and I_{sp}, we typically use them only for attitude control or limited orbital maneuvering on small spacecraft. Even so, they can serve as a good example of trading some of the basic rocket parameters we've talked about in this section.

Electromagnetic Acceleration

We've spent a lot of time in this section discussing thermodynamic expansion and acceleration of exhaust, using nozzles to convert propellant with thermodynamic energy into high-speed flow. But a second method for propellant acceleration is gaining wider use on spacecraft—electrodynamic acceleration. To take advantage of this method, we must start with a charged propellant.

A force of attraction (or repulsion) depends on the strength of the charges involved and the distance between them.We called this Coulomb's Law, which is an

Important Concept

Coulomb's Law: The force of attraction (or repulsion) between two charges is directly proportional to the amount of each charge and inversely proportional to the square of the distance between them. The higher the charge, or the closer the charges are, the higher the force of attraction (or repulsion). Like charges attract, unlike charges repel each other.

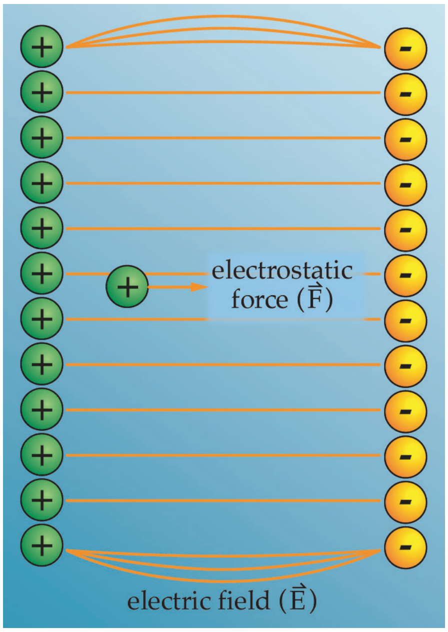

Figure 4.2.1-14. Electrostatic Force. An electric field exists when there is an imbalance between positive and negative charges in a confined region. This field will place an electrostatic force on a charged particle within the field, accelerating it.

An *electric field* exists when there is a difference in charge between two points. That is, a large imbalance exists between positive and negative charges in a confined region. We use the term *electrical potential* for the energy an electric field can transmit to a unit charge, described in terms of volts/m. The resulting force on a unit charge is called an *electrostatic force*.

If you've ever rubbed a balloon through your hair and stuck it to a wall, then you've seen a simple example of electrostatic force in action. The balloon picked up a net positive charge. When you placed it against the wall (initially neutral), the positive charges on the surface got pushed away, leaving a net negative charge. The opposite charges attract each other, creating a force strong enough to keep the balloon in place despite the pull of gravity. Figure 4.2.1-14 illustrates this principle. Notice the direction of the force is parallel to the electric field.

Electrodynamic rockets take advantage of this principle to create thrust. In the simplest application, they need only some charged propellant and an electric field. As with any rocket, the two key performance parameters are thrust, F, and specific impulse, I_{sp}. From Equation (4.2.1-1), we know thrust depends on the mass flow rate, mdot, and the effective exhaust velocity, C. That is,

$$F = \text{mdot}\ C$$

From Equation (4.2.1-3) we know specific impulse, I_{sp}, directly relates to C by

$$C = I_{sp} g_o$$

In an electrodynamic rocket, we achieve high mdot by having a high density of charged propellant. High exhaust velocity comes from having a strong electric field or from applying the electrostatic force for a longer time. We can summarize these effects on performance as follows

- Higher charge density → higher mdot → higher thrust
- Stronger electric field → stronger electrostatic force on the propellant → higher acceleration → higher exhaust velocity → higher I_{sp}

Thus, by varying the charge density and the applied field, we can create a wide range of thruster designs. Naturally, practical design issues limit how much we can increase each parameter. Let's start with charge density.

Charge density is limited by the nature of the propellant and how it is charged. Earlier, we defined an ion as a positively charged propellant molecule that has had one or more electrons "stripped off." Ions are handy in that they are simple to accelerate in an electric field. Unfortunately, when we try to pack lots of positive ions into a small, confined space, they tend to repel each other. This creates a practical limit to the achievable charge density.

One way around this density limit is to create a plasma with the propellant. A *plasma* is an electrically neutral mixture of ions and free electrons. Common florescent lamps or neon lights create a plasma when turned on. When a gas, such as neon, is in a strong electric field, the electrons become only weakly bound to the molecules, thus creating a "soup" of ions and free electrons. The glow results from electrons jumping back and forth between energy states within the molecule. Because it is electrically neutral, a plasma can contain a much higher charge density than a collection of ions alone.

So far we've considered only the acceleration effect from an applied electric field. However, whenever we apply an electric field to a plasma, it creates (induces) a magnetic field. Charged particles also accelerate because of magnetic fields but at right angles to the field, instead of parallel to it.

Some types of electrodynamic rockets rely on this combined effect to produce thrust. However, for most cases, the electrostatic force dominates, so we can ignore the effect of the magnetic field for simple analysis of performance. In Section 4.2.1.2 we'll look at some examples of electrodynamic thrusters and compare their performance.

Section Review

Key Concepts

- As a system, a rocket takes in mass and energy and converts them into thrust
  - Rocket thrust is a result of Newton's Third Law: "*For every action, there is an equal but opposite reaction.*" Rockets eject high-velocity mass in one direction, causing the rocket to go in the other direction.
  - Total thrust delivered depends on the velocity of the mass ejected (effective exhaust velocity, C) and how much mass is ejected in a given time (mass flow rate, mdot)
  - You can find the amount of velocity change, ΔV, a rocket delivers for a given amount of propellant by using the rocket equation
  - Specific impulse, I_{sp}, measures a rocket's efficiency in terms of propellant mass. The higher the I_{sp}, the less propellant mass needed to deliver the same total impulse. I_{sp} is a function of a rocket's exhaust velocity.
  - Density specific impulse, I_{dsp}, describes a rocket's efficiency in terms of propellant volume. The higher the I_{dsp}, the less propellant volume needed to deliver the same total impulse.
- Within a rocket system, two main processes are at work
  - First, energy must transfer to the propellant (in the form of heat, pressure, or charge)
  - Second, the energized propellant must convert to high-velocity exhaust
- We classify rockets based on the form of energy they use
  - Thermodynamic rockets—rely on thermodynamic energy (heat and pressure)
  - Electrodynamic rockets—rely on electrodynamic energy from charged particles moving in electric and magnetic fields
- Nozzle performance depends on the total expansion and the external atmospheric pressure
- Ideal specific impulse, I_{sp}, is a function of the combustion temperature and the molecular mass of the propellants. High I_{sp} results from the highest temperature and lowest molecular mass (e.g., hydrogen).

Continued on next page

Section Review (Continued)

Key Concepts

- ➤ Electrodynamic rockets use electric and magnetic fields to accelerate charged particles in a propellant. Charges can be either positive or negative. Like charges repel; opposite charges attract.
  - An electric field applies an electrostatic force to charged particles. The force of acceleration, hence the thrust and exhaust velocity, depends on the strength of the field and the charge on the particle.
  - Higher charge density → higher mdot → higher thrust. We produce ions when we strip electrons from neutral molecules, leaving a net positive charge. Plasmas can achieve a higher charge density because they are an electrically neutral mixture of ions and electrons.
  - Stronger electric field → stronger electrostatic force on the propellant → higher acceleration → higher velocity → higher exhaust velocity → higher I_{sp}. The available power limits the strength of the electric field.

4.2.1.2 Propulsion Systems

In This Section You'll Learn to...

- ☛ Describe the key components of propulsion subsystems
- ☛ Explain the basic operating principles for the different types of rockets in use and compare their relative advantages and disadvantages
- ☛ Discuss future concepts for exotic propulsion subsystems that produce thrust without mass

Section 4.2.1.1 gave us an exhaustive look at rockets as a system. We saw how they take two inputs, propellant plus energy, and convert them into thrust. But rockets, as important as they are, comprise only one part of an entire propulsion subsystem. In this section, we'll concentrate less on rocket theory and more on propulsion-system technology to learn what essential components we need and how they're put together.

Figure 4.2.1-15 shows a block diagram for an entire propulsion system. To design a specific system, we start with the desired thrust, usually at some very specific time. The propulsion-system controller manages these inputs and forms commands to send to the propellant-management actuators, which turn the flow of propellant on or off. For some systems, the controller also manages the energy input to the rocket. For example, in an electrodynamic rocket, the system has to work with the spacecraft's electrical-power subsystem (EPS) to ensure it provides the required power. The controller uses sensors often to monitor the propellant's temperature and pressure throughout the system.

One of the two key inputs to a rocket is propellant. In this section, we'll start by looking at propellant management, how to store liquid or gas propellants, and how to supply them to the rocket as needed. We'll then review in detail most of the thermodynamic and electrodynamic rocket technologies in use or on the drawing boards. Following this discussion, we'll look briefly at important factors for selecting and testing propulsion subsystems. Finally, rocket scientists are always striving to improve the propulsion subsystem's performance, so we'll look at what exotic concepts may someday take us to the stars.

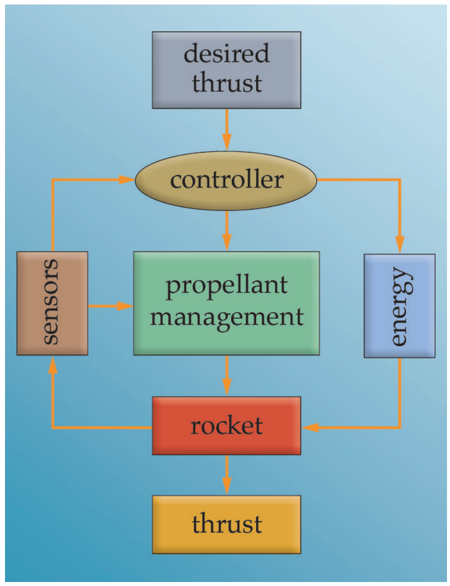

Figure 4.2.1-15. Block Diagram of a Complete Propulsion Subsystem. A propulsion subsystem uses the desired end state (specific thrust at a specific time), plus inputs from sensors, to determine commands for propellant management and energy control that produce the system output—thrust.

Propellant Management

All rockets need propellant. The job of storing propellant and getting it where it needs to go at the right time is called *propellant management*. The propellant management part of a propulsion subsystem has four main tasks

- Propellant storage
- Pressure control

Rocket scientists are very interested in the pressure inside a rocket engine. Pressure can be measured in terms of pounds per square inch (p.s.i.), pascals (Pa), or bar. 1 bar is one standard atmosphere of pressure at sea level (1 bar = 14.5 p.s.i.).

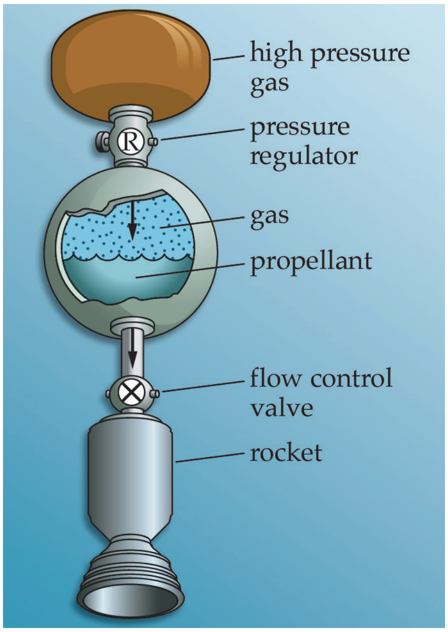

Figure 4.2.1-16. Pressure-fed Propellant System. In a pressure-fed propulsion subsystem, high pressure gas forces the liquid propellant into the combustion chamber under pressure, much like blowing liquid through a

- Temperature control
- Flow control

Let's look briefly at the requirements and hardware for each task.

Just as your car has a gas tank to store gasoline, propulsion subsystems need tanks to store propellant. We normally store gaseous propellants, such as nitrogen for cold-gas rockets, in tanks under high pressure to limit their volume. Typical gas-storage pressures are 200 bar (2900 p.s.i.) or more (that's about 200 times the pressure in your room, right now!). Unfortunately, we can't make a liquid propellant denser by storing it under pressure. However, depending on how we pressurize the liquid propellant for delivery to the combustion chamber, we may need to design the storage tanks to take high pressure as well. In any case, propellant tanks are typically made from aluminum, steel, or titanium and designed to withstand whatever pressure the delivery system requires.

As we presented in Section 4.2.1.1, combustion-chamber pressure is important in determining rocket thrust. This pressure depends on the delivery pressure of the propellants. Pressurizing the flow correctly is another function of propellant management. There are two approaches to achieving high-pressure flow: pressure-fed systems and pump-fed systems.

As Figure 4.2.1-16 shows, a *pressure-fed propellant system* relies on either a gaseous propellant stored under pressure or a separate tank attached to the main tank and filled with an inert, pressurized gas, such as nitrogen or helium, to pressurize and expel a liquid propellant. The high-pressure gas "squeezes" the liquid propellant out of the storage tank at the same pressure as the gas, like blowing water out of a straw.

To reduce volume, the storage pressure of the gas is typically much higher than the pressure needed in the combustion chamber. To regulate the high pressure in the storage tank to the lower pressure for propellant delivery, we typically use mechanical regulators. As high-pressure gas flows into a *regulator*, the gas pushes against a carefully designed diaphragm. The resulting balance of forces maintains a constant flow rate but at a greatly reduced output pressure. For example, a gas stored at 200 bar may pass through a regulator that reduces it to 20 bar before it goes into a liquid propellant tank. Pressure regulators are common devices, found in most rocket plumbing systems. Scuba tanks use regulators to reduce high-pressure air stored in the tank to a safe, lower pressure for breathing.

The main drawback of pressure-fed systems is that the amount of liquid propellant in the tank (or tanks) relates directly to the amount of pressurizing gas needed. For very large propulsion subsystems, such as on the Space Shuttle, the propellant-management subsystem must deliver enormous quantities of high-pressure propellant to the combustion chamber each second. To do this using a pressure-fed system would require more large, high-pressure gas tanks, making the entire launch vehicle larger and heavier. Instead, most launch vehicles use pump-fed delivery systems.

Pump-fed delivery systems rely on pumps to take low-pressure liquid and move it toward the combustion chamber at high pressure, as shown in Figure 4.2.1-17. Pumps impart kinetic energy to the propellant flow, increasing its pressure. Modern cars use electrical power to turn a small pump that moves gasoline from the tank to the engine under pressure. On the Space Shuttle, massive turbo pumps burn a relatively small amount of H_2 and O_2 to produce mechanical energy. This energy takes the liquid propellants normally stored at a few bars and boosts the feed pressure to more than 480 bar (7000 p.s.i.) at a flow rate of 2.45×10^5 liters/s (6.5×10^4 gal./s). Spinning at more than 30,000 r.p.m., the Shuttle's propellant pumps could empty an average-sized swimming pool in only 1.5 seconds! (Figure 4.2.1-18)

Regardless of the propellant-delivery system, the pressure of propellants and pressurizing gasses must be continually monitored. *Pressure transducers* are small electromechanical devices used to measure the pressure at various points throughout the system. This information is fed back to the automatic propellant controller and sent to ground controllers through telemetry channels.

Temperature control for propellant and pressurant gases is another important propellant-management function. The ideal gas law tells us that a higher gas temperature causes a higher pressure and vice versa. The propellant-management subsystem must work with the spacecraft's environmental control and life support subsystem (ECLSS) to maintain gases at the right temperature and to prevent liquid propellants from freezing or boiling. In the deep cold of outer space, propellants may freeze. For instance, hydrazine, a common spacecraft propellant, freezes at 0° C. Usually, the spacecraft's ECLSS maintains it well above this temperature, but in some cases exposed propellant lines and tanks may need heaters to keep them warm.

On launch vehicles, propellant thermal management often has the opposite problem. It must maintain liquid oxygen (LOX) and liquid hydrogen (LH_2) at temperatures hundreds of degrees below zero, centigrade. Using insulation helps control the temperature, however, some boil off of propellants prior to launch is inevitable and must be planned for, as shown in Figure 4.2.1-19.

Finally, the propellant-management subsystem must control the flow of gases and liquids. It does this using valves. Valves come in all shapes and sizes to handle different propellants, pressures, and flow rates. Technicians use fill and drain valves to fill (and sometimes, drain) the tanks before launch. Tiny, electrically controlled, low-pressure valves pulse cold-gas thrusters on and off to deliver precise, micro-amounts of thrust. Large pyrotechnic valves mounted below liquid-propellant tanks keep them sealed until ignition. When the command arrives, a pyrotechnic charge fires, literally blowing the valve open, allowing the propellant to flow. Of course, these types of valves are good for only one use.

To protect against over pressure anywhere in the system, *pressure-relief valves* automatically release gas if the pressure rises above a preset value. *Check valves* allow liquid to flow in only one direction, preventing back-flow in the wrong direction. Other valves throughout the system ensure

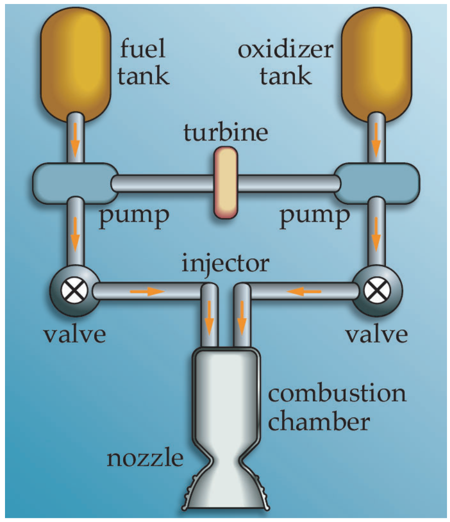

Figure 4.2.1-17. Pump-fed Propellant Management. In a pump-fed system, turbine-driven pumps use mechanical energy to increase the pressure of the propellants for delivery to the combustion chamber.

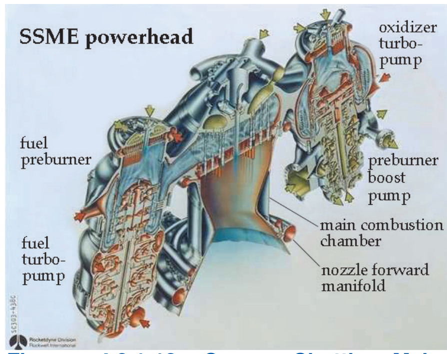

Figure 4.2.1-18. Space Shuttle Main Engine (SSME). The SSMEs use turbine pumps to feed liquid hydrogen and oxygen to the combustion chamber. *(Courtesy of NASA/Marshall Space Flight Center)*

Figure 4.2.1-19. Keeping Things Cool. Cryogenic propellants, such as liquid oxygen and liquid hydrogen on the Shuttle, must remain hundreds of degrees below zero. The cap on the top of the main tank helps control propellant boil off. *(Courtesy of NASA/Johnson Space Center)*

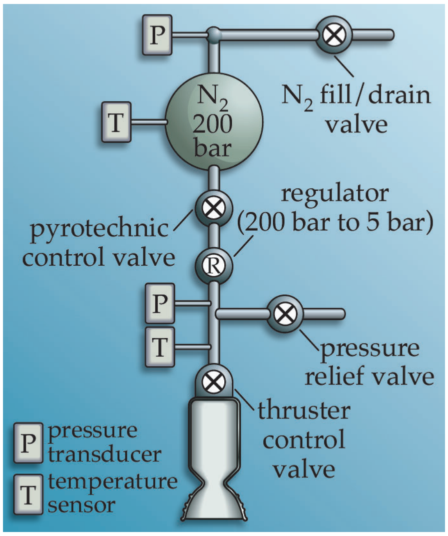

Figure 4.2.1-20. FireSat's Propulsion Subsystem. Even a relatively simple system such as a cold-gas thruster for a small satellite like FireSat requires tanks, valves, and sensors to measure and control the propellant flow.

Figure 4.2.1-21. Chemical Rockets. Chemical rockets use the energy stored in the propellants. The Space Shuttle's main engines and solid-rocket boosters are two examples of chemical rockets. *(Courtesy of NASA/Johnson Space Center)*

propellant flows where it needs to when the system controller sends the command. Some of these other valves lead to redundant lines that ensure the propellant flows even when a main valve stops working.

Let's briefly review the components needed for propellant management. Propellants and pressurant gas are stored in tanks. Below the tanks, valves control the flow throughout the system and regulators reduce the pressure where needed. Transducers and other sensors measure pressure and temperature at various points in the system. Figure 4.2.1-20 shows a possible schematic for the FireSat's propulsion subsystem, based on using a single, cold-gas thruster. Now that we've shown how propellant gets to the rocket, let's look at various types, shapes, and sizes of rockets.

Thermodynamic Rockets

As we described in Section 4.2.1.1, thermodynamic rockets transfer thermodynamic energy (heat and pressure) to a propellant and then convert the energized propellant into high-speed exhaust using nozzles. Various thermodynamic rockets are available or are being considered. We can classify these based on their source of energy

- Cold gas—use thermodynamic energy of a gas stored under pressure
- Chemical—rely on chemical energy (from catalytic decomposition or combustion of propellants) to produce heat
- Solar thermal—use concentrated solar energy to produce heat
- Thermoelectric—use the heat produced from electrical resistance
- Nuclear thermal—use the heat from a nuclear reaction

Because we examined simple cold-gas rockets in detail in the last section, here we'll review the other four types and compare their relative performances.

Chemical Rockets

The vast majority of rockets in use today rely on chemical energy. When we strike a match, the match head ignites the wood and the flame results from a combustion process. The fuel—the wood in the match—is chemically combining with the oxygen in the air to form various chemical by-products (CO, CO_2, water, etc.) and, most importantly, heat. In *chemical rockets*, the propellants release energy from their chemical bonds during combustion. The Space Shuttle relies on chemical rockets, as shown in Figure 4.2.1-21. In the Shuttle main engines, liquid hydrogen (H_2) and liquid oxygen (O_2) combine in the most basic of chemical reactions

$$2H_2 + O_2 \rightarrow 2H_2O + \text{Heat} \qquad (4.2.1\text{-}8)$$

All combustion reactions must have a *fuel* (such as hydrogen) plus an *oxidizer* (such as oxygen). These two combine, liberating a vast amount of heat and creating by-products that form the exhaust. The heat transfers to the combustion products, raising their temperatures. This chemical reaction and energy transfer take place in the *combustion chamber*. Although the propellants arrive in the combustion chamber under pressure, delivered by the propellant-management subsystem, this mechanical energy is small compared to the thermal energy released by the chemical reaction.

Chemical rockets generally fall into one of three categories: liquid, solid, or hybrid. Let's briefly review the operating principles and performance parameters of each type.

Liquid-chemical Rockets. Liquid-chemical rockets are usually one of two types: bipropellant or monopropellant. As the name implies, *bipropellant rockets* use two liquid propellants. One is a fuel, such as liquid hydrogen (LH_2), and the other is an oxidizer, such as liquid oxygen (LOX) (Figure 4.2.1-22). Brought together under pressure in the combustion chamber by the propellant-management subsystem, the two compounds chemically react (combust), releasing huge amounts of heat and producing combustion products (these vary depending on the propellants). To ensure complete, efficient combustion, the oxidizer and fuel must mix in the correct proportions. The *oxidizer/fuel ratio (O/F)* is the proportion, by mass, of oxidizer to fuel.

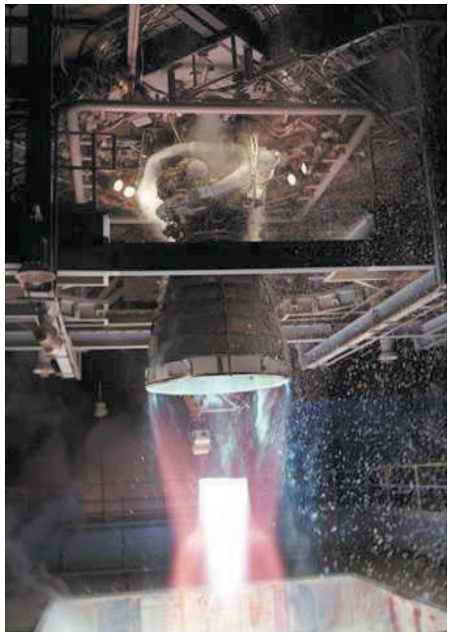

Figure 4.2.1-22. Space Shuttle Main Engine (SSME). This SSME uses liquid hydrogen and liquid oxygen in a test at the Stennis Research Center. *(Courtesy of NASA/Stennis Research Center)*

Some propellant combinations, such as hydrogen and oxygen, won't spontaneously combust on contact. They need an igniter, just as your car needs a spark plug, to get started. This need, of course, increases the system's complexity somewhat. So propellant chemists strive to find combinations that react on contact. We call these propellants *hypergolic* because they don't need a separate means of ignition. The combination of hydrazine (N_2H_4) plus nitrogen tetroxide (N_2O_4) is an example of hypergolic propellants.

Another important feature in selecting a propellant is its storability. Although the liquid hydrogen and liquid oxygen combination in the Space Shuttle's main engines offers high performance (specific impulse around 455 s), they require supercooling to hundreds of degrees below zero (centigrade). Because of their low storage temperature, we call these propellants *cryogenic*. Unfortunately, it is difficult to maintain these extremely low temperatures for long periods (days or months). When the mission calls for long-term storage, designers turn to *storable propellants*, such as hydrazine and nitrogen tetroxide, that can remain stable at room temperature for a very long time (months or even years).

The Titan, an early intercontinental ballistic missile (ICBM), used hypergolic, storable propellants because the missiles stayed deep in underground silos for many years. The Shuttle uses these propellants in its orbital-maneuvering engines and reaction-control thrusters. Most spacecraft use storable, hypergolic liquid rockets for maneuvering. The penalty paid for the extra convenience of spontaneous combustion and long-term storage is a much lower performance (I_{sp} ~300 s) than the cryogenic option. In addition, current hypergolic combinations are extremely toxic and require special handling to prevent propellant release. Table 4.2.1-2 summarizes key points about bipropellant rockets. Figure

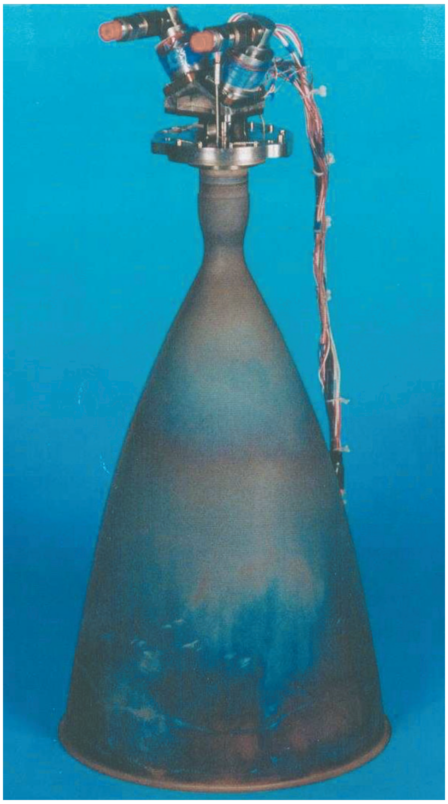

Figure 4.2.1-23. LEROS Bipropellant Engine. The LEROS engine, produced by the ARC Royal Ordnance in the United Kingdom, is just one example of a bipropellant rocket. It uses nitrogen tetroxide (N_2O_4) with hydrazine (N_2H_4) to deliver a total thrust of 400 N at 317 s specific impulse. This engine has been reliably used on a Mars mission and other deep-space and near-Earth missions for orbit insertion. *(Courtesy of British Aerospace Royal Ordnance)*

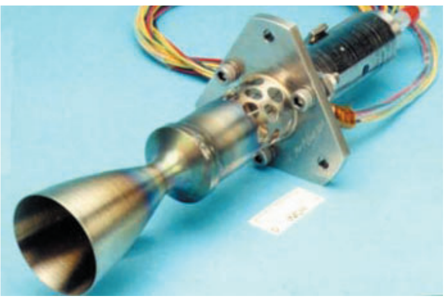

Figure 4.2.1-24. Monopropellant Rocket. This 22 N (5 lbf) hydrazine monopropellant engine built by Kaiser-Marquardt delivers 235 s specific impulse. At only 20 cm (8 in.) long by 4 cm (1.5 in.) wide, it can be easily integrated into a variety of spacecraft for attitude control and small orbital maneuvers. *(Courtesy of Kaiser-Marquardt)*

4.2.1-23 shows a a photograph of the LEROS hypergolic, bipropellant engine that has been used on several missions for final orbit insertion.

Table 4.2.1-2. Bipropellant Rockets.

Operating Principle	
A liquid oxidizer and a liquid fuel react in combustion, liberating heat and creating exhaust products that thermodynamically expand through a nozzle.	
Typical Propellants	
Oxidizers: Liquid oxygen (LOX), HTP = high-test hydrogen peroxide (>85% H_2O_2), nitrogen tetroxide (N_2O_4) Fuels: Liquid hydrogen (LH_2), kerosene (RP-1: "rocket propellant-1" C_4H_8), hydrazine (N_2H_4)	
Advantages	**Disadvantages**
• High I_{sp} • Can be throttled • Can be re-started	• Must manage two propellants • Intense combustion heat creates thermal-control problems for chamber and nozzle

As the name implies, *monopropellant* chemical rockets use only a single propellant. These propellants are relatively unstable and easily decompose through contact with a suitable catalyst.

Hydrogen peroxide (H_2O_2) is one example of a monopropellant. People use a low-concentration (3%), drug-store variety of this compound to disinfect a bad scrape, or to bleach hair. Rocket-grade hydrogen peroxide, also called high-test peroxide (HTP), has a concentration of 85% or more. It is relatively safe to handle at room temperatures but, when passed through an appropriate catalyst (such as silver), it readily decomposes into steam (H_2O) and oxygen, releasing significant heat. Typical HTP reactions exceed 630° C. This relatively high temperature, combined with the molecular mass of the reaction products, gives HTP monopropellant rockets an I_{sp} of about 180 s. The X-15 rocket plane and Scout launch vehicle successfully used these types of thrusters.

By far, the most widely used monopropellant today is hydrazine (N_2H_4). It readily decomposes when exposed to a suitable catalyst, such as iridium, producing an I_{sp} of about 230 s. The main disadvantage of hydrazine is its high toxicity. This problem means technicians need specialized handling procedures and equipment during all testing and launch operations.

The biggest advantage of monopropellant over bipropellant systems is simplicity. The propellant-management subsystem maintains only one set of tanks, lines, and valves. Unfortunately, there is a significant penalty in performance for this added simplicity (2/3 the I_{sp} of a comparable bipropellant system or less). However, for certain mission applications, especially station keeping and attitude control on large communication satellites, this trade-off is well worth it. The benefit grows when we use hydrazine as the fuel with nitrogen tetroxide in a large bipropellant rocket for initial orbit insertion, and then by itself in a smaller, monopropellant rocket for station keeping. Such "dual-mode" systems take advantage of the flexibility offered by hydrazine for best overall system performance and simplicity. Table 4.2.1-3 summarizes key points about monopropellant rockets. Figure 4.2.1-24 shows a typical monopropellant engine.

Table 4.2.1-3. Monopropellant Rockets.

Operating Principle
A single propellant decomposes using a catalyst; it releases heat and creates by-products that thermodynamically expand through a nozzle.

Typical Propellants
Hydrazine (N_2H_4), HTP = high-test hydrogen peroxide (>85% H_2O_2)

Advantages	Disadvantages
• Simple, reliable • One propellant to manage • Lower-temperature reactions mean fewer thermal problems in the chamber and nozzle	• Lower I_{sp} than bipropellant

Solid-chemical Rockets. The fireworks we watch on the 4th of July are a good example of solid rockets at work. Solid rockets date back thousands of years to the Chinese, who used them to confuse and frighten their enemies on the battlefield. In modern times, these rockets create thrust for intercontinental ballistic missiles, as well as space-launch vehicles.

Just as a liquid bipropellant rocket combines fuel and oxidizer to create combustion, a *solid rocket* contains a mixture of fuel, oxidizer, and a binder, blended in the correct proportion and solidified into a single package called a *motor*. A typical composite solid-rocket fuel is powdered aluminum. The most commonly used solid-rocket motor oxidizer is ammonium perchlorate (AP). Together, the fuel and oxidizer make up about 85%–90% of the rocket motor's mass, with an oxidizer/fuel ratio of about 8:1. The motor's remaining mass consists of a binder that holds the other ingredients together. Binders are usually a hard, rubber-like compound, such as hydroxyl-terminated polybutadiene (HTPB). During combustion, the binder also burns as fuel.

As we learned in Section 4.2.1.1, rocket thrust depends on mass flow rate. In a solid-rocket motor, this rate depends on the propellant's burn rate (kg/s) and the burning surface area (m^2). The faster the propellant burns and the greater the burning surface area, the higher the mass flow rate and the higher the resulting thrust. The propellant's burn rate depends on the type of fuel and oxidizer, their mixture ratio, and the binder material. The total burning area depends primarily on the inside shape of the solid propellant. During casting, designers can shape the hollow inner core (grain design) of the solid propellant to adjust the surface area available for burning, so they can control the burning rate and thrust (Figure 4.2.1-25). The Space Shuttle's solid-rocket motors, for example, have a star-shaped core, shown in Figure 4.2.1-26, specifically tailored so the thrust decreases 55 seconds into the flight to reduce acceleration and the effects of aerodynamic forces.

Because solid-rocket-motor combustion depends on the exposed propellant's surface area, manufacturers must carefully mold the propellant

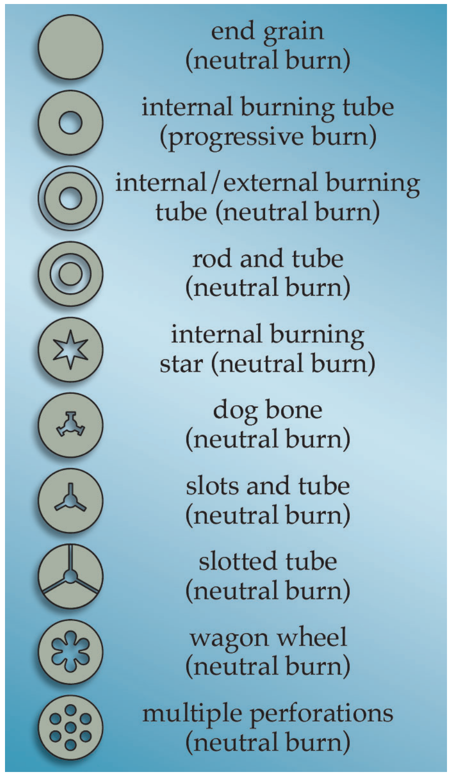

Figure 4.2.1-25. Solid-propellant Grain Designs. By altering the grain design, engineers cause progressive or neutral burn rates. Shaded areas indicate propellant, and blank areas indicate empty space. *(Courtesy of Space Propulsion Analysis and Design by Humble, et. al.)*

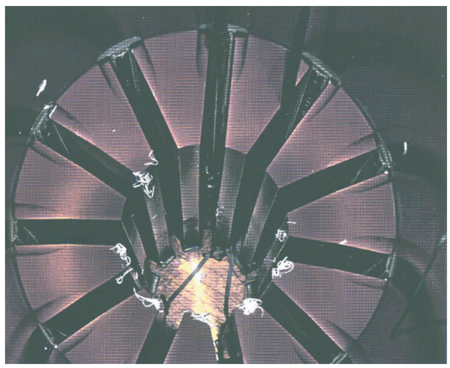

Figure 4.2.1-26. Solid-propellant Shape. The "star" shape of the Space Shuttle's SRB controls the burning rate, hence the thrust profile, of the motor. *(Courtesy of NASA/Kennedy Space Center)*

Figure 4.2.1-27. Solid-rocket Boosters. Many launch vehicles, such as the Delta II shown here, rely on solid-rocket motors to get them off the ground. *(Courtesy of NASA/ Marshall Space Flight Center)*

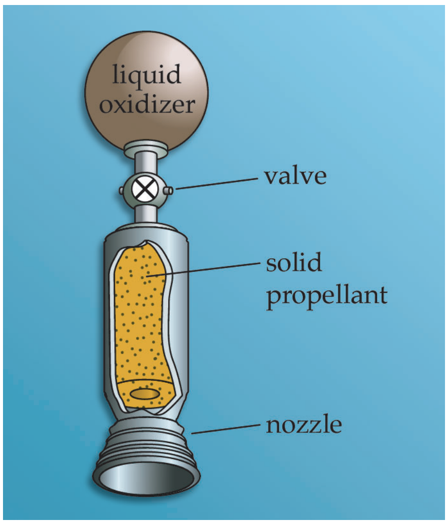

Figure 4.2.1-28. Hybrid Rocket Motor. A hybrid rocket uses a solid fuel with a liquid oxidizer. This offers the flexibility of a liquid system with the simplicity and density of a solid motor. Falling in between liquids and solids in performance, hybrids have yet to see applications on launch vehicles or spacecraft.

mixture to prevent cracks. Burning occurs on any exposed surface, even along undetected cracks in the propellant grain. Investigators linked the Space Shuttle Challenger's accident to an improperly sealed joint between solid-motor segments. This open seal exposed the motor case to hot gases, burning it through and causing the accident.

The Challenger disaster highlighted another drawback of solid motors—once they start, they are very difficult to stop. With a liquid rocket, we can command valves to close, turning off the flow of propellant and shutting off the engine. Solid motors burn until all the propellant is gone. To stop one before that requires blowing off the top or splitting it open along its side, releasing internal pressure and thus stopping combustion. These are not very practical solutions on the way to orbit!

Despite their drawbacks, various missions use solid motors because they offer good, cost-effective performance in a simple, self-contained package that doesn't require a separate propellant-management subsystem. One important use of solid motors is to augment liquid engines on launch vehicles. For instance, without the solid-rocket boosters, the Space Shuttle couldn't get off the ground. Several expendable launch vehicles use various combinations of strap-on solid motors to give users a choice in payload-lifting capacity, without the need to redesign the entire vehicle. For example, three, six, or nine solid motors can be added to the Delta II launch vehicle, shown in Figure 4.2.1-27, depending on the payload mass. Solid motors also provide thrust for strap-on upperstages for spacecraft needing a well defined velocity change (ΔV) to go from a parking orbit into a transfer orbit.

A solid-rocket motor's specific impulse depends on the fuel and oxidizer used. After mixing the propellants and casting the motor, manufacturers can't change the I_{sp} or thrust. Specific impulse for typical solid motors range from 200 to 300 seconds, somewhat more than a liquid monopropellant rocket but slightly less than a typical, liquid bipropellant engine. Their big performance advantage is in terms of I_{dsp}. For example, the Shuttle's solid-rocket boosters (SRBs), have a I_{dsp} 6% less than the I_{dsp} of the liquid main engines (SSMEs), even though the I_{sp} for the SSMEs is almost 70% higher. This makes solid motors ideal for volume-constrained missions needing a single, large ΔV. Table 4.2.1-4 summarizes key points about solid-rocket motors.

Hybrid-chemical Rockets. *Hybrid-propulsion systems* combine aspects of liquid and solid systems. A typical hybrid rocket uses a liquid oxidizer and a solid fuel. The molded fuel grain forms the combustion chamber and the oxidizer is injected into it, as shown in Figure 4.2.1-28. A separate sparking system or a superheated oxidizer initiates combustion. Hybrid combustion is similar to burning a log in the fireplace. Oxygen from the air combines with the log (fuel) in a fast oxidation process and burns. If we take away the air (turn off the flow of the oxidizer), the fire goes out. If we use a bellows or blow on the fire, we increase the flow of air, and the fire grows.

A properly designed hybrid rocket offers the flexibility of a liquid system with the simplicity and density of a solid motor. Hybrids are safe

Table 4.2.1-4. Solid Rockets.

Operating Principle An oxidizer and fuel blend with a binder in a single, solid grain. Combustion takes place along any exposed surface producing heat and by-products that expand thermodynamically through a nozzle.	
Typical Propellants Fuel: Aluminum; oxidizer: Ammonium perchlorate (AP); Binder: Hydroxyl-terminated polybutadiene (HTPB)	
Advantages	**Disadvantages**
• Simple, reliable	• Susceptible to cracks in the grain
• No propellant management needed	• Can't restart
• High I_{dsp} compared to bipropellant	• Difficult to stop
• No combustion chamber cooling issues	• Modest I_{sp}

to handle and store, similar to a solid, but can be throttled and restarted, similar to a liquid engine. Their efficiencies and thrust levels are comparable to solids. For example, one interesting hybrid configuration uses high-test peroxide (HTP) oxidizer with HTPB (rubber, the same used as a binder for solid motors) or with polyethylene (plastic) fuel. At an oxidizer-to-fuel ratio of 8:1, this system offers an I_{sp} of about 290 s and I_{dsp} of about 3.8×10^5 kg/m^3 s. It has the added advantage that the HTP can be used alone as a monopropellant, making it a "dual-mode" system. Unfortunately, for now, hybrid-rocket research and applications lag far behind liquid and solid systems and have yet to see operational use on launch vehicles or spacecraft. Their most dramatic, recent application has been on the attempt at a world speed record for two-wheeled vehicles, shown in Figure 4.2.1-29. Table 4.2.1-5 summarizes key points about hybrid rockets.

Figure 4.2.1-29. Maximum Impulse! The Gillette Mach 3 Challenger used HTP/HTPB hybrid motors producing more than 10,000 N (2248 lb.) thrust to reach a peak speed of 365 m.p.h. in an effort to set the world two-wheeled speed record. *(Courtesy of Richard Brown, Project Machinery)*

Table 4.2.1-5. Hybrid Rockets.

Operating Principle Hybrid rockets typically use a liquid oxidizer with a solid fuel. The oxidizer is injected into a hollow port (or ports) within the fuel grain, where combustion takes place along the boundary with the surface.	
Typical Propellants Oxidizers: Liquid oxygen (LOX), nitrous oxide (N_2O), high-test hydrogen peroxide (>85% H_2O_2) Fuels: HTPB = hydroxyl-terminated polybutadiene (rubber), PE = polyethylene (plastic)	
Advantages	**Disadvantages**
• Simpler than a bipropellant system with similar performance	• Limited heritage
• Safer, more flexible than solids	• Modest I_{sp}
• No combustion-chamber cooling issues	

Chemical-rocket Summary. Table 4.2.1-6 compares the I_{sp} of the thermodynamic rockets we've discussed in this section and compares their performance and key features.

Table 4.2.1-6. **Comparison of Thermodynamic Rocket.** LH_2 = liquid hydrogen; kerosene, RP-1 = "rocket propellant-1;" N_2O_4 = nitrogen tetroxide; N_2H_4 = hydrazine; HTPB = hydroxyl-terminated polybutadiene (rubber); PE = polyethylene (plastic); HTP = high-test hydrogen peroxide (>85% H_2O_2). Oxidizer-to-fuel (O/F) ratios are in parentheses after each propellant combination, followed by specific gravity in brackets.

Type	Propellant Combinations (O/F) [Specific Gravity]	I_{sp} (s)	Advantages	Disadvantages
Liquid	--	--	• High I_{sp} • Can be throttled • Can be re-started	• Must manage two propellants • Intense combustion heat creates thermal-control problems for chamber and nozzle
Bipropellant	LO_2/LH_2 (5 : 1) [1.15 : 0.07]	477	• High I_{sp} • Environmentally friendly propellants	• Cryogenic fuel and oxidizer difficult to store
	LO_2/Kerosene (RP-1) (2.25:1) [1.15 : 0.8]	370	• Storable fuel • Good I_{dsp}	• Cryogenic oxidizer
	N_2O_4/N_2H_4 (1.9 : 1) [1.43 : 1.00]	334	• Storable propellants • Good I_{sp}	• Toxic propellants
Mono-propellant	--	--	• Simple, reliable • One propellant to manage • Lower-temperature reactions means fewer thermal problems in chamber and nozzle	• Lower I_{sp} than bipropellant
	N_2H_4 (hydrazine) (N/A) [1.00]	245	• Large flight heritage	• Toxic
	H_2O_2 (90% hydrogen peroxide) (N/A) [1.37]	181	• Environmentally friendly propellant	• Little flight heritage
Solid	NH_4ClO_4 (AP)/Al (includes a binder e.g. HTPB) (3.5 : 1) [1.95 : 1.26]	300	• Simple, reliable • No propellant management needed • High I_{dsp} compared to bipropellant • No combustion-chamber cooling issues	• Susceptible to cracks in the propellant grain • Difficult to stop • Can't re-start • Modest I_{sp}
Hybrid	H_2O_2 (90%)/PE (8 : 1) [1.37 : 0.90]	333	• Simpler than a bipropellant system with similar performance • Safer, more flexible than solids • No combustion-chamber cooling issues • Restart	• Limited heritage • Modest I_{sp}

Solar-thermal Rockets

In chemical rockets, the heat is a by-product of a chemical reaction. But rockets can produce heat in other ways, then transfer it directly to the propellant using conduction or convection. One convenient source of heat is the Sun. If you've ever played with a magnifying glass on a sunny day, you've seen the power of solar energy to produce heat. By concentrating solar energy using mirrors or lenses, a rocket can create extremely high temperatures (up to 2400 K) on a focused point. A propellant, such as hydrogen, passing through this point can directly absorb the heat, reaching a very high temperature before expanding through a nozzle to achieve high exhaust velocity. In this way, *solar-thermal rockets* use the limitless power of the Sun to produce relatively high thrust with high I_{sp}.

Several concepts for solar-thermal rockets have been proposed, such as the one shown in Figure 4.2.1-30. But, up to now, none have been tested in orbit. Their natural advantage is the abundant source of solar energy, eliminating the need to produce the energy on the spot or carry it along as chemical energy. It can use nearly any propellant. The best I_{sp}, of course, comes from using hydrogen. Theoretical and experimental results indicate a liquid-hydrogen, solar-thermal rocket could achieve a specific impulse of more than 800 s. Basic engineering problems limit thrust levels due to inefficiencies in transferring heat between the thermal mass that absorbs solar energy and the propellant. However, thrusts in the several-newton range should be achievable.

Another important operational challenge for solar-thermal rockets is deploying and steering large mirrors to collect and focus solar energy. Naturally, they would not be effective in eclipse or for interplanetary missions far from the Sun. Table 4.2.1-7 summarizes key features of solar-thermal rockets.

Figure 4.2.1-30. Solar-thermal Rocket. This solar-thermal rocket concentrates solar energy on a thermal mass that reaches very high temperature (up to 2400 K). In this concept, liquid hydrogen flows through the thermal mass, absorbing the energy and then expanding through a nozzle, producing a thrust of more than 6 N (1.6 lbf) at an I_{sp} of 750 s. *(Courtesy of NASA/Marshall Space Flight Center)*

Table 4.2.1-7. Solar-thermal Rockets.

Operating Principle Lenses or mirrors concentrate solar energy onto a heat-transfer chamber. A propellant, such as liquid hydrogen, flows through the chamber, absorbs heat, and then expands through a nozzle.	
Typical Propellants Can use virtually any propellant, but hydrogen produces the best I_{sp}	
Advantages • Limitless energy supply, can be refueled and re-used • Potentially very high I_{sp} (~800 s with H_2)	**Disadvantages** • Needs intense, direct sunlight • Must carefully point a large mirror or lens • No flight heritage

Thermoelectric Rockets

Of course, solar energy is only available when the Sun is shining. A spacecraft in eclipse, or far from the Sun, needs another heat source. On Earth, we commonly use electrical energy to produce heat—to heat our homes or toast our bread. This heat comes from electrical resistance (friction) of the current flowing through a wire. If you hold your hand next to a conventional light bulb, you'll feel the heat produced by the resistance of the filament in the bulb. For space applications, the energy source is the electrical energy provided by the spacecraft's electrical-power subsystem (EPS). By running electricity through a simple resistor, or by creating an arc discharge, similar to a spark plug, we can create heat. *Thermoelectric rockets* transfer this heat to the propellant by conduction and convection.

One of the simplest examples of a thermoelectric rocket is a *resistojet*. This type works much like an electric tea kettle. As we show in Figure 4.2.1-31, electrical current flows through a metal-heating element inside a combustion chamber. The resistance (or electrical friction) in the metal causes it to heat up. As propellant flows around the heating element, heat

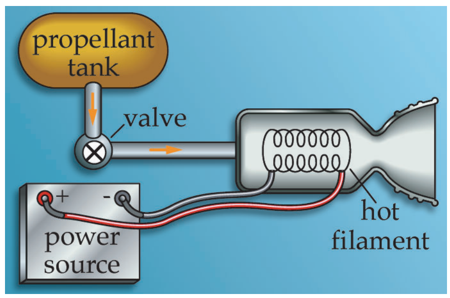

Figure 4.2.1-31. Resistojet. A resistojet uses electrical resistance to produce heat inside a thrust chamber. This heat transfers to the propellant by convection to the propellant flowing through the chamber, which then expands through a nozzle.

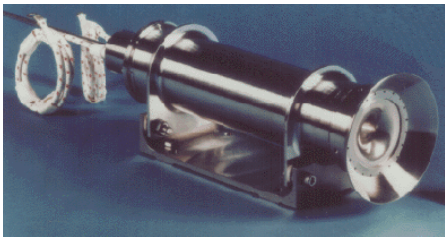

Figure 4.2.1-32. Resistojets at Work. The International Space Station uses resistojets, such as this one, to help maintain its orbit and attitude. *(Courtesy of NASA/Johnson Space Center)*

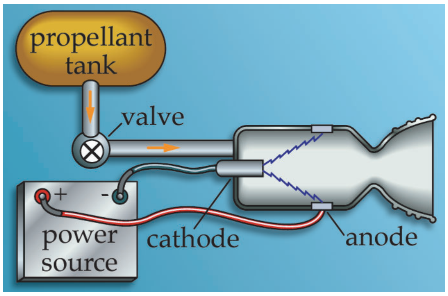

Figure 4.2.1-33. Arcjet Thruster. An arcjet thruster works by passing a propellant through an electric arc, rapidly increasing its temperature before expanding it out a nozzle.

Figure 4.2.1-34. Arcjets at Work. The Argos spacecraft, shown here, tested a powerful 26-kW ammonia (NH_3) arcjet, setting a record for the most powerful electric-propulsion system ever tested in orbit. Its I_{sp} was 800 s, and its thrust was 2 N. *(Courtesy of the U.S. Air Force)*

transfers to it by convection, increasing its temperature before it expands through a nozzle.

This simple principle can be applied to almost any propellant (NASA even investigated using urine as a propellant on the Space Station!). The resistojet concept can strongly increase the specific impulse of a conventional cold-gas rocket, making it, in effect, a hot-gas rocket with increased I_{sp}. Resistojets also improve the performance of conventional hydrazine monopropellant rockets by heating the exhaust products, thus boosting their I_{sp} by about 50% (from 200 s to over 300 s). The direct benefit of a resistojet rocket comes from adding heat to the propellant, so the hotter it gets, the higher its I_{sp} and I_{dsp}. Hydrazine resistojets are gaining wide use, as mission designers become increasingly able to trade extra electrical power for a savings in propellant mass. Astronauts on the International Space Station, for example, rely on hydrazine resistojets, shown in Figure 4.2.1-32, to maintain the ISS's final mission orbit and attitude.

Another method for converting electrical energy into thermal energy is by using a spark or electric arc. To form an arc, we create a gap in an electrical circuit and charge it with a large amount of electricity. When the electrical potential between the two points gets high enough, an arc forms (during a thunderstorm we see this as dazzling displays of lightning). An *arcjet rocket* passes propellant through a sustained arc, increasing its temperature. Arcjet systems can achieve relatively high I_{sp} (up to 1000 s) with small but significant thrust levels (up to 1 newton). Like resistojets, arcjets can use almost any propellant. Current versions use hydrazine, liquid hydrogen, or ammonia. We show a schematic for an arcjet system in Figure 4.2.1-33. The ARGOS spacecraft, shown in Figure 4.2.1-34, was launched in 1999 to test a 26-kW ammonia arcjet, producing a thrust of about 2 N with a specific impulse over 800 s.

As expected, the main limit on thermoelectric-rocket thrust and efficiency is the amount of power available. Using the relationship between power and thrust, we can fine tune the design of a thermoelectric thruster, trading thrust versus power versus specific impulse. For example, if we double the power input, we can increase thrust by a factor of 4 for the same specific impulse. Table 4.2.1-8 summarizes key features of thermoelectric rockets.

Nuclear-thermal Rockets

Another potentially useful heat source in space is nuclear energy. On Earth, nuclear reactors harness the heat released by the fission of uranium to produce electricity. Water absorbs this heat, making steam that turns turbine generators. In much the same way, a *nuclear-thermal rocket* uses its propellant, such as liquid hydrogen, to flow around the nuclear core, absorbing thermal energy. As we show in Figure 4.2.1-35, propellant enters the reaction chamber where it absorbs the intense heat from the nuclear reaction. From there, thermodynamic expansion through a nozzle produces high thrust (up to 10^6 N) and high I_{sp} (up to 1000 s using hydrogen).

Table 4.2.1-8. Thermoelectric Rockets.

Operating Principle Heat comes from an electric resistance or a spark discharge inside a heat-transfer chamber. A propellant flows through the chamber, absorbs heat, and then expands through a nozzle.	
Typical Propellants Hydrazine, water, ammonia, or almost any other propellant	
Advantages • Simple, reliable • Can use as an "add on" to conventional monopropellant rocket to boost I_{sp} ~50% • High-power arcjets offer very high I_{sp} (>800 s with NH_3)	**Disadvantages** • Requires large amounts of onboard electrical power • Relatively low thrust (<1 N)

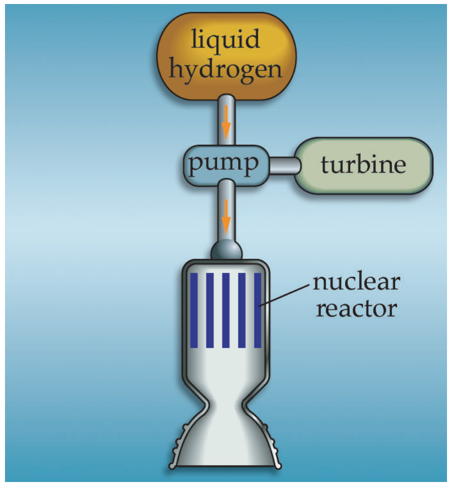

Figure 4.2.1-35. Nuclear-thermal Rocket. A nuclear-thermal rocket uses a nuclear reactor to heat a propellant, such as liquid hydrogen. The superheated propellant then expands through a nozzle.

Because of their relatively high thrust and better efficiencies, nuclear-thermal rockets offer a distinct advantage over chemical systems, especially for crewed planetary missions. These missions must minimize transit time to decrease the harmful effects of free fall, as well as exposure to solar and cosmic radiation on the human body, as discussed in Chapter 3. Ironically, future astronauts may escape the danger of space radiation by using the energy from a nuclear reactor to propel them to their destination faster. Extensive research into nuclear-thermal rockets occurred in the U.S. in the 1960s as part of the NERVA program, as shown in Figure 4.2.1-36. More work took place in the 1980s, when heat-transfer theory advanced greatly. Unfortunately, environmental and political concerns about safe ground testing of nuclear-thermal rockets (let alone the potential political problems of trying to launch a fully fueled nuclear reactor) have severely reduced research into this promising technology. Table 4.2.1-9 summarizes key features of nuclear-thermal rockets.

Table 4.2.1-9. Nuclear-thermal Rockets.

Operating Principle Heat comes from nuclear fission inside a reactor. A propellant, such as liquid hydrogen, flows through the reactor, absorbs heat, and then expands through a nozzle.	
Typical Propellants Can use virtually any propellant, but hydrogen produces the best I_{sp}	
Advantages • Long-term energy supply, can be refueled and re-used • Potentially very high I_{sp} (~1000 s with H_2) • High thrust (~10^6 N)	**Disadvantages** • Environmental and political problems with testing and launching nuclear reactors • No flight heritage

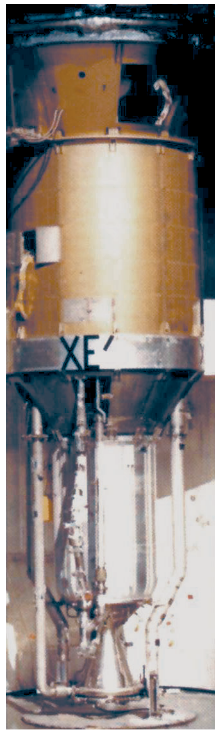

Figure 4.2.1-36. Nuclear Engine for Rocket Vehicle Applications (NERVA) Rocket. The NERVA program tested nuclear-thermal rockets from 1947 until 1972. Future missions may depend on their impressive performance to take humans to Mars. *(Courtesy of the Report of the Synthesis Group on America's Space Exploration Initiative)*

Electrodynamic Rockets

Although thermodynamic rockets offer relatively high thrust over a very wide range (10^{-1} to 10^6 newtons), basic problems in heat transfer limit the maximum specific impulse (up to 1000 s or so, for nuclear rockets). To achieve the higher efficiencies demanded by future, more challenging interplanetary and commercial missions, we need to take a different approach—electrodynamic rockets.

As we discussed in Section 4.2.1.1, electrodynamic rockets rely on electric or magnetic fields to accelerate a charged propellant to very high velocities (more than 10 times the exhaust velocity and I_{sp} of the Shuttle's main engines). However, this high I_{sp} comes with a price tag—high power requirement and low thrust. Power is always limited on a spacecraft. No matter how much there is, it's always nice to have more, especially for an electrodynamic thruster. However, given a finite amount of power, we can have higher exhaust velocity only at the expense of reduced thrust. As a result, practical limits on power availability make electrodynamic thrusters unsuitable for launch vehicles or when a spacecraft needs a quick, large impulse, such as when it brakes to enter a capture orbit. Even so, because electrodynamic rockets offer very high I_{sp}, mission planners are increasingly willing to sacrifice power and thrust (and the extra time it will take to get a spacecraft where it needs to go) in order to save large amounts of propellant mass.

There are several ways to use electric or magnetic fields to accelerate a charged propellant. Here we'll focus on the two main types of electrodynamic rockets operating today.

- Ion (or electrostatic) thrusters—use electric fields to accelerate ions
- Plasma thrusters—use electric and magnetic fields to accelerate a plasma

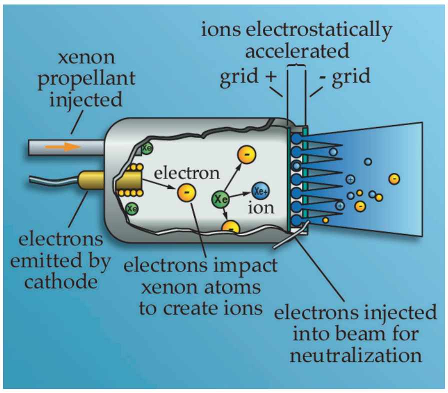

Figure 4.2.1-37. Simple Ion Thruster. An ion thruster is the simplest example of an electrodynamic rocket. A strong electric field accelerates an ionized propellant to high velocity (>30 km/s). To prevent charging of the spacecraft, negative ions are injected into the exhaust, neutralizing it.

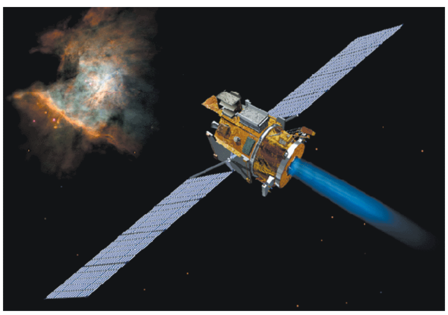

Figure 4.2.1-38. Ion Engines in Space. NASA's Deep Space 1 mission used an ion thruster for its primary propulsion. The engine operated at 2.3-kw, producing a thrust of 0.09 N with a specific impulse of 3100 s. *(Courtesy of NASA/Jet Propulsion Laboratory)*

Ion Thrusters

An *ion thruster* (also called an *electrostatic thruster*) uses an applied electric field to accelerate an ionized propellant. Figure 4.2.1-37 shows its basic configuration. To operate, the thruster first ionizes a propellant by stripping off the outer shell of electrons, making positive ions. It then accelerates these ions by applying a strong electric field. If the engine ejected the positive ions without neutralizing them, the spacecraft would eventually accumulate a negative charge from the leftover electrons. To prevent this, as Figure 4.2.1-37 illustrates, it uses a neutralizer source at the exit plane to eject electrons into the exhaust, making it neutrally charged.

The ideal ion-thruster propellant is easy to ionize, store, and handle. Early ion-thruster research used mercury and cesium because these metals are easy to ionize. Unfortunately, they are also toxic, making them difficult to store and handle. Currently, the most popular propellant for ion thrusters is xenon. Xenon is a safe inert gas that stores as a dense gas (1.1052 kg/l) under a moderate pressure of 58.4 bar at room temperature. This high-density propellant also gives ion thrusters excellent density specific impulse, I_{dsp}.

Ion thrusters offer an electrically efficient propulsion option with very high specific impulse (as high as 10,000 s). About 90% of the power goes to accelerate the propellant. Because of their efficiency, ion thrusters have been used on a variety of space missions. Perhaps their most exciting application is on interplanetary missions. NASA's Deep Space 1 mission, shown in Figure 4.2.1-38, was the first to rely on an ion rocket for the primary propulsion subsystem beyond Earth orbit.

Plasma Thrusters

As we discussed in Section 4.2.1.1, there is a practical limit to the number of ions that we can pack into a small volume inside a thruster. But a neutral plasma can have a much higher charge density. *Plasma thrusters* can take advantage of this fact to offer slightly higher thrust than ion thrusters for the same power input, at the expense of somewhat lower I_{sp} and electrical efficiency (we don't get something for nothing when it comes to rockets). Plasma thrusters use the combined effect of electric and magnetic fields to accelerate the positive ions within a plasma. Two types of plasma thrusters have been used in space

- Hall-effect thrusters (HET)
- Pulsed-plasma thrusters (PPT)

The most widely used type of plasma thruster is the *Hall-effect thruster (HET)*. HETs take advantage of a unique effect called a "Hall current" that occurs when we apply a radial magnetic field to a conducting plasma. The interaction of the magnetic field with the resulting electric field creates a force that accelerates the positive ions in the plasma, as shown in Figure 4.2.1-39. Figure 4.2.1-40 shows a photograph of an operating HET. Note the circular-shaped plume that results from using the radial magnetic field. Russian scientists pioneered many of the modern advances in HETs, having run them for several years for orbital station-keeping applications. Because the propellant requirements for plasma thrusters are the same as for ion thrusters, xenon is also the most widely used propellant.

A second type of plasma thruster is called a pulsed-plasma thruster (PPT). Unlike all other types of rockets that operate continuously, *pulsed-plasma thrusters (PPT)* operate in a noncontinuous, pulsed mode. Unlike ion and plasma thrusters, PPTs use a solid propellant, usually Teflon (PTFE). A high-voltage arc pulses over the propellant's exposed surface, vaporizing it and creating an instant plasma. The resulting induced magnetic field accelerates the plasma. Figure 4.2.1-41 shows a schematic for a simple PPT. A number of missions have used PPTs for spacecraft station keeping because they have precisely controlled, low thrust levels. Because they operate in a pulsed mode, they don't need continuous high power. Instead, they can gradually store electrical energy in a capacitor for release in high-power bursts (the same technique used in a camera flash). This low-power, pulsed operating mode makes them suitable for many small-satellite applications.

Compared to ion and stationary plasma thrusters, PPTs have relatively low energy-conversion efficiency (20%). But they provide respectable I_{sp} (700 s to 1500 s) with low thrust (10^{-3} to 10^{-5} N). Their biggest potential advantage is in ease of integration. Because they don't require any more propellant management, we can build them as simple, self-contained units. In principle, we can easily bolt them onto a spacecraft. Table 4.2.1-10 summarizes key information about the electro-dynamic rockets we've discussed.

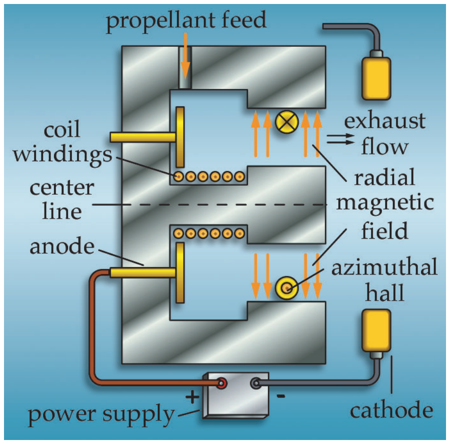

Figure 4.2.1-39. Hall-effect Thruster (HET) Diagram. In an HET, the interaction of an applied magnetic field with the resulting electric field creates the force that accelerates the positive ions within the plasma. This diagram shows a cross-section of the radial chamber.

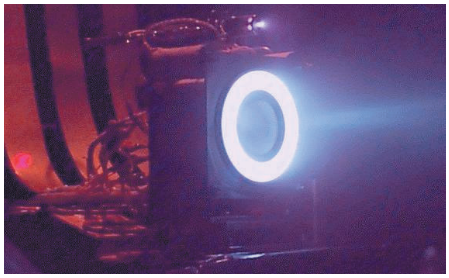

Figure 4.2.1-40. Hall-effect Thruster (HET) in Operation. Notice the circular shape of the plasma. HETs take advantage of the unique properties of a radial magnetic field to accelerate a propellant, such as Xenon, that has been heated to create a plasma. *(Courtesy of Primex Aerospace Company)*

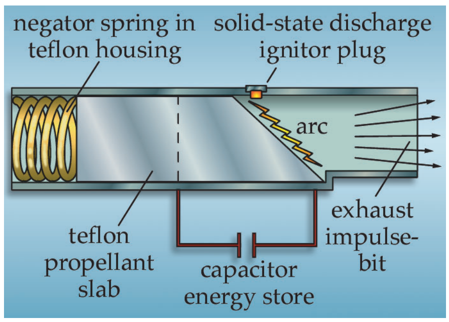

Figure 4.2.1-41. Pulsed-plasma Thruster (PPT). PPTs create a plasma by pulsing an electric arc over the surface of a solid propellant, such as Teflon (PTFE). The induced magnetic field accelerates the plasma. As the teflon slab shrinks, the negator spring gradually feeds it into the arc.

Table 4.2.1-10. Electrodynamic Rockets. *(Adapted from Space Propulsion Analysis and Design).*

Type	Propellant	Operating Principle	Electrical Efficiency	Thrust (N)	I_{sp} (s)
Ion (or electrostatic) thruster	Xenon	Applied electric field accelerates an ionized propellant	90%	0.1 – 1.0	2000 – 10,000
Hall-effect thruster (HET)	Xenon	Combined electric and magnetic fields produce a "Hall effect" that accelerates ions within a plasma	60%	0.1 – 1.0	~2000
Pulsed-plasma thruster (PPT)	Teflon (PTFE)	An electric arc pulses over a solid propellant, vaporizing it and creating a plasma. Interaction between the applied electric field and resulting magnetic field accelerates the plasma.	20%	10^{-5} – 10^{-3}	~1500

System Selection and Testing

So far, we've looked at all the pieces that make up propulsion subsystems and many of the rocket-technology options available. In Chapter 11, we presented the orbital-control budget, which tells us the total ΔV needed throughout the mission, as one important driver of the propulsion subsystem's design. Using the tools from this chapter, such as the rocket equation, we can translate these values into propellant mass and volume requirements for a given rocket technology. But many questions about propulsion-subsystem design and applications remain.

- How do mission planners select the best-technology rocket from this large menu of available systems? How do researchers decide which is the best technology to pursue for future applications?
- How are new or improved systems tested and declared fit for flight?

Let's start with the problem of technology selection. As with most technology decisions, there is rarely one, best answer for any given application. Sometimes, as with the case of our FireSat example, the severe constraints on volume, power, and mass, coupled with the modest ΔV requirements, leave only a few realistic options—cold-gas thrusters or, possibly, a monopropellant system. Even when we narrow the field, the choice of the right propulsion subsystem for a given mission depends on a number of factors that we must weigh together.

One way to trade various rocket options is to select one with the lowest total cost. But here, cost represents much more than simply the engine's price tag. The total cost of a propulsion system includes at least eight other factors, in addition to the bottom-line price tag, that we must consider before making a final selection [Sellers, 1998]. These factors are

- Mass performance—thrust produced by a given mass of propellant
- Volume performance—thrust produced by a given volume of propellant

- Time performance—how fast it completes the needed ΔV, measured by total thrust
- Power requirements—how much total power the propulsion system needs to operate
- Safety costs—how safe the system (including its propellant) is and how difficult it is to protect people working with the system
- Logistics requirements—how difficult it is to transport the system and propellant to the launch site and service them for flight
- Integration cost—how difficult the system is to integrate and operate with other spacecraft subsystems and the mission operations concept
- Technical risk—what flight experience it has or how it performed in testing

Different missions (and mission planners) naturally place a higher value on some of these factors than on others. Example 4.2.1-1 showed that for the FireSat mission, a helium cold-gas system had lower mass cost, but its volume cost was prohibitive. Other missions, such as a complex commercial mission, may place high priority on reducing technical risk. For them, a new type of plasma rocket, even if it offers lower mass cost, may be too risky when they consider all other factors. When asking what's the best option for a given mission, "it depends" is usually the best answer!

After selecting a system, engineers must rigorously test and qualify it to declare it safe for use. New rocket development usually progresses from relatively crude, engineering-model testing under atmospheric conditions, to more elaborate testing of flight models under high-altitude or vacuum conditions. Of course, for specialized systems such as electrodynamic thrusters (ion thrusters or HETs), engineers can test only under vacuum conditions, using highly accurate thrust stands to measure micronewtons (10^{-3} N) of thrust. During experimental testing, rocket scientists carefully measure mass flow rates, chamber pressures, temperatures, and other parameters, and compare them to predicted values based on thermochemical and other models.

Because rockets typically involve high pressures, high temperatures, high voltages, and hazardous chemicals, safety issues are key. These concerns carry through from initial development of new rockets to servicing of proven systems while preparing them for flight. In the case of launch-vehicle propulsion, lives may depend on safe, reliable operation. As discussed earlier, special loading procedures and equipment ensure safe handling of hazardous propellants. Figure 4.2.1-42 shows skilled technicians loading propellant.

Figure 4.2.1-42. Propellant Loading Operations. Transferring toxic propellants from storage containers to rocket tanks is dangerous and requires safety suits with breathing apparatus and special handling equipment. *(Courtesy of British Aerospace Royal Ordinance)*

Ensuring system reliability involves a complex series of ground tests that measure performance over many conditions. These conditions can range from relatively simple tests, to ensure the system doesn't leak at flight pressure, to complicated tests that require widely varying O/F ratios and expansion conditions. In addition to performance, all the typical space-environment testing done for other subsystems, such as thermal and vacuum testing, also must occur for the propulsion

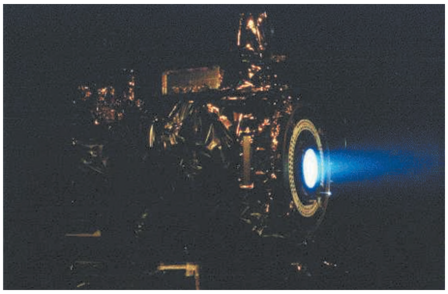

Figure 4.2.1-43. Rocket Testing. From initial development through flight testing, rockets and propulsion systems undergo rigorous testing to measure performance and ensure safe, reliable operations. This photograph shows the NSTAR ion thruster used for the NASA Deep Space 1 mission in its test-stand configuration. *(Courtesy of NASA/Jet Propulsion Laboratory)*

subsystem. Figure 4.2.1-43 shows an ion-thruster setup for testing in a vacuum chamber.

Exotic Propulsion Methods

Chemical rockets have given us access to space and taken spacecraft beyond the solar system. Electrodynamic rockets offer a vast increase in mass efficiency, making exciting new missions possible. However, to open space to colonization and allow people to challenge the stars, we need bold, new approaches. *Exotic propulsion systems* are those "far out" ideas still on the drawing boards. While there are many exotic variations to the rockets we've already discussed (such as using high-energy density or meta-stable chemicals, nuclear fusion, or antimatter to create superheated products), here we focus on even more unconventional types of propulsion—ones that produce thrust *without* ejecting mass

- Solar sails
- Tethers

We'll first look at how these far-out concepts may one day give us even greater access to the solar system. Then we'll go beyond that to look at the unique challenges of interstellar flight.

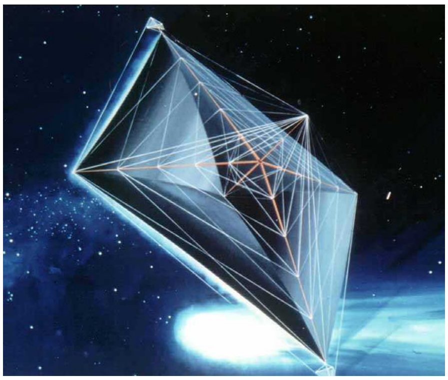

Figure 4.2.1-44. Solar Sail. A solar sail captures the minute pressure exerted by solar radiation. Even a very large surface area (1 km^2) would generate only about 5 N of thrust. But this thrust is essentially "free" because no mass is expended. Thus, the solar sail is free to sail around the inner solar system (where solar radiation is most intense). *(Courtesy of NASA/Jet Propulsion Laboratory)*

Solar Sails

Light, when thought of as photons, imparts a tiny force to any surface it strikes. Just as a conventional sail harnesses the force of the wind to move a ship, a *very* large *solar sail* can harness the force of solar pressure to propel a spaceship without ejecting mass! Of course, the farther it goes from the sun the less solar pressure it can collect, so a solar sail would work best inside Mars' orbit. Figure 4.2.1-44 shows an artist's concept of a solar sail.

How large would a sail need to be? To produce just five newtons (about one pound) of thrust near Earth, we'd need one square kilometer (0.62 mi. on a side) of sail! To achieve escape velocity from a low-Earth orbit (assuming a total spacecraft mass of only 10 kg), this force would have to be applied for more than 17 years! Of course, a solar sail uses no propellant, so the thrust is "free." As long as travellers aren't in a hurry, a solar sail offers a cheap way to get around. Some visionaries propose that solar sails can be used to maneuver mineral-rich asteroids closer to Earth to allow for orbital mining operations.

Tethers

Another imaginative means of propulsion that doesn't need propellant, *tethers*, uses very long cables. Recall that Isaac Newton described that the gravitational force decreases with the square of the distance from the center of the Earth. This is true even when the distance is fairly small. Imagine a dumb bell in space with one end closer to the Earth than the other. The force of gravity on the lower end will be slightly bigger than the force on the other end, causing the dumb bell to align itself vertically, like a pendulum. By using a small mass at the end of a very long tether, tens or even hundreds of kilometers long, we produce the same effect. But even more interesting effects become possible as well.

Picture a large spacecraft, such as the Shuttle, in a circular orbit. Now, imagine a small payload deployed upward (away from Earth), from the Shuttle at the end of a very long tether, as shown in Figure 4.2.1-45. We assume we are dealing with point masses, affected only by gravity. From an orbital-mechanics standpoint, this point-mass assumption is valid only at the center of mass of the Shuttle/payload system. If the payload mass is small compared to the Shuttle's mass, the system's center of mass will not move significantly when it deploys. Thus, the orbital velocity of the system will stay about the same.

What does this mean for the payload? Secured by the tether, it is pulled along in orbit at the Shuttle's orbital velocity. But the payload is well above the Shuttle. Remember, orbital velocity depends on the distance from Earth's center. Therefore, because the payload is higher than the Shuttle, its proper circular, orbital velocity should be somewhat *slower* than the velocity it maintains due to the tether. Or, said another way, the tether forces the payload to travel *faster* than orbital mechanics would dictate for its altitude.

Now, what happens if we suddenly cut the tether? Orbital mechanics would take over and the payload would suddenly find itself at a velocity too fast for a circular orbit at its altitude. The situation would be as if its velocity were suddenly increased by firing a rocket. It would enter an elliptical orbit with a higher apogee, one-half orbit later. Analysis indicates this new apogee altitude would be higher than the original circular orbit by 7 times the length of the tether [Humble et. al., 1995]. In other words, if the payload's original altitude were 310 km and the tether's length were 10 km, the payload's new elliptical orbit would be 310 × 380 km, as illustrated in Figure 4.2.1-46.

If the payload were deployed downward instead of upward, the opposite would happen. Its orbit would shrink, so that half an orbit after the tether releases, the payload would reach perigee. This technique was used by the Small Expendable-tether Deployment System (SEDS) mission in 1993 to successfully deorbit a small payload [Humble et. al., 1995].

Of course, tether propulsion isn't completely "free." We still need to add the mass of the tether and its deployment motors and gears to a spacecraft. And we need extra electrical power to operate the tether-deployment mechanisms. However, once we put these systems in place, we could use the tether system repeatedly to boost or de-orbit payloads.

Space Shuttle astronauts have done a number of experiments to investigate the exciting possibilities of tethers. So far, these experiments have focused on the practical problems of deploying, controlling, and reeling in a small payload at the end of a long tether. Figure 4.2.1-47 shows an artist's concept of a tether experiment. Future applications for tethers are truly unlimited. A series of rotating tether stations could be used to "sling-shot" payloads, passing them from one to the other, all the way

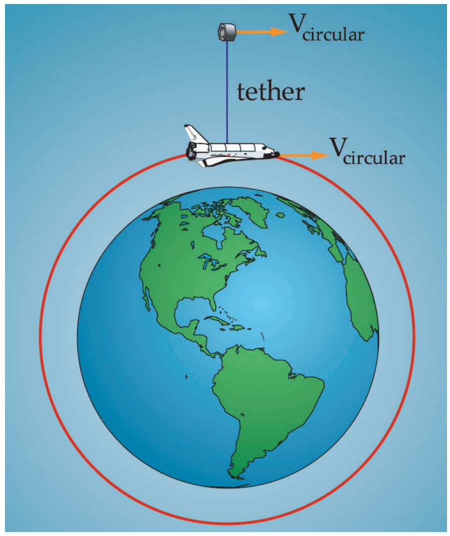

Figure 4.2.1-45. Space Tether Deployment. This diagram illustrates a payload deployed upward, away from Earth's center, at the end of a long tether.

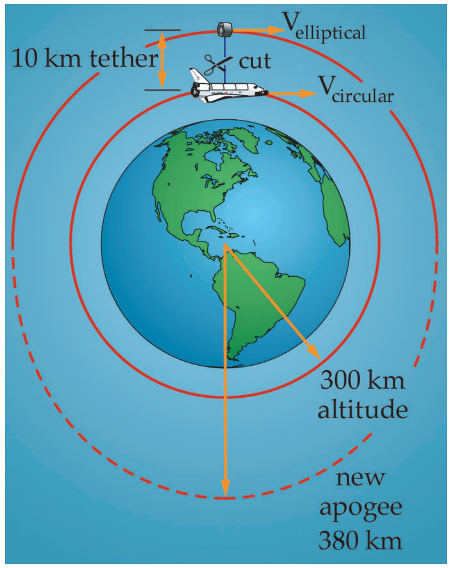

Figure 4.2.1-46. Tether Orbit Boost. A payload deployed 10km higher than the Space Shuttle in a 300 km orbit will be boosted to a 310 × 380 km orbit when the tether is cut.

Figure 4.2.1-47. Tether Experiment. This artist's concept shows a small mass deployed downward on a long tether. *(Courtesy of NASA/Marshall Space Flight Center)*

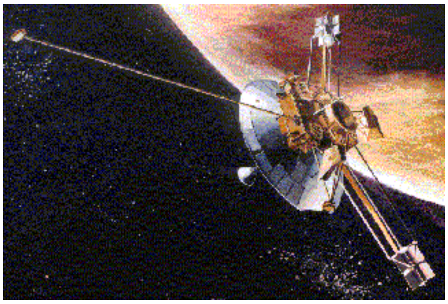

Figure 4.2.1-48. Pioneer 10 Boldly Goes. NASA's Pioneer 10 spacecraft became the first interstellar probe when it left the solar system to start a million-year journey to the stars. *(Courtesy of NASA/Jet Propulsion Laboratory)*

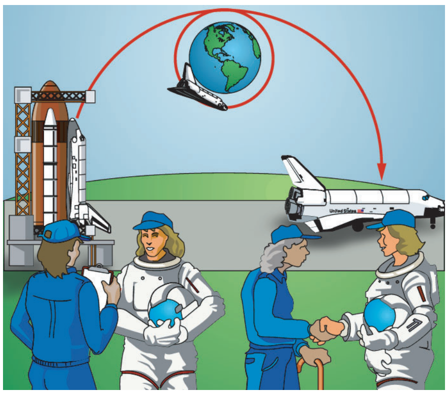

Figure 4.2.1-49. Twin Paradox. Einstein's theory of relativity tells us that if one twin leaves Earth and travels at speeds near the speed of light, when she returns she'll find her twin will have aged more than she.

from low-Earth orbit to the Moon. Another exiting use of tethers is for power generation. A conducting tether passing through Earth's magnetic field could generate large amounts of electrical power. [Forward, SciAm, Feb. 99].

Interstellar Travel

The ultimate dream of space exploration is someday to travel to other star systems, as depicted in TV shows such as *Star Trek* and *Babylon 5*. Actually, the first human-built "star ships" are already on their way out of the solar system. Launched in 1972 and 1973, NASA's Pioneer 10, shown in Figure 4.2.1-48, and Pioneer 11 probes became the first spacecraft to leave our local planetary neighborhood and begin their long journey to the stars. Unfortunately, at their present velocities, they're not expected to pass near another stellar body in more than 2 million and 4 million years, respectively!

Obviously, these travel times are far too long to be useful for scientists who want to be around to review the results from the mission. Hollywood's version of rocket science can take advantage of hyperspace and warp drive to allow round-trip times to nearby stars during a single episode. Unfortunately, real-world rocket science is far from using these amazing means of propulsion.

Assuming we could develop efficient, onboard energy sources, such as fusion or antimatter, and rely on ion or other extremely efficient types of rockets to achieve very high specific impulse, the speed of light still limits travel. If a rocket could thrust continuously for several years, even at a low thrust level, it would eventually reach a very high velocity. However, as its speed approached a significant fraction of the speed of light, interesting things would begin to happen.

One aspect of Albert Einstein's theory of relativity says that, as an object's velocity approaches light speed, its perception of time begins to change relative to a fixed observer. This time adjustment leads to the so-called "twin paradox," illustrated in Figure 4.2.1-49. To visualize this concept, imagine a set of twin sisters. If one sister leaves her twin and departs on a space mission that travels near the speed of light, when she returns, she'll find her twin much older than she is! In other words, although the mission may seem to have lasted only a few years for her, tens or even hundreds of years may have passed for her twin on Earth.

We express this *time dilation* effect, sometimes called a tau (τ) factor, using the Lorentz transformation

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Important Concept

The faster an object goes, the slower time passes for it relative to a stationary observer. This time dilation effect becomes significant as the object approaches the speed of light.

This is summarized as

$$\tau = \frac{t_{starship}}{t_{Earth}} = \sqrt{1 - \frac{V^2}{c^2}} \qquad (4.2.1\text{-}9)$$

where

$t_{starship}$ = time measured on a starship (s)
t_{Earth} = time measured on Earth (s)
V = starship's velocity (km/s)
c = speed of light = 300,000 km/s

The *tau factor, τ*, tells us the ratio of time onboard a speeding starship compared to Earth time. As the spacecraft's velocity approaches light speed, τ gets very small, meaning that time on the ship passes much more slowly than it does on Earth. While this may seem convenient for readers thinking about a weekend journey to the star Alpha Centauri (4.3 light years away), Einstein's theory also places a severe "speed limit" on would-be space travelers. As a spacecraft's velocity increases, its effective mass also increases. Thus, as the ship's velocity approaches light speed, it needs more thrust than it did at lower speeds to get the same velocity change. To attain light speed, it would need an infinite amount of thrust to accelerate its infinite mass. For this reason alone, travel at or near the speed of light is well beyond current technology.

But who knows what the future holds? For years, scientists and engineers said travel beyond the speed of sound, the so-called "sound barrier," was impossible. But in October 1947, Chuck Yeager proved them all wrong while piloting the Bell X-1. Today, jet planes routinely travel at speeds two and three times the speed of sound. Perhaps by the 23rd century some future Chuck Yeager will break another speed barrier and take a spacecraft beyond the speed of light.

Section Review

Key Concepts

➤ All propulsion subsystems have the same basic elements

- Controller—to control and manage all the other elements
- Energy source—either "built-in" to the propellant (in cold-gas or chemical systems), supplied by the electrical-power subsystem (in the case of electrothermal, electrostatic, or electromagnetic thrusters), or supplied from other sources, such as solar or nuclear energy
- Propellant-management subsystem—to regulate and control the propellant flow
- Sensors—to monitor temperature, pressure, and other important parameters
- Rocket—to produce thrust

➤ Chemical rockets are the most common rockets in use. Three basic types are

- Liquid
- Solid
- Hybrid

Table 14-1 compares the types of chemical systems

➤ Solar-thermal rockets use concentrated solar energy to heat a propellant to high temperature

➤ Nuclear-thermal rockets use the heat produced by a nuclear reaction to produce high-temperature propellant

➤ Thermoelectric rockets use heat produced by electrical resistance to create high-temperature propellant These include

- Resistojets
- Arcjets

➤ Electrodynamic systems include

- Ion (also called electrostatic) thrusters— applied electric field accelerates an ionized propellant, such as xenon
- Plasma thrusters
  - Hall-effect thrusters (HETs)—combine electric and magnetic fields to produce a "Hall-effect" current that accelerates ions within a plasma (such as xenon)
  - Pulsed-plasma thrusters (PPTs)—a pulsed electric arc discharges over a solid propellant, vaporizing it and creating a plasma. The interaction between the applied electric field and the resulting magnetic field accelerates the plasma.

➤ Exotic propulsion methods allow for ΔV without expending propellant. These ideas include

- Solar sails—capture the minute pressure of solar photons to produce thrust just as conventional sails capture the force of the wind
- Tethers—take advantage of gravity-gradient differences to raise and lower spacecraft orbits

➤ Exotic systems may one day propel spacecraft at near light speed. When this happens, we'll have to worry about time dilation and other problems predicted by Einstein's theory of relativity.

4.2.1.3 Launch Vehicles

In This Section You'll Learn to...

- ☛ Discuss the various subsystems that make up a launch vehicle
- ☛ Discuss the advantages of launch-vehicle staging

Now that we've seen the types of rockets available and how propulsion subsystems fit together, let's see how they're used to solve perhaps the most important problem of astronautics—getting into space. Launch vehicles come in many different shapes and sizes, from the mighty Space Shuttle to the tiny Pegasus, as shown in Figure 4.2.1-50. In this section, we start by examining the common elements of modern launch vehicles. Looking at launch vehicles as systems, we'll review the various subsystems that work together to deliver a payload into orbit and focus on the unique requirements for the massive propulsion subsystems needed to do the job. Finally, we'll look at staging to see why launch vehicles come in sections that are used and discarded on the way to orbit.

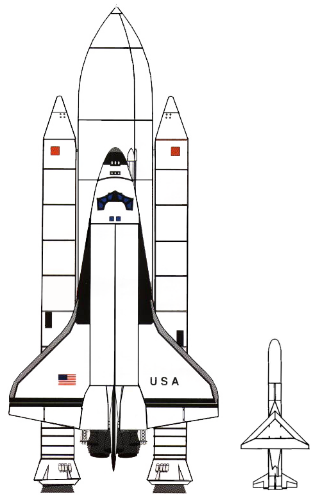


Figure 4.2.1-50. Comparing Launch-vehicle Sizes. Launch vehicles come in all shapes and sizes, from the massive Space Shuttle with a total lift-off mass of 2,040,000 kg to the tiny Pegasus (XL) at a mere 24,000 kg. *(Courtesy of NASA/Johnson Space Center and Orbital Sciences Corporation)*

Launch-vehicle Subsystems

A launch vehicle needs most of the same subsystems as a spacecraft to deliver a payload (the spacecraft) from the ground into orbit. The two biggest differences between a launch vehicle and a spacecraft are the total operation time (about 10 minutes versus 10+ years) and the total velocity change needed (>8 km/s versus 0–1 km/s). Let's start by looking at the challenges of launch-vehicle propulsion to see how we must adapt the technologies discussed earlier in this chapter to the challenging launch environment. Then we'll briefly review the other subsystems needed to support these large rockets to safely deliver spacecraft (and people) into space.

Propulsion Subsystem

The launch-vehicle propulsion subsystem presents several unique challenges that sets it apart from the same subsystem on a spacecraft. These include

- Thrust-to-weight ratio—must be greater than 1.0 to get off the ground
- Throttling and thrust-vector control—may need to vary the amount and direction of thrust to decrease launch loads and to steer
- Nozzle design—nozzles face varying expansion conditions from the ground to space

Let's go through each of these challenges in more detail.

Thrust-to-weight ratio. To get a rocket off the ground, the total thrust produced must be greater than the vehicle's weight. We refer to the ratio of the thrust to the vehicle's weight as the *thrust-to-weight ratio*. Thus, a launch-vehicle's propulsion system must produce a thrust-to-weight ratio greater than 1.0. For example, the thrust-to-weight ratio at lift-off for the Atlas launch vehicle is about 1.2, and for the Space Shuttle it's about 1.6.

Even though chemical rockets aren't as efficient as some rocket types discussed in the last section, they offer very high thrust and, more importantly, very high thrust-to-weight ratios. For this important reason, current launch vehicles use only chemical rockets, specifically cryogenic ($LH_2 + LO_2$), storable (hydrazine + N_2O_4) bipropellant, or solid rockets.

Throttling and thrust-vector control. For virtually all spacecraft applications, rocket engines are either on or off. There is rarely a need to vary their thrust by *throttling* the engines. However, launch vehicles often need throttling, greatly adding to the complexity (and cost!) of their propulsion subsystems.

One reason for throttling has to do with the high aerodynamic forces on a vehicle as it flies through the atmosphere. Within the first minute or so of launch, the vehicle's velocity increases rapidly while it is still relatively low in altitude, where the atmosphere is still fairly dense. Passing through this dense atmosphere at high velocity produces *dynamic pressure* on the vehicle. Without careful attention to design and analysis, these launch loads could rip the vehicle apart. During design, engineers assume some maximum value, based on their extensive analysis of expected launch conditions, that the vehicle can't exceed without risking structural failure. Before each launch, they must carefully measure and analyze the winds and other atmospheric conditions over the launch site to ensure the vehicle won't exceed its design tolerances. In many cases, they must design in a specifically tailored thrust profile for the vehicle, which decreases or "throttles down" during the peak dynamic pressure. The Space Shuttle, for example, reduces the main engines' thrust from 104% to 65%, during this phase of flight, and the burn profile of the solid-rocket boosters' propellant grain is tailored to reduce thrust a similar amount to keep dynamic pressure below a predetermined, safe level.

Figure 4.2.1-51. Throttle Back for Landing. The Lunar Excursion Module (LEM) used a throttleable bipropellant engine, allowing the astronauts to control their descent to the lunar surface. *(Courtesy of NASA/Johnson Space Center)*

Another reason for throttling is to keep total acceleration below a certain level. Astronauts strapped to the top of a launch vehicle feel the thrust of lift-off as an acceleration or *g-load* that pushes them back into their seats. From Newton's laws in Chapter 4, we know the total acceleration depends on the force (thrust) and the vehicle's total mass. If the engine thrust is constant, the acceleration will gradually increase as the vehicle gets lighter due to expended propellant. This means the acceleration tends to increase over time. To keep the overall g-load on the Space Shuttle under 3 g's, the main engines throttle back about six minutes into the launch to decrease thrust so it matches the burned propellant.

Some vehicles also need throttling for landing. The decent-stage engine in the Lunar Excursion Module (LEM), shown in Figure 4.2.1-51, used during the Apollo missions, allowed astronauts to throttle the engine over a range of 10%–100%, so they could touch down softly on the lunar surface.

Finally, launch-vehicle rockets often have the unique requirement to vary their thrust direction for steering. This *thrust-vector control (TVC)* can gimbal the entire engine to point the thrust in the desired direction. The

Space Shuttle, for example, can vary the thrust direction for each main engine by ±10 degrees. Of course, the mechanical gears and hydraulic actuators needed to move massively thrusting rocket engines can be quite complicated. Earlier rockets used simpler methods of thrust-vector control. The V-2 rocket, for example, used large, movable ablative vanes stuck directly into the exhaust stream to change the vehicle's direction. Other launch vehicles use separate steering rockets or direct injection of gasses into the exhaust flow to change the thrust direction.

Nozzle design. In Section 4.2.1.1, we discussed the importance of the external atmospheric pressure and the nozzle expansion ratio to overall engine performance. We prefer not to have a rocket nozzle either over-expanded or under-expanded, but instead designed for ideal expansion. In comparison, spacecraft rocket engines always work within a vacuum, so designers simply use the greatest expansion ratio practical for the best performance. For launch-vehicle rocket engines, the choice of expansion ratio isn't so simple.

During launch, the external pressure on the first stage engines goes from sea level (1 bar or 14.5 p.s.i.) to near zero (vacuum) in just a few minutes. Ideally, we want the nozzle to increase its expansion ratio throughout the trajectory to change the exit pressure as atmospheric pressure decreases. Unfortunately, with current technology, the hardware to do this weighs too much. Instead, the nozzle is typically designed to reach ideal expansion at some design altitude about 2/3 of the way from the altitude of engine ignition to the altitude of engine cutoff.

For example, if we design a rocket to go from sea level to 60,000 meters, a reasonable choice for the design exit pressure would be the atmospheric pressure at about 40,000 meters altitude. As a result, our rocket would (by design) be over-expanded below 40,000 meters and under-expanded above 40,000 meters. As we see in Figure 4.2.1-52, a nozzle designed in this way offers better overall performance than one designed to be ideally expanded only at sea level.

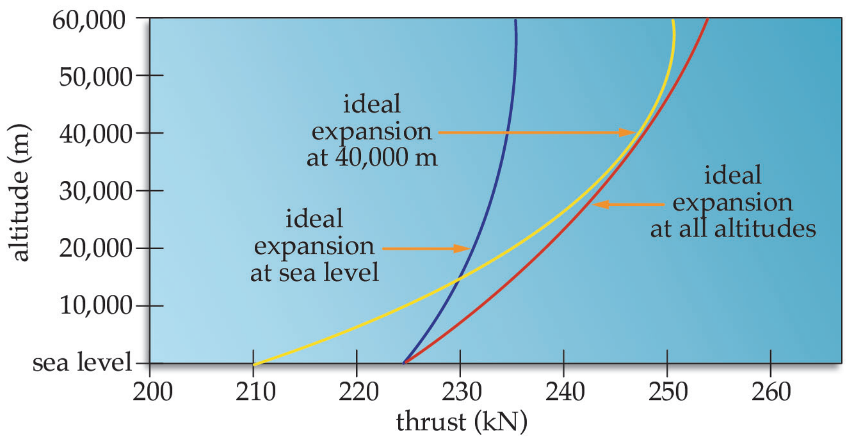


Figure 4.2.1-52. Thrust Versus Altitude for Different Nozzle Designs. Because we can't build an ideally expanded nozzle for all altitudes, we typically design them for ideal expansion 2/3 of the way up. In this example, we design a nozzle that must work from sea level to 60,000 m altitude for ideal expansion at 40,000 m. This design offers better overall performance than a nozzle designed for ideal expansion at either sea level or 60,000 m.

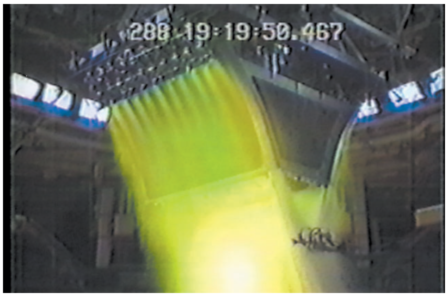


Figure 4.2.1-53. An Inside-out Nozzle. Unlike a conventional bell-shaped nozzle, the linear aerospike nozzle, being developed by Boeing/Rocketdyne for NASA's X-33 program allows expansion to take place outside. This offers the advantage of near ideal expansion from lift-off to orbit adding up to 10% efficiency, crucial for the goal of a single-stage-to-orbit rocket. *(Courtesy of NASA/Marshall Space*

One ingenious way around this nozzle-design problem is to use a completely different kind of nozzle. During our discussion of nozzle expansion issues in Section 4.2.1.1, we focused on conventional "bell-shaped" nozzles for simplicity. However, another more versatile design may one day be used on launch vehicles—an aerospike. An old idea, the aerospike nozzle has only recently become the focus of large-scale development to support NASA's X-33 program. Unlike a conventional bell nozzle, in which all exhaust-gas expansion takes place inside the nozzle, the aerospike allows expansion on the outside. In the linear aerospike design being developed by Boeing/Rocketdyne, shown in Figure 4.2.1-53, the throat is at the edge of a sloping "ramp" that forms the nozzle. The total expansion is determined by the atmospheric pressure, as well as the shape and length of the ramp. The big advantage of this design for a launch vehicle is that it offers near ideal expansion from lift-off to orbit, adding up to 10% efficiency—crucial for the goal of single-stage-to-orbit vehicles. We'll see what makes single-stage-to-orbit so challenging later in this section.

Navigation, Guidance, and Control Subsystem

In Section 4.3.1, we discuss the control problems handled by the spacecraft's attitude and orbit control subsystem (AOCS). A launch vehicle must deal with these same problems in a much more dynamic environment. The navigation, guidance, and control (NGC) subsystem keeps the launch vehicle aligned along the thrust vector to prevent dangerous side loads, keeps the thrust vector pointed according to the flight profile, and ensures the vehicle reaches the correct position and velocity for the desired orbit.

As with all control systems, the NGC subsystem has actuators and sensors. The primary launch-vehicle actuators are the main engines, which use thrust vector control and throttling to get the rocket where it needs to go. NGC sensors typically include accelerometers and gyroscopes to measure acceleration and attitude changes. Even though the accuracy of these sensors drifts over time, they are usually accurate enough for the few minutes needed to reach orbit. New launch vehicles are starting to rely on the Global Positioning System (GPS) for more position, velocity, and attitude information.

Communication and Data Handling

Throughout launch, the vehicle must stay in contact with the Launch Control Center. There, flight controllers continually monitor telemetry from the launch-vehicle subsystems to ensure they're working properly. To do this, the vehicle needs a communication and data-handling subsystem to process onboard data and deliver telemetry to the control center. Data-handling equipment for launch vehicles is very similar to the equipment used on spacecraft. Computers process sensor information and compute commands for actuators, as well as monitor other onboard processes. On expendable vehicles, these subsystems can be relatively simple because they need to work for only a few minutes during launch and won't be exposed to long periods of space radiation. However, the vibration and acoustic environments require these systems to be very rugged.

Communication equipment is also very similar in concept to those found on spacecraft. However, for safety reasons, operators need an independent means of tracking a launch vehicle's location on the way to orbit. In the Launch Control Center, Range Safety Officers monitor a launch vehicle's trajectory using separate tracking radar, ready to send a self-destruct command if it strays beyond the planned flight path to endanger people or property.

Electrical Power

Electrical-power requirements for launch vehicles are typically modest compared to a spacecraft's. Launch vehicles need only enough power to run the communication and data-handling subsystems, as well as sensors and actuators. Because of their limited lifetimes, expendable launch vehicles typically rely on relatively simple batteries for primary power during launch. The Space Shuttle uses fuel cells powered by hydrogen and oxygen.

Structure and Mechanisms

Finally, we must design the launch vehicle's structures and mechanisms to withstand severe loads and do the many mechanical actuations and separations that must happen with split-second timing. A typical launch vehicle can have tens or even hundreds of thousands of individual nuts, bolts, panels, and load-bearing structures that hold the subsystems in place and take the loads and vibrations imposed by the engines' thrust and the atmosphere's dynamic pressure.

Because most of a launch vehicle's volume contains propellant tanks, these tanks tend to dominate the overall structural design. Often, they become part of the primary load-bearing structure. For example, the Atlas launch vehicle, shown in Figure 4.2.1-54, uses a thin-shelled tank that inflates with a small positive pressure to create the necessary structural rigidity.

In addition to the problem of launch loads and vibrations, hundreds of individual mechanisms must separate stages and perform other dynamic actions throughout the flight. These mechanisms are usually larger than similar mechanisms on spacecraft. During staging, large sections of the vehicle's structure must break apart, usually through explosive bolts. Gimbaling the massive engines to change their thrust direction requires large hinges, hydraulic arms, and supporting structure.

Launch-vehicle designers have the challenge of carefully integrating all of these structures and mechanisms with the engines, tanks, and other subsystems to create a compact, streamlined vehicle. Sadly, for expendable vehicles, all the painstaking design and expensive construction and testing to build a reliable launch vehicle burns up or drops in the ocean within 10 minutes after launch! Figure 4.2.1-55 shows a cut-away view of the Ariane V launch vehicle. As you can see, the structure is mostly propellant tanks

Figure 4.2.1-54. Atlas Inflated for Launch. To provide structural rigidity on the Atlas launch vehicle, the thin aluminum skin of the propellant tanks were inflated like balloons. *(Courtesy of the U.S. Air Force)*

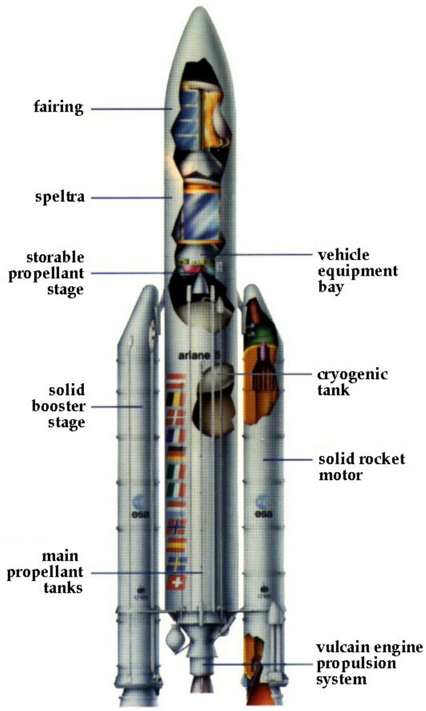


Figure 4.2.1-55. Ariane V Cut-away. Most of the mass and volume of this giant booster consists of propellant tanks. *(Courtesy of Arianespace/European Space Agency/Centre National D'Etudes Spatiales)*

and engines. All the other subsystems squeeze into small boxes, tucked into the secondary structure. Notice this vehicle, and all launch vehicles in use, have several sets of engines. Each set comprises a separate stage. Next, we'll see why all these stages are needed to get a spacecraft to orbit.

Staging

Getting a payload into orbit is not easy. As we showed in Section 4.2.1.2, the state-of-the-art in chemical rockets (the only type available with a thrust-to-weight ratio greater than 1.0) can deliver a maximum I_{sp} of about 470 s. Designers must account for the velocity change, ΔV, needed to get into orbit and the hard realities of the rocket equation. So they must create a launch vehicle that is mostly propellant. In fact, more than 80% of a typical launch vehicle's lift-off mass is propellant. Large propellant tanks that also add mass contain all this propellant. Of course, the larger the mass of propellant tanks and other subsystems, the less mass is available for payload.

One way of reducing the vehicle's mass on the way to orbit is to get rid of stuff that's no longer needed. After all, why carry all that extra tank mass along when the rocket engines empty the tanks steadily during launch? Instead, why not split the propellant into smaller tanks and then drop them as they empty? Fighter planes, flying long distances, use this idea in the form of "drop tanks." These tanks provide extra fuel for long flights and can be dropped when they are empty, to lighten and streamline the plane. This is the basic concept of staging.

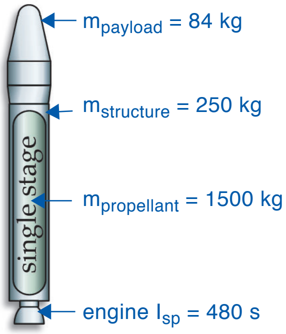
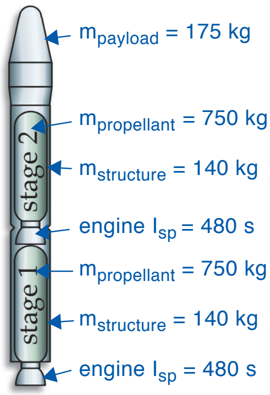
Figure 4.2.1-56. Saturn I during Staging. When a launch vehicle, such as the Saturn I shown here in an artist's concept, stages, it shuts off the lower-stage rocket, separates it, and ignites the rocket on the next stage to continue into orbit. *(Courtesy of NASA/Kennedy Space Center)*

Stages consist of propellant tanks, rocket engines, and other supporting subsystems that are discarded to lighten the launch vehicle on the way to orbit. As the propellant in each stage is used up, the stage drops off, and the engines of the next stage ignite (hopefully) to continue the vehicle's flight into space. As each stage drops off, the vehicle's mass decreases, meaning a smaller engine can keep the vehicle on track into orbit. Figure 4.2.1-56 shows an artist's concept of the Saturn I vehicle staging on the way to orbit.

Table 4.2.1-11 gives an example of how staging can increase the amount of payload delivered to orbit. For this simple example, notice the two-stage vehicle can deliver more than twice the payload to orbit as a similar-sized, single-staged vehicle with the same total propellant mass—even after adding 10% to the structure's overall mass to account for the extra engines and plumbing needed for staging. This added payload-to-orbit capability is why all launch vehicles currently rely on staging.

In Table 4.2.1-11, for both cases, the mass of the payload delivered to orbit compared to the mass of the entire launch vehicle is pretty small—5% or less. About 80% of a typical vehicle is propellant. The other 15% or so includes structure, tanks, plumbing, and other subsystems. Obviously, we could get more payload into space if the engines were more efficient. However, with engines operating at or near the state-of-the-art, the only other option is to shed empty stages on the way into orbit.

Table 4.2.1-11. Comparing Single-stage and Two-stage Launch Vehicles.

<table>
<tr><th>Launch Vehicle</th><th>Parameters</th><th>Payload to Orbit</th></tr>
<tr><td>Single Stage

</td><td>ΔV_{design} = 8000 m/s
I_{sp} = 480 s
$m_{structure}$ = 250 kg
$m_{propellant}$ = 1500 kg</td><td>$m_{payload}$ = 84 kg</td></tr>
<tr><td>Two Stage

</td><td>ΔV_{design} = 8000 m/s
Stage 2
I_{sp} = 480 s
$m_{structure}$ = 140 kg
$m_{propellant}$ = 750 kg
Stage 1
I_{sp} = 480 s
$m_{structure}$ = 140 kg
$m_{propellant}$ = 750 kg</td><td>$m_{payload}$ = 175 kg</td></tr>
</table>

Overall, staging has several unique advantages over a one-stage vehicle. It

- Reduces the vehicle's total mass for a given payload and ΔV requirement
- Increases the total payload mass delivered to space for the same-sized vehicle
- Increases the total velocity achieved for the same-sized vehicle
- Decreases the engine efficiency (I_{sp}) required to deliver a same-sized payload to orbit

But, as the old saying goes, "There ain't no such thing as a free lunch" (or launch)! In other words, all these staging advantages come with a few drawbacks

- Increased complexity because of the extra sets of engines and their plumbing
- Decreased reliability because we add extra sets of engines and the plumbing

- Increased total cost because more complex vehicles cost more to build and launch

Another interesting limitation of staging has to do with the law of diminishing returns. So far, you may be ready to conclude that if two stages are good, four stages must be twice as good. But this isn't necessarily the case. Although a second stage significantly improves performance, each added stage enhances it less. By the time we add a fourth or fifth stage, the increased complexity and reduced reliability offset the small performance gain. That's why most launch vehicles in use have only three or four stages.

Getting into space is expensive. In some cases, the price per kilogram to orbit is more than the price per kilogram of gold! In an ongoing effort to reduce the cost of access to space, researchers are looking for ways to make launch vehicles less expensive. One of the most promising ways is to make the entire vehicle reusable. One company, Kistler Aerospace, is trying to do this with a two-stage vehicle design (see the Mission Profile at the end of this chapter).

Figure 4.2.1-57. Single-stage-to-orbit (SSTO). Although it never got off the ground as shown in this artist's conception, the X-33 program pioneered many key technologies. They may one day help us build an efficient rocket that uses a single stage to orbit. *(Courtesy of NASA/Marshall Space Flight Center)*

The ultimate goal would be a single-stage-to-orbit vehicle that could take off and land as a single piece, offering airline-like operations. But the technical challenges in propulsion and materials to overcome the limitations of a single stage are formidable. The goal of NASA's X-33 program, shown in Figure 4.2.1-57, was to push the state of the art in rocket engines (the aerospike design described earlier), materials, computer-aided design and fabrications, and operations. One day, the successors to this pioneering program may give all of us the ability to live and work in space routinely.

Section Review

Key Concepts

- Launch-vehicle subsystems are similar in many ways to spacecraft subsystems, discussed in Chapter 13. The main differences include
  - Total lifetime (minutes rather than years)
  - Propulsion subsystem requirements (see the next bullet)
- Launch-vehicle propulsion subsystems must be designed for
  - Thrust-to-weight ratio greater than 1.0
  - Throttling and thrust-vector control
  - Optimum ratio of nozzle expansion
- By staging launch vehicles, we can
  - Reduce the total vehicle mass for a given payload and ΔV requirement
  - Increase the total mass of the payload delivered to space for the same-sized vehicle
  - Increase the total velocity achieved for the same-sized vehicle
  - Decrease the engine efficiency (I_{sp}) required to deliver a same-sized payload to orbit
- But staging also has several disadvantages
  - Increased complexity because the vehicle needs extra engines and plumbing
  - Decreased reliability because we add extra sets of engines and the plumbing for the upper stages
  - Increased total cost because a more complex vehicle costs more to build and launch

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