**AEROSPACE PALACE ACADEMY, NIGERIA**
**(A subsidiary of Aerospace Palace International, Nigeria)**

# LESSON 79: RIDING A SPACE SHUTTLE SOLID ROCKET BOOSTER

For many years, the Space Shuttle was the workhorse of NASA's space program. On launch, it consisted of the Shuttle itself, an external tank, and two Solid Rocket Boosters, or SRBs. The two Solid Rocket Boosters provided the extra lift necessary to get the entire assembly off the ground and about 28 miles up into the atmosphere, going at a final speed of about 3,000 miles per hour in just over two minutes of flight time. Then they would detach from the Space Shuttle and fall back to Earth, landing in the Atlantic Ocean to be retrieved and reused. On two missions, NASA attached cameras to the Solid Rocket Boosters and recorded their part of the mission. Then they published a video of what the cameras recorded. This lesson examines that video.

Next Generation Science Standards (NGSS):

- Disciplinary: Forces and Interactions
- Crosscutting Concept: Force and Motion
- Science & Engineering Practice: Asking Questions and Defining Problems

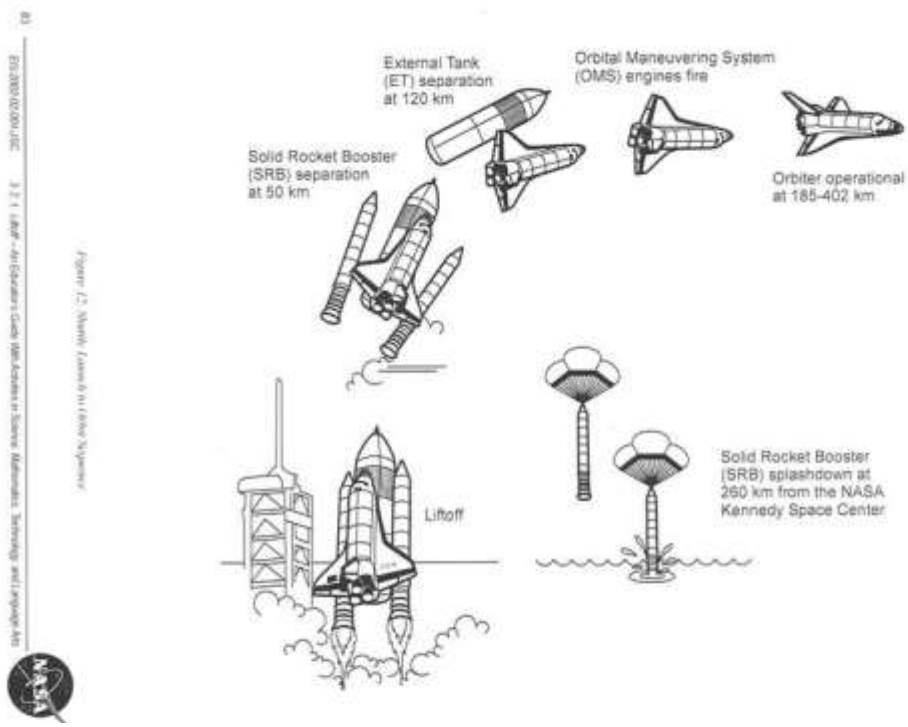
## GRADES K-2

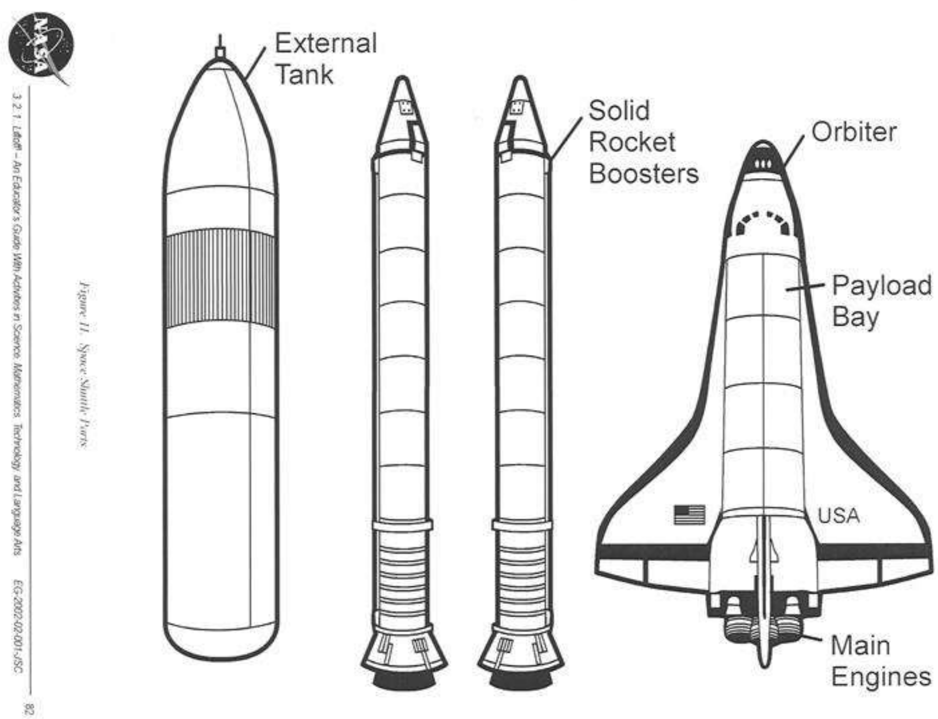
K-PS2-2. Analyze data to determine if a design solution works as intended to change the speed or direction of an object with a push or a pull.

The Space Shuttle was a reusable spacecraft. It could be launched and then used for another mission after it landed. The five Space Shuttles conducted 135 missions over thirty years from the first mission in 1981 until the program was ended in 2011.

The Orbiter was the part of the Shuttle that resembles an airplane. The Shuttle astronauts traveled inside the Orbiter, living there during their mission and conducting science experiments in it as they orbited the Earth. It had a section called the payload bay that opened up for deploying satellites and other EVA parts of the mission. Later during the program the Shuttle was used to take astronauts and equipment to and from the ISS.

The other parts of the Shuttle are the Solid Rocket Boosters and the External Fuel Tank.
The SRBs are the white rocket shapes that were jettisoned about 2 minutes after the launch. They contained solid propellant rather than liquid fuel. The External Tank is the large orange shape along the underside of the orbiter. While the SRBs would splash down into the ocean and be recovered for use on later launches, the External Tank was jettisoned much later in the flight and burned up in the atmosphere.




Kidsatronomy.com has an article on the Space Shuttle program, including a video with launch and landing highlights (about 5 minutes in length). NASA also has information on the history of the Space Shuttle in their student resources. The images on the next page are from the NASA Educator Guide, 3..2..1..Liftoff! One shows the parts of the Shuttle labeled very clearly, and the other has a diagram of the sequence showing the launch and the SRB splashing down. If you visit the guide online, you will see there are even directions for making an edible model of the Space Shuttle.

## GRADES 3-5

3-PS2-1. Plan and conduct an investigation to provide evidence of the effects of balanced and unbalanced forces on the motion of an object.

The Space Shuttle's Solid Rocket Motors were the first solid propellant motor ever developed for space flight and the most powerful rockets of that type ever flown. Rocket engines are divided into solid-fueled and liquid-fueled. Rocket engines that use liquid fuel are similar to the engines in automobiles: the fuel and the oxygen (or an oxygen substitute) are pumped into a combustion chamber where they burn and produce the energy that the rocket uses. Solid-fueled rockets contain both the fuel and the oxidizer bound up into one mass of solid propellant, which burns where it is packed and provides the rocket's energy. Fireworks use something very much like solid rocket fuel and bottle rockets are very small solid-fueled rockets. Cosmos Magazine has an article which describes the difference between rockets with liquid or solid fuel, including a diagram of the interior of the rockets.

The pair of Solid Rocket Boosters made up over half the mass of the entire shuttle assembly. Each SRB weighed around 1,300,000 pounds at launch. The propellant itself made up 1,100,000 pounds of that weight. In comparison, the external tank (or ET), weighed 78,100 pounds when empty and 1,585,400 pounds when filled with fuel and oxygen. (Can your students figure out the weight of the fuel and oxygen? It is a simple subtraction.) The Space Shuttle used liquid hydrogen as fuel and liquid oxygen as oxidizer; these two substances react in a ratio of 8 parts oxygen to 1 part hydrogen. (Can your students figure out how much hydrogen and how much oxygen the ET carried? As a hint, the numbers do not work out exactly.)

The principle behind a rocket is quite simple: exhaust is pushed in one direction and the rocket is pushed in the other direction in accordance with Newton's Third Law. In practice, through, the Space Shuttle was anything but simple. Indeed, it had more than a million different moving parts. To push the propellant out at such high speed needs a high pressure in the combustion chamber of a liquid-fueled motor or in the propellant of a solid-fueled motor; the rocket needs to be strong enough to withstand the high pressure. Liquid hydrogen evaporates at -423°F and liquid oxygen at -297°F; by comparison, absolute zero—the lowest temperature that can be achieved under any circumstances—is -460°F. Having enough insulation so that the hydrogen and oxygen did not boil away before the Space Shuttle could use them took careful engineering design. Designing an engine to receive fuel and oxidizer that are so cold and that burn to form exhaust that is over 5,000°F is an engineering marvel.

## ***GRADES 3-5 (CONTINUED)***

Watching the "Riding the Booster" video, you can use the speed levels at different times after launch to calculate average accelerations. For example, at about one minute into the video you can see that thirty seconds into the flight (the number in the upper left-hand corner) the Shuttle is traveling at about 500 miles per hour (the number in the upper right-hand corner). (This may also be an opportunity to discuss rounding numbers and significant figures.) Dividing the one by the other gives an acceleration of about 17 miles per hour per second (24 ft/sec$^2$), which is about the same as you would get from a sports car. (The difference is that the Shuttle is a lot heavier than a sports car and can sustain its acceleration a lot longer.) Twenty seconds later in the video, at a time of flight of 45 seconds, the speed is around 760 miles per hour, giving about the same acceleration. Comparing speeds and flight times at 1:45 and 1:53 in the video (1,985 mph at 90 seconds into the flight and 2,962 mph at 120 seconds into the flight) shows that the acceleration has doubled to 32 miles per hour per second (48 ft/sec$^2$, or about one and a half times the acceleration due to gravity).

~~NASA has an up-close, high-definition video of Kennedy Space Center's solid rocket booster (SRB) recovery ships retrieving SRB segments from the Atlantic Ocean following a space shuttle launch~~. ~~NASA also has information about the Space Shuttle program for upper elementary and middle school students~~.

## ***GRADES 6-8***

MS-PS2-2. Plan an investigation to provide evidence that the change in an object's motion depends on the sum of the forces on the object and the mass of the object.

The Space Shuttle was the workhorse of the manned American space program for three decades. It was designed to be the "pickup truck" of spacecraft—the rugged hardworking vehicle that carried things into space cheaply and easily. While it never fulfilled the "cheaply and easily" promise—its advanced technology prevented that—it did carry many things into space, including essentially all the components that were assembled into the International Space Station.

The video "Riding the Booster" makes much more sense if one knows how a Space Shuttle was launched. NASA has produced another, shorter video with more conventional camera angles which provides an excellent description of a Shuttle launch.

## *GRADES 6-8 (CONTINUED)*

Most rockets that the United States launches into space are launched from the East Coast. This is because to stay in space near the Earth, a spacecraft needs to be in orbit; to be in orbit, the spacecraft needs to be moving very quickly (around 15,000 miles per hour!); and the Earth's rotation provides a boost for rockets launched near the Equator of about 1,000 miles per hour to get into an orbit that goes from west to east. When lower stages of the rocket use up their fuel and are jettisoned, they fall back to Earth; if the rocket is launching a spacecraft into a west-to-east orbit, they fall back to Earth many miles east of the launch point. We do not want spent rocket stages falling onto the land where they might hit people or things. For this reason, we put our launch sites on the East Coast where the spent stages will fall into the Atlantic Ocean. Besides the Kennedy Space Center, there is a smaller launch facility at Wallops Island, Virginia. There is another launch site on the Pacific coast of the United States at Vandenberg Air Force Base in California; rockets launched there usually send spacecraft into polar orbits. The rockets take off from there flying southward over the Pacific Ocean and avoiding the land.

Both Shuttle Missions STS-117 and STS-127 lifted off from Launch Pad 39A of the Kennedy Space Center. You can see flashes of the launch pad's auxiliary buildings as the Shuttle rises past them around 0:34-0:38 in the video. It may be interesting for the students to compare the brief view with the satellite view of the launch complex from Google Maps; at the very least, the square building to the west of the launch position and the retractable assembly (you can see the circular tracks) to the southwest are easily identified. More of the site, although obviously in less detail, can be seen at 0:51 in the video; east-southeast is to the right at this point. The roads and coastline visible at 1:03 are due north of the launch site. The launch site is visible again in the distance at 1:23 in the video.

## *GRADES 9-12*

HS-ETS1-3. Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics as well as possible social, cultural, and environmental impacts.

Let us begin at the beginning. At 0:15 into the video, you see the Space Shuttle on the launch pad, sitting above an open area with jets of water streaming into it. Can your students figure out the purpose of the water? It is to absorb heat, both by warming up and being by evaporated into steam (and it takes more than ten times as much heat to vaporize a

## ***GRADES 9-12 (CONTINUED)***

kilogram of water into steam as it does to heat it up by 50°C or 90°F), so that the rocket exhaust will not damage the launch pad any more than it does.

Several seconds before liftoff (around 0:20 in the video), the Space Shuttle Main Engines (SSMEs) ignite. The SSMEs were liquid-fueled engines and could be throttled up and down as needed, varying the amount of thrust that they delivered, and could also be shut off. They were turned on several seconds before launch to ensure that they would work properly; if an engine did not work, all the SSMEs could be cut off and the launch scrubbed. By contrast, the Solid Rocket Motors (SRMs) were (as their name implies) solid rockets and once ignited, could not be turned off. When the SRMs ignited, the mission was on. At 0:25, you can see the whole Shuttle rock slightly under the push of the SSMEs.

The geography of the launch site is visible in the video around 0:34-0:38, 0:51, 1:03, and 1:23 as described in the Grades 6-8 lesson above.

At 1:13 in the video, condensation clouds appear around the sides of the Shuttle. A few seconds later, text appears identifying this with the Shuttle "going transonic," or acceleration through the speed of sound. Why this causes condensation is not direct, but can be explained. When a body travels faster than the speed of sound, a "bow shock" builds up in front of it of air that is unable to get out of the way in time. As this air flows around the sides of the vehicle, it expands and cools. Cooler air is not able to hold as much water vapor as warmer air and the excess water condenses out to form the clouds. Higher up, the air is drier and does not form the clouds. Because the cameras are riding on the vehicle that is flying faster than the speed of sound, they do not experience a sonic boom.

Around 1:45 in the video, the camera view shifts forward again and we can see the blackness of space. The Shuttle is not into space yet—your writer estimates very roughly that it is only about a third of the way there, or perhaps less—but the air above it is thin and rarefied enough that it does not scatter enough sunlight to look blue. You can see the lower atmosphere like a fuzzy blanket over the Earth's surface extending to the upper left in the video frame.

Ten seconds later, at 1:57, there is a sudden change as the Solid Rocket Boosters separate from the Shuttle. (The full assemblage is called the Solid Rocket Booster; the motor part of the SRB, which forms the lion's share of the assemblage but not all of it, is the Solid Rocket Motor.) As they fall away from the Shuttle at 1:59, you can see their bright exhaust



plumes. The SSMEs, in contrast, has hardly any plume at all. This is because the SSMEs burned hydrogen and oxygen, producing water vapor as their exhaust, while the SRMs burned a solid propellant that produced an exhaust with many different components, including some tiny particles. These particles glowed brilliantly when hot. You can see some "flames" as the exhaust of the SSMEs plays on the very back of the other SRB in the picture at 2:01. You can also see as the SRBs fall away and stop flying straight forward that their exhaust plumes start to curve. The black smoke that curves more sharply is SRM exhaust that has met the (very thin) air around it and cooled and slowed down so that it no longer glows and no longer moves as fast. The plume lessens as the SRM runs low on fuel and does not burn so quickly.

The bright object in the sky at 2:08 in the video is the Sun. STS-117 launched at 7:38 PM on June 8, 2007 while STS-127 launched at 6:03 PM on July 15, 2009. Both of those times are Eastern Daylight Time and the Sun set around 8:20 PM on those dates. In addition, at an altitude of about 30 miles, the horizon is about seven degrees below the horizontal, putting the apparent position of the Sun even higher in the sky than it would be from a vantage point on the ground. Using the half-degree apparent diameter of the Sun as a guide, your writer estimates very roughly that it is about 15 degrees above the horizon, meaning that this cut in the video was probably shot from STS-117 with its later launch time.

The next several seconds show the booster separation again from the vantage point of a camera that is pointed toward the External Tank. After the SRB separates, the camera shows the other SRB also separating from the tank. Because the camera is attached to the booster, it rotates with it and shows the other SRB almost stationary as the world (literally!) revolves around it. The bright spots flying by at 2:26 are particles from the SRM exhaust, just as you can see the exhaust from the other SRM flying past the other booster in the distance. At this moment the SRBs are flying backwards through the air, still ascending from the momentum that they had before they separated from the Shuttle.

The clip starting at 2:32 in the video shows the booster separation a third time, this time from the position of a camera pointing forward toward the nose of the Shuttle. (Because the camera shows the Shuttle wing, you can tell that it is mounted quite far back toward the tail of the SRB, but it is pointing forward.) At 2:48 and again at 3:04 you can see briefly in the upper left part of the frame the trail of smoke that the Shuttle left behind as it ascended

## GRADES 9-12 (CONTINUED)

through the atmosphere. You can also see the Sun, although its light saturates the camera to enough of an extent that your writer cannot estimate its distance from the horizon.

The next half-minute or so shows the SRB turning lazily in space—or at least in the extreme high reaches of the atmosphere. Again, because the camera is fixed to the SRB, it appears that the booster is standing still while the world revolves around it. At times the camera shows the other SRB turning in the distance. The booster reaches apogee, its highest point above the Earth, around 3:48 in the video, or around 195 seconds after launch, at an altitude of about 41 miles. You can tell that it is apogee because the speed stops decreasing and starts to increase under the pull of gravity. At some points it looks like the camera is showing the curvature of the Earth, but it is really an artifact of the camera lens; at other points it looks like the Earth is actually concave.

As the boosters continue with their "graceful tumble," as the video says, you can see briefly at 4:23 what appears to be the exhaust plume of the Shuttle in the upper right as it continues on upward into space. (It may actually be the exhaust of the spent SRB; your writer is not definite on this point.) The Sun comes into view again at 5:03, playing havoc with the image, and the smoke trail of the Shuttle coming up from the ground is visible again at 5:07. The long smoke trail between the Sun and the trail coming up from the ground, visible around 5:05, must be more exhaust coming from the spent SRM, even though it may look like it is coming toward the camera rather than moving away from the camera. The only other object that could generate such a trail is the Shuttle, and the Shuttle is east of the SRB while the camera is looking westward toward the launch point and the setting Sun.

Right around this point, at 5:07 in the video, the air resistance on the SRB starts to become significant. You can see in the previous several seconds how the steady rotation of the booster changes to a less regular tumbling. At 5:07 the booster's speed peaks at 2,924 miles per hour and the booster starts decelerating. This happens because the air resistance to the booster has risen to the level of gravitational acceleration and above it. (Note that because the SRB has a significant forward speed, the deceleration is in the forward direction as the vertical speed continues to increase.) At 5:11 and especially a few seconds later, you can see the effect of the air as it pushes the exhaust from the still-burning SRM in various directions. Your writer does not know what the small pieces seen coming off at 5:18 are.

## *GRADES 9-12 (CONTINUED)*

The booster spends the next minute in the video plunging through the thickening atmosphere, continuing to slow down as the air around it gets ever denser. At 6:02 you can catch a glimpse of the other SRB as it is doing the same, leaving a trail of smoke from its spent SRM. A few seconds later it slows down below the speed of sound (around 700 mph) without visible effect.

At 6:47 in the video the view changes abruptly from a back-facing camera showing the SRM nozzle and the clouds to a forward-facing camera showing the deployment of the three parachutes. The parachutes begin with a cord around each one preventing it from opening fully; if they opened fully at 200 miles per hour the air resistance would rip them off. At 6:51 you can also see the small drogue chute that pulls the main parachutes out. The video does not show the parachutes deploy fully; at 7:03, at 145 mph, they are still rigged, but when you next see them at 7:08 at a speed of 120 mph, they are fully deployed.

In between the two views of the parachutes, you can see at 7:05 the jettisoning of SRM nozzle so that the shock of hitting the water does not jam it up into the motor itself. The debris from the jettison flies up around the camera and past the parachutes. At 7:15 you can see the splash as the nozzle hits the ocean and seven seconds later the booster itself splashes down.

After the SRB splashes down, all is confusion until 7:30 when the view clears enough to see the ocean surface, with the wave from the splashdown visible around 7:37 moving away. A piece of parachute cord falls in front of the camera at 7:45 and in the distance you can see ships coming to retrieve the booster. Five seconds later there appears at the top of the frame the other SRB, suspended from its parachutes coming in for a splashdown of its own.

The Solid Rocket Booster's flight lasts in all just under seven minutes. But what a seven minutes it is! It takes the SRB from the launch pad up to the edge of space, to speeds of thousands of miles per hour, down to a landing in the Atlantic Ocean. It is a ride like no other.

Splashdown was not the end of the story for the Solid Rocket Boosters. After they splashed down, NASA ships went out and retrieved them, bringing them back to shore to be refurbished and reused on another Space Shuttle flight.

## *GRADES 9-12 (CONTINUED)*

The video that this lesson analyzes is not the only video of the Space Shuttle launches that NASA has produced. There is a 35-minute video that consists of continuous, uncut, and unenhanced videos from individual cameras on the SRBs from the STS-134 launch; after you have been through the present video you will be able to recognize many events in the SRB flight even though they are not noted. There is a similar video of the SRB flights from STS-135, the last Shuttle mission. For those with less time, a ten-minute video of the STS-133 launch or a seven-minute video of the STS-132 launch may be preferable. A quick internet search will reveal many more.

Sixty Years Ago in the Space Race:

February 6, 1959: The United States Air Force's Titan ICBM had its first test launch from Cape Canaveral, FL.