Getting to Orbit

5

Rocket Science and Engineering

THE way rockets work is still a bit of a mystery to most people. A common misconception is the belief that they do not work unless the rocket exhaust has something to push against. I still have a vivid memory of this myself as a child; it was obvious to me that the early rockets taking the first pioneering astronauts into orbit rose majestically from their launching pads only because they were able to push against the ground and atmosphere. Clearly, my powers of thought did not stretch to face the dilemma of what happened once the rocket was whizzing about in space, with nothing to push against!

Another false impression in my view is the idea that rocket science is something that is really complicated. As we know, the phrase itself has become a byword in colloquial English for something that is complex and difficult to understand. For example, a neighbor of mine finds herself living between me on the one side and a hospital surgeon on the other, and recently commented that she felt wedged between a rocket scientist and brain surgeon! However, it is my humble opinion that the business of brain surgery is a lot more complicated, and in this chapter I hope to convince readers that the science of rockets is conceptually simple.

On the other hand, the engineering of rockets is another matter entirely. The rocket engine poses major challenges to the engineers who wish to transform the simple concept into high performance hardware. We can get a feeling for this challenge if we think about what happens each time a space shuttle is launched into Earth orbit. The shuttle orbiter's mass is on the order of 100 metric tonnes, and needs to be accelerated to a speed of approximately 8 km/sec (5 miles/sec) to reach orbit. When you consider that the amount of energy needed to do this is equivalent to around 700 metric tonnes of the high explosive TNT, you begin to appreciate the magnitude of the problem. This amount of energy has to be released gradually and in a controlled manner over a period of minutes by the rocket engines, and the consequences of a mistake are catastrophic. The processes involved in this controlled release of energy places the rocket hardware

G. Swinerd, *How Spacecraft Fly: Spaceflight Without Formulae,*
DOI: 10.1007/978-0-387-76572-3_5,

under significant mechanical and thermal stresses that are difficult for the engineers to manage.

This is why the business of launching spacecraft into orbit is such a risky business. For most current launcher systems, a *reliability* of 90%, that is, nine flights in 10 are successful, is considered to be acceptable. With the most reliable launch system, the space shuttle, the reliability increases to around 99%, which is considered to be very good for a conventional launch system. However, if you think of it in terms of the reliability of civil air transport, clearly space transportation has a great deal of room for improvement. If you were told that you had one chance in 100 of not reaching your holiday destination on an airliner, my guess is that you would probably stay at home!

Many people have become rather blasé about the whole business of manned space flight, but when the chips are down, the men and women who do this are literally staking their lives on the successful operation of a highly stressed piece of rocket hardware. If you are a young scientist or engineer, and wish to make your name and fortune, then a new and safer way of achieving orbit is a problem worth addressing. But it is a rather difficult one to crack; perhaps one of those "Beam me up, Scotty" machines that some of us have grown up with on *Star Trek* would be a contender!

Replacing Newton's Cannon

In Chapter 2, we discussed the nature of orbital motion using Newton's cannon as a means of achieving orbit. Clearly we do not have a handy 200-km-high (124-mile-high) mountain upon which to build such a structure, so instead we resort to rocket-powered launch vehicles to place our satellites into orbit. It is fairly easy to see how the substitution is made. As we saw earlier, to enter a low orbit around Earth, a cannonball needs to be traveling horizontally out of the cannon's barrel at around 8 km/sec (5 miles/sec) at an altitude of 200 km. Thereafter, we saw that the curvature of the cannonball's trajectory matched that of Earth's surface, thus avoiding ground impact and ensuring the cannonball's orbital state. If we wish to launch a satellite installed on top of a launch vehicle into the same orbit, then we have to ensure that the same *initial conditions* are met; if the launcher can lift the satellite to an altitude of 200 km and boost its speed to the required 8 km/sec in a horizontal direction, then the same orbital motion will result.

The launch vehicle is more versatile than the cannon, as the latter is somewhat constrained in its performance by being fixed to its supporting platform—the mountain—at a 200-km altitude. If the launcher is powerful enough, it can lift the satellite to higher altitudes, and vary the satellite's initial speed and direction to enter a variety of orbits as discussed in Chapter 2. For example, if the launch vehicle were to release its payload at a height of 700 km (435 miles) in a horizontal direction with a speed of 7.5 km/sec (4.7 miles/sec), the satellite will enter a circular orbit at that altitude. Furthermore, if the satellite was to be released in the same way at this height with a speed of 10.6 km/sec (6.6 miles/sec), then it would eventually escape Earth on a parabolic trajectory (see Chapters 1 and 2).

It *Is* Rocket Science . . .

The surprising thing about a rocket engine, as we have already intimated, is that the concept is not at all complicated. It does not have complex mechanisms like pistons going up and down as in an automobile engine. Instead, it comprises only three basic parts: a *propellant feed system*, a *combustion chamber* where the fuel is burned, and a *nozzle* out of which the resultant hot gases are exhausted. And that's it.

If we're thinking about rocket engines used on launch vehicles, then it is obvious that they need to be big. For example, all the components of a space shuttle sitting on the launch pad have a combined mass of about 2000 metric tonnes! The rocket engines—five of them in this case—have to produce enough thrust between them to match the vehicle weight, and then a bit more to move it vertically off the pad, as beautifully illustrated in Figure 5.1. Two types of rocket engine are used by the shuttle to gain orbit, the *solid propellant motor* and the *liquid propellant motor*, and these are the most commonly used systems on launchers.

The *solid propellant motor* (Fig. 5.2a) is a bit like a giant firework, inasmuch as you light it, and it burns to produce thrust until the solid propellant is exhausted. To burn the fuel in any rocket system, we need oxygen. In an airplane, the fuel is burned using oxygen taken from the atmosphere through the engine intakes. However, since there is no atmospheric oxygen available as the launcher approaches orbital altitudes, the rocket system has to take its own oxygen with it. For a solid propellant motor, the fuel and oxidizer are mixed together in a gooey substance, which is then poured into molds to set hard. Often the molds are shaped to produce sections of solid propellant like giant disks with a hole punched through the middle, which are then stacked in the rocket's cylindrical casing to produce the configuration shown in Figure 5.2b. The rocket is then lit by a *pyrotechnic device*, usually at the top of the rocket, and the propellant burns from the inside of the cylinder outward toward the metal casing, until depleted.

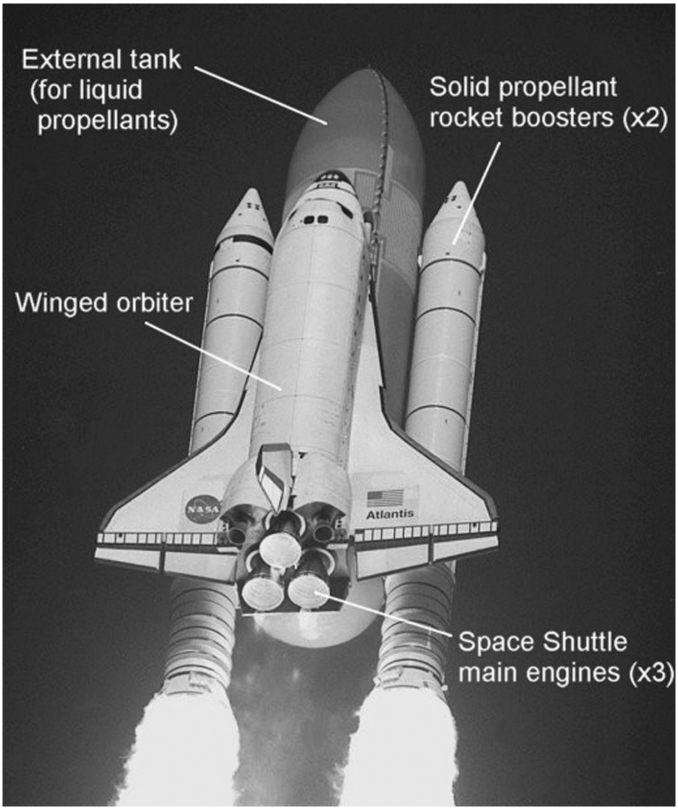

Figure 5.1: The components that make up the space shuttle launch system. (Image courtesy of the National Aeronautics and Space Administration [NASA].)

The space shuttle uses two large solid propellant rocket boosters for its first two minutes of flight, which use a combined fuel and oxidizer solid propellant. When the system was designed in the 1970s, a decision was made to use solid propellant boosters, mainly to constrain costs. Many of the rocket scientists involved were unhappy about their use on a system designed to carry people. The basis of this concern was the fact that solid rockets are less controllable than their liquid propellant counterparts, the main worry being that once a solid rocket is ignited, it cannot be stopped until the fuel is exhausted. The boosters used on the shuttle have a large thrust, and have to be ignited simultaneously at the moment of lift off. If one were to fail to ignite at that critical moment, the resulting asymmetry in the vehicle's thrust would be catastrophic.

The *liquid propellant rocket motor* (Fig. 5.3) is a little more complicated, requiring a propellant feed system, in addition to the combustion chamber

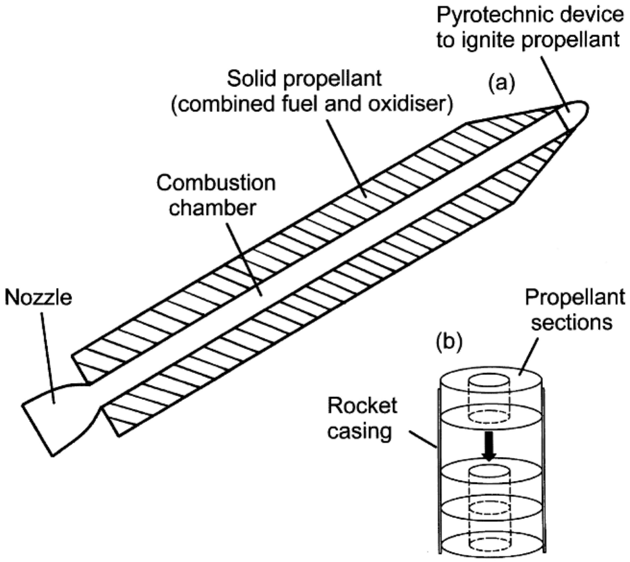

Figure 5.2: (a) The elements comprising a typical solid propellant rocket. (b) The assembly of the solid propellant sections in the rocket casing.

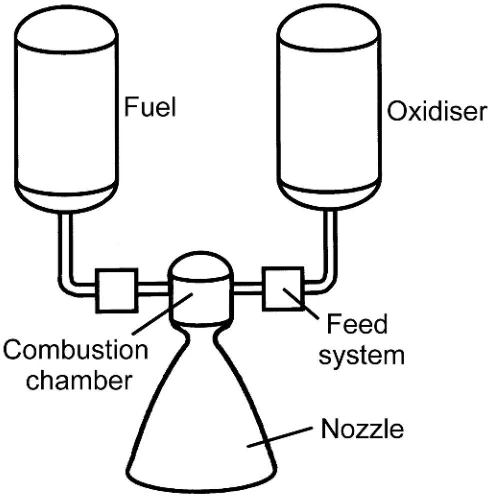

Figure 5.3: Schematic of the components of a liquid propellant rocket motor.

and rocket nozzle. In this case, the launcher carries its fuel and oxidizer in separate tanks, with a feed system—usually pumps—to shift the liquids into the combustion chamber, where they are ignited to produce a highly pressurized hot gas that exits through the nozzle of the engine to produce thrust. As we will see in a moment, the faster the exhaust gases exit the nozzle, the better. The internal cross section of the nozzle has a particular profile, first converging to form a *throat* and then diverging to form the familiar bell shape. The exhaust gases accelerate as they squeeze through the throat, typically reaching the local speed of sound. Thereafter, the gases continue to accelerate and expand in the *divergent section*, ensuring a high *exit speed* and ideally an *exit pressure* near to the ambient atmospheric pressure.

Since the propellant can be supplied to the combustion chamber in a controlled manner through the feed system, liquid propellant rockets are inherently more controllable, allowing the thrust level to be varied and the rocket to be turned on and off if required. There are a variety of fuel and oxidizer combinations, but commonly used ones are *hydrogen/oxygen* and *kerosene/oxygen*.

In addition to the two solid propellant boosters mentioned above, the space shuttle also requires the use of three liquid propellant rocket motors to acquire orbit; these are referred to as the *space shuttle main engines* (SSMEs). It is these liquid-powered rocket engines that continue to operate to take the vehicle to orbit, once the solid propellant boosters are depleted and fall away. The SSMEs use a combination of hydrogen and oxygen as fuel and oxidizer, respectively. These gases need to be cooled to very low temperatures to produce a *cryogenic liquid*, and these are stored in the large insulated external fuel tank prior to launch (see Fig. 5.1).

Action and Reaction

Why does exhausting a hot gas through a nozzle produce a force that propels the rocket vehicle to high speeds? Once again, Isaac Newton comes to the rescue in answering this question.

There are two main thrust effects occurring to allow the rocket vehicle to accelerate in the atmosphere, and in the vacuum of space where there is nothing to push against! They are referred to as pressure thrust and impulse thrust, the latter being by far the dominant source of thrust force in a rocket system.

The way that *pressure thrust* works is easily understood by thinking about a bottle of carbonated soda (Fig. 5.4). When the bottle is sealed, the pressure forces inside are equal on all sides of the container, and there is no resultant force. However, if we remove the cap, an imbalance occurs producing a net force (which is small in this case). The bottle with the cap removed is analogous to the rocket engine combustion chamber with the open exit nozzle; there is some propulsive force produced by the pressure imbalance.

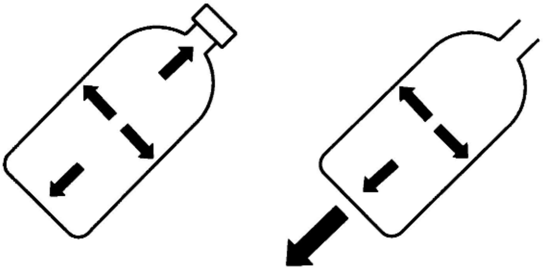

Figure 5.4: A pressure imbalance produces pressure thrust.

To understand the dominant propulsive effect, the *impulse thrust,* we need to recall Newton's laws of motion discussed in Chapter 1, and in particular his third law: to every action there is an equal and opposite reaction. Put simply, the action of a rocket engine is to throw lots of mass at high speed out the back of a launch vehicle, and the reaction is to cause the vehicle as a whole to accelerate in the opposite direction. To see this more clearly, we can propose an experiment to demonstrate the principle, but, again, do not try this at home! All you need for this is a high-velocity rifle, a skateboard, and a good sense of balance to stop you falling off the skate board when you fire the gun! A fired rifle produces a "kick": when the trigger is pulled, the bullet flies out of the barrel at high speed in one direction, and the gun reacts alarmingly by kicking back on the shooter's shoulder. It is this kick that can be harnessed as a propulsive force if we fire the gun while standing on the skateboard (Fig. 5.5). Let's suppose that the combined mass of the shooter, the rifle, and the skateboard is 75 kg. Let's suppose that the bullet has a mass of 50 g and leaves the barrel of the gun at 1500 m/sec (4920 feet/sec). We can

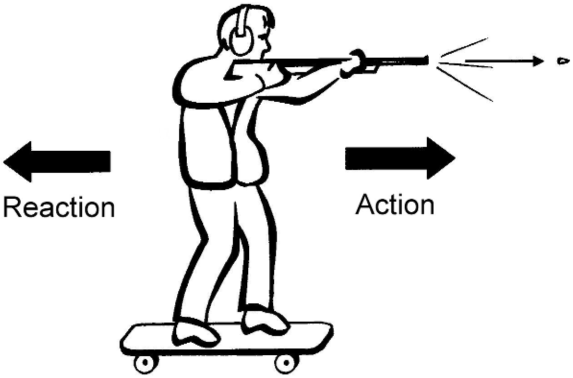

Figure 5.5: A "thought experiment" involving a high-velocity rifle and a skateboard!

do some simple calculations to show that if the shooter gets on the skateboard and fires the gun, the kick will give them a speed of 1 m/sec (3 feet/sec) in the other direction. That's just over 2 mph, which is less than a good walking pace, so our improvised rocket system is not that good at producing propulsive force. But it does illustrate the effect of impulsive thrust. In a real rocket system, the designers strive to eject lots of "bullets"—in this case the *exhaust gases* from the engine nozzle—at high speed to maximize the reaction to accelerate the vehicle in the opposite direction.

Note that the two sources of rocket thrust are closely related. Clearly, the hole in the combustion chamber where the nozzle exit is located causes a pressure imbalance, giving a measure of pressure thrust. Also, equally clearly, if you have a hole with high pressure gas inside and low pressure gas outside, then you are definitely going to get mass coming out, providing impulse thrust. Although the two effects are distinguishable in the mathematics of rockets systems, physically they are closely linked.

Some Fundamental Propulsion System Numbers

There are principally two numbers that rocket scientists use to assess a rocket's performance and to compare one system with another: thrust and specific impulse.

Thrust is a fairly intuitive idea, and is basically the level of force provided by the rocket to accelerate the vehicle. You may recall from Chapter 3 (see the discussion on aerodynamic forces on spacecraft) that the thrust force is usually measured in Newtons. A Newton of force has a formal definition, but you may remember our approximate and informal definition, which is that it is about the weight of a (smallish) apple! Another helpful measure, when thinking about the large forces associated with launcher engines, is that a metric tonne weight is about 10,000 Newtons. Again, in the space shuttle system each of the three SSMEs has a thrust of the order of 2 MN (a MN is a MegaNewton, which is 1,000,000 N), and the thrust of each of the two solid propellant boosters is approximately 10 MN.

Specific impulse, measured in units of seconds, is not an intuitive concept, but it is an important one since it gives a measure of how much change in speed can be achieved by a rocket system for a given mass of propellant. For example, a liquid propellant rocket motor using hydrogen/oxygen as a fuel/oxidizer combination has a typical specific impulse of 450 seconds, whereas a solid propellant rocket has a value around 250 seconds. To see the relevance of the specific impulse, we can envisage two rocket vehicles with the same initial mass, one powered by the liquid propellant motor and one with a solid motor. If each rocket burns exactly the same amount of propellant, the change in speed achieved by the liquid propelled vehicle will be 450/250, that is ~1.8 times the speed change achieved by the solid propelled vehicle. The reason why the liquid powered rocket does so much better is that it is ejecting exhaust gases out of its rocket nozzle at a much higher speed than that achieved by the solid propellant motor. This observation provides another, perhaps more physical interpretation of the specific impulse parameter—a high specific impulse implies a high exhaust velocity. Generally speaking, the higher the specific impulse, the better.

Some More "Gee-Whiz" Information About the Space Shuttle

The rocket systems that we have discussed are fundamentally simple in concept, but as we have already said at the beginning of this chapter, it is the engineering implementation of these simple concepts that represent the major challenges for launch vehicle designers and manufacturers. The SSMEs, with a specific impulse of around 450 seconds, are considered to be the best you can do currently for a chemical propulsion system. They are designed to be reusable, which is extraordinary when you consider the mechanical and thermal stresses involved in their 8 minutes of operation from ground to orbit.

The shuttle has three liquid-fueled SSMEs, and the description of the attributes of just one of these fills me with admiration for the engineers who have transformed the concept into reality! The combustion chamber operates routinely at a temperature of around 3300°C, which is approximately twice the melting point of steel. To get the high exhaust velocity, the combustion chamber pressure is equivalent to about 200 times atmospheric pressure. With this magnitude of pressure, the propellant feed system has to be substantial to be able to push the fuel and oxidizer into the chamber against that pressure. The turbopumps that perform this function rotate at about 37,000 rpm to provide chamber inlet pressures of 305 atmospheres for the liquid oxygen and 420 atmospheres for the liquid hydrogen, with a total fuel flow rate of 470 kg/sec—nearly half a metric tonne a second! The resulting thrust level is around 2 MN, with a nozzle exhaust velocity of roughly 4500 m/sec (14,800 feet/sec).

At the moment of takeoff, the space shuttles engines are throwing an awful lot of hot gas down into the flame trench of the launch pad, about one and a half metric tonnes per second of exhaust gases, traveling at about 4500 m/sec, from the three SSMEs, and about 8 metric tonnes per second at a speed of 2500 m/sec (8200 feet/sec) from the two solid propellant boosters—a little bit more of a kick than our 50-g high-velocity bullet traveling at 1500 m/sec! There is clearly a lot of destructive power here that needs to be managed to prevent damaging the launch pad. To deal with this, what might be called the "space shuttle swimming pool" comes to the rescue. In a recent IMAX big screen 3D film of the International Space Station, one spectacular sequence showed the launch of a space shuttle at close quarters. The controlled power of the vehicle was overwhelming to watch! But one striking thing that came over clearly was the cascade of water that is released into the flame trench from the "swimming pool" just prior to ignition of the SSMEs. The energy in the high-speed jets of hot gas from the engines is consumed in the process of converting all that water into steam rather than causing significant damage to the launch pad.

Ascent to Orbit

There are a variety of types of launch vehicle, ranging from expendable to totally reusable. However, most of the traffic to orbit currently is in the form of *expendable launch vehicles* (ELVs). As the name implies, these vehicles are used only once, and their various components are jettisoned on the ascent or abandoned in orbit. In *semi-reusable launch vehicles,* of which the space shuttle is the only current example, some parts of the vehicle are destined for reuse on subsequent flights, such as the winged orbiter and the solid propellant booster casings (see Fig. 5.1). Other parts such as the huge orange external fuel tank are jettisoned on the ascent, and subsequently reenter the atmosphere and burn up over, or plunge into, the ocean.

In *reusable launch vehicles,* of which there is are no current examples, the launcher is operated somewhat like an airplane to significantly reduce operational costs. The development of such a launch system is the "Holy Grail" of rocket scientists at the moment, but, as we will see later, the technical challenge is significant, and the likely development cost a deterrent! It seems probable that this will first be achieved under the umbrella of a military program, where financial resources are perhaps less of an issue. The description *man-rated* can also be applied to any of the three types mentioned above, which implies that the launch vehicle has been developed to carry people into orbit; for example, the shuttle can be referred to as a man-rated semi-reusable launch vehicle. Applying the man-rated label to a launch vehicle has major technical implications, as the reliability must be significantly better than the 90% or so, typical of an unmanned ELV system. And the required improvements in reliability will cause a significant increase in the launch vehicle's development costs.

Dynamics of the Launcher

We now turn to the dynamics of the launcher as it rises to orbit. The launch of a spacecraft is conducted in a particular way, in order to ensure that the launch vehicle can carry a good payload mass into orbit. Three of the most commonly used strategies to attempt to maximize the launcher's payload mass are discussed in the following subsections.

Staging

A typical expendable launch vehicle adopts the method of *staging* to reach orbit, which involves shedding mass on the ascent. The vehicle is made up of stages, usually three, as illustrated in Figure 5.6. The launcher is lifted from its pad using the first-stage engines. The vehicle then climbs and accelerates until the first-stage fuel is exhausted. At this point, the first stage separates and falls back to Earth; there is no need to lift the first stage to orbit since it would serve no purpose there. It is jettisoned to save the expenditure of precious propellant in accelerating useless mass to orbit. After separation, small rocket thrusters are often fired in the first stage to slow the rocket down and move it away from the second-stage engines. At this point, prior to the ignition of the second-stage engines, the upper stages and satellite payload are in a state of free-fall—like the hypothetical elevator discussed in Chapter 2. As a consequence, the second-stage propellant and oxidizer are effectively in a state of weightlessness in the tanks. To settle the liquids again at the base of the tanks, in order to feed them into the combustion chamber, small rocket thrusters attached to the second stage are fired to speed it up. This acceleration produces a bit of artificial gravity to aid this necessary management of the propellant. The second-stage main engines are then fired to continue the powered ascent to orbit. When the second-stage fuel is used up, the process is repeated; the second stage too is jettisoned, before the third-stage engine is lit to take the satellite payload to orbital speed and altitude. It is often the case that the third stage and satellite payload are both injected into the final orbit.

Staging is a vital strategy in the operation of a conventional expendable launch vehicle. Fuel mass is not wasted accelerating rocket components to orbit where they would be useless, but instead is used to maximize the mass of the spacecraft being launched. Also the change in speed required to reach orbit is acquired using conservative engine technology in each stage. Rocket

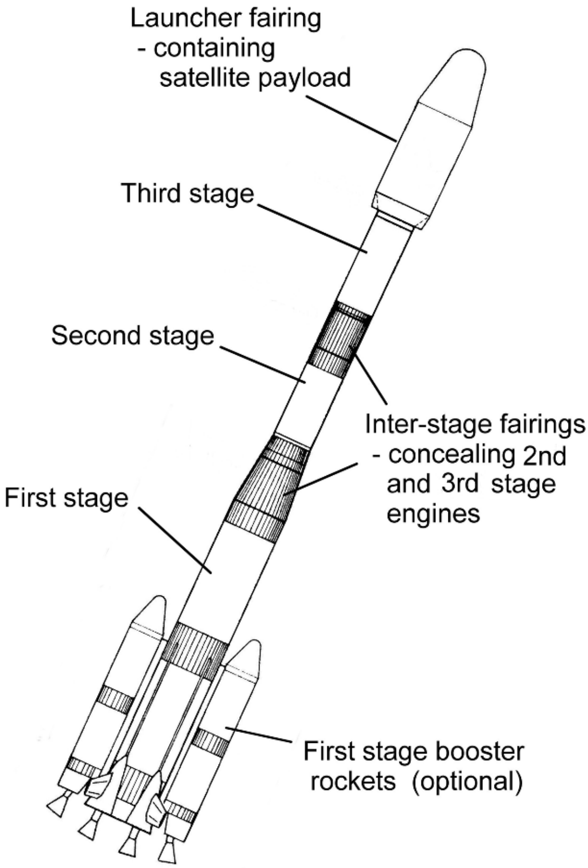

Figure 5.6: The components of a typical three-stage expendable launch vehicle. (Backdrop image courtesy of Arianespace.)

engines having lower specific impulses can be used (lower certainly than the high performance space shuttle main engines), which implies lower combustion temperatures and pressures. This in turn means that the level of mechanical and thermal stress imposed on the engine components is generally less, which is good news for engine reliability and costs.

Ascent Trajectory Optimization

Another aspect ensuring that the launch vehicle can carry a good payload mass into orbit is the optimization of the ascent trajectory. This is a mathematics- and computer-intensive activity, usually carried out by the launch agency, to minimize the amount of rocket propellant needed to reach the desired orbit. If we achieve this minimization of fuel mass, then it follows that we can invest the resulting mass savings in making the spacecraft payload that the launcher it is carrying bigger and more capable. Clearly, the ascent trajectory optimization is an important task, and if not done correctly it can seriously compromise the vehicle's launch capability.

Despite the mathematical complexities of the process, we can gain some understanding of the ascent optimization by thinking about the tasks achieved by the launcher's propellant on the ascent. First, and most obviously, propellant mass is used to gain speed; the launcher starts out with effectively zero speed on the launch pad, and has to be accelerated to around 8 km/sec (5 miles/sec) to achieve a low Earth orbit (LEO). Second, and perhaps less obviously, propellant mass is used to overcome the forces of gravity and aerodynamic drag, which act on the launcher during its ascent.

Expending propellant to overcome gravity is referred to as *gravity loss.* This idea is nicely illustrated by a vertical takeoff aircraft, like a Harrier jump jet, when it hovers just above the ground. In this state, it is using its fuel entirely for the purpose of overcoming the force of gravity. Similarly, if a launcher's ascent trajectory has an uphill slope—and yes, of course, it would have to in order to reach orbit—then some part of its fuel is being used the overcome the force of gravity. When the launch vehicle is initially climbing vertically from its launch pad, the gravity loss incurred is large, but if it can roll over into a more gently sloping flight path soon afterward, the gravity loss is reduced.

Propellant is also used to overcome aerodynamic forces (see also the discussion of aerodynamic forces acting on spacecraft in Chapter 3), principally drag, acting on the launch vehicle during the ascent. This is referred to as *drag loss.* We can feel the effect of aerodynamic drag by holding a hand out of an open car window on a summer's day; the flow of air produces a force on your hand that resists its motion through the air. By this simple means we can also get an idea of how the drag force varies with speed. For example, the drag force on your hand feels much more significant at 60 mph than at 30 mph. If you were able to measure it, you would find the force at 60 mph to be four times bigger than the force at 30 mph, suggesting that the drag force varies as the square of the speed. As the launcher's speed doubles, the drag force increases by a factor of 4 (2^2), and as its speed trebles the drag increases by a factor of 9 (3^2), and so on. Given the speed that the launcher ultimately attains to reach orbit, this sounds like bad news, but the saving grace is that the drag loss occurs only in the lower, denser part of the atmosphere from which the launcher can escape fairly quickly.

The magnitudes of the gravity and drag losses are dependent on the launch vehicle being used, but typically if we are having to accelerate to a speed of 8 km/sec to reach orbit, we would have to burn propellant equivalent to an additional 1.0 to 1.5 km/sec to overcome gravity, and something like an extra 0.3 km/sec to combat the effects of drag.

Returning to our discussion of optimization of the ascent trajectory, we can now see that we want to design the flight path to ensure that most fuel is used to acquire speed, and that the amount used to overcome gravity and drag losses is minimized. One way of acquiring orbit is to ascend vertically to orbital height, and then rotate the launcher's flight path into the horizontal direction to inject into orbit. Although this strategy will minimize drag loss—the vehicle climbs vertically through the denser part of the atmosphere quickly—it does, however, entail accumulating a huge gravity loss. Alternatively, the launcher can climb into orbit on a gently sloping trajectory, like that of an airplane, with a small climb angle. In this case the gravity losses would be minimized, but the vehicle would spend a long time climbing out of the denser part of the atmosphere, thus yielding a large drag loss. An optimized trajectory, therefore, tries to take a path between these two extremes. Consequently, the launcher will climb vertically for a relatively short period to escape the denser part of the atmosphere (to minimize drag loss), and then roll over into a shallow climb (to minimize gravity loss) to acquire orbit. Figure 5.7 shows a space shuttle adopting this strategy.

Using Earth Rotation

As well as staging and trajectory optimization, a third way of improving the mass that a launch vehicle can take to orbit is to use Earth rotation. To get a feeling for this, we note that when the launcher is just sitting on its pad doing nothing, it is already moving eastward at significant speed due to the fact that Earth is rotating. The only places where this is not true are the North and South Poles, and I am not aware of any launch facilities in these polar regions, apart from perhaps submarines in the Arctic Ocean! The magnitude of this speed depends on the location of the launch site, or more precisely on its latitude. If the site is located on the equator, at zero latitude, then by virtue of Earth rotation it is traveling at about 465 m/sec (1525 feet/sec) in an eastward direction. This speed decreases as we move away from the equator; for example, at a latitude of 28 degrees north, corresponding to the Cape Canaveral launch site in Florida, the launch pads are moving at a rate of around 410 m/sec (1350 feet/sec). Further north at a latitude of 60 degrees, the eastward movement of Earth's surface has reduced to half of that at the equator, and at the North Pole it has reduced to zero. As I write this in southern England at a latitude of 52 degrees, it is amazing to think that I am rushing eastward due to Earth rotation at about 285 m/sec (940 feet/sec), but I cannot feel a thing!

Figure 5.7: A space shuttle launch, illustrating an optimized ascent strategy. (Image courtesy of NASA.)

Getting back to our launch vehicle, we can see that if we take off vertically but then roll over and head down range in an easterly direction, we can take advantage of the effect of Earth's rotation. For example, a rocket launched from my garden is already moving east at 285 m/sec before I light the blue touch paper, so if it is guided down range toward the east, it will burn less fuel to reach orbital speed. This means that the saving in propellant mass can be used to increase the size of the satellite payload being lifted to orbit. Another consequence of this eastward-directed launch strategy is that the orbital inclination (see Chapter 2) of the resulting orbit is about the same as the latitude of the launch site. The geometry of this is illustrated in Figure 5.8. Consequently, a space shuttle launched in this way from Cape Canaveral at a latitude of 28 degrees will end up in a LEO inclined at 28 degrees to the equator.

A result of all this is that large spacecraft, for example, the Hubble Space Telescope, the Space Shuttle, and the International Space Station, orbit in low-inclination LEOs. The savings in fuel usage as a result of using Earth rotation allow generally larger payloads to be launched into this type of orbit. Also launch sites for satellites destined for geostationary Earth orbit (GEO) (see Chapter 2) are usually sited near the equator with good range safety to the east. The safety requirement usually means no human habitation beneath the flight path, which is often satisfied by having an expanse of ocean to the east of the launch site. A good example of this is the launch facility at Kourou in French Guyana, at a latitude of 5 degrees north,

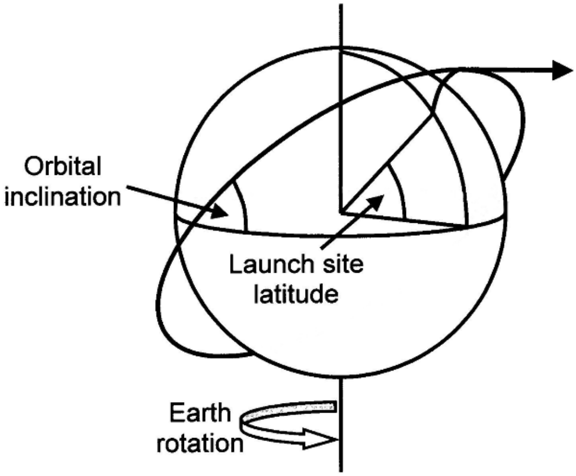

Figure 5.8: A launch in an easterly direction results in an orbit with an inclination approximately equal to the latitude of the launch site.

from where the Ariane family of expendable launch vehicles are launched predominately, eastward over the Atlantic Ocean.

But rockets are not always launched toward the east. For example, if the inclination of the mission orbit is required to be near 90 degrees, then the launch vehicle would have to fly either north or south from the launch site to achieve this. Therefore, Earth rotation is of no benefit, and reaching orbit is more costly in terms of fuel mass. Consequently, this increase in fuel mass must be compensated for by having a lower satellite payload mass, all other things being equal. Generally speaking, launcher performance is reduced in terms of payload mass when, for example, a near-polar mission orbit is required.

Launch Vehicle Environment and Its Effects on Spacecraft Design

Another attribute of the launch process, which has a major effect on the spacecraft design, is the *launch vehicle environment*. Usually the structural design of the spacecraft (see Chapter 9) is not governed by its lifetime in orbit, which could be 10 years, but rather by the few minutes it spends climbing to orbit on the launch vehicle. We have already seen how much energy has to be released in a controlled manner during this relatively short period of time to achieve an orbital state for the spacecraft. It is not too surprising, therefore, to realize that the spacecraft is exposed to a lot of *noise* and *vibration*, and is subject to significant levels of *acceleration* to boost its speed from effectively zero to 8 km/sec (5 miles/sec) in a few minutes to reach orbit.

For launch spectators, one overriding impression is the wall of sound that hits them a few seconds after they see the rocket engines ignite, despite the fact that they are kept at a safe distance from the launch complex. Launch is a very noisy affair, and even more so for the satellite payload sitting on top of the rocket. The acoustic field encountered by the satellite is harsh, despite the satellite being contained within the launcher fairing. Large amplitude and damaging vibrations can be excited in flexible structures, such as solar panels or large antennas, by this level of noise.

Similarly, it is not surprising that the energetic processes occurring in the propellant feed pumps, the combustion chambers, and the rocket nozzles at the base of the launch vehicle cause a high level of vibration. Astronauts riding a man-rated launch vehicle to orbit invariably report quite a rough ride!

In addition to noise and vibration, the third main environmental effect to which the spacecraft is exposed during launch is acceleration. Figure 5.9 shows a typical acceleration profile against time for an Ariane 5 launch vehicle, where the acceleration is given in units of *g*'s. To understand the impact this has on the spacecraft design, we need to recall the discussion in Chapter 1 about the force of gravity at Earth's surface. If you drop something, it will accelerate toward Earth's center, increasing its speed by 10 m/sec (32 feet/sec) for every second it falls. This acceleration of 10 m/sec/sec, usually denoted by 10 m/sec^2, is the reason we stay stuck to the floor. This environment, in which we experience our normal weight, is sometimes called a 1*g* environment. However, when we ride to the top of a skyscraper in a high-speed elevator, while the elevator is accelerating upward to gain speed we feel heavier (see Fig. 2.2b). And so it is with launch vehicles. Figure 5.9 shows that the level of acceleration for this particular launch vehicle can be in excess of 4*g*—four times Earth's surface gravitational acceleration—which means that the spacecraft and its component parts effectively weigh four times their normal Earth surface weight. It is not too difficult to see the effect this has on the spacecraft structure, since its job is to mechanically support all the various parts of the spacecraft—payload instruments and subsystem elements—which are effectively much heavier under severe acceleration.

Clearly, the spacecraft structure design engineer has to take into account the launch vehicle flight environment to ensure that the spacecraft does not fall apart on the ascent to orbit.

Next-Generation Launchers

Perhaps the most striking thing about launching spacecraft using conventional ELVs is how inefficient and costly it is. Typically only about 1% of the mass that sits initially on the launch pad reaches orbit and is usefully employed to fulfill the mission objective. The remaining 99% is jettisoned either on the ascent or in orbit. What can be done about that? Well, a great deal. Rocket scientists want to develop a launch vehicle with operating characteristics similar to a civil aircraft: a launcher that takes off from a conventional runway, delivers a payload to orbit, and returns to a runway landing without jettisoning big lumps of itself on the way. If this can be achieved, then the cost of access to orbit would be significantly reduced, which would accelerate the exploitation of space in the existing areas of application satellites and scientific research. If this revolution can be achieved in a way that increases the reliability of launchers to match civil

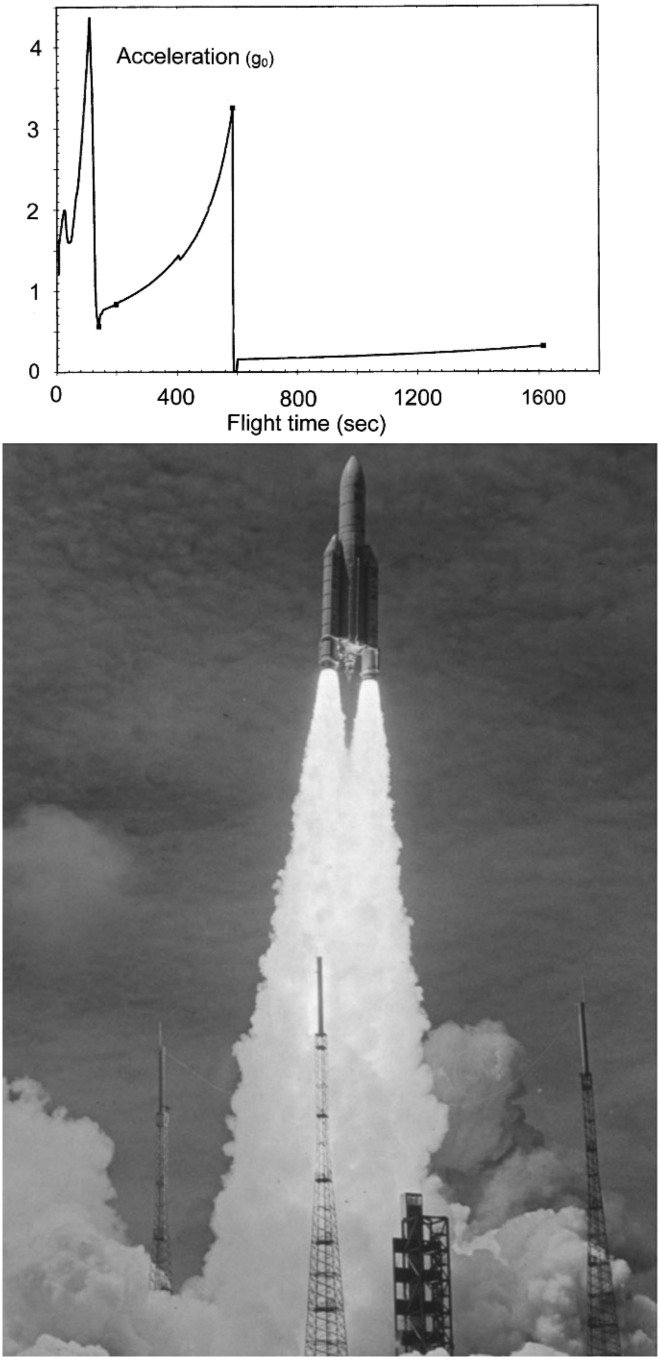

Figure 5.9: The acceleration of an Ariane 5 launch vehicle, expressed in *g*'s, as a function of flight time. (Images courtesy of Arianespace.)

airplanes, the exploitation of space as a potential holiday destination also becomes a reality.

However, the principal obstacles to achieving this vision of the future are the technical challenges that it poses, which go hand-in-hand with the large costs that would be incurred in the development of such a new generation of launch vehicles.

What are the technical challenges? The sort of launcher we are envisioning is referred to as a *single-stage-to-orbit* (SSTO) vehicle, and if you do the calculations to see if we can reach orbit with this type of vehicle, you find that it is just beyond our reach in terms of our current rocket technology. It almost feels like God created the planet, in terms of size and gravity field, so that it would be just that little bit too difficult to reach orbit with a SSTO vehicle using our current level of launcher technology. However, this paranoiac notion is tempered by the fact that this situation only applies now—to our capability at the turn of the 21st century. As time goes on, technology will develop, and it seems likely that the SSTO launcher will fly sometime in the next few decades, probably under the banner of a military research program.

What do we need to do to inject a useful payload mass into orbit using a SSTO vehicle? There are a number of approaches to the problem that can be taken, and a successful solution would probably combine all of them. The principal measures that can be taken include the following:

- An improvement in vehicle structural efficiency
- The enhancement of the process of optimization of the ascent trajectory to reduce the level of gravity and drag losses incurred
- The redesign and improvement of the performance of launcher's propulsion system

We discuss these measures in terms of the level of technical challenge they pose.

Structural efficiency: A conventional launcher typically carries hundreds of metric tonnes of liquid propellant and oxidizer, contained within large tanks distributed throughout the various stages of the vehicle. The safe containment of this mass of liquid in a harsh launch environment (of high acceleration and vibration levels) is a challenge to the structural designer of the launcher. The crux of this challenge is to manage this safe containment with the minimum of structural mass, so as not to compromise the launcher's ability to inject a good payload mass into orbit. A measure of the structural efficiency of a launcher is the ratio of the mass of its structure to the mass of fuel on board. Currently values of this ratio are on the order of 0.1, which means that for every 100 metric tonnes of fuel on board, we need typically 10 metric tonnes of structure to safely carry it. The challenge for structural designers and material scientists is to reduce the value of this ratio—equivalent to improving structural efficiency—in order that the mass saving in launcher structure can be invested in increasing the mass of the spacecraft payload.

Trajectory enhancement: The process of optimization of the ascent trajectory would probably mean adopting a horizontal runway takeoff and a fairly gentle climb to orbit (to reduce gravity loss). The vehicle would then spend more time in the lower, denser part of the atmosphere, potentially causing an increase in drag loss. To overcome this, significant technical effort would have to be invested in the optimization of the shape of the launcher to make it more aerodynamic over the prescribed flight path. The objective would be to ensure that overall losses are reduced

Propulsion system: The improvement of the performance of the launcher's propulsion system is probably the most difficult technical challenge in the development of a SSTO vehicle. With a conventional launcher system, the oxygen needed to burn the propellant in the rocket engines is carried, usually in liquid form, in large massive tanks. The overall performance of the launch vehicle can be enhanced significantly if we can devise a way of reducing this mass by extracting the required oxygen from the atmosphere. This is, after all, how a conventional aircraft operates, burning its fuel using the oxygen coming in through the engine intakes. This type of propulsion is referred to as *air-breathing.* There are some difficulties here, though, perhaps the most obvious one being that as the launcher climbs to near-orbital altitudes there is no usable atmosphere left from which to extract the oxygen. Another issue is perhaps a little more subtle, and has to do with operating air-breathing propulsion systems at high speeds. To understand this, we need to think about fast aircraft and the jet engines they use to sustain high-speed flight. Usually people use the word *supersonic* to suggest high speed, but this actually means that the aircraft is traveling at a speed in excess of the speed of sound. At sea level, the speed of sound is around 340 m/sec (1115 feet/sec), which is about 760 mph. An airplane traveling at this speed does seem fast, but it is actually traveling quite slowly compared to a launch vehicle, which needs to reach speeds of 8 km/sec (5 miles/sec) to reach a LEO, which is of the order of 18,000 mph.

Another way of addressing how fast an aircraft travels is to compare its speed with the local speed of sound using a *Mach number.* An aircraft moving at the speed of sound is said to be traveling at Mach 1, and one moving at, say, three times the sound speed, at Mach 3. Thinking in this way, *ramjet*-powered airplanes can reach speeds up to about Mach 5, which is a quite impressive 3500 to 4000 mph. At such high speeds, the air is rammed into the intake, which compresses the air sufficiently to be able to dispense with much of the mechanical complexity that you normally find in jet engines. Consequently, the ramjet is a relatively simple device—effectively a tube with an intake at one end, an exhaust nozzle at the other, and a combustion section in the middle. The inflowing air is mixed with fuel (for example, kerosene) and ignited. The pressure produced by the high-speed flow into the intake compresses the air and fuel mixture, and effectively directs the explosively ignited gas out of the exhaust nozzle to produce thrust.

One critical attribute of the ramjet is that the intake air flow has to be managed to reduce its speed to a subsonic level in the combustor, in order to ensure that combustion takes place. If it were otherwise, the air-fuel mixture would not be there long enough for the burning of the fuel to take place. The reason why this is critical is that the process of slowing the incoming air actually produces a kind of drag force on the engine, which is why the maximum operating speed of a ramjet is limited to about Mach 5. Given that we require higher speed operation for an air-breathing launcher propulsion system, this factor seems to be a bit of a problem.

To attempt to overcome it, an air-breathing propulsion system called a supersonic combustion ramjet, also known as a *scramjet* for short, has been proposed to potentially increase flight speeds up to around Mach 15. As the name implies, the scramjet is similar to the ramjet, but combustion takes place in the air-fuel mix while it is flowing at supersonic speeds within the engine. As a result, some of the limitations of the ramjet are overcome, but further technical challenges are posed, not the least of which is the problem implied above about sustaining the engine combustion in such a high-speed flow. Another issue with a scramjet-powered launcher is that the entire underside shape of such a vehicle needs to be designed and optimized as part of the propulsion system. The underside forebody becomes part of the engine intake system, ensuring high-speed flow into the engine, and the underside aft section becomes part of the engine exhaust jet designed to maximize the resulting thrust.

As if all this wasn't difficult enough, another challenge posed by operating at such high speeds in the atmosphere is the heat generated in the launcher's structure caused by *atmospheric friction*. The vehicle's forebody and the leading edges of the wings will reach very high temperatures, leading to a requirement to develop appropriate cooling techniques and materials, so that the vehicle does not fall apart due to this extreme heating.

Recently, experimental flight test programs have been established, by both civilian and military agencies, to attempt to demonstrate high-speed flight using scramjet propulsion, and to look at the challenges of the hypersonic

Figure 5.10: Artist's impression of a X-43 flight vehicle. (Image courtesy of NASA.)

aerodynamic design of such vehicles. Figure 5.10 shows an artist's impression of a scramjet-powered vehicle in flight, in this case from NASA's X-43 experimental aircraft program. At the time of this writing, however, these programs have had limited success, demonstrating scramjet-powered flight up to speeds of around Mach 10, with powered flight sustained for only a short period, of the order of tens of seconds.

Regarding the fully reusable, single-stage-to-orbit launch vehicle with aircraft-like operations, we can now see that the vehicle propulsion has to operate in a variety of different ways in order to accommodate the ground-to-orbit *flight envelope*. The takeoff from an airport runway would require the use of conventional jet engines, to take the speed to about Mach 2 or 3 when ramjet operation becomes effective. At around Mach 5, the engines would need to switch operation to scramjets, taking the launcher to around Mach 15 and to an altitude where the air is too thin for continued air-breathing operation. The last boost to orbit speed and height would require the engines to operate as rockets. To achieve this *combined-cycle* operation for the propulsion system, while limiting the overall mass of the engines, poses difficult technical challenges—so much so that many rocket scientists have expressed doubts that a single-stage-to-orbit manned vehicle, taking off from a conventional runway, will ever be achievable. But then perhaps this is an overly pessimistic view. After all, commercial air transport was a similar pipe dream a century ago.