Returning from Space: Re-entry

4.1.7

In This Section You'll Learn to...

- Describe the competing design requirements for re-entry vehicles
- Describe the process for analyzing re-entry motion
- Describe the basic trajectory options and trade-offs in re-entry design (enrichment topic)
- Describe the basic vehicle options and trade-offs in re-entry design (enrichment topic)
- Describe how a lifting vehicle changes the re-entry problem

Outline

Walking along the shore of a tranquil lake on a sunny, spring day, most of us have indulged in one of life's simplest pleasures: skipping stones. When the wind is calm, the mirror-like surface of the water practically begs us to try our skill. Searching through pebbles on the sandy bank, we find the perfect skipping rock: round and flat and just big enough for a good grip. We take careful aim, because we want the stone to strike the water's surface at the precise angle and speed that will allow its wide, flat bottom to take the full force of impact, causing it to skip. If we have great skill (and a good bit of luck), it may skip three or four times before finally losing its momentum and plunging beneath the water. We know from experience that, if the rock is not flat enough or its angle of impact is too steep, it'll make only a noisy splash rather than a quiet and graceful skip.

Returning from space, astronauts face a similar challenge. Earth's atmosphere presents to them a dense, fluid medium, which, at orbital velocities, is not all that different from a lake's surface. They must plan to hit the atmosphere at the precise angle and speed for a safe landing. If they hit too steeply or too fast, they risk making a big "splash," which would mean a fiery end. If their impact is too shallow, they may literally skip off the atmosphere and back into the cold of space. This subtle dance between fire and ice is the science of atmospheric re-entry.

In this chapter we explore the mission requirements of vehicles entering an atmosphere—whether returning to Earth or trying to land on another planet. We consider what engineers must trade in designing missions that must plunge into dense atmospheres (Figure 4.1.7-1). When we're through, you may never skip rocks the same way again!

Space Mission Architecture. This chapter deals with the Trajectories and Orbits segment of the Space Mission Architecture.

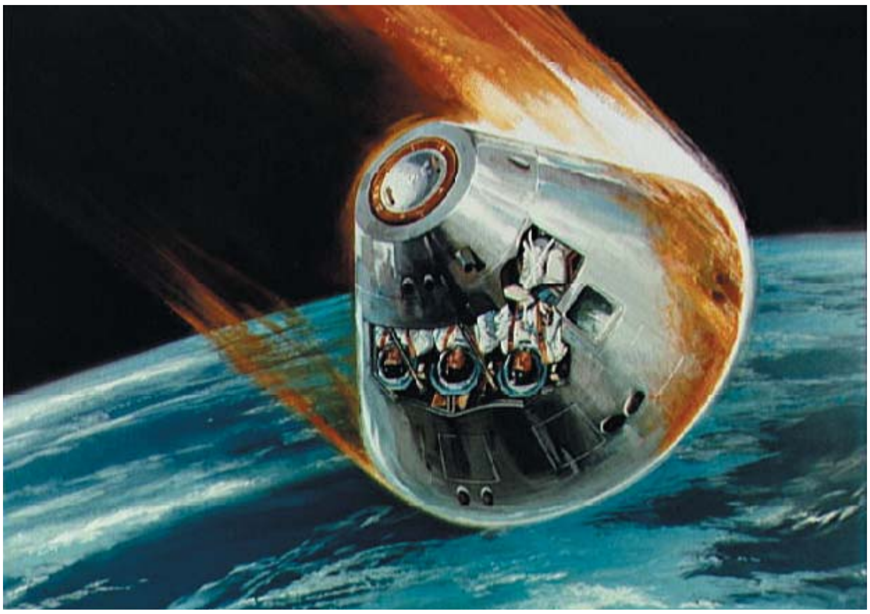


Figure 4.1.7-1. Apollo Capsule Re-entry. This artist's concept of the Apollo re-entry shows that air friction causes the capsule to glow red hot. The astronauts inside stay cool, thanks to the protective heat shield. *(Courtesy of NASA/Johnson Space Center)*

4.1.7.1 Understanding Re-entry Motion

In This Section You'll Learn to...

- List and discuss the competing requirements of re-entry design
- Define a re-entry corridor and discuss its importance
- Apply the motion analysis process (MAP) checklist to re-entry motion and discuss the results

Trade-offs for Re-entry Design

All space-mission planning begins with a set of requirements we must meet to achieve mission objectives. The re-entry phase of a mission is no different. We must delicately balance three, often competing, requirements

- Deceleration
- Heating
- Accuracy of landing or impact

The vehicle's structure and payload limit the maximum deceleration or "g's" it can withstand. (One "g" is the gravitational acceleration at Earth's surface—9.798 m/s^2.) When subjected to enough g's, even steel and aluminum can crumple like paper. Fortunately, the structural g limits for a well-designed vehicle can be quite high, perhaps hundreds of g's. But a fragile human payload would be crushed to death long before reaching that level. Humans can withstand a maximum deceleration of about 12 g's (about 12 times their weight) for only a few minutes at a time. Imagine eleven other people with your same weight all stacked on top of you. You'd be lucky to breathe! Just as a chain is only as strong as its weakest link, the maximum deceleration a vehicle experiences during re-entry must be low enough to prevent damage or injury to the weakest part of the vehicle.

But maximum g's aren't the only concern of re-entry designers. Too little deceleration can also cause serious problems. Similar to a rock skipping off a pond, a vehicle that doesn't slow down enough may literally bounce off the atmosphere and back into the cold reaches of space.

Another limitation during re-entry is heating. The fiery trail of a meteor streaking across the night sky shows that re-entry can get hot! This intense heat is a result of friction between the speeding meteor and the air. How hot can something get during re-entry? To find out, think about the energies involved. The Space Shuttle in orbit has a mass of 100,000 kg (220,000 lb.), an orbital velocity of 7700 m/s (17,225 m.p.h.), and an altitude of 300 km (186 mi.). In Section 4.1.3 we showed that an object's total mechanical energy depends on its kinetic energy (energy of motion) and its potential energy (energy of position). If we were to get out our calculators and punch in the numbers for the Space Shuttle, we'd find that its total mechanical energy is

$$E = 3.23 \times 10^{12} \text{ joules} = 3.06 \times 10^{9} \text{ Btu}$$

Let's put this number in perspective by recognizing that heating the average house in Colorado takes only about 73.4×10^{7} Btu/year. So, the Shuttle has enough energy during re-entry to heat the average home in Colorado for 41 years!

Note: One British thermal unit (Btu) is the amount of heat required to raise one pound of water one degree Fahrenheit. 1 Btu = 252 calories = 1055.1 joules.

The Shuttle has kinetic energy due to its speed of 7700 m/s and potential energy due to its altitude. It must lose all this energy in only about one-half hour to come to a full stop on the runway (at Earth's surface). But, remember, energy is conserved, so where does all the "lost" energy go? It converts to heat (from friction) caused by the atmosphere's molecules striking its leading edges. This heat makes the Shuttle's surfaces reach temperatures of up to 1477° C (2691° F). We must design the re-entry trajectory, and the vehicle, to withstand these high temperatures. As we'll see, we have to contend with the total heating and the peak heating rate.

The third mission requirement is accuracy. Beginning its descent from more than 6440 km (4000 mi.) away, the Space Shuttle must land on a runway only 91 m (300 ft.) wide. The re-entry vehicle (RV) of an Intercontinental Ballistic Missile (ICBM) has even tighter accuracy requirements. To meet these constraints, we must again adjust the trajectory and vehicle design.

On the other hand, if a vehicle can land in a larger area, the accuracy constraint becomes less important. For example, the Apollo missions required the capsules to land in large areas in the Pacific Ocean—much larger landing zones than for an ICBM's RV payload. Thus, the Apollo capsule was less streamlined and used a trajectory with a shallower re-entry angle. In all cases, designers adjust the trajectory and vehicle shape to match the accuracy requirement.

As you can see from all these constraints, a re-entry vehicle must walk a tightrope between being squashed and skipping out, between fire and ice, and between hitting and missing the target. This tightrope is actually a three-dimensional *re-entry corridor*, shown in Figure 4.1.7-2, through which a re-entry vehicle must pass to avoid skipping out or burning up.

The size of the corridor depends on the three competing constraints—deceleration, heating, and accuracy. For example, if the vehicle strays below the lower boundary (undershoots), it will experience too much drag, slowing down rapidly and heating up too quickly. On the other hand, if the vehicle enters above the upper boundary (overshoots), it won't experience enough drag and may literally skip off the atmosphere, back into space. If designers aren't careful, these competing requirements may lead to a re-entry corridor that's too narrow for the vehicle to steer through!

Whereas the above three constraints determine the re-entry corridor's size, the vehicle's control system determines its ability to steer through the re-entry corridor. In this chapter we concentrate on describing what affects the corridor's size. We'll discuss limits on the control system in Section 4.3.1.

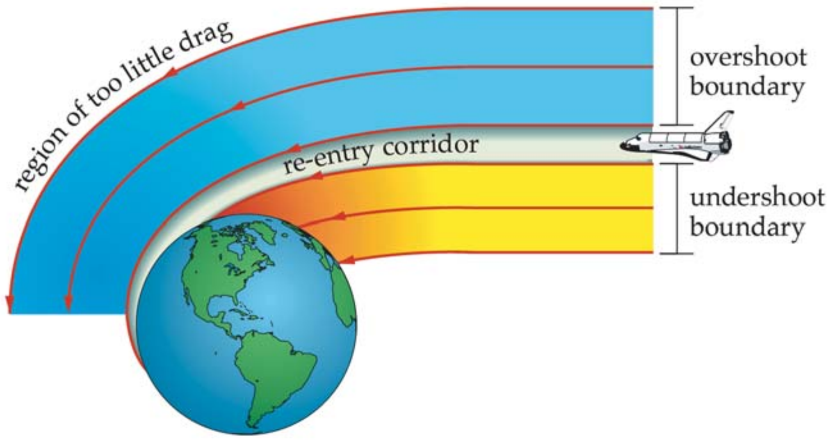


Figure 4.1.7-2. Re-entry Corridor. The re-entry corridor is a narrow region in space that a re-entering vehicle must fly through. If the vehicle strays above the corridor, it may skip out. If it strays below the corridor, it may burn up.

Re-entry Motion

Imagine one of Earth's many small, celestial companions (say, an asteroid) wandering through space until it encounters Earth's atmosphere at more than 8 km/s, screaming in at a steep angle. Initially, in the upper reaches of the atmosphere, there is very little drag to slow down the massive chunk of rock. But as the meteor penetrates deeper, the drag force builds rapidly, causing it to slow down dramatically. This slowing is like the quick initial deceleration experienced by a rock hitting the surface of a pond. At this point in the meteor's trajectory, its heating rate is also highest, so it begins to glow with temperatures hot enough to melt the iron and nickel within. If anything is left of the meteor at this point, it will continue to slow down but at a more leisurely pace. Of course, most meteors burn up completely before reaching our planet's surface.

The meteor's velocity stays nearly constant through the first ten seconds, when the meteor is still above most of the atmosphere. But things change rapidly over the next ten seconds. The meteor loses almost 90% of its velocity—almost like hitting a wall. With most of its velocity lost, the deceleration is much lower—it takes 20 seconds more to slow down by another 1000 m/s.

Of course, unlike the meteor, in establishing a trajectory for a re-entry vehicle, we must keep the vehicle intact. Thus, we must trade deceleration, heating, and accuracy to calculate the correct trajectory for each vehicle. But first, to understand these trade-offs, we need to understand the motion of re-entering objects.

Before we can see how to juggle all these re-entry constraints, we need to develop a way of analyzing re-entry motion, to see how various trajectories and vehicle shapes affect its re-entry. Whether it's a rock hitting the water or a spacecraft hitting the atmosphere, we still have a dynamics problem, one we can solve by applying our trusty motion analysis process (MAP) checklist, as shown in Figure 4.1.7-3.

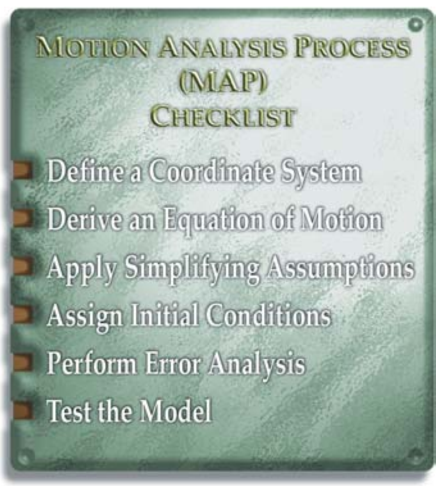


Figure 4.1.7-3. Motion Analysis Process (MAP) Checklist. This checklist is the same one we introduced in Section 4.1.3.

First on the list is defining a coordinate system. We still need an inertial reference frame (so Newton's laws apply), which we call the re-entry coordinate system. To make things easy, we place the origin of the *re-entry coordinate system* at the vehicle's center of mass *at the start of re-entry*. We then analyze the motion with respect to this fixed center.

The fundamental plane is the vehicle's orbital plane. Within this plane, we can pick a convenient principal direction, which points "down" to Earth's center. (By convention, the axis that points down is the $\hat{Z}$ direction.) We define the $\hat{X}$ direction along the local horizontal in the direction of motion. The $\hat{Y}$ direction completes the right-hand rule. However, because we assume all motion takes place in plane, we won't worry about the $\hat{Y}$ direction. Figure 4.1.7-4 shows the re-entry coordinate system.

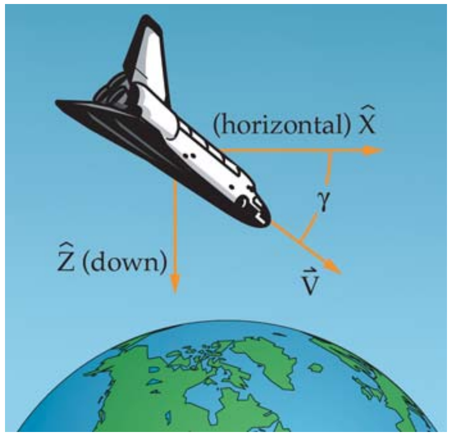


Figure 4.1.7-4. Re-entry Coordinate System. Our re-entry-coordinate system uses the center of the vehicle at the start of re-entry as the origin. The orbital plane is the fundamental plane, and the principal direction is down. The re-entry flight-path angle, γ, is the angle between local horizontal and the velocity vector.

We also define the *re-entry flight-path angle, γ*, which is the angle between the local horizontal and the velocity vector. (Note this angle is the same as the orbital flight-path angle, ϕ, used earlier, but re-entry analysts like to use gamma, γ, instead, so we play along.) Similar to ϕ, a re-entry flight-path angle below the horizon (diving toward the ground) is negative, and a flight-path angle above the horizon (climbing) is positive.

To truly understand the motion of a re-entering Shuttle, we have to start by listing what forces might affect it. After a bit of thought, we could come up with the following short list of forces to worry about:

- The force of gravity
- The force of drag
- The force of lift
- Other forces just in case

We discussed gravity, as described by Sir Isaac Newton, back in Section 4.1.3. Drag and lift are two other forces that any object traveling through the atmosphere must deal with. "Other" forces cover us in case we forgot something. These forces are illustrated in Figure 4.1.7-5.

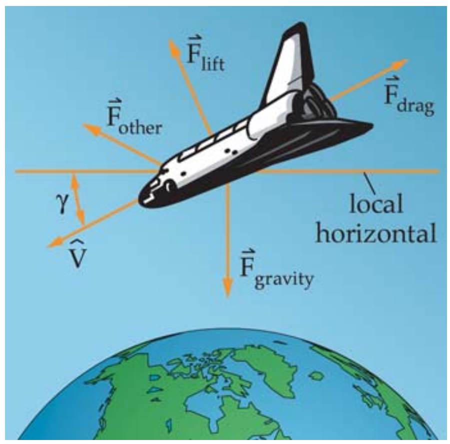


Figure 4.1.7-5. Significant Forces on a Re-entry Vehicle. A re-entry vehicle could potentially encounter lift, drag, and gravity forces. Of these, drag is by far the most important.

Drag is a force that resists motion through the atmosphere. If you were to put your hand out the window of a fast-moving car and turn your palm into the wind, you'd feel the force of drag pushing back on your hand. The drag force acts in the direction opposite to your motion.

Lift is a force produced at a right angle to the direction of motion as a result of air moving over an object's surface. An object with the correct shape, such as an airplane's wing, will generate enough lift force to overcome the force of gravity and "lift" it into the air.

For Shuttles, meteors, and ICBMs entering the atmosphere at near orbital velocities, it turns out that

- The re-entry vehicle is a point mass
- Drag is the dominant force—all other forces, including lift and gravity, are insignificant. (We'll see why this is a good assumption later.)

For meteors entering the atmosphere, the lift force is almost zero. Even for the Space Shuttle, lift is relatively small when compared to drag. For these reasons, we can assume for now that our vehicle produces no lift; thus, $\vec{F}_l = 0$. (Actually, the lift generated by the Space Shuttle is enough to significantly alter its trajectory, as we'll see in Section 4.1.7.2. But this assumption will greatly simplify our analysis and allow us to demonstrate the trends in re-entry design.) Thus, we can assume gravity doesn't affect the vehicle and the vehicle produces no lift.

To better understand atmospheric re-entry, let's think about some things that enter hundreds of times per day—meteors. If you've been lucky, on a very clear night, maybe you've seen meteors (sometimes called "shooting stars") blazing a trail across the sky. We've just seen that the main force acting on these meteors is drag.

Determining how big the drag force is on a meteor entering the atmosphere requires us to know several things: how fast it is moving (its velocity); how big it is (its cross-sectional area, A); how dense the air is; and how streamlined it is. We can describe how streamlined, or "draggy," the meteor is by using a unique property of vehicle shape—*coefficient of drag, C_D*. Engineers compute and validate this quantity using wind tunnels. Knowing all these things, we can come up with this

Important Concept

The drag force on an object depends on

- Its size (cross-sectional area exposed to the wind)
- Its drag coefficient (how streamlined it is)
- Its velocity (how fast it's going)
- The density of the air

Equation (4.1.7-1) summarizes these concept.

$$F_{drag} = \frac{1}{2}\rho\, V^2\, C_D\, A \tag{4.1.7-1}$$

where

F_{drag} = drag force on a vehicle (N)

C_D = drag coefficient (unitless)

A = vehicle's cross-sectional area (m^2)

ρ = atmospheric density (kg/m^3)

V = vehicle's velocity (m/s)

Now, if we know the meteor's mass and the drag force acting on it, Newton's Second Law tells us how to determine its acceleration. Remember, drag is pushing the meteor backward as it enters, so the acceleration in this case is called *deceleration* because it slows the meteor down. Thinking about a useful expression for the acceleration on an entering object results in this

Important Concept

The acceleration on an object re-entering the atmosphere due to drag depends on

- Its size (cross-sectional area exposed to the wind),
- Its drag coefficient (how streamlined it is),
- Its velocity (how fast its going),
- The density of the air

Equation (4.1.7-2)—often called the equation of motion—summarizes this concept.

$$\grave{a} = \frac{1}{2}\rho V^2 \frac{C_D A}{m} \tag{4.1.7-2}$$

Ever since engineers began to analyze the trajectories of cannon balls, this quantity ($C_D A/m$) has had a special significance in describing how an object moves through the atmosphere. By convention, engineers invert this term and call it the *ballistic coefficient, BC.*

$$BC = \frac{m}{C_D A} \tag{4.1.7-3}$$

where

BC = vehicle's ballistic coefficient (kg/m^2)

m = vehicle's mass (kg)

C_D = vehicle's drag coefficient (unitless)

A = vehicle's cross-sectional area (m^2)

From these basic relationships, we can show that the amount of deceleration an object experiences while traveling through the atmosphere is inversely related to the object's ballistic coefficient. An *inverse relationship* between two things means that if one goes up, the other goes down. For example, the height of two kids on a see-saw is inversely related because as one goes up, the other goes down. The same goes for deceleration and BC.

Let's take a moment to see what BC really represents. Suppose a 60-kg (150-lb.) skydiver and a 60-kg (150-lb.) sack of potatoes fall out of an airplane at the same time (same mass, same initial velocity). If the skydiver and the potatoes have about the same mass, m; cross-sectional area, A; and drag coefficient, C_D, they have the same BC. Thus, the drag force on each is the same, and they fall at the same rate, as shown in Figure 4.1.7-6.

Figure 4.1.7-6. Comparing Ballistic Coefficients. A sack of potatoes and a skydiver have about the same ballistic coefficient (BC).

What happens when the skydiver opens his parachute? He now slows down significantly faster than the sack of potatoes. But what happens to his BC? His mass stays the same, but when his chute opens, his cross-sectional area and C_D increase dramatically. When C_D and area increase,

Figure 4.1.7-7. Changing BC. With his parachute open, the skydiver greatly increases his area, A, and drag coefficient, C_D, thus decreasing his ballistic coefficient, BC, and slowing down much faster than the potatoes.

his BC goes down compared to the sack of potatoes, slowing his descent rate, as shown in Figure 4.1.7-7. From this example, we see

---

Important Concept

An object with a low BC slows down much quicker than an object with a high BC.

In everyday terms, we would say a light, blunt vehicle (low BC) slows down much more rapidly than a heavy, streamlined (high BC) one, as shown in Figure 4.1.7-8.

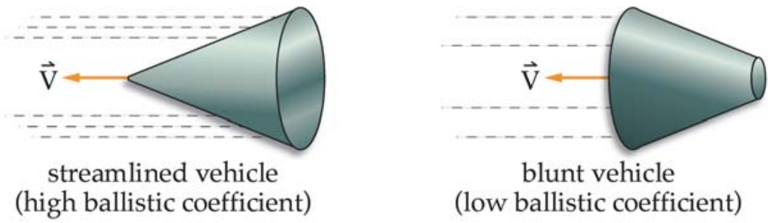


Figure 4.1.7-8. Blunt Versus Streamlined Vehicles. A light, blunt vehicle (low BC) slows down much more rapidly due to drag than a heavy, streamlined (high BC) one.

So what does all this have to do with our meteor entering the atmosphere? A meteor hitting the Earth's atmosphere is travelling fast--really fast. The Earth itself is moving at about 26 kilometers per second! So if the Earth just runs into a meteor that happens to be minding its own business in interplanetary space, the entry velocity (V_{entry}) will be about 26 km/s. As it first enters the atmosphere, high above the Earth's surface, the density of the air is very thin, so the initial deceleration is relatively low. But as the meteor dives deeper into the atmosphere, the air gets thicker and the deceleration builds rapidly, slowing down the meteor even more.

Now, remember we said earlier that an object entering the atmosphere also has tremendous kinetic energy due to its speed and potential energy due to its position. Where does all this energy go as the meteor slows down? It turns to heat. If you've ever tried to stop your bicycle by dragging the soles of your feet on the ground, you've experienced turning speed into heat. Because of the extremely high energies involved, the amount of heat generated on a meteor is so great that most meteors burn up long before they can hit Earth. Section 4.1.7.3 describes ways to protect astronauts from the fiery heat of re-entry. The enrichment topic in Section 4.1.7.2 will describe methods for trading off the various options in re-entry design.

Section Review

Key Concepts

- We must balance three competing requirements for re-entry design
  - Deceleration
  - Heating
  - Accuracy
- We base the re-entry coordinate system on the
  - Origin—vehicle's center of gravity at the beginning of re-entry
  - Fundamental plane—vehicle's orbital plane
  - Principal direction—down
- During re-entry, we can assume
  - Re-entry vehicle is a point mass
  - Drag is the dominant force—all other forces, including gravity and lift, are insignificant
- Ballistic coefficient, BC, quantifies an object's mass, drag coefficient, and cross-sectional area and predicts how drag will affect it
  - Light, blunt vehicle—low BC—slows down quickly
  - Heavy, streamlined vehicle—high BC—doesn't slow down quickly

4.1.7.2 Options for Trajectory Design

In This Section You'll Learn to...

- Describe the process for re-entry design and discuss its importance
- Explain how changing the re-entry velocity and flight-path angle affects deceleration and heating rates
- Determine the maximum deceleration and the altitude at which this deceleration occurs for a given set of re-entry conditions
- Determine the maximum heating rate and the altitude at which this rate occurs for a given set of re-entry conditions
- Explain how changing the re-entry velocity and flight-path angle affects accuracy and size of the re-entry corridor

Depending on the mission and vehicle characteristics, planners can do only so much with the re-entry trajectory. For example, the amount of propellant the Space Shuttle can carry for the engines in its orbital maneuvering system (OMS) limits how much it can alter velocity and flight-path angle at re-entry. Re-entry conditions for ICBM re-entry vehicles, depend on the velocity and flight-path angle of the booster at burnout. In either case, we must know how the re-entry trajectory affects a vehicle's maximum deceleration, heating, and accuracy, as well as the re-entry corridor's size.

Re-entry Motion Analysis in Action

To better understand re-entry motion, we need to understand how acceleration affects a vehicle's velocity and, in turn, its position during re-entry.

If we give an object a constant acceleration, we can determine its velocity after some time, t, from

$$\vec{V}_{final} = \vec{V}_{initial} + \vec{a}t \qquad (4.1.7\text{-}4)$$

where

$\vec{V}_{final}$ = final velocity (m/s)
$\vec{V}_{initial}$ = initial velocity (m/s)
$\vec{a}$ = acceleration (m/s^2)
t = time (s)

The final position of the object is

$$\vec{R}_{final} = \vec{R}_{initial} + \vec{V}_{initial}\,t + \frac{1}{2}\vec{a}t^2 \qquad (4.1.7\text{-}5)$$

Unfortunately, a re-entry vehicle's acceleration isn't constant. Notice in Equation (4.1.7-2) that drag deceleration is a function of velocity, but the velocity changes due to drag! How do we deal with this tail-chasing situation? We use a method first developed by Isaac Newton—numerical integration. Sound complicated? Actually it's not that bad.

To apply this method we assume that over some small time interval, Δt, the acceleration *is* constant (a good assumption if Δt is small enough). This allows us to use the velocity and position equations for constant acceleration during that time interval. By adding the acceleration effects during each time interval, we can determine the cumulative effect on velocity and position. (Of course this means lots of calculations, so it's best to use a computer. We could either write a new computer program or use the built-in flexibility of a spreadsheet. We did all the analysis in this chapter using a spreadsheet.)

Let's start by applying this numerical analysis technique to the motion of the meteor entering the atmosphere, as we discussed earlier. Recall, its velocity is pretty much constant initially, while it is high in the thin atmosphere. But then, it hits a wall as the atmosphere thickens and it slows rapidly. The results of the numerical integration for this example are shown in Figure 4.1.7-9. We can see from the graph what we expected to find from our discussion. Notice in the figure that the velocity stays nearly constant through the first ten seconds, when the meteor is still above most of the atmosphere. But conditions change rapidly over the next ten seconds. The meteor loses about 90% of its velocity—almost like hitting a wall. With most of its velocity lost, the vehicle decelerates much more slowly—it takes 20 seconds more to slow down by another 1000 m/s.

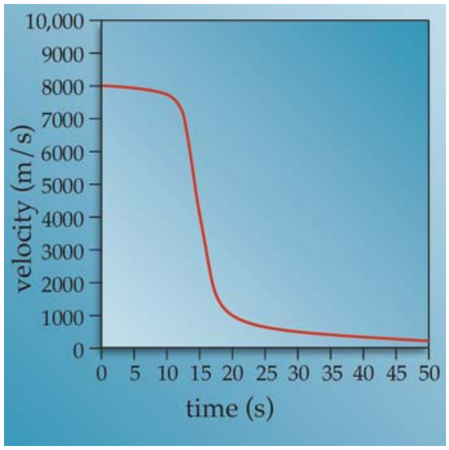


Figure 4.1.7-9. Meteor Re-entering the Atmosphere. Notice how abruptly a meteor slows down—similar to a rock hitting the surface of a pond.

We now have a precise mathematical tool to analyze re-entry characteristics. We can use this tool to balance all the competing mission requirements by approaching them on two broad fronts

- Trajectory design, which includes changes to
  - Re-entry velocity, $V_{re\text{-}entry}$
  - Re-entry flight-path angle, γ
- Vehicle design, which includes changes to
  - Vehicle size and shape (BC)
  - Thermal-protection systems (TPS)

Trajectory design involves changing the re-entry initial conditions, defined by the vehicle's velocity as it enters the effective atmosphere. These initial conditions are the *re-entry velocity, $V_{re\text{-}entry}$*, and re-entry flight-path angle, γ. Vehicle design includes changing the vehicle's shape to alter the BC or designing a thermal-protection systems (TPS) to deal with re-entry heating.

As seen in Figure 4.1.7-10, re-entry design requires iteration. Mission requirements affect the vehicle design. The design drives deceleration, heating, and accuracy. These parameters, in turn, affect trajectory options, which may change the vehicle design, and so on. In practice, we must continually trade between trajectory and vehicle design, until we reach some compromise vehicle that meets mission requirements. In the next

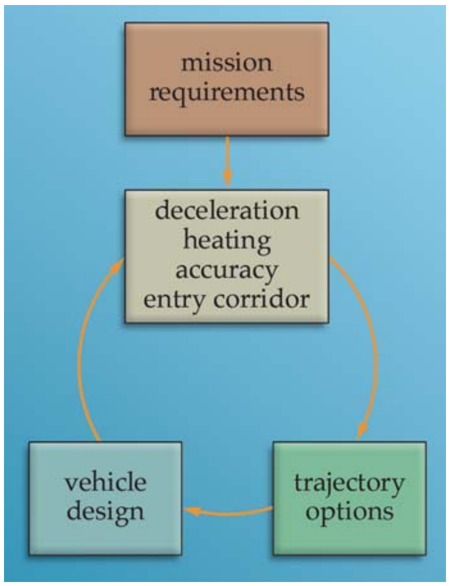


Figure 4.1.7-10. Re-entry Design. Re-entry design begins with mission requirements. Then engineers must work the trade-offs between vehicle design, deceleration, heating, accuracy, re-entry corridor, and trajectory options.

few sections, we'll explore trajectory options and vehicle design in greater detail.

Trajectory and Deceleration

As we showed with our meteor example in the last section, a vehicle re-entering from space takes time to make its way into the denser layers of the atmosphere. Deceleration builds gradually to some maximum value, a_{max}, and then begins to taper off. To see how varying the re-entry velocity and angle affects this maximum deceleration, let's apply our numerical tool to the re-entry equation of motion we developed in the last section. We begin by keeping all other variables constant and change only the initial re-entry velocity, $V_{re\text{-}entry}$, to see its effect on a_{max}. We can plot the deceleration versus altitude for various re-entry velocities, if we set the following initial conditions

Vehicle mass = 1000 kg

Nose radius = 2 m

Cross-sectional area = 50.3 m^2

$C_D = 1.0$

BC = 19.9 kg/m^2

Re-entry flight-path angle, $\gamma = 45°$

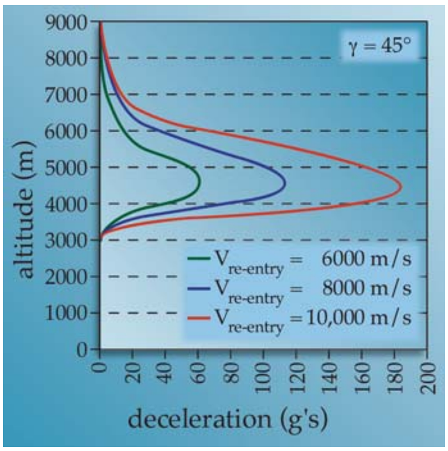


Figure 4.1.7-11. Deceleration Profiles for Various Re-entry Velocities. For a given re-entry flight-path angle, the higher the re-entry velocity, the greater the maximum deceleration.

Figure 4.1.7-11 shows that a higher re-entry velocity means greater maximum deceleration. This should make sense, if we think again about skipping rocks. The harder we throw a rock at the water (the higher the $V_{re\text{-}entry}$), the bigger the splash it will make (greater a_{max}). Without going into a lengthy derivation, we can find the vehicle's maximum deceleration, and the altitude at which it occurs, from

$$a_{max} = \frac{V^2_{re-entry}\beta \sin\gamma}{2e} \qquad (4.1.7\text{-}6)$$

$$\text{Altitude}_{a_{max}} = \frac{1}{\beta}\ln\left(\frac{\rho_o}{BC\ \beta\ \sin\gamma}\right) \qquad (4.1.7\text{-}7)$$

where

a_{max} = vehicle's maximum deceleration (m/s^2)

$V_{re\text{-}entry}$ = vehicle's re-entry velocity (m/s)

β = atmospheric scale height, a parameter used to describe the density profile of the atmosphere = 0.000139 m^{-1} for Earth

γ = vehicle's flight-path angle (deg or rad)

e = base of the natural logarithm = 2.7182. . .

ln = natural logarithm of the quantity in parentheses

ρ_o = atmospheric density at sea level = 1.225 kg/m^3

BC = vehicle's ballistic coefficient (kg/m^2)

Notice the maximum deceleration depends on the re-entry velocity and flight-path angle, but the altitude of a_{max} depends only on the flight-path angle (see Equation (4.1.7-7)). So, as Figure 4.1.7-11 shows, no matter what the velocity, the altitude of a_{max} will be the same for a given flight-path angle.

Now that we know how $V_{re\text{-}entry}$ affects deceleration, let's look at the other trajectory parameter—flight-path angle, γ. Keeping the same initial conditions and fixing the re-entry velocity at 8 km/s, we can plot the deceleration versus altitude profiles for various re-entry flight-path angles.

In Figure 4.1.7-12, we show that the steeper the re-entry angle the more severe the peak deceleration. Once again, this should make sense from the rock-skipping example, in which a steeper angle causes a bigger splash. In addition, we show that a vehicle with a steeper re-entry angle plunges deeper into the atmosphere before reaching the maximum deceleration.

Now let's look at the amount of maximum deceleration (in g's) for varying re-entry velocities and flight-path angles. Notice the maximum deceleration is over 160 g's! Because the acceleration from gravity is defined as 1 g, we can conclude the dominant force on a vehicle during re-entry is drag. This justifies our earlier decision to ignore gravity.

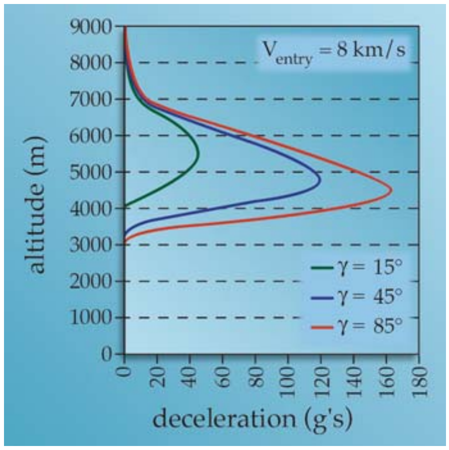


Figure 4.1.7-12. Deceleration Profile for Various Re-entry Flight-path Angles. For a given velocity, the higher the re-entry flight-path angle (steeper the re-entry) the greater the maximum deceleration experienced.

Trajectory and Heating

Earlier, we described *why* a re-entry vehicle gets hot—all the orbital energy it starts with must go somewhere (conservation of energy). Before looking at *how* the vehicle gets hot, let's review how heat transfers from one place to another by radiation, conduction, and convection. *Radiation* or *radiative heat transfer*, discussed in Section 4.1.2, involves the transfer of energy from one point to another through electromagnetic waves. If you've ever held your hand in front of a glowing space heater, you've felt radiative heat transfer.

Conduction or *conductive heat transfer* moves heat energy from one point to another through some physical medium. For example, try holding one end of a metal rod and sticking the other end in a hot fire. Before too long the end you're holding will get HOT (ouch)! The heat "conducts" along the metal rod.

Finally, *convection* or *convective heat transfer* occurs when a fluid flows past an object and transfers energy to it or absorbs energy from it (depending on which object is hotter). This is where we get the concept of "wind chill." As a breeze flows past us, heat transfers from our body to the air, keeping us cool.

So what's all this have to do with a re-entering vehicle? If you've ever been on a ski boat, plowing at high speeds through the water, you may have noticed how the water bends around the hull. At the front of the boat, where the hull first meets the water, a bow wave forms so the moving boat never appears to run into the still water. This bow wave continues around both sides of the boat, forming the wake of turbulent water that's so much fun to ski through.

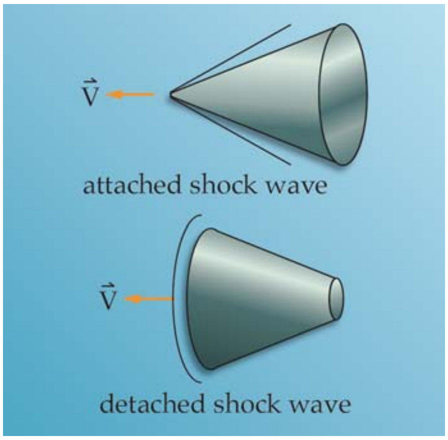


Figure 4.1.7-13. Attached and Detached Shock Waves. As a vehicle plows into the atmosphere from space a shock wave forms out in front. This shock wave attaches to streamlined vehicles (high BC) but detaches from blunt vehicles (low BC).

A spacecraft re-entering the atmosphere at high speeds must plow into the fluid air, much like the boat. Because of the extremely high re-entry speeds, even the wispy upper atmosphere profoundly affects a vehicle. In front of the re-entering spacecraft, a bow wave of sorts forms. This *shock wave* results when air molecules bounce off the front of the vehicle and then collide with the incoming air. The shock wave then bends the air flow around the vehicle. Depending on the vehicle's shape, the shock wave can either be attached or detached. If the vehicle is streamlined (high BC, like a cone), the shock wave may attach to the tip and transfer a lot of heat, causing localized heating at the attachment point. If the vehicle is blunt (low BC, like a rock), the shock wave will detach and curve in front of the vehicle, leaving a boundary of air between the shock wave and the vehicle's surface. Figure 4.1.7-13 shows both types of shock waves.

So how does the vehicle get so hot? As the shock wave slams into the air molecules in front of the re-entering vehicle, they go from a cool, dormant state to an excited state, acquiring heat energy. (To see why, strike a metal object, such as a nail, with a hammer many times and feel the object get hot.) Similar to the energetic re-entry vehicle, transferring energy to air molecules, the hammer converts its kinetic energy into heat, which it transfers to the metal object on contact.

These hot air molecules then transfer some of their heat to the vehicle by convection. Convection is the primary means of heat transfer to a vehicle entering Earth's atmosphere at speeds under about 15,000 m/s. (For a re-entry to Mars or some other planet with a different type of atmosphere, this speed will vary.) Above this speed, the air molecules get so hot they begin to transfer more of their energy to the vehicle by radiation.

Without going into all the details of aerodynamics and thermo-dynamics, we can quantify the *heating rate,* $\dot{q}$ ("q dot" or rate of change of heat energy) a re-entry vehicle experiences. We express this quantity in watts per square meter, which is heat energy per unit area per unit time. It's a function of the vehicle's velocity and nose radius, and the density of the atmosphere. Empirically, for Earth's atmosphere, this becomes approximately

$$\dot{q} \cong 1.83 \times 10^{-4}\ V^3 \sqrt{\frac{\rho}{r_{nose}}} \qquad (4.1.7\text{-}8)$$

where

$\dot{q}$ = vehicle's heating rate (W/m^2)

V = vehicle's velocity (m/s)

ρ = air density (kg/m^3)

r_{nose} = vehicle's nose radius (m)

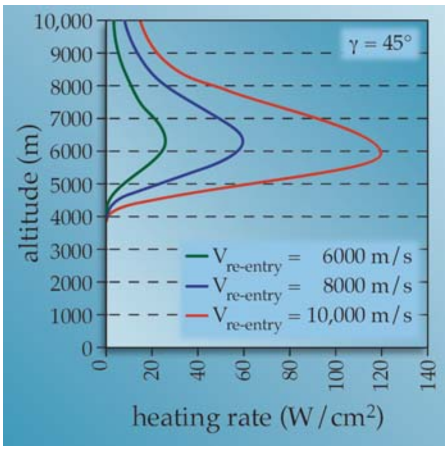


Figure 4.1.7-14. Variation in Heating Rate for Three Re-entry Velocities. As the re-entry velocity increases, the peak heating rate, $\dot{q}$, also increases.

Returning to our numerical analysis of a generic re-entry vehicle with the same initial conditions as before, we can plot heating rate, $\dot{q}$, versus altitude for various re-entry velocities. In Figure 4.1.7-14 we show that the maximum heating rate increases as the re-entry velocity goes up. We can find the altitude and velocity where the maximum heating rate occurs using

$$\text{Altitude}_{\dot{q}_{max}} = \frac{1}{\beta}\ln\left(\frac{\rho_o}{3BC\ \beta\ \sin\gamma}\right) \qquad (4.1.7\text{-}9)$$

where

β = atmospheric scale height = 0.000139 m^{-1} for Earth

ρ_o = atmospheric density at sea level = 1.225 kg/m^3

BC = vehicle's ballistic coefficient (kg/m^2)

γ = vehicle's flight-path angle (deg or rad)

and

$$V_{\dot{q}_{max}} \approx 0.846\ V_{\text{re-entry}} \qquad (4.1.7\text{-}10)$$

where

$V_{\dot{q}_{max}}$ = vehicle's velocity when it reaches maximum heating rate (m/s)

$V_{re-entry}$ = vehicle's re-entry velocity (m/s)

From Equation (4.1.7-10), we learn that the velocity for the maximum heating rate is about 85% of the re-entry velocity.

We also can vary the re-entry flight-path angle, γ, to see how it affects the maximum heating rate. Let's use a re-entry velocity of 8 km/s again. Keeping all other initial conditions the same and varying γ, we can plot $\dot{q}$ versus altitude for various re-entry flight-path angles, as shown in Figure 4.1.7-15.

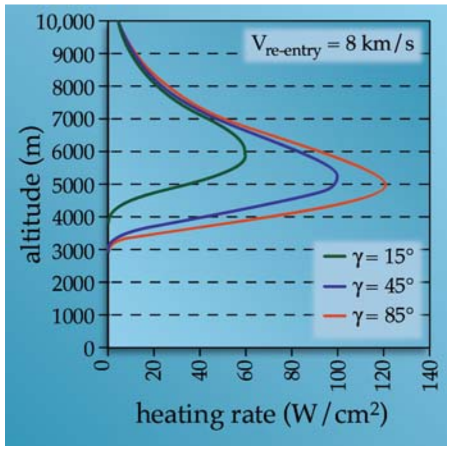


Figure 4.1.7-15. Variation in Heating Rate at Different Re-entry Flight-Path Angles. The steeper the re-entry angle, γ, [Equation (4.1.7-9)] the higher the peak heating rate, $\dot{q}$.

Notice the correlation between steepness of re-entry and the severity of the peak heating rate. Recall from our earlier discussion that the steeper the re-entry the deeper into the atmosphere the vehicle travels before reaching maximum deceleration. This means the steeper the re-entry angle, the more quickly the vehicle reaches the ground, creating an interesting dilemma for the re-entry designer

- Steep re-entry angles cause high maximum heating rates but for a short time
- Shallow re-entry causes low maximum heating rates but for a long time

A steep re-entry causes a very high heating rate but for a brief time, so the overall effect on the vehicle may be small. On the other hand, shallow re-entries lead to much lower heating rates. However, because heating continues longer, the vehicle is more likely to "soak up" heat and be damaged.

To understand this difference, imagine boiling two pots of water. For the first pot we build a fire using large, thick logs. They'll build up a low, steady heating rate, lasting for a long time. Under the second pot we place an equal mass of wood but in the form of sawdust. The sawdust will burn much faster than the logs but will also burn out much more quickly. Which option will boil the water better? Because the logs burn at a lower heat rate but for much longer, the water is more likely to soak up this heat and begin to boil. The sawdust burns so fast that the pot can't absorb it quickly enough, so most of its heat simply escapes into the air.

This example underscores the importance of considering the heating rate, $\dot{q}$, along with the total heat load, Q. *Total heat load, Q*, is the total amount of thermal energy (J/m^2) the vehicle receives. We find Q by integrating or summing all the $\dot{q}$'s over the entire re-entry time. As we've already seen, $\dot{q}$ varies with re-entry velocity. Q also varies with velocity but *not* with flight-path angle. This makes sense when we consider the heat results from mechanical energy dissipating during re-entry, which is independent of re-entry angle. This means, the higher the re-entry velocity, the higher the total heat load, as shown in Figure 4.1.7-16. Thus, although the peak heating rate varies with flight-path angle, the total heat load for a given re-entry velocity is constant.

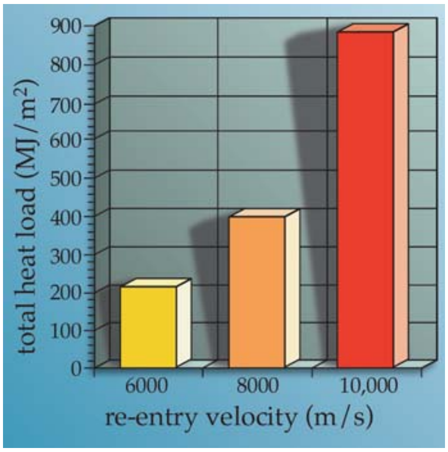


Figure 4.1.7-16. Total Heat Load for Various Re-entry Velocities. The higher the re-entry velocity, the greater the total heat load,

Again, we face an acute engineering dilemma for manned re-entry vehicles. We'd like a shallow re-entry to keep the maximum deceleration low (don't crush the crew), but this means a greater risk of soaking up the re-entry heat. Fortunately (for the crew), we have ways to deal with this heat energy, as we'll see in the next section.

Trajectory and Accuracy

Next, we can look at how trajectory affects accuracy. Consider what the atmosphere does to a re-entering vehicle. Drag and lift forces perturb its trajectory from the path it would follow under gravity alone. When we modeled these effects, we used several parameters to quantify how the atmosphere affects the vehicle. Whether we're modeling the density, ρ, or the drag coefficient, C_D, the values we use are, at best, only close to the real values and, at worst, mere approximations. Thus, the actual trajectory path will be somewhat different, so when we try to aim at a particular target we might miss!

To reduce these atmospheric effects, and improve our accuracy, we want a trajectory that spends the least time in the atmosphere. So we choose a high re-entry velocity and a steep re-entry angle. But as we've just seen, this increases the severity of deceleration and heating. Thus, to achieve highly accurate re-entry for ICBMs, we build these vehicles to withstand extremely high g forces and peak heating. Manned vehicles, on the other hand, accept lower accuracy to get much lower peak deceleration and heating.

Trajectory and the Re-entry Corridor

From the definition of re-entry corridor, we can think of the upper or overshoot boundary as the "skip out" boundary. A vehicle entering the atmosphere above this boundary risks bouncing off the atmosphere and back into space. While hard to quantify exactly, this boundary is set by the minimum deceleration needed to "capture" the vehicle. Changes to re-entry velocity or flight-path angle don't move this boundary significantly. Therefore, we can change the size of the re-entry corridor most effectively by tackling the lower or undershoot boundary.

As we've just shown, maximum deceleration and maximum heating rate, the two parameters that set the undershoot boundary, increase directly with increased re-entry velocity, $V_{re\text{-}entry}$, or re-entry flight-path angle, γ, (steeper re-entry). Most programs limit maximum deceleration and maximum $\dot{q}$ to certain values. Thus, we could still expand the re-entry corridor by decreasing $V_{re\text{-}entry}$ or γ. This change would give us a larger margin for error in planning the re-entry trajectory and relieve requirements placed on the control system. Unfortunately, for most missions, $V_{re\text{-}entry}$ and γ are set by the mission orbit and are difficult to change significantly without using rockets to perform large, expensive ΔVs. Therefore, as we'll see in the next section, our best options for changing the re-entry corridor size lie in the vehicle design arena.

Table 4.1.7-1 summarizes how trajectory options affect deceleration, heating, accuracy, and re-entry-corridor size.

Table 4.1.7-1. Trajectory Trade-offs for Re-entry Design. Notice that maximum deceleration and maximum heating rates vary directly with velocity and re-entry flight-path angle. For a constant velocity, altitudes for maximum deceleration and maximum heating rate vary inversely with flight-path angle. For a constant re-entry flight-path angle, altitudes for maximum deceleration and maximum heating rate are independent of velocity. total heat load varies directly with velocity and is independent of re-entry flight-path angle.

Parameter	Maximum Deceleration	Altitude of Maximum Deceleration	Maximum Heating Rate	Altitude of Maximum Heating Rate	Accuracy	Corridor Width
Re-entry velocity, $V_{re\text{-}entry}$ (constant γ)						
High	High	Same	High	Same	High	Narrow
Low	Low	Same	Low	Same	Low	Wide
Re-entry flight-path angle, γ (constant $V_{re\text{-}entry}$)						
Steep	High	Low	High	Low	High	Narrow
Shallow	Low	High	Low	High	Low	Wide

Section Review

Key Concepts

- To balance competing requirements, we tackle the problem of re-entry design on two fronts
  - Trajectory design—changes to re-entry velocity, $V_{re\text{-}entry}$, and re-entry flight-path angle, γ
  - Vehicle design—changes to a vehicle's size and shape (BC) and thermal-protection systems (TPS)
- We can meet re-entry mission requirements on the trajectory front by changing
  - Re-entry velocity, $V_{re\text{-}entry}$
  - Re-entry flight-path angle, γ
- Increasing re-entry velocity increases
  - Maximum deceleration, a_{max}
  - Maximum heating rate, $\dot{q}_{max}$
- Compared to the drag force, the gravity force on a re-entry vehicle is insignificant
- Increasing the re-entry flight-path angle, γ, (steeper re-entry) increases
  - Maximum deceleration, a_{max}
  - Maximum heating rate, $\dot{q}_{max}$
- The more time a vehicle spends in the atmosphere, the less accurate it will be. Thus, to increase accuracy, we use fast, steep re-entry trajectories.
- To increase the size of the re-entry corridor, we decrease the re-entry velocity and flight-path angle. However, this is often difficult to do.
- Table 4.1.7-1 summarizes the trajectory trade-offs for re-entry design

4.1.7.3 Designing Re-entry Vehicles

In This Section You'll Learn to...

- Discuss the effect of changing the ballistic coefficient on deceleration, heating rate, and re-entry-corridor width
- Discuss three types of thermal-protection systems and how they work

Once we've exhausted all trajectory possibilities, we can turn to options for vehicle design. Here, we have two ways to meet mission requirements

- Vehicle size and shape
- Thermal-protection systems (TPS)

In this section, we'll look at both methods.

Vehicle Shape

The re-entry vehicle's size and shape help determine the ballistic coefficient (BC) and the amount of lift it will generate. Because adding lift to the re-entry problem greatly complicates the analysis, we'll continue to assume we're dealing only with non-lifting vehicles. In the next section, we'll discuss how lift affects the re-entry problem.

The hardest component of BC to determine for re-entry vehicles is the drag coefficient, C_D, which depends mainly on the vehicle's shape. At low speeds, we could just stick a model of the vehicle in a wind tunnel and take specific measurements to determine C_D. But at re-entry speeds approaching 25 times the speed of sound, wind tunnel testing isn't practical because no tunnels work at those speeds. Instead, we must create mathematical models of this hypersonic flow to find C_D. The most accurate of these models requires us to use high-speed computers to solve the problem. This approach is now a specialized area of aerospace engineering known as *computational fluid dynamics (CFD)*.

Fortunately, a simpler but less accurate way will get us close enough for our purpose. We can use an approach introduced more than 300 years ago called *Newtonian flow*. Yes, Isaac Newton strikes again. Because Newton looked at a fluid as simply a collection of individual particles, he assumed his laws of motion must still work. But they didn't at low speeds. Centuries later, however, Newton was vindicated when engineers found his model worked quite well for flow at extremely high speeds. So the grand master of physics was right again—but only for certain situations. Figure 4.1.7-17 summarizes these two approaches to analyzing fluid dynamics. Using Newton's approach, we can calculate C_D and thus find BC. We show three examples using this approach for three simple shapes in Table 4.1.7-2.

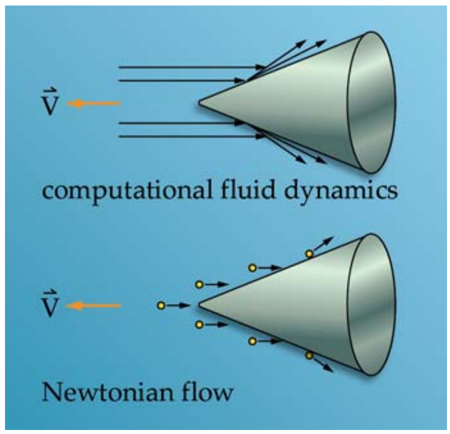
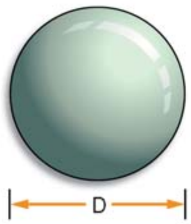
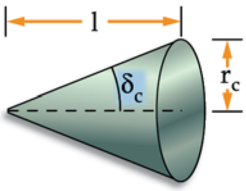
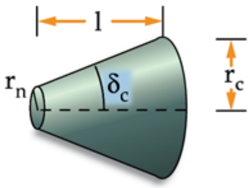


Figure 4.1.7-17. Computational Fluid Dynamics (CFD) Versus Newtonian Flow. In CFD, high-speed computers numerically model the fluid flow. Newton's approach models the fluid flow as many individual particles impacting the vehicle.

Table 4.1.7-2. Examples of Estimating BC Using Newton's Approach.

Shape	Example Values	Estimated Ballistic Coefficient
Sphere  	$D = 2$ m $C_D = 2.0$ $m = 2094$ kg (Assumes density = 500 kg/m^3)	BC $\cong$ 333 kg/m^2
Cone  	$l = 3.73$ m $\delta_c = 15°$ = cone half angle $r_c = 1$ m = cone radius $C_D \cong 2\ \delta_c^2\ = 0.137$ $m = 1954$ kg (Assumes density = 500 kg/m^3)	BC $\cong$ 4543 kg/m^2
Blunted cone  	$l = 3.04$ m $\delta_c = 15°$ = cone half angle $r_c = 1$ m = cone radius $r_n = 0.304$ m $m = 1932$ kg (Assumes density = 500 kg/m^3) $C_D = (1 - \sin^4\delta_c)\left(\frac{r_n}{r_c}\right)^2$ $+ 2\sin^2\delta_c\left[1 - \left(\frac{r_n}{r_c}\right)^2\cos^2\delta_c\right]$ $C_D \cong 0.188$	BC $\cong$ 3266 kg/m^2

Effects of Vehicle Shape on Deceleration

Now that we have a way to find BC, we can use the numerical tools we developed earlier to see how varying BC changes a re-entry vehicle's deceleration profile. Let's start by looking at three very different vehicles entering Earth's atmosphere at an angle of 45° and a velocity of 8000 m/s. Notice something very interesting in Figure 4.1.7-18: the maximum deceleration, a_{max}, is the same in all cases! But the altitude of a_{max} varies with BC. The higher the BC (the more streamlined the vehicle), the deeper it plunges into the atmosphere before reaching a_{max}. This means a streamlined vehicle spends less time in the atmosphere and reaches the ground long before a blunt vehicle.

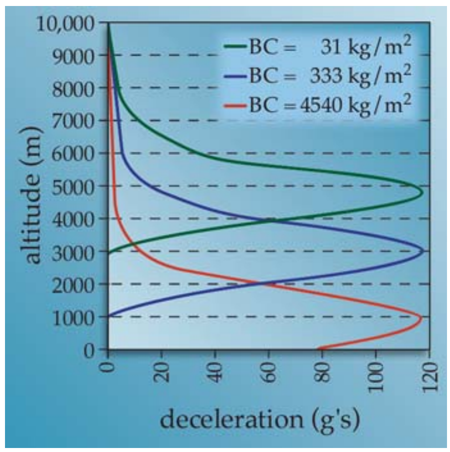


Figure 4.1.7-18. Deceleration Profiles for Various Ballistic Coefficients (BC). Note that, regardless of shape, all the vehicles experience the same maximum deceleration but at different altitudes.

Effects of Vehicle Shape on Heating Rate

Now let's see how varying BC affects the maximum heating rate. In Figure 4.1.7-19, notice the maximum heating rate is much more severe for the high-BC (streamlined) vehicle and occurs much lower in the atmosphere. The shape of the shock wave surrounding each vehicle causes this difference. The nature of shock waves for blunt and streamlined vehicles, shown in Figure 4.1.7-20. Blunt vehicles have detached shock waves that spread the heat of re-entry over a relatively large volume. Furthermore, the air flow near the surface of blunt vehicles tends to inhibit convective heat transfer. Thus, the heating rate for blunt vehicles is relatively low.

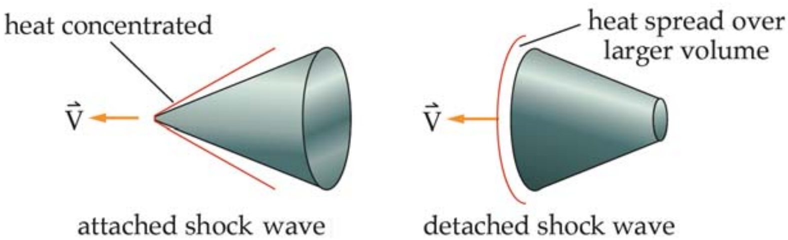


Figure 4.1.7-20. Shock Waves and Heating. For streamlined vehicles (high BC), the shock wave is attached, concentrating heat at the tip. For blunt vehicles (low BC), the shock wave is detached, spreading the heat over a larger volume.

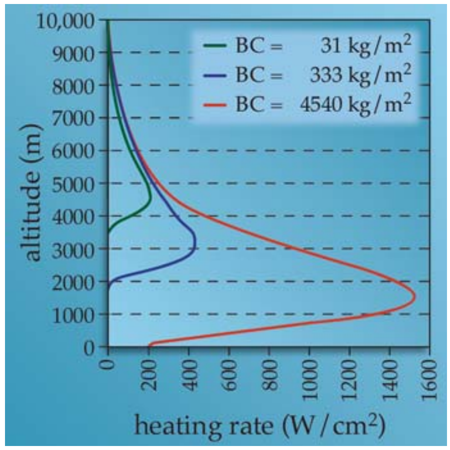


Figure 4.1.7-19. Heating Rate Profiles for Various Ballistic Coefficients (BC). Streamlined vehicles have a much higher maximum heating rate, lower in the atmosphere, than blunt vehicles.

Streamlined vehicles, on the other hand, have attached shock waves. This situation concentrates a large amount of heat near the sharp tip causing it to reach very high temperatures—hot enough to melt most materials. In addition, the heat around the vehicle stays in a smaller volume, and the air flow near the surface doesn't inhibit heat transfer as well. As a result, the overall heating rate is higher as illustrated in Figure 4.1.7-19. For these reasons, "needle-nosed" vehicles (like you see in some science fiction movies) aren't very practical. In practice, even relatively streamlined vehicles have slightly rounded noses to keep the tips from burning off.

Effects of Vehicle Shape on Accuracy

As we've seen, a more streamlined (high-BC) vehicle reaches maximum deceleration much lower in the atmosphere than a blunt (low-BC) vehicle; thus, it reaches the ground more quickly. We know from earlier discussion that the atmosphere can greatly decrease re-entry accuracy, so we want our vehicle to spend as little time in the atmosphere as possible. As a result, we want a streamlined vehicle for better accuracy, even though we must accept more severe heating rates. As we'll see, thermal-protection systems can deal with this heating.

Effects of Vehicle Shape on the Re-entry Corridor

We already said that the re-entry corridor's upper or overshoot boundary depends on the minimum deceleration for atmospheric capture.

Variations in vehicle shape don't affect this end of the corridor significantly. However, we can change the lower or undershoot boundary by changing the limits on deceleration or heating rate. But maximum deceleration is independent of the BC, so a vehicle's shape doesn't affect this boundary either. On the other hand, as we've seen, decreasing the BC can dramatically decrease the maximum heating rate. Thus, when the corridor's lower boundary is set by the maximum heating rate, decreasing BC can be helpful. This decrease expands the re-entry corridor and gives us more margin for navigational error.

Table 4.1.7-3 summarizes how vehicle shape affects re-entry parameters.

Table 4.1.7-3. Summary of Ballistic Coefficient (BC) Trade-offs for Re-entry Design.

Ballistic Coefficient (BC)	Maximum Deceleration	Altitude of Maximum Deceleration	Maximum Heating Rate	Altitude of Maximum Heating Rate	Accuracy
High (streamlined)	Same	Low	High	Low	High
Low (blunt)	Same	High	Low	High	Low

Thermal-protection Systems

As you know by now, during re-entry, things get hot. How do we deal with this massive heat accumulation without literally burning up? We use specially formulated materials and design techniques called thermal-protection systems (TPS). We'll look at three approaches to TPS

- Heat sinks
- Ablation
- Radiative cooling

Heat Sinks

Engineers first dealt with the problem of massive re-entry heating for ICBMs, in the 1950s. Initially, they couldn't get rid of the heat, so they decided to spread it out and store it in the re-entry vehicle, instead. In other words, they created a *heat sink*—using extra material to absorb the heat, keeping the peak temperature lower.

To see how a heat sink works, let's consider what happens when we put a five-liter pan and a ten-liter pan of water over a fire. Which pan will boil first? The five-liter pan will because less water is storing the same amount of heat, so the water heats faster. Similarly, a vehicle with less material will heat faster during re-entry. Thus, whenever a vehicle faces a fixed amount of heat energy (such as for a given set of re-entry conditions), designers can lower the peak temperature by increasing the volume of its material to "soak up" more heat.

The heat sink, although heavy, was a simple, effective solution to re-entry heating of early ICBMs. These missions used high re-entry angles, giving better accuracy, because the vehicle traveled more quickly through the atmosphere. Thus, the heat sink had to absorb heat for a relatively short period. Unfortunately, for a given launch vehicle, as designers increased a heat sink's mass, they had to drastically limit the available payload mass. Because payload is what they were trying to put on target, they had to consider alternatives to the simple, but heavy, heat sink.

Ablation

How do you keep your sodas cold on a hot day at the beach? You put them in a cooler full of ice. At the end of the day, the ice is gone, and only cold water remains. Why don't you just fill your cooler with cold water to start with? Because ice at 0° C (32° F) is "colder" than water at the same temperature! Huh? When ice goes from a solid at 0° C to a liquid at the same temperature, it absorbs a lot of energy. By definition, 1 kilocalorie of heat energy will raise the temperature of one liter of water by 1° C. (1 kilocalorie = 1 food calorie, those things we count every day as we eat candy bars.) But to melt 1 kg of ice at 0° C to produce one liter of water at the same temperature requires 79.4 kilocalories! This phenomenon, known as the *latent heat of fusion*, explains why your sodas stay colder on ice.

So what does keeping sodas cold have to do with a re-entry vehicle? Surely we're not going to wrap it in ice? Not exactly, but pretty close! A re-entry-vehicle designer can take advantage of this concept by coating the vehicle's surface with a material having a very high latent heat of fusion, such as carbon or ceramics. As this material melts or vaporizes, it soaks up large amounts of heat energy and protects the vehicle. This melting process is known as *ablation*.

Ablation has been used on the warheads of ICBMs and on all manned re-entry vehicles, such as the Apollo capsule shown in Figure 4.1.7-21, until the time of the Space Shuttle. Russia's manned vehicles still use this process to protect cosmonauts during re-entry. But ablation has one major drawback. By the time the vehicle lands, part of it has disappeared! This means we must either build a new vehicle for the next mission or completely refurbish it. To get around this problem, engineers, faced with designing the world's first reusable spaceship, devised a new idea—radiative cooling.

Figure 4.1.7-21. Ablative Cooling. The bottom side of the Apollo re-entry capsule shown here was coated with a ceramic material that literally melted away during re-entry. As it melted, it took away the fierce heat and kept the astronauts safe and comfortable. *(Courtesy of NASA/Johnson Space Center)*

Radiative Cooling

Stick a piece of metal in a very hot fire and, before long, it will begin to glow red hot. Max Planck first explained this process. When you apply heat to an object, it will do three things—transmit the heat (like light through a pane of glass), reflect it (like light on a mirror), or absorb it (like a rock in the Sun). If an object absorbs enough heat, it warms up and, at the same time, radiates some of the heat through *emission*. This emission is what we see when a metal piece begins to glow. If heat energy continues to strike the object, it heats until the energy emitted balances the energy absorbed. At this point, it's in *thermal equilibrium*, where its temperature levels off and stays constant.

The amount of energy emitted per square meter, E, is a function of the object's temperature and a surface property called emissivity. *Emissivity, ε*, is a unitless quantity ($0 < \varepsilon < 1.0$) that measures an object's relative ability to emit energy. A perfect black body would have an emissivity of 1.0. We determine the energy emitted using an

---

Important Concept

Stefan-Boltzmann relationship: The energy emitted by an object depends on its temperature and its basic ability to store or give off heat (its emissivity).

Equation (4.1.7-11) summarizes this Stefan-Boltzmann relationship.

$$E = \sigma \varepsilon T^4 \qquad (4.1.7\text{-}11)$$

where

E = object's emitted energy (W/m^2)

σ = Stefan-Boltzmann constant = $5.67 \times 10^{-8}\ W/m^2\ K^4$

ε = object's emissivity ($0 < \varepsilon < 1.0$) (unitless)

T = object's temperature (K)

Example 4.1.7.1 shows how to use this relationship to find an object's temperature. If an object being heated has a high emissivity, it will emit almost as much energy as it absorbs. This means it reaches thermal equilibrium sooner, at a relatively low temperature. This process of reducing equilibrium temperatures by emitting most of the heat energy before a vehicle's structure can absorb it is known as *radiative cooling*. However, even for materials with extremely high emissivities, equilibrium temperatures during re-entry can still exceed the melting point of aluminum.

Figure 4.1.7-22. Shuttle Tiles. Space Shuttle tiles composite material has high emissivity and is an efficient high-temperature insulator. *(Courtesy of NASA/Johnson Space*

The high temperatures of re-entry pose two problems for us in finding materials for radiative cooling. First, we must select a surface-coating material that has a high emissivity and a high melting point, such as a ceramic. Second, if we place this surface coating directly against the vehicle's aluminum skin, the aluminum would quickly melt. Therefore, we must isolate the hot surface from the vehicle's skin with very efficient insulation having a high emissivity.

This artful combination of a surface coating on top of a revolutionary insulator describes the, now famous, Shuttle tiles. The insulation in these tiles is made of a highly refined silicate (sand). At the points on the Shuttle's surface where most of the heating takes place, a special coating gives the tiles an emissivity of about 0.8, as well as their characteristic black color, as shown in Figure 4.1.7-22.

Section Review

Key Concepts

➤ We can meet mission requirements on the design front by changing
- Vehicle size and shape, BC
- Vehicle thermal-protection systems (TPS)

➤ Increasing the vehicle's ballistic coefficient, BC,
- Doesn't change its maximum deceleration, a_{max}
- Increases its maximum heating rate, $\dot{q}$

➤ There are three types of thermal-protection systems
- Heat sinks—spread out and store the heat
- Ablation—melts the vehicle's outer shell, taking heat away
- Radiative cooling—radiates a large percentage of the heat away before the vehicle can absorb it

Example 4.1.7.1

Problem Statement

Long-range sensors determine a re-entry capsule is emitting 45,360 W/m^2 of energy during re-entry. If the emissivity of the capsule's surface is 0.8, what is its temperature?

Problem Summary

Given: $E = 45{,}360\ W/m^2$

$\varepsilon = 0.8$

Find: T

Conceptual Solution

1) Solve Stefan-Boltzmann relationship for T

$$E = \sigma \varepsilon T^4$$

$$T = \sqrt[4]{\frac{E}{\sigma\varepsilon}}$$

Analytical Solution

1) Solve Stefan-Boltzmann equation for T

$$T = \sqrt[4]{\frac{E}{\sigma\varepsilon}}$$

$$T = \sqrt[4]{\frac{45{,}360\frac{W}{m^2}}{\left(5.67\times10^{-8}\frac{W}{m^2K^4}\right)(0.8)}}$$

$$T = 1000\ K$$

Interpreting the Results

During re-entry, the capsule's surface reached 1000 K. With the surfaces' emissivity, this means 45,360 W/m^2 of energy is emitted. Imagine 450 100-watt light bulbs in a 1 m^2 area!

4.1.7.4 Lifting Re-entry

In This Section You'll Learn to...

- Discuss the advantages offered by lifting re-entry
- Explain aerobraking and discuss how interplanetary missions can take advantage of it

In Sections 4.1.7.1 through 4.1.7.3, we assumed the force of lift on our re-entering vehicle was zero, so we could more simply investigate the trade-offs between re-entry characteristics. Adding lift to the problem takes it beyond the scope of our simple model but gives us more flexibility. For example, we can use the lifting force to "stretch" the size of the corridor and allow a greater margin of error in re-entry velocity or angle.

Controlling lift also improves accuracy over a strictly ballistic re-entry. We can change the vehicle's *angle of attack* (angle between the vehicle's nose and its velocity vector) to improve lift, making the vehicle fly more like an airplane than a rock. This allows the pilot or onboard computer to guide the vehicle directly to the desired landing area, as shown in Figure 4.1.7-23.

Figure 4.1.7-23. An Astronaut's View of Landing. The Space Shuttle uses the lift from its wings to guide it to a pin-point landing on a tiny runway. This photograph shows the pilot's view of the landing strip at Edwards Air Force Base. *(Courtesy of NASA/Johnson Space Center)*

The Space Shuttle is a great example of a lifting-re-entry vehicle. About one hour before landing, re-entry planners send the Shuttle crew the necessary information to do a deorbit burn. This burn changes the Shuttle's trajectory to re-enter the atmosphere by establishing a –1° to – 2° re-entry flight-path angle. After this maneuver, the Shuttle is on "final approach." Because it has no engines to provide thrust in the atmosphere, it gets only one chance to make a landing!

Preparing to hit the atmosphere (just like a skipping stone), the Shuttle rotates its nose to a 40° angle of attack, that means the nose is pitched up 40° with respect to the velocity vector. This high angle of attack exposes it's wide, flat bottom to the atmosphere. At an altitude of about 122,000 m (400,000 ft.), the re-entry interface takes place. Here the atmosphere begins to be dense enough for the re-entry phase to begin. From this point, more than 6400 km (4000 mi.) from the runway, the Shuttle will land in about 45 minutes! Figure 4.1.7-24 shows a graph of the Shuttle's re-entry profile.

Throughout re-entry, the Shuttle rolls to change lift direction in a prescribed way, keeping maximum deceleration well below 2 g's. These roll maneuvers allow the Shuttle to use its lift to steer toward the runway. In contrast, Apollo and Gemini capsules had minimal lifting ability, so they re-entered much more steeply and didn't roll much, so they endured up to 12 g's. Figure 4.1.7-25 compares these re-entry profiles.

Another exciting application of lifting re-entry is *aerobraking*, which uses aerodynamic forces (drag and lift) to change a vehicle's velocity and, therefore, its trajectory. In Section 4.1.6 we explored the problem of interplanetary transfer, and we saw that to get from Earth orbit to another planet required us to use the spacecraft's rockets twice: one ΔV to start the transfer at Earth and a second ΔV to capture it into orbit around the target planet. But if the target planet has an atmosphere, there's another

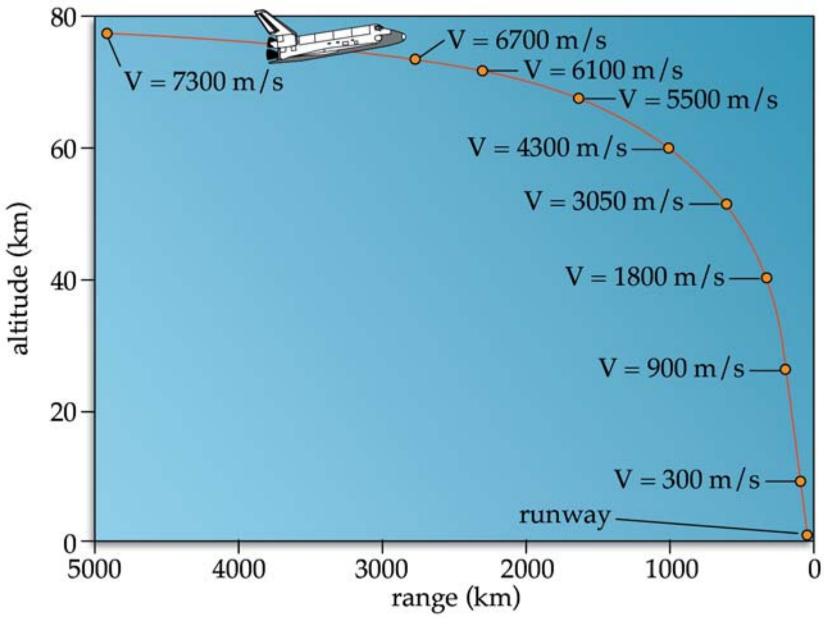


Figure 4.1.7-24. Re-entry Profile for the Space Shuttle. This graph shows the Space Shuttle's altitude and velocity profile for a typical re-entry.

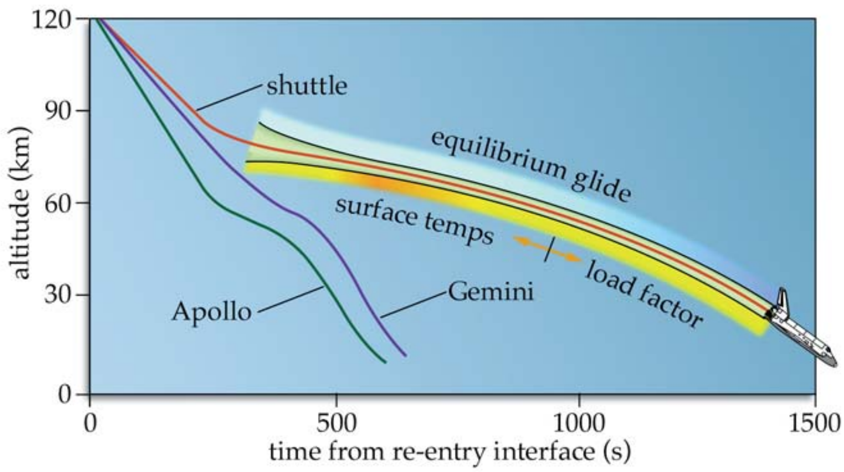


Figure 4.1.7-25. Re-entry Profiles for the Shuttle Versus Gemini and Apollo. This graph shows the difference between re-entry profiles for Apollo, Gemini, and the Space Shuttle. Notice Gemini and Apollo re-entered much more steeply than the Space Shuttle. The Shuttle's re-entry profile must stay within a tight corridor between equilibrium glide, which ensures it will slow enough to avoid skipping out and not over shoot the runway, and surface temperature/load factor requirements, which determine maximum heating and deceleration.

option. Instead of using engines to slow the spacecraft enough to enter a parking orbit, we can plan the hyperbolic approach trajectory to take it right into the atmosphere and then use drag to do the equivalent of the second ΔV burn. We then use its lift to pull it back out of the atmosphere before it crashes into the planet! By getting this "free" ΔV, we can save a huge amount of fuel.

Calculations show that using aerobraking, instead of conventional rocket engines, is almost ten times more efficient. This efficiency could mean a tremendous savings in the amount of material that must be put into Earth orbit to mount a mission to Mars. Figure 4.1.7-26 shows an artist's conception of an aerobraking vehicle. In his novel *2010: Odyssey Two,* Arthur C. Clarke uses aerobraking to capture a spaceship into orbit around Jupiter. The movie made from this novel dramatically depicts the aerobraking maneuver.

Figure 4.1.7-27 shows an aerobraking scenario. On an interplanetary transfer, the spacecraft approaches the planet on a hyperbolic trajectory (positive specific mechanical energy with respect to the planet). During aerobraking, it enters the atmosphere at a shallow angle to keep maximum deceleration and heating rate within limits. Drag then reduces its speed enough to capture it into an orbit (now it has negative specific mechanical energy with respect to the planet). To "pull out" of the atmosphere, it changes its angle of attack, lift. Basically, the vehicle dives into the atmosphere, and then "bounces" out. In the process it loses so much energy that it is captured into orbit. This atmospheric encounter now leaves the vehicle on an elliptical orbit around the planet. Because periapsis is within the atmosphere, the vehicle would re-enter if it took no other actions. Finally, it completes a single burn, much smaller than the ΔV needed without the aerobraking to put the vehicle into a circular parking orbit well above the atmosphere.

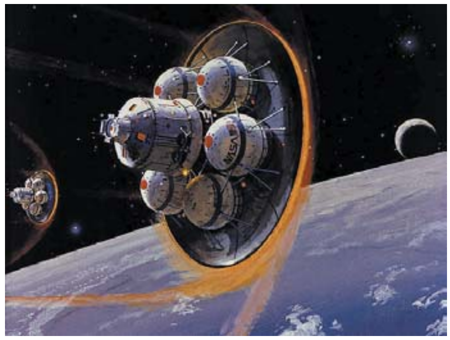


Figure 4.1.7-26. Aerobraking Concept. This artist's concept shows a heat shield that could be used for aerobraking at Mars or Earth. *(Courtesy of NASA/Goddard Space Flight Center)*

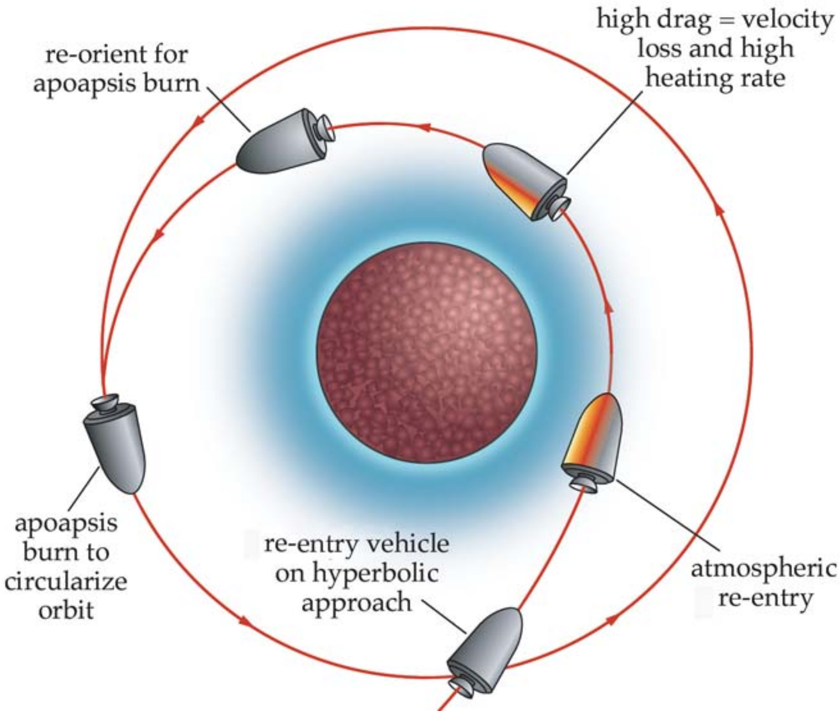


Figure 4.1.7-27. Aerobraking. The aerobraking maneuver allows a vehicle to get "free" ΔV by diving into the atmosphere and using drag to slow down.

Figure 4.1.7-28. Mars Global Surveyor. The Mars Global Surveyor spacecraft was the first interplanetary mission that was designed to use aerobraking to lower itself into its final mission orbit. *(Courtesy of NASA/Jet Propulsion Laboratory)*

The Mars Global Surveyor spacecraft, shown in Figure 4.1.7-28, was the first interplanetary spacecraft designed to take advantage of aerobraking. it was initially captured into a relatively high elliptical orbit around Mars using conventional rocket engines, and, over the course of several months, it used aerobraking to lower itself to the final mission orbit, saving many kilograms of precious propellant.

Section Review

Key Concepts

- Applying lift to the re-entry problem allows us to stretch the size of the re-entry corridor and improve accuracy by flying the vehicle to the landing site.
- The Space Shuttle is a good example of a lifting-re-entry vehicle. It uses its lift to keep re-entry deceleration low and fly to a pinpoint runway landing.
- Aerobraking can greatly decrease the amount of mass needed for interplanetary transfer. During an aerobraking maneuver, the vehicle dives into the target planet's atmosphere, using drag to slow enough to be captured into orbit.

References

Chapman, Dean. *An Analysis of the Corridor and Guidance Requirements for Supercircular Entry Into Planetary Atmospheres*. NASA TR R-55, 1960.

Concise Science Dictionary. Oxford: Oxford University Press, U.K. Market House Books, Ltd., 1984.

Eshbach, Suoder, (ed.). *Handbook of Engineering Fundamentals*. 3rd edition. New York, NY: John Wiley & Sons, Inc., 1975.

Entry Guidance Training Manual. ENT GUID 2102, NASA Mission Operations Directorate, Training Division, Flight Training Branch, NASA/Johnson Space Center, Houston, TX, December 1987.

Regan, Frank J. *Reentry Vehicle Dynamics*. AIAA Education Series, J.S. Przemieniecki series ed. in chief. New York, NY: American Institute of Aeronautics and Astronautics, Inc., 1984.

Tauber, Michael E. *A Review of High Speed Convective Heat Transfer Computation Methods*. NASA Technical Paper 2914, 1990.

Tauber, Michael E. *Atmospheric Trajectories*. Chapter for AA213 Atmospheric Entry. NASA/Ames Research Center, Stanford University, 1990.

Tauber, Michael E. *Hypervelocity Flow Fields and Aerodynamics*. Chapter for AA213 Atmospheric Entry. NASA/Ames Research Center, Stanford University, 1990.

Voas, Robert B. *John Glenn's Three Orbits in Friendship 7*. National Geographic, Vol. 121, No. 6. June 1962.