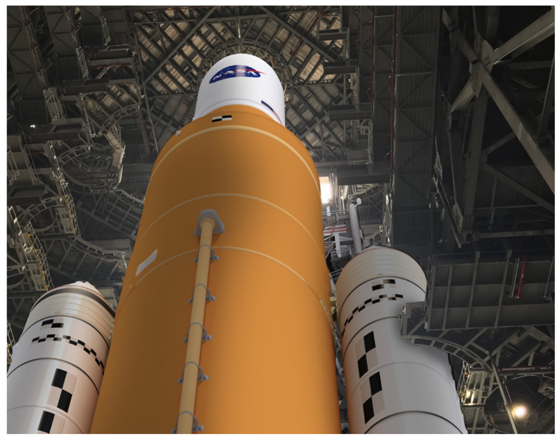
National Aeronautics and Space Administration

Spacecraft Structures

A Lesson in Engineering



engineering is out of this world

Cover Illustrations:

Artist concepts of NASA's Space Launch System and the launch pad at Kennedy Space Center.

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1. Overview

Space Transportation

NASA engineers at Marshall Space Flight Center, along with their partners at other NASA centers and in private industry, are designing and building the next generation of rockets and spacecraft to transport cargo, equipment, and human explorers to space. Known collectively as Deep Space Exploration Systems, the Space Launch System (SLS) rocket, the Orion spacecraft, and ground systems at Kennedy Space Center are carrying out a bold vision of human space exploration. Space Policy Directive 1 (SPD-1), signed in December 2017, provides for a U.S.-led, integrated program with private sector partners for a human return to the Moon, followed by missions to Mars and beyond. This design challenge focuses on the SLS rocket, an advanced launch vehicle that provides the foundation for human exploration beyond Earth's orbit.

Connecting to Engineering and Science

The Engineering Design Challenge connects students with the work of NASA engineers by engaging them in similar design challenges of their own. With some simple and inexpensive materials, you, the teacher, can lead an exciting unit that focuses on a specific problem that NASA engineers must solve and the process they use to solve it. In the classroom, students design, build, test, and revise their own solutions to problems that share fundamental science and engineering issues with the challenges facing NASA engineers.

The Design Challenge

The challenge: Build a model thrust structure (Figure 1) that is as light as possible, yet strong enough to withstand the load of a "launch to orbit" three times. Students first determine the amount of force needed to launch a model rocket to 3.3 feet [1 meter (m)], which represents low-Earth orbit. Then they design, build, and test their own structure designs. They revise their designs over several design sessions, trying to maintain or increase the strength and reduce the weight of their structure. They document their designs with sketches and written descriptions. As a culmination, students compile their results into a poster and present them to the class.

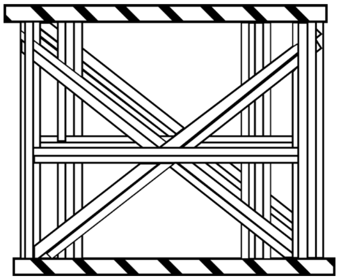


Figure 1. Model thrust structure.

Time Required

The design challenge can be carried out in six 45-minute class periods, but you could easily extend it for twice that length of time. We provide some ideas for extensions at the end of the guide.

You will need to invest 4 – 8 hours gathering the materials, building the test stand, trying out your own designs, reading the guide, and preparing the classroom.

Value to Students

This activity will provide your students with the opportunity to solve a challenge based on a real-world problem that is part of the space program and to use creativity, cleverness, and scientific knowledge in doing so. During these activities, students will have many opportunities to learn about forces, structures, and energy transfer. The culminating activity gives students an opportunity to develop their presentation and communication skills.

Research Opportunities

Appendix A (p. 41) of this guide includes many web sites where students can obtain additional information.

2. Next Generation Science Standards

MS-ETS1 – Engineering Design

STANDARDS:

MS-ETS1-1: Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions.

MS-ETS1-2: Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.

MS-ETS1-3: Analyze data from tests to determine similarities and differences among several design solutions to identify the best characteristics of each that can be combined into a new solution to better meet the criteria for success.

MS-ETS1-4: Develop a model to generate data for iterative testing and modification of a proposed object, tool, or process such that an optimal design can be achieved.

DISCIPLINARY CORE IDEA:

ETS1.A: The more precisely a design task's criteria and constraints can be defined, the more likely it is that the designed solution will be successful. Specification of constraints includes consideration of scientific principles and other relevant knowledge that is likely to limit possible solutions.

ETS1.B: A solution needs to be tested, and then modified on the basis of the test results, in order to improve it.

ETS1.C: Although one design may not perform the best across all tests, identifying the characteristics of the design that performed the best in each test can provide useful information for the redesign process—that is, some of those characteristics may be incorporated into the new design.

CROSS-CUTTING CONCEPTS:

Engineering, Technology, and Science on Society and the Natural World

HS-ETS1 – Engineering Design

STANDARDS:

HS-ETS1-2: Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.

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.

DISCIPLINARY CORE IDEA:

ETS1.B: When evaluating solutions it is important to take into account a range of constraints including cost, safety, reliability and aesthetics, and to consider social, cultural and environmental impacts.

CROSS-CUTTING CONCEPTS:

Engineering, Technology, and Science on Society and the Natural World

MS-PS2 – Motion and Stability: Forces and Interactions

STANDARDS:

MS-PS2-1: Apply Newton's Third Law to design a solution to a problem involving the motion of two colliding objects.

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.

MS-PS3-5: Construct, use, and present arguments to support the claim that when the kinetic energy of an object changes, energy is transferred to or from the object.

DISCIPLINARY CORE IDEAS:

PS2.A: For any pair of interacting objects, the force exerted by the first object on the second object is equal in strength to the force that the second object exerts on the first, but in the opposite direction (Newton's third law).

PS3.C: When two objects interact, each one exerts a force on the other that can cause energy to be transferred to or from the object.

HS-PS2 – Motion and Stability: Forces and Interactions

STANDARDS:

HS-PS2-3: Apply scientific and engineering ideas to design, evaluate, and refine a device that minimizes the force on a macroscopic object during a collision.

HS-PS3-2: Develop and use models to illustrate that energy at the macroscopic scale can be accounted for as a combination of energy associated with the motions of particles (objects) and energy associated with the relative position of particles (objects).

DISCIPLINARY CORE IDEA:

PS2.A: If a system interacts with objects outside itself, the total momentum of the system can change; however, any such change is balanced by changes in the momentum of objects outside the system.

PS3.A: Energy is a quantitative property of a system that depends on the motion and interactions of matter and radiation within that system. That there is a single quantity called energy is due to the fact that a system's total energy is conserved, even as, within the system, energy is continually transferred from one object to another and between its various possible forms.

CROSS-CUTTING CONCEPTS:

Cause and Effect
Energy and Matter

3. Common Core State Standards Mathematics

Mathematics Practices:

2. Reason abstractly and quantitatively.
6. Attend to precision.

STANDARDS:

Expressions and Equations

- 6.EE: Apply and extend previous understandings of arithmetic to algebraic expressions.
- 8.EE: Understand the connections between proportional relationships, lines, and linear equations.

Geometry

- 6.G: Solve real-world and mathematical problems involving area, surface area, and volume.

Ratios and Proportional Relationships

- 7.RP: Analyze proportional relationships and use them to solve real-world and mathematical problems.

Functions

- 8.F: Define, evaluate, and compare functions.
- 8.F: Use functions to model relationships between quantities.

4. Background

Space Launch System

America's Rocket for Deep Space Exploration

NASA's Space Launch System, or SLS, is an advanced launch vehicle that provides the foundation for human exploration beyond Earth's orbit. With its unprecedented power and capabilities, SLS is the only rocket that can send Orion, astronauts, and large cargo to the Moon on a single mission.

Offering more payload mass, volume capability, and energy to speed missions through space than any current launch vehicle, SLS is designed to be flexible and evolvable and will open new possibilities for payloads, including robotic scientific missions to places like the Moon, Mars, Saturn, and Jupiter.

The Power to Explore Beyond Earth's Orbit

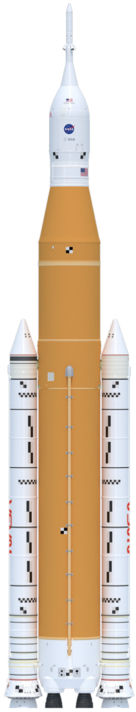
To fulfill America's future needs for deep space missions, SLS will evolve into increasingly more powerful configurations. SLS is designed for deep space missions and will send Orion or other cargo to the Moon, which is nearly 1,000 times farther than where the space station resides in low-Earth orbit. The rocket will provide the power to help Orion reach a speed of at least 24,500 miles per hour (mph) [39,425 kilometers per hour (kph)] needed to break out of low-Earth orbit and travel to the Moon. That is about 7,000 mph (11,265 kph) faster than the space station travels around Earth.

Every SLS configuration uses the core stage with four RS-25 engines. The first SLS vehicle, called Block 1, can send more than 59,000 pounds (lbs.) [27 metric tons (t)] to the Moon's vicinity. It will be powered by twin five-segment solid rocket boosters and four RS-25 liquid propellant engines generating 8.8 million lbs. [39,144 kilonewton (kN)] of thrust. After reaching space, the Interim Cryogenic Propulsion Stage (ICPS) sends Orion on to the Moon.

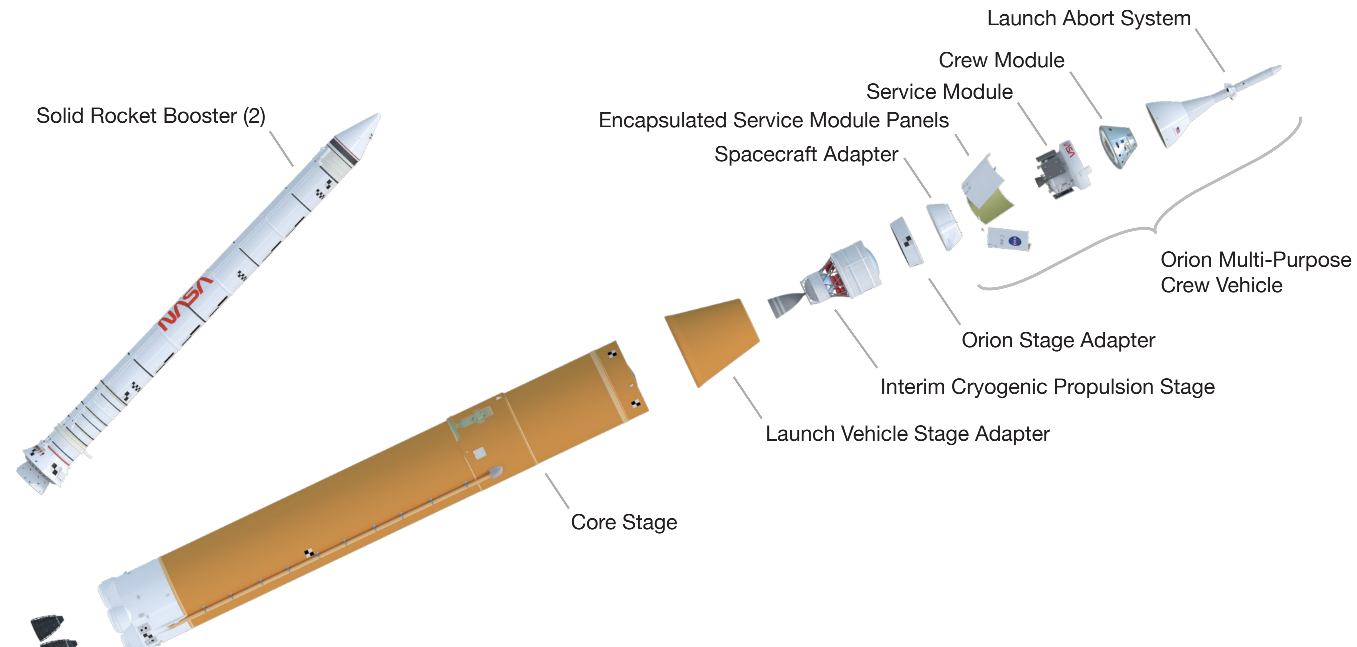
The next planned evolution of the SLS, the Block 1B crew vehicle, will use a new, more powerful Exploration Upper Stage (EUS) to enable more ambitious missions. The Block 1B vehicle can, in a single launch, carry the Orion crew vehicle along with exploration systems like a deep space habitat module.

The Block 1B crew vehicle can send approximately 83,500 lbs. (38 t) to deep space including Orion and its crew. Launching with cargo only, SLS has a large volume payload fairing to send larger exploration systems or science spacecraft on solar system exploration missions.

The next SLS configuration, Block 2, will provide 9.5 million lbs. (42,258 kN) of thrust. It will be the most powerful variant and will be used for carrying large payloads to the Moon, Mars, and other deep space destinations. SLS Block 2 crew will be designed to lift more than 94,700 lbs. (43 t) to deep space. The design for SLS Block 2 cargo will allow for over 101,000 lbs. (46 t) to be lifted into deep space. An evolvable design provides the nation with a rocket able to pioneer new human spaceflight missions.



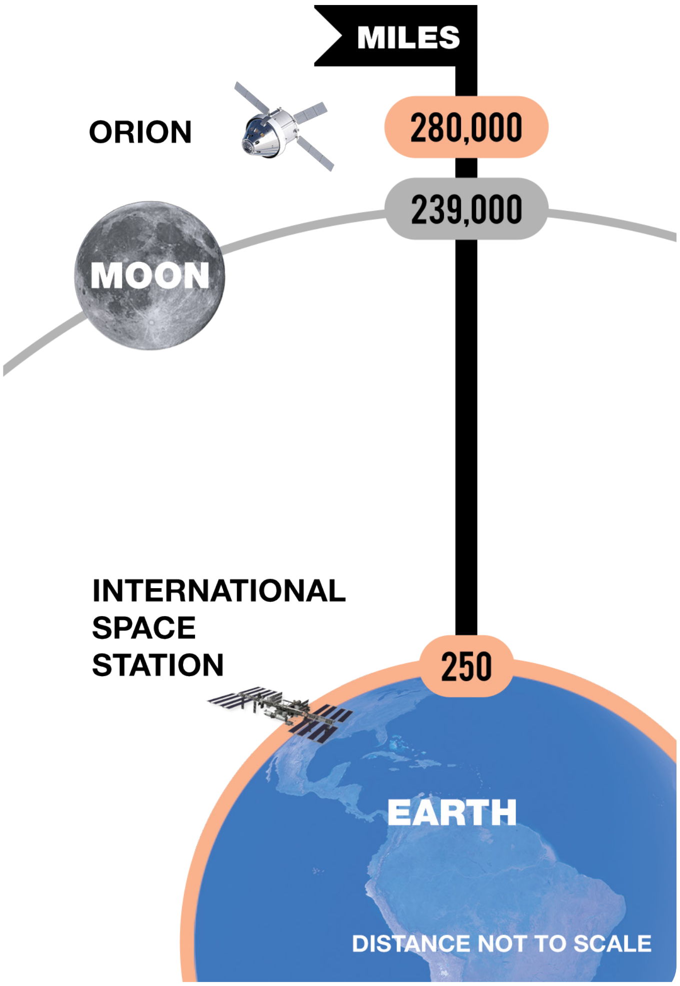
Block 1 – Initial SLS Configuration



Space Launch System Missions

Artemis I, the first integrated flight of SLS and Orion, uses the Block 1 configuration, which stands 322 feet (ft.) [98.1 meters (m)], taller than the Statue of Liberty, and weighs 5.75 million lbs. [2.6 million kilograms (kg)]. SLS will produce 8.8 million lbs. (39,144 kN) of maximum thrust, 15 percent more thrust than the Saturn V rocket.

For Artemis I, Block 1 will launch an uncrewed Orion spacecraft to an orbit 40,000 miles [64,374 kilometers (km)] beyond the Moon, or 280,000 miles [450,616 km) from Earth. This mission will demonstrate the integrated system performance of SLS, Orion, and Exploration Ground Systems teams prior to a crewed flight to send Orion to lunar orbit. SLS will also carry 13 small satellites, each about the size of a shoebox, to be deployed in deep space.



NASA's Space Launch System is powerful enough to send the Orion spacecraft beyond the Moon. For Artemis I, Orion will travel 280,000 miles from Earth—farther in deep space than any spacecraft built for humans has ever ventured.

Core Stage

The Boeing Company, in Huntsville, Alabama, is building the SLS core stage, including the avionics that will control the vehicle during flight. Towering more than 212 ft. (64.6 m) with a diameter of 27.6 ft. (8.4 m), the core stage will store 733,000 gallons (2.77 million liters) of super-cooled liquid hydrogen and liquid oxygen that will fuel the RS-25 engines.

The core stage is being built at NASA's Michoud Assembly Facility in New Orleans using state-of-the-art manufacturing equipment, including a friction-stir-welding tool that is the largest of its kind in the world. The SLS avionics computer software is being developed at NASA's Marshall Space Flight Center in Huntsville.

SLS core stage Liquid Oxygen Tank (top) and Liquid Hydrogen Tank (bottom)

RS-25 Engines

Propulsion for the SLS core stage will be provided by four RS-25 engines. Aerojet Rocketdyne of Sacramento, California, is upgrading an inventory of 16 RS-25 shuttle engines to SLS performance requirements, including a new engine controller, nozzle insulation, and required operation at 512,000 lbs. (2,277 kN) of thrust. During the flight, the four engines provide around 2 million lbs. (8,896 kN) of thrust.

Following the installation of the engines into the fully assembled Artemis I core stage, NASA's Pegasus barge transported the entire stage to Stennis Space Center near Bay St. Louis, Mississippi, for testing. Once testing is complete, Pegasus will take the core stage to Kennedy Space Center in Florida where it will be prepared for launch. Aerojet Rocketdyne has started development testing of new, advanced components to make the engines more affordable and powerful for future missions.

Boosters

Two shuttle-derived solid rocket boosters will be used for the initial flights of the SLS. To provide the additional power needed for the rocket, the prime contractor for the boosters, Northrop Grumman, of Redondo Beach, California, has modified the original shuttle's configuration of four propellant segments to a five-segment version. The design includes new avionics, propellant design, and case insulation, as well as eliminates the recovery parachutes.

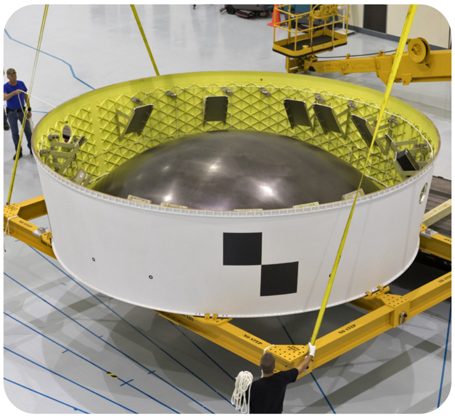
At the Utah facility, Northrop Grumman has cast all booster segments needed for Artemis I. At Kennedy, engineers are refurbishing and upgrading space shuttle booster components to meet SLS requirements. Trains will carry booster segments from Utah to Kennedy Space Center where they will be stacked with other booster components. The boosters' avionics systems are being tested at Kennedy and Marshall.

Artemis I Booster Aft Segment

Spacecraft and Payload Adapter, Fairings, and In-Space Stage

The Orion stage adapter will connect Orion to the Interim Cryogenic Propulsion Stage (ICPS) on the SLS Block 1 vehicle and is the place where the small satellites will ride to space. Teledyne Brown Engineering of Huntsville, Alabama, has built the launch vehicle stage adapter (LVSA) that will connect SLS's core stage to the upper part of the rocket.

The initial capability to propel Orion out of Earth's orbit for Block 1 will come from the ICPS, based on the Delta Cryogenic Second Stage used successfully on United Launch Alliance's Delta IV family of rockets. It uses one RL10 engine made by Aerojet Rockedyne. The engine is powered by liquid hydrogen and liquid oxygen and generates 24,750 lbs. (110 kN) of thrust.



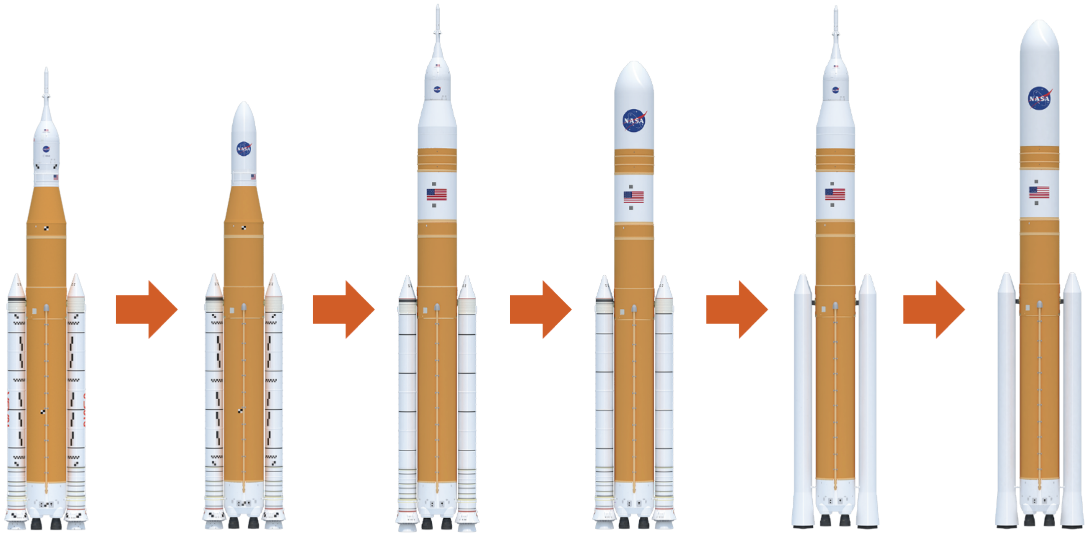
Orion Stage Adapter

Launch Vehicle Stage Adapter

Interim Cryogenic Propulsion Stage

	SLS Block 1 Crew	SLS Block 1 Cargo	SLS Block 1B Crew	SLS Block 1B Cargo	SLS Block 2 Crew	SLS Block 2 Cargo
Payload to TLI/Moon	> 27 t (59.5k lbs)	> 27 t (59.5k lbs)	38 t (83.7k lbs)	42 t (92.5k lbs)	> 43 t (94.7k lbs)	> 46 t (101.4k lbs)
Payload Volume	N/A*	8,118 ft^3 (229.9m^3)*	10,100 ft^3 (286m^3)*	21,930 ft^3 (621.1 m^3)	10,100 ft^3 (286 m^3)*	34,910 ft^3 (988 m^3)
Maximum Thrust	8.8M lbs	8.8M lbs	8.9M lbs	8.9M lbs	9.5M lbs	9.5M lbs

* Not including Orion/ Service Module volume



SLS Evolution

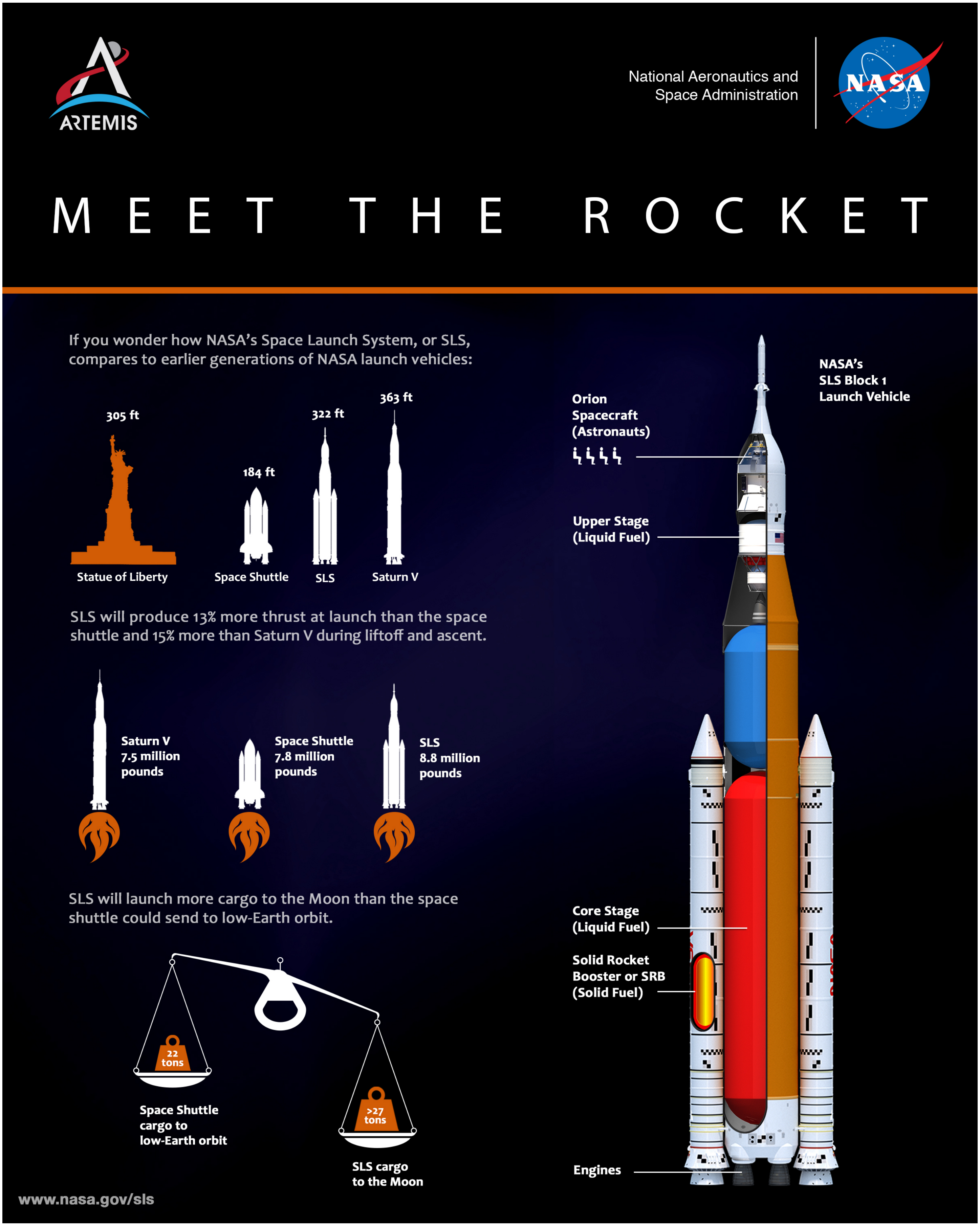
NASA has designed the Space Launch System as the foundation for a generation of human exploration missions to deep space, including missions to the Moon and Mars. SLS will leave low-Earth orbit and send the Orion spacecraft, its astronaut crew, and cargo to deep space. To do this, SLS has to have enough power to perform a maneuver kown as trans-lunar injection, or TLI. This maneuver accelerates the spacecraft from its orbit around Earth onto a trajectory toward the Moon. The ability to send more mass to the Moon on a single mission makes exploration simpler and safer.

Spacecraft Structures

Every pound that is carried to space requires fuel, whether that pound is cargo, crew, fuel, or part of the spacecraft itself. The more the vehicle and fuel weigh, the fewer passengers and smaller payload the vehicle can carry. Designers try to keep all the parts of the vehicle, including the skeleton (or structure), as light as possible. To design a lightweight structure is very difficult because it must be strong enough to withstand the tremendous thrust (or force) of the engines during liftoff. Throughout the history of space vehicles, engineers have used various strategies for the structure.

In order to make the SLS spacecraft as light as possible, NASA engineers are constructing it with lightweight, strong materials, such as aluminum alloys and composites. NASA engineers also design structures that use as little material as possible to achieve the strength and rigidity they need. So, for example, they machine a waffle grid pattern into the inside of the core stage panels to keep them rigid with minimum weight.

This engineering design challenge focuses on the thrust structure, which attaches the four liquid fuel engines to the body of the rocket. The thrust structure is an essential part of the spacecraft, which must be kept lightweight. As they burn, the four RS-25 engines on the SLS produce about 2 million lbs. (8,896 kN) of thrust. The thrust structure must not only withstand this force, it must transfer it to the vehicle in a balanced way, without damaging the vehicle.



ARTEMIS

National Aeronautics and Space Administration

MEET THE ROCKET

If you wonder how NASA's Space Launch System, or SLS, compares to earlier generations of NASA launch vehicles:

SLS will produce 13% more thrust at launch than the space shuttle and 15% more than Saturn V during liftoff and ascent.

SLS will launch more cargo to the Moon than the space shuttle could send to low-Earth orbit.

www.nasa.gov/sls

NASA's Space Launch System is powerful enough to send the Orion spacecraft beyond the Moon.

Questions for Class Discussion

1. Why is it important to make launch vehicles (rockets) as lightweight as possible?

2. What are some ways NASA engineers could make the Space Launch System as lightweight as possible?

3. If it costs $10,000 to lift 0.5 kg (1 lb.) of payload into orbit, calculate the cost of sending yourself into space. How much would it cost to send you and your family?

Answers

1. To maximize the amount of payload it can launch to orbit.

2. Answers will vary. Examples: use composite materials; remove excess/unneeded materials from hardware

3. Answers will vary.

5. Teacher Preparation

Materials for Students to Use for Challenge

Material	Minimum Quantity for a few teams (60 structures)	Minimum Quantity for 12 - 15 teams (120 structures)	For each additional team (10 structures)
Craft sticks	1,500	3,000	250
Dowels	5	5	0
Hot-melt glue sticks (low-temperature type)	12	20	2
Corrugated cardboard squares	60	120	10
35 mm film canisters (without lid) or other container	10	20	1
1-liter bottle	8	20	1
2-liter bottle	3	5	0
Weight	25–50 lbs. (11–23 kg)		
Brass tubing	4	8	1
Package tape	1 roll	1 roll	0
4-oz. paper cup (waxed)	12	36	3
Safety glasses/goggles	Equal to # of teams	Equal to # of teams	Equal to # of teams

Notes on Materials for Students

Dowels: ⅛ -, 3/16 -, and ¼ -in will be handy

Corrugated cardboard: Cut into 3 ½ inches (in.) [9 centimeters (cm)] squares

35mm film canisters: 1 ¼ x 2 in. [32 x 51 millimeters (mm)]

Weight: You will need to know how much weight you are using. A sturdy cloth bag about the size of a loaf of bread containing about 15 – 20 lbs. (7 to 9 kg) of sand or fine gravel will work well. If you plan to do calculations using the mass of the dropped weight, 22 lbs. (10 kg) provides a convenient figure. Lead shot makes an excellent filler for the drop weight.

Brass tubing: You need brass tubing that fits inside each other, sometimes called "telescoping tubing." It normally comes in 12-in. lengths. A 9/16 in. outer diameter should fit easily over the ring stand used for launching. The tubing will need to be cut into lengths of 4 in. (10 cm).

Package tape: Any sturdy tape 2 – 3 in. wide will work. Transparent tape is best.

Tools:

- Safety glasses/goggles
- Glue gun – low temperature type
- Cardboard cutter/utility knife/box cutter
- Strong scissors
- Ruler
- Yard/meter stick

Build the Launcher

Materials for Launcher

- **Ring Stand**

  This will be used as the launch rod. A ring stand of the type used in chemistry labs with a vertical rod ½ in. in diameter and approximately 3 ft. (1 m) tall works well. The kind with a large heavy base is best.

  You can use any straight metal rod ½ in. in diameter and 3 to 4 ft. (0.9 to 1.2 m.) long if it can be attached to a suitable base. If you have a way to thread such a rod for several inches at one end, you can then attach it to a base with nuts and washers.

- **Wooden 2 by 3**

  1 piece 50 in. (1.3 m) long
  (for the launch lever)

  1 piece 4 in. (10 cm) long
  (for the mounting block)

  You can use a 2 by 4 in place of the 2 by 3 but it is heavier than necessary.

- **Plywood Base Board**

  ¾ or ½ in. thick, 10 by 14 in.
  (25.4 by 35.6 cm)

- **Hinge**

  A "T" style hinge is ideal. A good size has one flap 3 ½ in. (9 cm) wide (in the direction of the pivot pin) and about 1 in. (2.54 cm) long. The other flap is triangular, about 1 ½ in. (3.8 cm) wide at the pin and about 4 in. (10 cm) long. You may use almost any kind of sturdy hinge that can be attached to the launch lever and the mounting block.

- **Flat Head Wood Screws**

  These attach the hinge to both 2 by 3s and the 2 by 3 to the base board. Anything that fits will work fine. The hinge needs screws that match the hinge and the mounting block should be mounted with screws long enough to go solidly into the block.

Construction

It will be easiest to assemble the launcher if you begin by locating the places where screws will go and drill pilot holes for all of them before you screw together any of the parts.

1. Place the hinge on the launch lever (2 by 3 wood length) so that the pivot pin of the hinge is at the midpoint of the length of the launch lever. Mark the location for the screws.

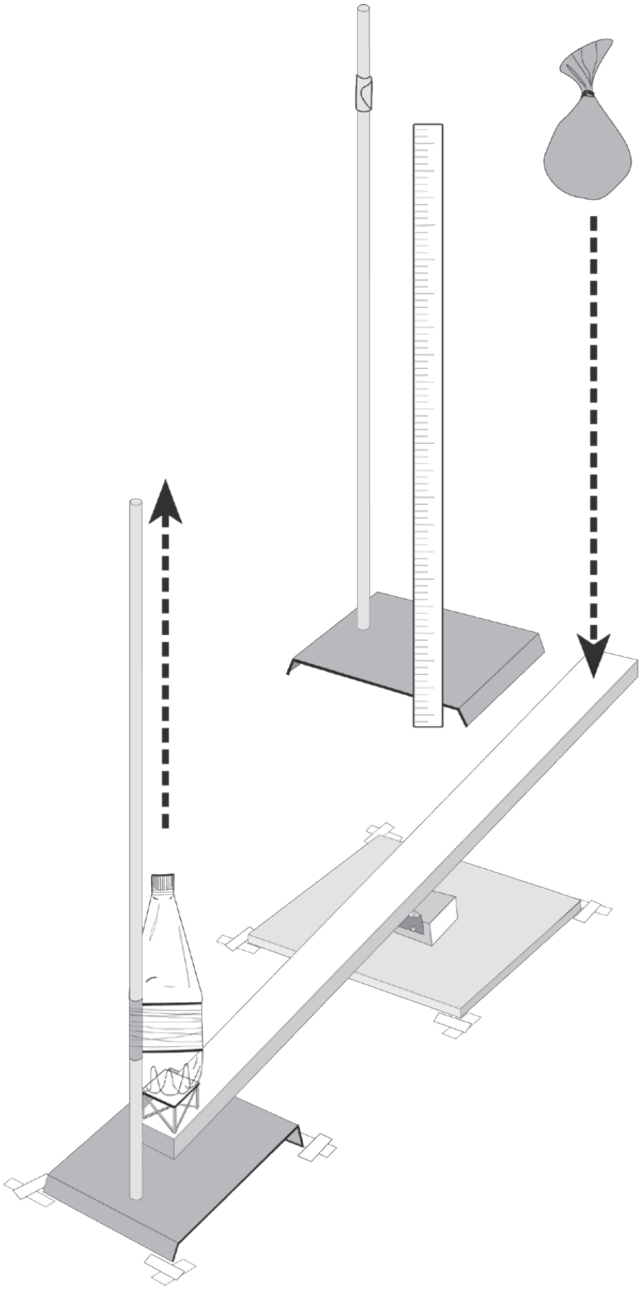


Figure 2. Example launcher.

Construction (Continued)

2. Put the mounting block next to the short flap of the hinge. Mount the hinge at a height so that the launch lever will be 2 to 3 in. (5 to 8 cm) from horizontal. If you mount the hinge too low, the lever will be able to swing in only one direction; its motion in the other direction will be blocked by the mounting block. Mark the location for those screws on the mounting block.
3. Place the mounting block in the center of the base board and mark on the bottom of the base board the location for the screws to attach the mounting block to the baseboard.
4. Drill pilot holes through the base board into the mounting block.
5. Drill pilot holes for the hinge mounting screws in the mounting block and launch lever.
6. Drill clearance holes for the wood screws in the baseboard and countersink them. The heads of the screws need to sink into a prepared depression so they are flush with or below the baseboard surface.
7. Screw the short flap of the hinge to the mounting block, screw the long flap of the hinge to the launch lever, and screw the mounting block to the base board.

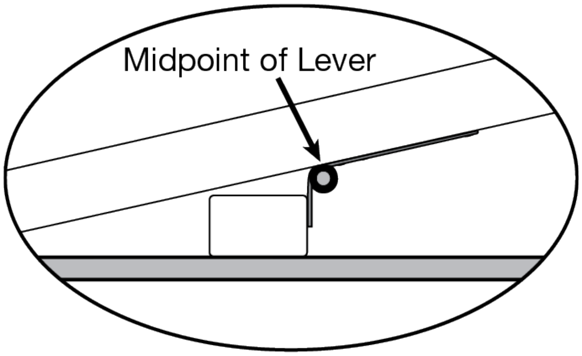


Figure 3. Side view of base, hinge, block, and lever.

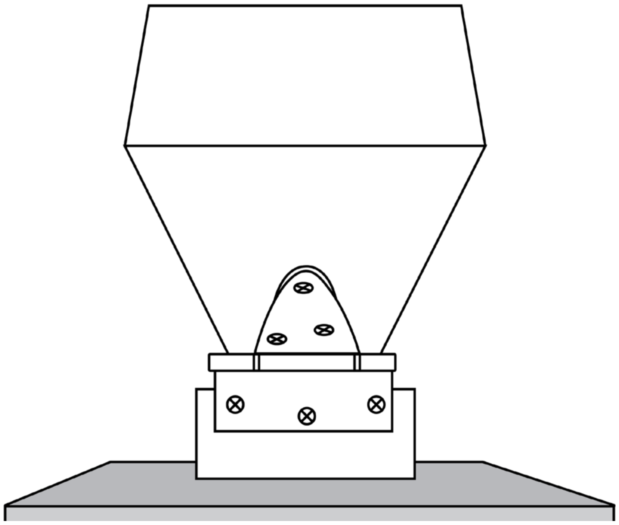


Figure 4. Endview of base, hinge, block, and lever.

Build the Rockets

Materials for Rockets:

- **Soda Bottles (and Caps)**

  You will use the 1-liter bottle for most of the rockets, but it is good to have some 2-liter bottles on hand as well. The bottles that have a 5-lobe base are better for this activity than other kinds (Figure 5).

- **Brass Launch Tubes**

  Craft, art supply, and hobby stores sell brass tubing in sizes that just fit inside each other, so it is sometimes called "telescoping tubing." It comes in 12-in. lengths. A 9/16 in. outside diameter is just right to fit easily over the launch rod (the ring stand). The tubing will need to be cut into lengths of 4 in. (10 cm), which you can do with a tubing cutter or a fine saw. You can also use PVC pipe with a similar diameter.

- **Package Tape**

  This is used to attach the launch tube to the soda bottle.

Construction

Fill the bottle with water or sand and cap it tightly. Tape a 4-in. (10-cm) length of tube to the flat cylindrical part of the bottle. Be sure the tube is vertical (Figure 6).

Practice Launching the Rocket

Once you have constructed the launcher, rockets, and a sample thrust structure, you will want to try some models yourself to become familiar with adjusting the launcher and assuring consistent test conditions.

You will need at least one other person, or two if you want to observe the launch procedure rather than doing it yourself. One person will drop the weight on the end of the lever. The other person will catch the bottle after it reaches its peak and begins descending.

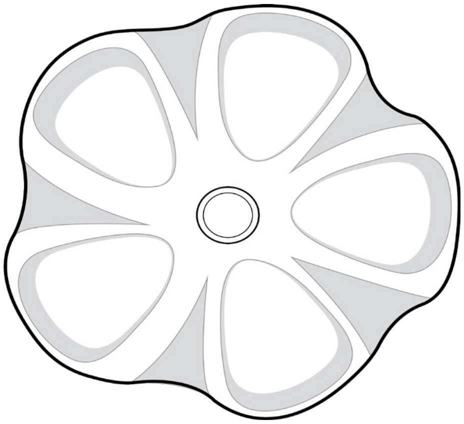


Figure 5. Bottle with 5-lobe base.

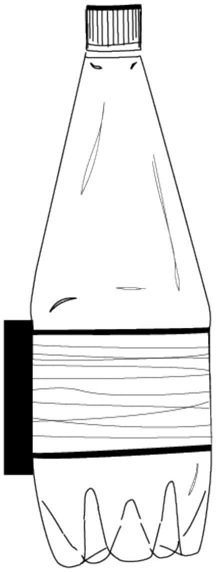


Figure 6. Brass tube attached to bottle with package tape.

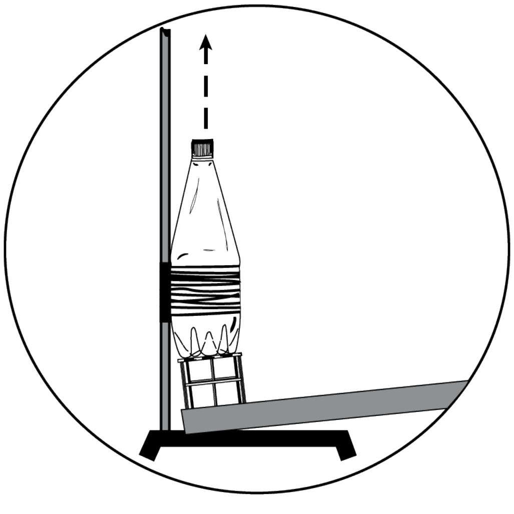


Figure 7. Rocket on launch lever.

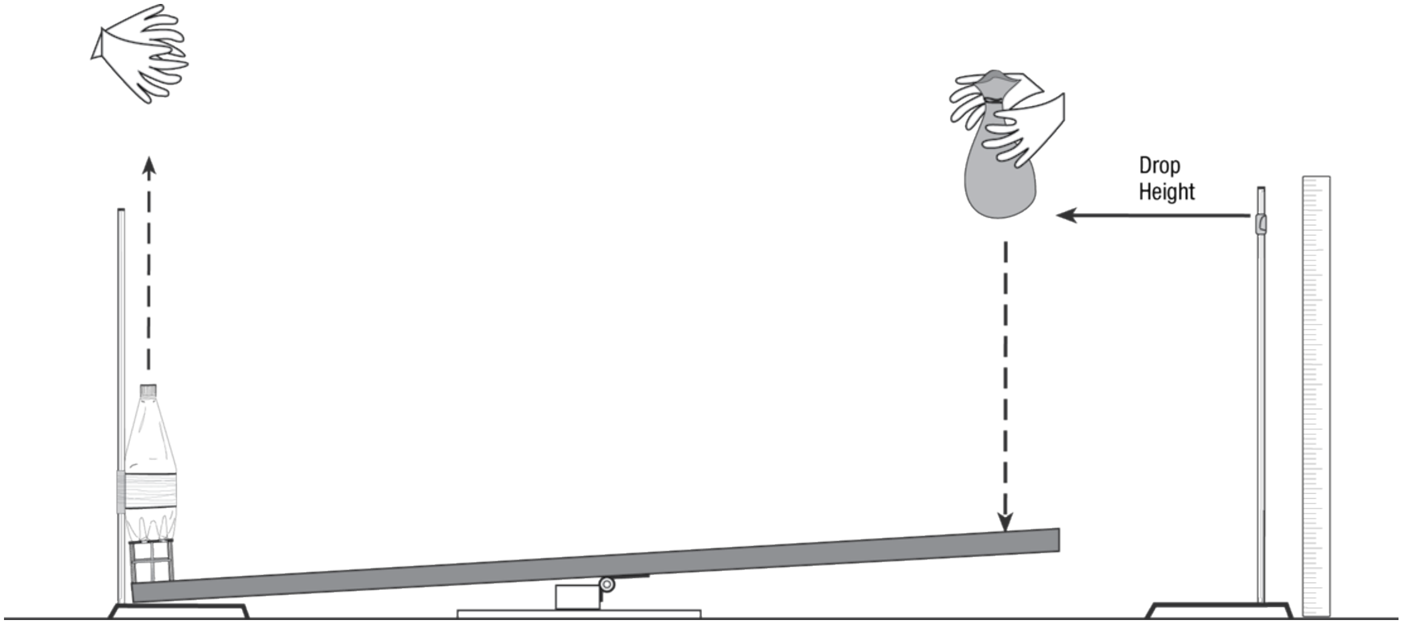


Figure 8. Testing the thrust structure.

Slide the rocket tube onto the ring stand and center the bottle on the end of the launch lever (Figure 7).

The end of the lever should be as close to the ring stand as it can get without hitting it as it pivots. The "catcher" should stand behind or to the side of the launch rod and signal when ready for the launch. At this signal, the "dropper" should count down and drop the weight from about knee-high squarely on the other end of the lever (Figure 8).

Notice the lever and the launch rod may move slightly out of alignment during each launch. You will want to make sure that the lever is square with the launch rod and that the bottle (and the thrust structure when there is one under the bottle) is centered on the lever before each launch.

Prepare the Classroom

You may wish to assemble the materials into kits before distributing them to students. In this way you can reduce the amount of time spent distributing materials. You can also ensure that all design teams receive the same materials. If you choose to incorporate the additional design constraint of a budget (described in the Modifications and Extensions section on page 40), assembling kits in advance will simplify tracking the budget.

Team Work Area

Set up the classroom for laboratory work to be done in teams. Each pair or group of students should have a clear work area near an electrical outlet (for the glue gun) where they can organize their materials and build their designs. A classroom desk or table will do.

Launcher

Set up the launcher in a central location away from walls where students can gather around.

Safety

In the interest of ensuring the safety of the students and yourself, you should be aware of several safety guidelines during this activity.

- Hot glue guns or glue pots have hot metal surfaces that can burn the skin when touched. Show students which areas are hot and advise them to be careful. The hot glue itself can be painful, but is unlikely to cause any serious burn. Nonetheless, students should be warned that the glue is hot.

- When launching rockets, students should follow a strict procedure of notifying one another verbally when they are ready to launch and then counting down to the launch. This will ensure that a rocket is not launched when the "catcher" is unprepared.
- Require that the "catcher" wear eye protection.

Teaching Strategies for an Engineering Design Challenge

- Like any inquiry-based activity, this Engineering Design Challenge requires the teacher to allow students to explore and experiment, make discoveries, and make mistakes. The following guidelines are intended to help you make this activity as productive as possible.
- Be sure to discuss the designs before and after testing. Discussing the designs before testing forces students to think about and communicate why they have designed as they have. Discussing the designs after testing, while the test results are fresh in their minds, helps them reflect on and communicate what worked and what did not and how they can improve their design the next time.
- Watch carefully what students do and listen carefully to what they say. This will help you understand their thinking and help you guide them to better understanding.
- Remind them of what they have already done and compare their designs to previous ones they have tried. This will help them learn from the design-test-redesign approach.
- Steer students toward a more scientific approach. If they have changed multiple aspects of a design and observed changes in results, ask students which of the things they changed caused the difference in performance. If they are not sure what caused the change, suggest they try changing only one or two of the aspects. This helps them learn the value of controlling variables.
- Be aware of differences in approach between students. For example, some students will want to work longer on a single design to get it "just right." Make it clear that getting the structure designed, tested, and documented on time is part of the challenge. If they do not test a lot of models, they will not have a story to tell at the end. Remind them that engineers must come up with solutions in a reasonable amount of time.
- Model brainstorming, careful observation, and detailed description using appropriate vocabulary.
- Ask open-ended "guiding" or "focusing" questions. For example: "How does the force get from the launch lever to the rocket?" or "What made this design stronger than another?" Keep coming back to these questions as the students try different designs.
- Require students to use specific language and be precise about what they are describing. Encourage them to refer to a specific element of the design (column, strut, joint, brace, etc.) rather than "it."
- Compare designs to those of other groups. Endorse borrowing. After all, engineers borrow a good idea whenever they can. However, be sure that the team that came up with the good idea is given credit in documentation and in the pretest presentation.
- Emphasize improvement over competition. The goal of the challenge is for each team to improve its own design. However, there should be some recognition for designs that perform extremely well. There should also be recognition for teams whose designs improve the most, for teams that originate design innovations that are used by others, for elegance of

design, and for quality construction.

- Classify designs and encourage the students to come up with their own names for the designs to be used in the class.
- Encourage conjecturing. Get students to articulate what they are doing in the form of, "I want to see what will happen if . . ."
- Connect what students are doing to what engineers do. It will help students see the significance of the design challenge if they can see that the process they are following is the same process that adult engineers follow.

Helping Students Understand the Design Process

Engineering involves systematically working to solve problems. To do this, engineers employ an iterative process of design-test-redesign until they reach a satisfactory solution (Figure 9). In this Engineering Design Challenge, students experience this process.

Once students have sufficient experience in designing, building, and testing models, it is valuable for them to formally describe the design process they are undertaking. Students require a significant amount of reinforcement to learn that they should study not just their own results, but the results of other teams as well. They need to realize that they can learn from the successes and failures of others, too.

Select a time when you feel the students have had enough experience with the design process to be able to discuss it. Make a copy of the Design Process (p. 43) for each team. Go through the process step-by-step. It is useful to hold up a thrust structure model and point out specific features that may be the result of studying the test data, unsuccessful builds, or additional research. For example, using a particular model, ask "How did this feature come about? Where did you get the idea? Was it the result of a previous test, done by either you or by another team?"

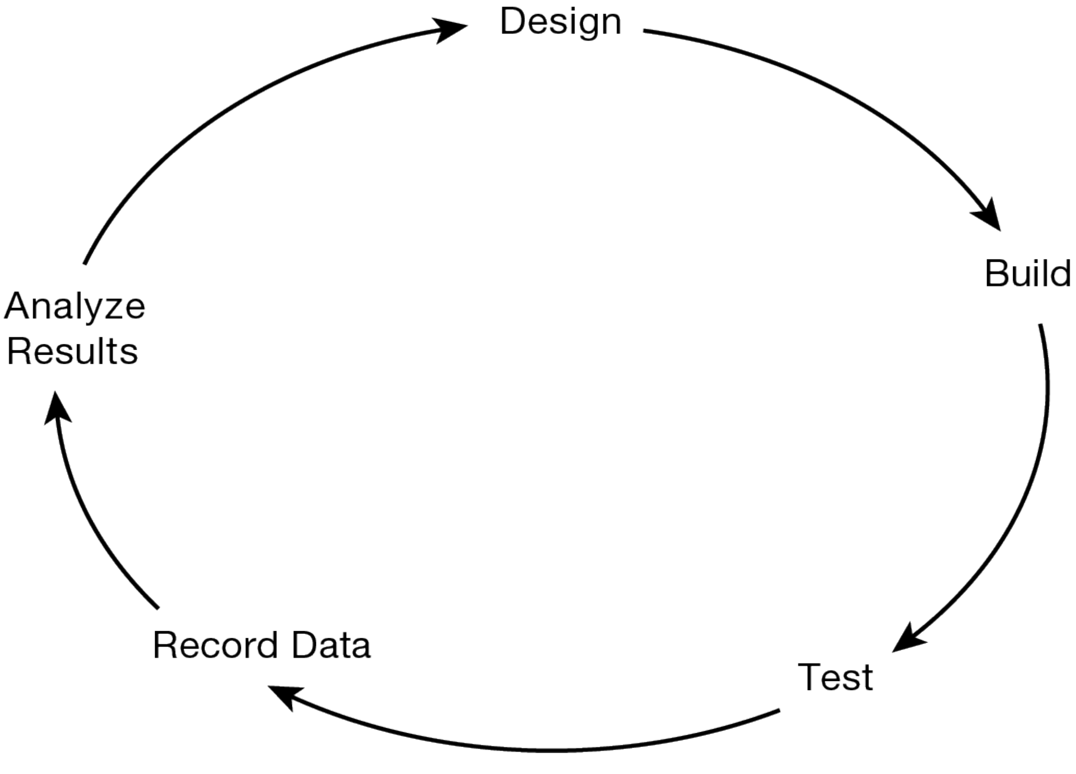


Figure 9. The Design Process.

6. Classroom Sessions

Session 1

Introducing the Challenge and Getting Started

In this first session, you will introduce the activity and provide students with background information about NASA, the Space Launch System (SLS) rocket, and spacecraft structures. You will define the challenge and discuss how engineers approach a design problem. Students will practice dropping the sandbag until they can consistently launch the bottle rocket to orbit. You will conclude the session by launching a teacher-built model thrust structure and challenging students to build models that are lighter-weight.

Learning Goals

- Understand and define thrust structure.
- Recognize the need for models.
- Understand the relationship between a model and the actual object being designed.
- Recognize a need for a standard test procedure.
- Make observations and collect data.
- Understand the need for averaging.
- Calculate averages.

Materials

- Handouts (Masters can be found in Appendix B; pp. 42 – 49)
- Launch stand (includes launch lever, ring stand, weight to drop, bottle rocket, and yard stick or ring stand with file card to set drop height)
- A too-heavy overbuilt thrust structure built by the teacher (See part 6 in this session for a model)
- Yard stick (or meter stick)
- File card or similar size piece of a manila folder
- Wall chart (or chalkboard) for recording drop heights and launch results

1. Introduce the Unit

Elicit students' knowledge of the Space Shuttle, the International Space Station, the Apollo missions to the Moon, and spacecraft in general. Use the background information in the previous section, pictures, and videos of the SLS rocket (see Appendix A; p. 41) to introduce the vehicle. Ask about what needs to be considered in designing a rocket that must launch a spacecraft into space. Discuss the significance of mass (optional: discuss the difference between weight and mass). Explain to students that they will take on the role of engineers for this unit. They will attempt to solve a problem that NASA engineers must solve – building a lightweight, but strong thrust structure for the rocket.

2. Introduce the Challenge

Bring out the launch stand and choose a student to be the catcher. Launch a rocket, but drop the weight so that the rocket barely moves. Ask students to identify which parts of the rocket each part of the model represents. (The lever is the "engine" providing the thrust, the sandbag weight represents the energy of the engines, and the bottle is the body of the rocket.)

Explain to students that the thrust structure is the part of the rocket's skeleton that holds the engine on to the rest of the vehicle. Explain that, unlike the demonstration in which the bottle "rocket" gets one big push from the lever "engine" and then separates from it, a launch vehicle must be pushed constantly by the engine until it reaches orbit. The push of the engine must travel through the thrust structure to the rest of the rocket.

Explain to students that during the following three class sessions, they will design a thrust structure, launch it, record the results, and then try to improve on the design by making it lighter and stronger. They will get at least four chances to improve on the design.

Define the challenge (Figure 10). It is recommended you write this on the board.

The Challenge:

Build the lightest weight thrust structure that will withstand the force of launch to orbit at least three times.

Launch to orbit = propelling a 1-liter bottle of water or sand to the height of approximately 3 ft. (1 m) into the air.

Design Constraints:

Use only the materials provided.

The thrust structure must be taller than 2 in. (5 cm) and must allow space in the center for fuel lines and valves (represented by a 35mm film canister, or other container of similar size, without its lid).

Figure 10. The Challenge.

3. Explain the Culminating Activity

Explain that each team will spend one class period at the end of the challenge constructing a poster that will tell the story of the development of their thrust structure. Using the poster, each team will then make a presentation to the class explaining the evolution of their design.

The poster should contain at least three of the team's recording sheets. If possible, students should attach three of the actual tested models (or photos of each). The poster should show the evolution of the team's design from its initial to intermediate and final design stages. Essentially, it should "tell the story" of the design process and explain how and why the design changed. It should conclude with a concise statement of "what we learned."

In addition to completing the recording sheets, direct students to keep running notes, diagrams, questions, research findings, data, etc., in a log. These logs will provide an excellent resource for documenting their experience when they need to make their poster.

4. Determine the "Engine Thrust"

Explain to students that their first task will be to determine the necessary thrust to propel the bottle rocket "to orbit." They will determine a drop height for the sandbag so that the rocket just flies off the ring stand. Discuss with students why you do not want it to fly too far off the launch rod. (That would be subjecting the structure to more force than necessary and overshooting "orbit.")

Choose a volunteer to drop the sandbag and another to catch the rocket. (Launch this rocket without a thrust structure.) Measure the height of the drop with a yard stick or measuring tape. Have the students start by dropping the weight from a very low height and gradually increase the drop height until the bottle just barely flies off the ring stand. You might have a different pair of students perform the launch with each increase in drop height.

Continue to launch the rocket until students can consistently launch the bottle three times to the desired height of 3 ft. (1 m). You might want several pairs of students to confirm the height.

When you have determined the optimal drop height, record it and post it in the same place as the challenge. If a second ring stand is available, mark it at that height with masking tape. Optional: Tie a string between the two ring stands at the drop height.

Optional: Use Different Drop Mass and Drop Height

If you are able to conveniently change the mass being dropped, you could choose a drop height and then find the required mass for launching the bottle to orbit using that weight. Students could record the results of using different amounts of sand in a table such as this:

Trail #	Launch Mass (lbs. or kg)	Drop Mass (lbs. or kg)	Drop Height (in. or cm)	Altitude of Rocket (in. or cm)	Orbit? (Y/N)
1					
2					
3					

Extension:

Graph the data in this table to determine the relationship between mass and height.

5. Discuss the Results

Ask students:

- How much mass are we launching to orbit? (Answer: Weight of "rocket" – with water or sand)
- What's the source of the propulsive force? (Answer: Weight of bag of sand)
- What forces are acting on the bag of sand when it is suspended in the air before the drop? (Answer: Gravity and the student's muscles)
- What force(s) are acting on the bag when it is released? (Answer: Gravity)
- What is the path of the force? (Answer: Down on one side when weight is dropped; up the other end of the lever when the rocket is launched)

Have students compare the characteristics below for the bottle rocket and the actual SLS.

	Bottle Rocket	SLS
Source of the thrust	Lever	2 solid rocket boosters + 4 liquid engines
Source of engine energy	Gravity on sandbag	Combustion of fuel in boosters and engines
Thrust duration	Fraction of a second	~8 – 9 minutes
Thrust Magnitude	Small	8.8 million lbs. (39,144 kN)
Mass of rocket	~2.2 lbs. (1kg)	5.75 million lbs. (2.6 million kg)
Thrust depends on	Mass of sandbag Drop height Strength of gravity	Energy density of fuel Mass of fuel burned/sec Engine design

6. Demonstrate a Poorly Designed Baseline Model

> **NOTE:** If time does not allow for this demonstration in this session, it can be left until Session 2, Part 6.

In order to provide a baseline model for a thrust structure, you should build one that is truly a juggernaut (Figure 11). For example, use 3-in. (7.6-cm) lengths of ¼-in. dowels clustered in threes and attached to cardboard plates on top and bottom using a generous amount of glue. This structure will have a mass of a little more than 4 oz. (113 g) but will certainly withstand numerous launches. Students will quickly see ways to improve upon this crude design and will take pleasure in building a model that is better than the teacher's.

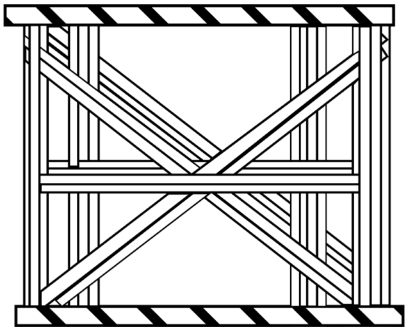


Figure 11. A heavy design thrust structure.

7. Wrap-up

Show students the craft sticks and the square of cardboard they will use for their first design. Ask them to think about thrust structure designs before the next session.

Session 2

Design 1

In this session, students design and build their first thrust structure using the provided materials. It is important during this session to establish consistent procedures for testing including:

- Pre-test approval of design and recording sheet.
- Oral presentation of key design features by students before launch.
- Accurate testing and reporting of results on Test Results Sheet.
- Post-test discussion of the design and the test results.

Learning Goals

- Practice construction techniques including use of glue gun or glue pot.
- Recognize the need for clear documentation.
- Practice documenting design.
- Practice making and recording observations.
- Begin thinking about how to make designs strong and lightweight.

Materials

- Launch stand, sand bag, and ring stand
- Craft sticks
- Glue guns and glue sticks
- 3 ½ in. (9 cm) square of corrugated cardboard
- Paper cups (optional)
- Chart paper (or chalkboard) for recording launch results
- A balance or scale accurate to a tenth of a gram
- Handouts of Design Specifications Sheet and Test Results Sheet (pp. 50 – 51)

1. Review the Design Challenge and the Design Constraints

Make sure students understand the challenge and the constraints applied to their work.

2. Introduce the Materials

Explain to students that they must build a thrust structure using the craft sticks and hot melt glue. The structure should be attached at the top to a square of cardboard on which the bottle will sit. The structure is NOT attached to cardboard at the bottom.

3. Review Safety Issues

Point out to students that the tip of the glue gun and the metal strip at the front of the glue pot are hot and should be avoided. Review the procedure for burns. Remind students to wear safety goggles when launching their model.

4. Introduce the Recording Sheets

Introduce the Design Specifications and Test Results Sheets. Tell students that these are where they will record all the details of their designs and the results of their testing. Explain that engineers need to keep careful records. Ask students why recordkeeping is so important. Discuss each part of the sheets. Make sure students understand that one sheet shows their model before testing and that the other shows it after testing.

Remind students to keep track of their designs by numbering their recording sheets. Remind them that they will use their recording sheets to construct a poster at the end of the challenge.

Explain to students the importance of a detailed sketch of their design. Their goal in sketching should be that someone looking only at the sketch could reconstruct their design. You may wish to show a completed recording sheet as a sample.

Two sketching techniques to introduce are detail views and section or cut-away views. A detail view is a separate close-up drawing of a particular portion of the design that may be difficult to show clearly in the drawing of the full design. A cut-away view shows what the design would look like if it were sliced in half. It enables the artist to show hidden parts of the design.

In addition to answering the questions on the Design Specifications Sheet, students should also keep running notes, diagrams, questions, research findings, data, etc., in a log. These logs can be as simple as notes taken on the back of the Design Specifications Sheet. A log will provide an excellent resource for documenting the experience when a student needs to make the final poster.

5. Explain the Test Procedure

- When their design is completed, the team completes a Design Specifications Sheet and brings the model and the sheet to the teacher.
- The teacher checks the sheet for completeness and accuracy.
- The teacher checks that the model has conformed to all design constraints.
- Before their model is tested, each team must do a brief oral presentation (for the entire class) in which they describe the key features of the design.
- During the testing, the team should carefully observe and record the performance of their design.

  Extension:

  Have students try to reconstruct another team's design using only the Design Specifications Sheet. Assess the recording group on the quality of the sketch and the constructing group on their ability to interpret the sketch.

6. Students Design and Build Their Models

If you did not have time to complete the demonstration of a poorly designed model in Session 1, do it now.

Allow 10–15 minutes for this first design and build. Establish a cut-off time when you will begin testing. Teams that do not have designs ready to test by the cut-off time must wait until the next round of testing.

7. Approving Models for Testing

When a team delivers their design and recording sheet for testing, check the following:

- Model uses only allowable materials
- Model is at least 2 in. (5 cm) tall
- A 35mm film canister (without lid) fits entirely inside the thrust structure.
- The model has a team name or identifying mark on it.
- The Design Specifications Sheet is completely filled out, including a satisfactory sketch.

If the model is approved, place it on the testing station table. You might call this “being on deck.”

8. Test the Models

Begin testing when most of the teams’ designs have been approved. Have students stop working and gather around the launch station.

Older students may be able to continue working while other teams have their models tested. For this arrangement to work, you will need to locate the launch station in a central location where students can view it from their work areas.

Before launching, have a member of each team stand and hold up the model or show it around to all other students. The representative should explain:

- Key features of the design
- Why those features were used
- Where the idea came from (a previous design, another team’s design, another type of structure, etc.)

Assign a student to record the results of each test either on a chart on the chalkboard or on a large sheet of paper. The chart should look like the one below.

Team	Design #	Launch to Orbit (Y/N)?		
		1	2	3

With no repairs allowed between launches, test each team's model three times in succession. If you have more time, you may wish to increase the number of launches per model. Inspect the model after each launch. Students should make notes about which structural members failed or are in danger of failing.

A failed launch occurs when the rocket does not make it into orbit. A failed launch also occurs when the design no longer meets the design constraints, that is, it is less than 2 in. (5 cm) high or a film canister no longer fits inside. (Important: Do not leave the film canister in the model when launching.)

9. Discuss the Results of Testing

The post-test discussion is critical to expanding students' learning beyond the design and construction techniques and connecting their design work with the science concepts underlying their work.

Encourage students to hold the model and use it to illustrate their point when they talk about a particular design feature.

For each model, you should pose the same guiding question:

"How did this structure transmit the force of launch from the lever to the bottle?"

Other discussion questions might include:

- What happened to each part of the thrust structure during the testing?
- Did any parts of the design seem to fail before the rest? Why?
- Which design features were most effective? What made the designs effective?

Record (or have a student record) the most successful design features on a wall chart. This list should be expanded and revised throughout the activity as the students collectively discover which designs are strong and lightweight.

If any of the columns in the structure have buckled, help students think about how to strengthen the posts, for example, through bracing. Here is an interesting demonstration of buckling: Take a flexible ruler or yard stick. Stand it up on the floor or table. Press straight down on the top end until the ruler begins to bow out or buckle (Figure 12).

Try the same experiment with rulers of different lengths, but of the same thickness. Show that any post or column buckles if placed under a sufficient load. Notice, however, that the shorter rulers can support more load without buckling. Then ask a student to grasp and hold steady the middle of the ruler. Repeat the pressure on top with your hand. Show that because the ruler is braced in the middle, it is effectively two short columns rather than one long one.

You could also demonstrate the relationship between buckling and the length of a column by using a toilet paper tube and a paper towel tube. Load both with books. The longer one will buckle first. (Make sure they are the same diameter and made of the same thickness of cardboard.)

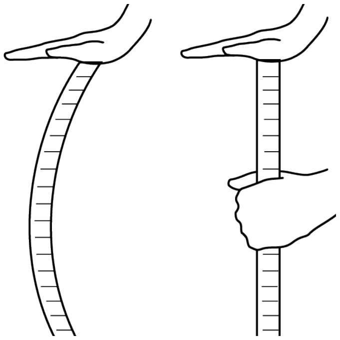


Figure 12. Bracing a ruler to prevent buckling.

Sessions 3 and 4

Designs 2 – 5

Using what they have learned from the first design, students revise and redesign their thrust structure in several more design-build-test cycles.

Learning Goals

- Distinguish between effective and ineffective design features.
- Incorporate design strategies gleaned from experimentation and observation.
- Refine observation skills.
- Draw conclusions based on analysis of test result data.
- Record test data.
- Analyze test data and draw conclusions.
- Refine understanding of structures and forces.

Materials

- Launch stand
- Craft sticks
- Glue guns and glue
- 2-liter bottles, filled with water or sand, with guide tubes attached
- 3 ½ in. (9 cm) squares of corrugated cardboard
- Ring stands to be used for static testing
- Handouts of Design Specifications Sheet and Test Results Sheet (pp. 50 – 51)

1. Review the Previous Session

If a day or longer has passed since the previous session, review the results of the first round of testing. Review the successful and unsuccessful design features.

2. Design, Build, Test, and Discuss Results

Continue to add successful design features to the list you started on chart paper in the previous session. Continue to ask students how the thrust is transferred from the lever to the bottle and to have students trace the load paths on paper or directly on the model.

In the post-test discussion, lead students to make conclusions about the probable success of a thrust structure built of a certain number of craft sticks.

Allow students approximately 15 minutes to design, build, and complete a Test Results Sheet for each model.

3. Introduce Static Testing

Up to this point, the students have been testing their designs by launching them. This kind of testing may destroy the models if they are not strong enough. The models that are "plenty strong enough" will not be destroyed, but models that are just a little bit too weak may be damaged in testing. This is unfortunate because the student may have to start over from scratch, whereas if the model were still intact, it might be possible to make some minor change that would make the model strong enough to survive three launches. As the students get closer and closer to their optimum designs (as lightweight as possible, but still strong enough), they should become more attuned to the need for non-destructive testing before actual launch. You might refer to this as pre-testing or static testing.

Introduce this section by asking the class whether they think it would be desirable to have a way of testing the models that would not destroy those that were just a little bit too weak. Point out, if you wish, that engineers prefer non-destructive proof testing of their designs whenever possible. Ask students to think of non-destructive ways they could test their models that would give them information about the model's strength, but would not suddenly destroy the model as sometimes happens during a launch.

They will probably come up with ideas of squeezing the model, compressing it, or somehow gradually applying a load to it. The problem, of course, is they do not know how much to squeeze or how much weight to load onto the model because they do not know how much compressive force the model experiences at launch. There are several ways you might determine the compressive force at launch. Here are two approaches:

1. Build a thrust structure model that will deform. Launch it, look at the deformation, and then load up an identical model with enough weight to achieve the same deformation. For example, glue a paper cup onto the cardboard square (Figure 13).

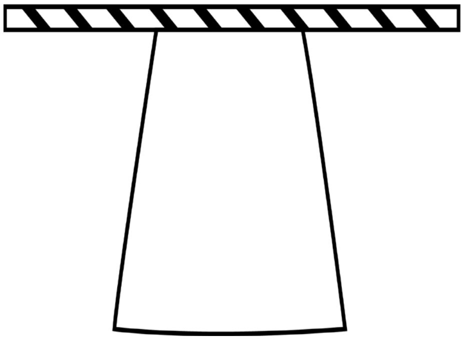


Figure 13. Paper cup used as a thrust structure.

   Launch a bottle using this thrust structure. Note the amount of deformation (crushing) of the cup. Take a second paper cup thrust structure and load it up with enough weight to achieve the same deformation. Note the amount of weight. This is the static weight any thrust structure must withstand at launch. If a student model withstands this amount of weight (and maybe a bit more), then it should be able to survive launching.

2. A second way to figure out how much weight a model needs to be able to support is to build a test model that is exactly strong enough for launch and then to see how much weight it can support. For example, using paper cups for the thrust structure, see if a single cup can withstand the force of launch to orbit three times. If it cannot, then add a second cup, nested onto the first. See if two cups can withstand launch force. If not, then add another cup. When you finally have enough cups to withstand three launches, you have an adequate thrust structure. Then see how much weight this model can support. Any model that can support the same weight or more should be able to survive the force of launch. You can use a table like the one that follows to record the results of gradually strengthening the paper cup thrust structure.

The static weight that causes the structure to fail is the weight to use in future static tests. If a design can support that weight, it should be able to withstand three launches to orbit.

Ask students what they would look for in a static test. Here are some possible ideas:

- Structural members buckling
- Glue joints loose or unstable
- Entire structure unsteady when moved slightly side to side

Remind students they should record the results of static testing directly on their Test Results Sheet or in their logs for use in creating their poster.

You can lead from this introduction of static testing into a discussion of the similarities and differences between static and dynamic loads. Refer to Linking Design Strategies and Observations to Science Concepts (pp. 32 – 37) for a more detailed description of the concepts involved.

	# of Launches to Orbit	Weight Required to Crush in Static Test
Structure 1 (1 paper cup)		
Structure 2 (2 paper cups)		
(Etc.)		

Loading static weight onto a thrust structure will be easy if you use the bottle rockets themselves as the weights and use the ring stand to steady them. Place the thrust structure on the base of the ring stand, slide the bottle's brass sleeve onto the ring stand, and lower it gently onto the structure. Add more bottles as needed. They should stack up nicely, held in place in a vertical stack by the ring stand. You can use bottles of different sizes filled to different levels with water or sand in order to create a set of weights. Of course, you will need to determine the weight of your "weights," and this, in itself, is an interesting exercise for the students. To make static testing easy and accessible to the class, set up a "static test stand" permanently in the room. Then you will have a static test stand and a dynamic test stand.

Session 5

Create a Poster

As a culminating activity, each team will create a poster that documents the evolution of their thrust structure designs from initial stage to intermediate stage to final stage. The poster provides students with a way of summarizing and making sense of the design process. It provides opportunities for reflection and enables students to see how their design work has progressed from simple to more sophisticated and effective designs.

Learning Goals

- Summarize and reflect on results.
- Organize and communicate results to an audience.

Materials

- Poster boards / large sheets of paper approximately 2 by 3 ft. (61 by 91.5 cm), one per team
- Markers, crayons, color pencils, etc.
- Plastic sandwich bags for holding models
- Glue or tape for attaching recording sheets and models to poster

1. Explain the Assignment

Explain to students that they will create a poster that will tell the story of their thrust structure design. Explain that professional conferences usually include poster sessions where researchers present the results of their work.

The poster should include recording sheets, tested models, and any other artifacts they think are necessary. It should include brief text that describes how their design evolved through at least three stages: beginning, intermediate, and final. If students have kept logs during the design process, they should use some of the notes from their logs.

Students may attach their completed recording sheets or re-copy the information onto the poster. If possible, they should attach the actual tested models to the poster. Placing the model in a plastic bag and attaching the bag to the poster works well.

2. Define the Assessment Criteria

Explain to students that their posters will be evaluated on the following criteria:

- A clear storyline, organized to show the development of the design
- Shows at least three designs
- Contains clear sketches with key features identified
- Includes test results and description of what happened to the design during the tests
- Includes conclusion about the most effective thrust structure design and why it is effective
- Uses scientific vocabulary
- Has an appealing layout with a title
- Uses correct grammar and spelling

You may optionally assign additional research or invite students to do research on their own initiative. Research findings could also be included. See Appendix A (p. 44) for suggested starting points.

Students could investigate:

- Internal structure used in rockets
- Internal structure used in other devices and vehicles
- Load bearing properties of materials

3. Create the Poster

Give students at least one entire class session to create their posters. You might take this opportunity to encourage students to practice sketching detail and section views of the models.

You might also want to assign several students to prepare a “results” poster for the entire class. This poster would make use of the charts on which you recorded data from each test session. The overall improvement of the class could be calculated and displayed.

Session 6

Student Presentations

When all posters have been completed, have put them on display in the classroom. Allow students time to browse among the posters. Encourage conversation. Then reconvene the class and allow each team a few minutes to present their poster.

Another option is to conduct a poster session as might occur at a professional conference. Half the teams would remain with their posters to answer questions while the other teams browse. After about 15 minutes, the browsing teams stand by their posters while the other teams browse. Browsing teams should ask questions and engage the presenting teams in conversation.

The poster session provides an opportunity to invite parents, other teachers, and students from other classes to view student work.

Learning Goals

- Communicate results to an audience.

Linking Design Strategies and Observations to Science Concepts

An important opportunity for science learning through this Engineering Design Challenge comes from the connections that students make between their design solutions, their observations, and the underlying scientific principles. As you observe students designing, conducting the testing, and discussing the test results, there will be numerous opportunities to draw connections between what the students are doing and the scientific principles of motions and forces. This section provides suggestions and background information to help you draw those connections at the moment they arise, the "teachable moment," when students are highly engaged and receptive to new information. This section is organized according to observations the students might make and design strategies they might employ.

Observation: Tracing the Path of the Force

Students should be able to trace the path of the force from the lever through their structure to the bottle. They can do this simply by pointing out the path the force will take or by drawing a sketch with arrows showing the direction of the force. They can also color the structural members in the model. This will provide an opportunity to discuss the advantages of distributing force over a wide area.

Design Strategy: Balanced Loads

Students should recognize that evenly distributed support will evenly divide the force of launch. You might point out that the bottom of the bottle is axially symmetric and that there must be a reason for that design (Figure 14). Ask students to think about why many structures in the natural world, as well as the "built world," are symmetrical. Perhaps it has to do with balanced loads.

Observation: Compressive Forces

As students think about the forces on their model, they will realize that the main force on it during launch is compression, the direct result of the bottle pressing down and the lever pressing up on the thrust structure. Thinking about these compressive forces offers an opportunity for learning more about what is actually going on before, during, and after launch. Before launch, as the thrust structure and rocket rest on the launch lever, the forces are balanced and, therefore, there is no acceleration. During launch, there clearly is acceleration, and, therefore, there must be unbalanced forces on the thrust structure and the rocket because they accelerate. After launch, there is, again, acceleration (or deceleration, depending on the frame of reference) as the rocket gradually slows down and stops at its apogee. So, there must be unbalanced forces causing this acceleration. Acceleration would continue (downwards) if the catcher did not catch the rocket and prevent it from falling.

If students have done static testing, they will have an idea of the amount of force exerted on the thrust structure during launch. This will be the weight that they determined the thrust structure had to support. This is the force that the bottle experiences during launch. Force can be calculated using the following formula: F=ma. Using a=F/m, they can calculate the acceleration the bottle experiences. This is the so-called "g-force."

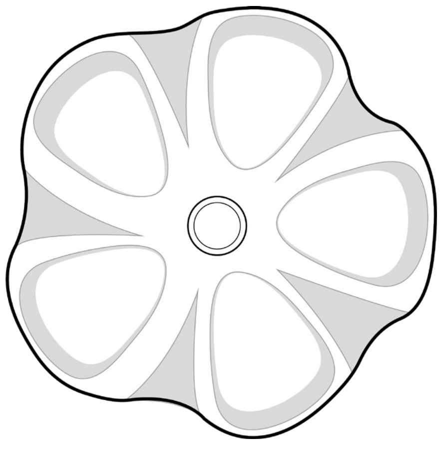


Figure 14. The base of the bottle has 5-fold axial symmetry.

Squeezing a Thrust Structure

If each hand (Figure 15) presses on the thrust structure with a force of 1 newton (1 N), then the compressive force the launch structure experiences is 1 N (0.22 lbs.-force). When forces of equal strength are exerted on opposite sides of an object, the compressive force on the object is the size of one of the equal forces. The object does not accelerate because the forces on it are balanced.

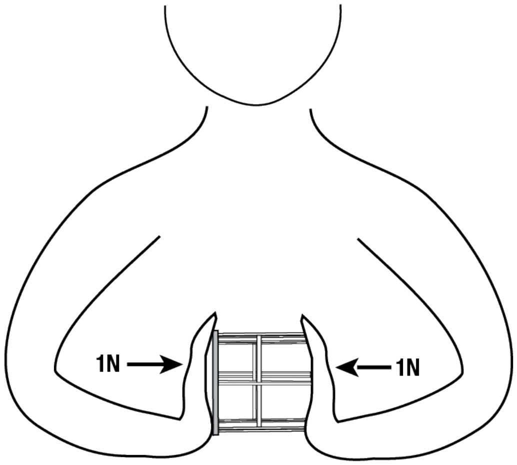


Figure 15. Balanced compressive forces.

Forces on the Thrust Structure

When the thrust structure rests by itself on the lever, there is no compressive force on the structure. The structure presses down on the lever with a force equal to its weight—say 0.1 N (0.022 lbs.-force), and the lever exerts a matching force of 0.1 N upwards on the structure. There is a force pressing up on the bottom of the structure, but no force pressing down on its top, so there is no compressive force on the whole thrust structure (Figure 16).

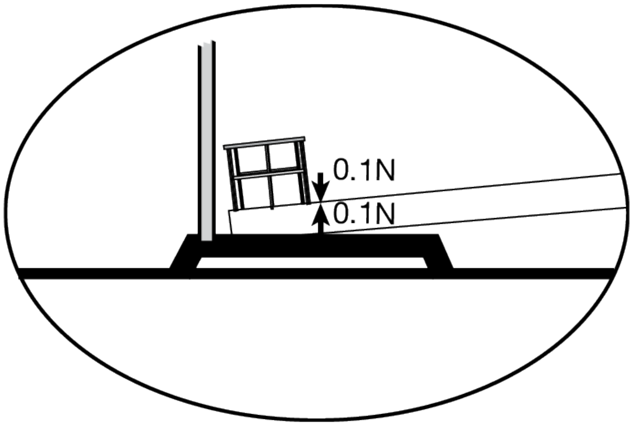


Figure 16. No compressive force on the thrust structure.

> **Note:** The thrust structure's weight creates a compressive force on the individual elements that make up the structure because every piece of the structure (except the top) is pressed down by the parts of the structure above it and supported by the parts below it. The very bottom of the thrust structure experiences a compressive force equal to the structure's weight. In very heavy objects like skyscrapers, this internal compressive force is very important to the design of the building. However, the weight of a thrust structure is so small compared to the compressive forces due to launching a bottle that we can ignore the internal compressive forces due to the structure's own weight.

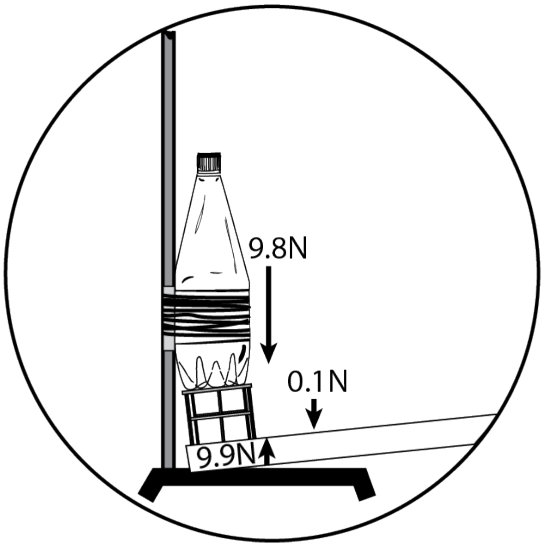


Figure 17. A compressive force of 9.8 N.

If a "rocket" presses down on a thrust structure with a force of 9.8 N (2.20 lbs.-force) without breaking it, the structure transfers this 9.8 N force to the lever supporting it. The structure also continues to push down on the lever because of its own weight of 0.1 N (0.022

lbs.-force), so the total force the thrust structure exerts on the lever is 9.9 N (Figure 17). The lever pushes back with a force of 9.9 N (2.22 lbs.-force). The compressive force on the structure is 9.8 N, the amount of force it experiences from both directions at once. (The extra 0.1 N [0.022 lbs.-force] comes only from below, not from above, so it does not contribute to the compressive force on the structure.)

When a force is exerted down on an object that is resting on a surface, the compressive force on the object is the size of that downward force.

Force during Acceleration

If you were to use the launch lever to launch the thrust structure horizontally behind a toy car, you would need to push hard enough to make both the structure and the car accelerate forward (Figure 18). The structure transmits some of the force exerted by the lever to the car. The car pushes back on the structure with the same amount of force.

If the structure accelerates, this means that the forces on it must be unbalanced. That is, the forward force exerted by the lever (say, 2.5 N) must be stronger than the backward force exerted on the structure by the car (say, 1.5 N).

The compressive force on the structure is the amount of force exerted on it from both directions, or 1.5 N. The remaining 1.0 N of the force exerted by the lever went into accelerating the structure and the car. Compare this situation to the bottle sitting on the thrust structure: while a non-accelerating object (that is not deformed) transmits all of the force exerted on one side of it to the object on the other side of it, accelerating objects transmit only some of the force exerted in the direction of their acceleration.

When forces of different strengths are exerted on opposite sides of an object: the compressive force on the object is the size of the smaller force; and the object is accelerated by the difference between the two forces (also called the net force on the object).

A ***newton*** is a unit of force. Despite being a metric unit of measure, the newton is commonly used as a measure of force in the customary U.S. and the metric system alike. A force of 1 newton (1 N) acting on a one-kilogram mass gives it an acceleration of one meter/second^2. A kilogram weighs about 9.8 N and about 2.2 pounds at the surface of the Earth.

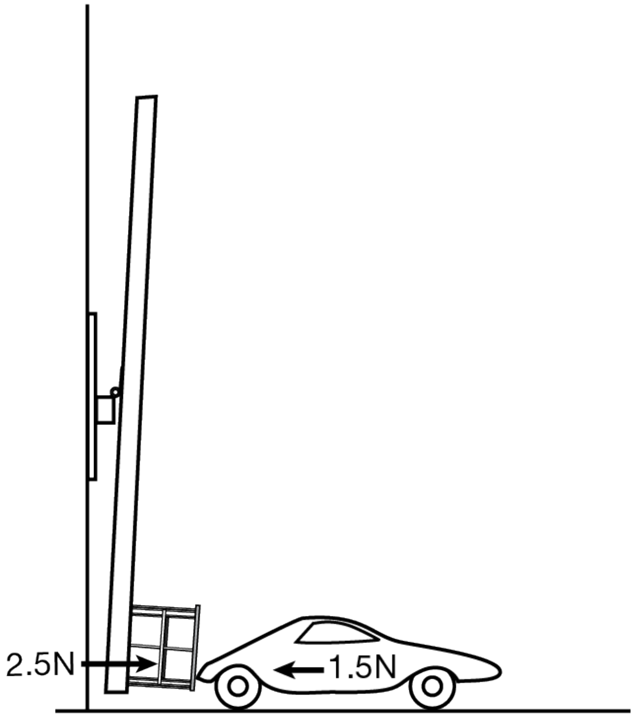


Figure 18. A compressive force of 9.8 N.

Observation: Static and Dynamic Loads

Students should recognize that the amount of time a force is applied matters. When launching the bottle, the force is applied for a very short time. This is called a dynamic load. When static testing, the force is applied for a relatively long time. A load applied slowly is called a static load. Salvadori's book, *Architecture and Engineering*, contains many excellent activities for investigating forces including the one below:

Pour sand into a jar on a scale and stop when the weight of the sand is 2.2 lbs. (1 kg). If the jar weighs 9 oz. (0.25 kg), the total static load on the scale is 2.75 lbs. (1.25 kg). Now hold the filled jar just above the scale and release it suddenly. The scale hand will show a maximum of about 5.5 lbs. (2.5 kg). Repeat the experiment and ask students to follow the scale hand carefully to determine its maximum position. Notice that the scale measures approximately twice the weight of the filled jar. This is the dynamic load on the scale.

There are many practical instances where the time that a force is acting makes a big difference. For example, impact barriers are designed to exert a small force over a long time in order to stop a vehicle more gently than by directly hitting a wall. A baseball player brings in his arms as he catches a ball in order to cushion the ball and bring it to rest more slowly. Boxers "roll with the punch" in order to increase the contact time of the glove with their body and absorb the punch more gradually. Tennis players and golfers "follow through" in order to increase the time that the racket or club is in contact with the ball.

Observation: Tension

If students construct a band around the columns to keep the columns from buckling outward, the columns will be in tension during the launch. Point out to students the difference in the performance of the craft sticks under tension (the sticks are extremely resistant to breaking when a pulling force is applied to the ends) and under compression (as described in the section above). Have the students color their models using one color for columns under compression and another color for those columns under tension.

Design Strategy: Strong Posts

To overcome the tendency of vertical posts to buckle, students might make them stronger by doubling or tripling sticks. This, of course, increases the weight.

Design Strategy: Bracing

Another strategy to overcome buckling is to add a cross brace. The brace might be a band around multiple columns or a diagonal piece from the midpoint of a column to the base. These bracing strategies divide the column into shorter columns, which have less tendency to buckle (Figure 19).

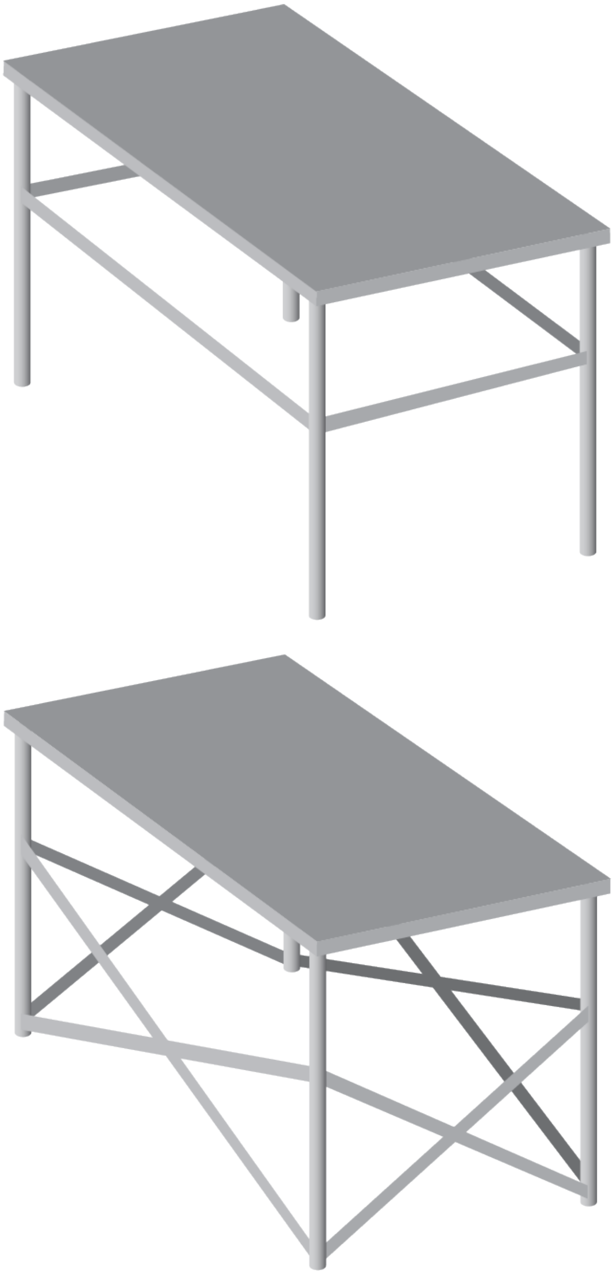


Figure 19. Cross brace design strategies.

Design Strategy: Solid Joints

Designs that fail at the joints may simply need more glue. However, they may not be carefully aligned either, with the result that the force is applied entirely to one member at the joint rather than evenly to all the members at the joint.

Understanding Energy Transfers during Launch

One of the many ways to understand what happens during the launch of the bottle rocket is to analyze the energy transfers that take place. After students have had experience building thrust structures and using them to launch bottle rockets, take time out to discuss with them the energy transfers that take place during a launch. Make copies of "Testing a Thrust Structure" (p. 46) for each student or team.

In order to engage in this exercise, students need some basic understanding of energy as the ability to do work. It also would be helpful if students have had a prior introduction to gravitational potential energy and to kinetic energy.

While looking at the handout, review what happens during a launch. (Sandbag falls, lever moves, pushes thrust structure, which pushes rocket, rocket rises, reaches apogee, and gets caught.)

Then ask students whether energy is needed to launch the bottle rocket. (Yes!)

Next, ask them to explain where the energy for the launch comes from. They may say, "From the sandbag." If so, probe further by asking:

- How does the sandbag have energy? (By virtue of its position.)
- How does it get its energy? (From the pull of gravity on it.)
- Does it have energy when it is sitting on the ground or only when it is held aloft? (It has useful energy with respect to the launch lever only when it is held aloft. Of course, it has energy in its atomic structure all the time, but we are not concerned with that kind of energy here.)
- Would it have more energy if it were more massive? (Yes.)
- Would it have more energy if it were held higher? (Yes.)
- Where does the energy come from that moves the sandbag from the floor to its position above the launch lever? (Human muscles, which are powered by chemical reactions.)
- Would the sandbag have the same energy if it were positioned the same height above the surface of the Moon? (No, because the gravitational field of the Moon is less than that of the Earth. It would also take less muscular effort to lift the sandbag into position on the Moon. An interesting question is: If you replicated the whole launch on the Moon would the bottle rocket rise to the same height? What would be different on the Moon? What would be the same?)
- What do we call the kind of energy that the sandbag has due to its position? (Gravitational potential energy, abbreviated PE.)

Then ask, "How does the sandbag transfer energy to the thrust structure and the rocket?"

Students may be able to explain that as the sandbag falls it loses height and simultaneously accelerates. It gains kinetic energy and loses potential energy. When it hits the launch lever, some of its kinetic energy is transferred to the lever, which transfers energy to the thrust structure. The thrust structure accelerates and gains kinetic energy. It pushes on the bottle, which accelerates and also gains kinetic energy. The bottle rises and as it does so, it slows down and reaches a maximum height of about 39 in. (one meter). (It slows down because gravity decelerates it.) At its apogee (highest point) it has no kinetic energy and has its maximum gravitational potential energy.

For students in grades 6 – 8, this explanation of energy transfer may be sufficient. However, students in ninth grade may be able to use an easy formula to calculate gravitational potential energy (PE).

$$PE = mgh$$

where m = the mass of the object

g = the acceleration due to gravity

h = the height above the Earth

In the case of the sandbag, if it has a mass of 10 kilograms and is about 0.5 meter above the Earth, and if g is approximately 10 m/sec/sec, then PE = 10 × 0.5 × 10 = 50 joules. [1 joule = 1 kg · m^2/sec^2]

Using this formula, students can calculate the PE of the bottle at apogee. When they do this, they find that the PE of the sandbag before launch and the PE of the bottle after launch are very unequal. Then, they can try to understand where the "missing energy" went. The answer, in general, is that it went into sound and heat. From the point of view of launch, these are energy losses. They can calculate the efficiency of the system—the ratio of the energy output to the energy input—and find it to be about 20%.

Students can then go on to consider kinetic energy. They can calculate the kinetic energy and velocity of the sandbag and the kinetic energy and velocity of the bottle after launch. This is discussed in the section that follows.

What is Kinetic Energy and How Do We Measure It?

Kinetic energy is the energy an object has by virtue of its motion. Clearly, objects in motion have the ability to affect other objects and do work on them. A speeding bullet and a speeding train are examples. Both have energy because they are in motion. Which has more energy, the bullet or the train? Why?

The kinetic energy (KE) of an object depends on two things:

Its mass (m) and its velocity,
or speed (v).

Knowing these, we can calculate the KE of an object.

$$KE = \tfrac{1}{2}mv^2$$

The speeding freight train has more kinetic energy than the speeding bullet, even though the bullet is traveling faster because the train is so much more massive than the bullet.

Notice that in the formula for kinetic energy the velocity is squared. Without explaining why this is so, let us consider its implications, which are important for rocket propulsion. Because velocity is squared and mass is not, changing an object's velocity has more of an effect on its kinetic energy than changing its mass. Doubling the velocity quadruples the KE, while doubling the mass only doubles the KE.

Because the KE of an object depends on v^2, it is important for engine designers to give the exhaust gases the highest possible velocity they can. In this way, they boost the KE available from a given mass of fuel.

When students have a basic understanding of kinetic energy, they can easily calculate the kinetic energy and velocity of the sandbag as it hits the launch lever.

We know that at the moment the sandbag hits the launch lever its PE is approximately zero and that its KE is equal to the PE it had before it was released, which was 50 joules. Thus,

$$KE = \tfrac{1}{2}\,mv^2 = 50 \text{ joule}$$
$$\tfrac{1}{2} \cdot 10 \text{ kg} \cdot v^2 = 50 \text{ kg} \cdot \text{m}^2/\text{sec}^2$$
$$5 \text{ kg} \cdot v^2 = 50 \text{ kg} \cdot \text{m}^2/\text{sec}^2$$
$$v^2 = 10 \text{ m}^2/\text{sec}^2$$
$$v = \surd\ (\textbf{SQUARE ROOT})\ 10 \text{ m}^2/\text{sec}^2$$
$$v = 3.2 \text{ m/sec}$$

So, the sandbag is traveling about 3 m/sec when it hits the lever.

How fast are the thrust structure and the rocket going when they "take off?"

We know that the PE of the bottle at apogee = 10 joules. This must also be approximately equal to its kinetic energy at "take off."

$$KE = \tfrac{1}{2}\,mv^2 = 10 \text{ joules}$$
$$\tfrac{1}{2} \cdot 1 \text{ kg} \cdot v^2 = 10 \text{ kg} \cdot \text{m}^2/\text{sec}^2$$
$$\tfrac{1}{2} \text{ kg} \cdot v^2 = 10 \text{ kg} \cdot \text{m}^2/\text{sec}^2$$
$$v^2 = 20 \text{ m}^2/\text{sec}^2$$
$$v = \surd\ (\textbf{SQUARE ROOT})\ 20 \text{ m}^2/\text{sec}^2$$
$$v = 4.5 \text{ m/sec}$$

Therefore, the velocity of the thrust structure and bottle rocket are about 4 m/sec at launch.

Logically, since the launch lever is a solid piece of wood, hinged at its midpoint, the speed of each arm must be equal though in opposite directions. So, the final velocity (speed) of the sandbag must equal the initial velocity (speed) of the bottle rocket. In this example, they are not exactly equal (3.2 vs. 4.5) because we have used rough approximations of the drop height and launch apogee, etc. We have also ignored the "travel" of the lever, etc. You and your students can do better by taking more precise measurements and by thinking carefully about what is happening. The main point is that by understanding how PE is converted to KE and back to PE you can derive velocities from measurements of mass and height of drop and height of launch.

How do these energy transfers compare to those in launching the SLS Block 1?

The SLS Block 1 is powered by the chemical energy of its rocket engines and solid motors, not by a launch lever. Still, that chemical energy transfers the potential and kinetic energy on the Earth's surface just before launch into the potential and kinetic energy of the launch vehicle and payload when they reach their targeted orbit (-47x130 nautical miles).

The SLS Block 1 can launch itself, about 251,500 lbs. (114,100 kg) after all propellant has been used, plus a payload of about 201,700 lbs. (91,500 kg) into a -47x130 nautical mile orbit. At SLS Main Engine Cutoff, around 80 nautical miles (148 km) altitude, the rocket and its payload, around 453,200 lbs. (205,600 kg), are traveling about 17,400 mph (7,800 meters per second [m/s]). It has kinetic energy due to its velocity and potential energy due to its position above the Earth. At the injection altitude, the gravitational pull is about 96% of its value at the surface of the Earth, so at this altitude, g is approximately 9.6 m/sec/sec. Therefore, at orbital injection:

PE_{SLS} = mgh = about 205,600 kg x 9.6 m/s/s x 148,000 m = 2.9 x 1011 joules

Because both the SLS rocket and payload are in an orbit traveling at 17,400 mph (7,800 m/s) they have kinetic energy as well. This kinetic energy is

$KE = \frac{1}{2} mv^2$

$KE = \frac{1}{2} \times 205{,}600\ \text{kg} \times (7{,}800\ \text{m/s})^2$

KE = 6.25 x 1012 joules

Much more of the SLS launch vehicle's energy is in the form of kinetic energy than in the form of potential energy - about 20 times as much. This tells us that most of the work of putting the SLS and its payload into orbit is used during accelerating it to its high speed rather than raising it to its injection height of 80 nautical miles (148 km).

7. Modifications and Extensions

Change the Cardboard Plate

The thrust structure model has been tested in a number of permutations with satisfactory results. The challenge seems to have the optimal level of difficulty when only one cardboard square is used, and it is placed at the top of the structure. However, you may wish to use an additional piece of cardboard on the bottom of the structure. This will make the structure stronger, but will also make it more difficult to see the results of specific loads on the structural members. You may also wish to use a different shape, size, or thickness of cardboard or give students the option of modifying the cardboard. Doing away with the cardboard altogether will make the challenge much more difficult.

Allow Repairs

If students discover the beginning stages of a design failure before they have successfully launched three times, they can be allowed to stop testing and repair their design. A team electing to repair its design should go to the end of the testing queue. The team should also weigh its model again before testing, record the new mass, and record the design changes on the Design Specifications Sheet.

Increase the Rocket Mass

You may find, especially with advanced students, that students reach a plateau in reducing the weight of their structure. At this stage, you may want to add additional design constraints to increase the challenge. The most obvious modification would be to add mass to the rocket.

Limit Designs by Cost

Mass reduction is not the only goal in spacecraft design. Engineers must also strive to lower costs.

Ask students to brainstorm about what NASA engineers must do to reduce the cost of getting to space. Showing a model of the SLS or referring to a poster will be useful in stimulating student ideas. You might want to discuss such facts about the SLS as how much fuel it uses, how much it weighs, cost of materials used to build, etc. Possible answers include: Make the vehicle lighter so it uses less fuel, use less expensive materials, make a better engine that uses less fuel, make the engine more powerful so you can carry more on a single launch, use less expensive fuel. Students are less likely to come up with process ideas for cutting costs such as designing faster and testing more efficiently.

Assign a cost to each material and start students with a set budget. Allow students to purchase materials. You may also attach a cost to testing each design. Students must stay under budget while designing the thrust structure model. Compare designs from teams on the basis of weight and cost. Have students find the ratio of cost to weight for each design and plot the results on a graph.

8. Appendices

Appendix A: Resources

Explore Moon to Mars
https://www.nasa.gov/specials/moon2mars/

The Space Launch System
https://www.nasa.gov/sls

Aerojet Rocketdyne: RS-25 Engine
https://www.rocket.com/space/liquid-engines/rs-25-engine

Boeing: Core Stage
https://www.boeing.com/space/space-launch-system/

Northrop Grumman: Solid Rocket Boosters
https://www.northropgrumman.com/space/nasas-artemis-program/

Rockets and Launch Vehicles
https://www.faa.gov/about/office_org/headquarters_offices/avs/offices/aam/cami/library/online_libraries/aerospace_medicine/tutorial/media/III.4.2.1_Rockets_and_Launch_Vehicles.pdf

Orion Spacecraft
https://www.nasa.gov/orion

Exploration Ground Systems
https://www.nasa.gov/egs

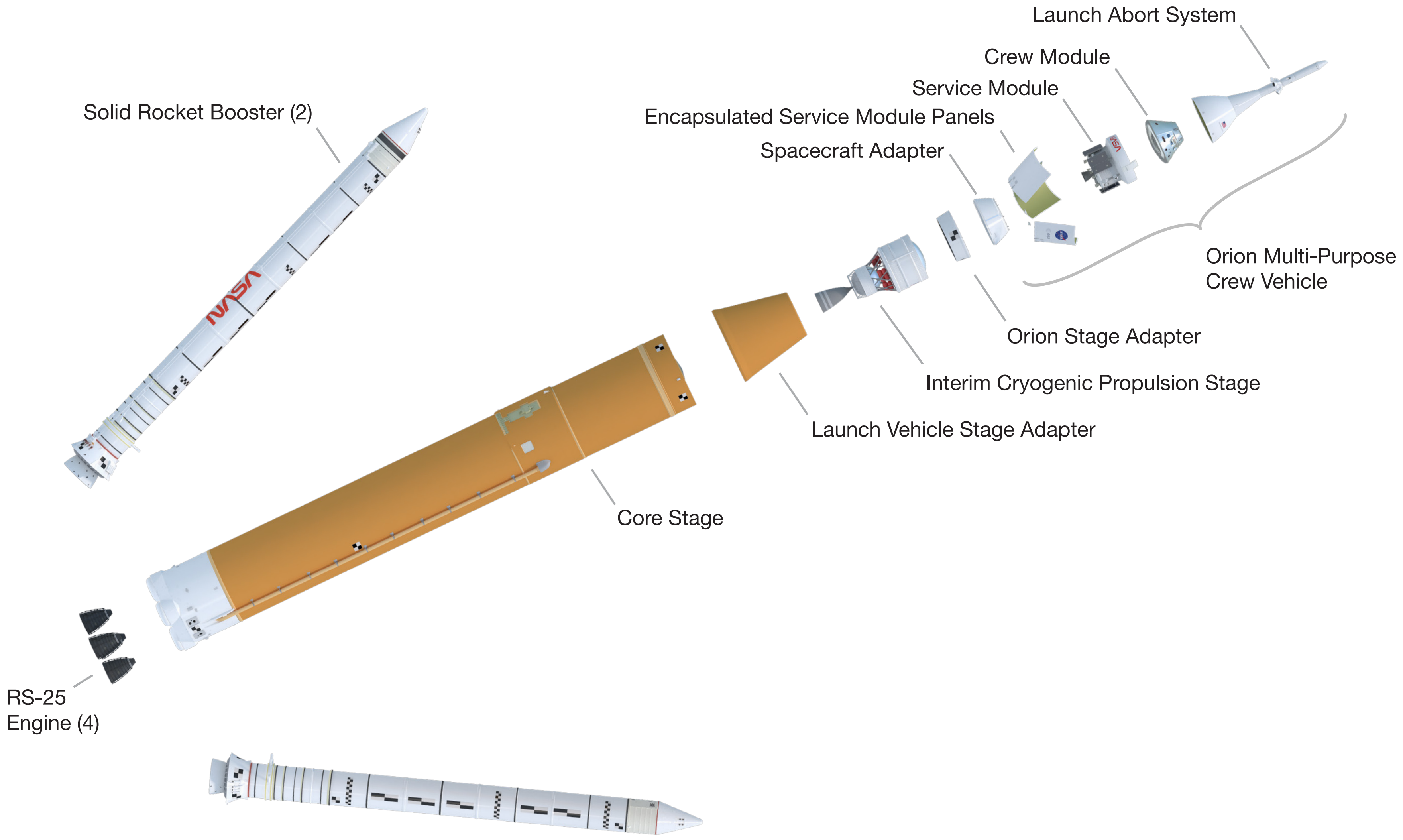
Exploring Careers at NASA
https://www.nasa.gov/audience/forstudents/careers/index.html

Marshall Space Flight Center
https://www.nasa.gov/centers/marshall/home/index.html

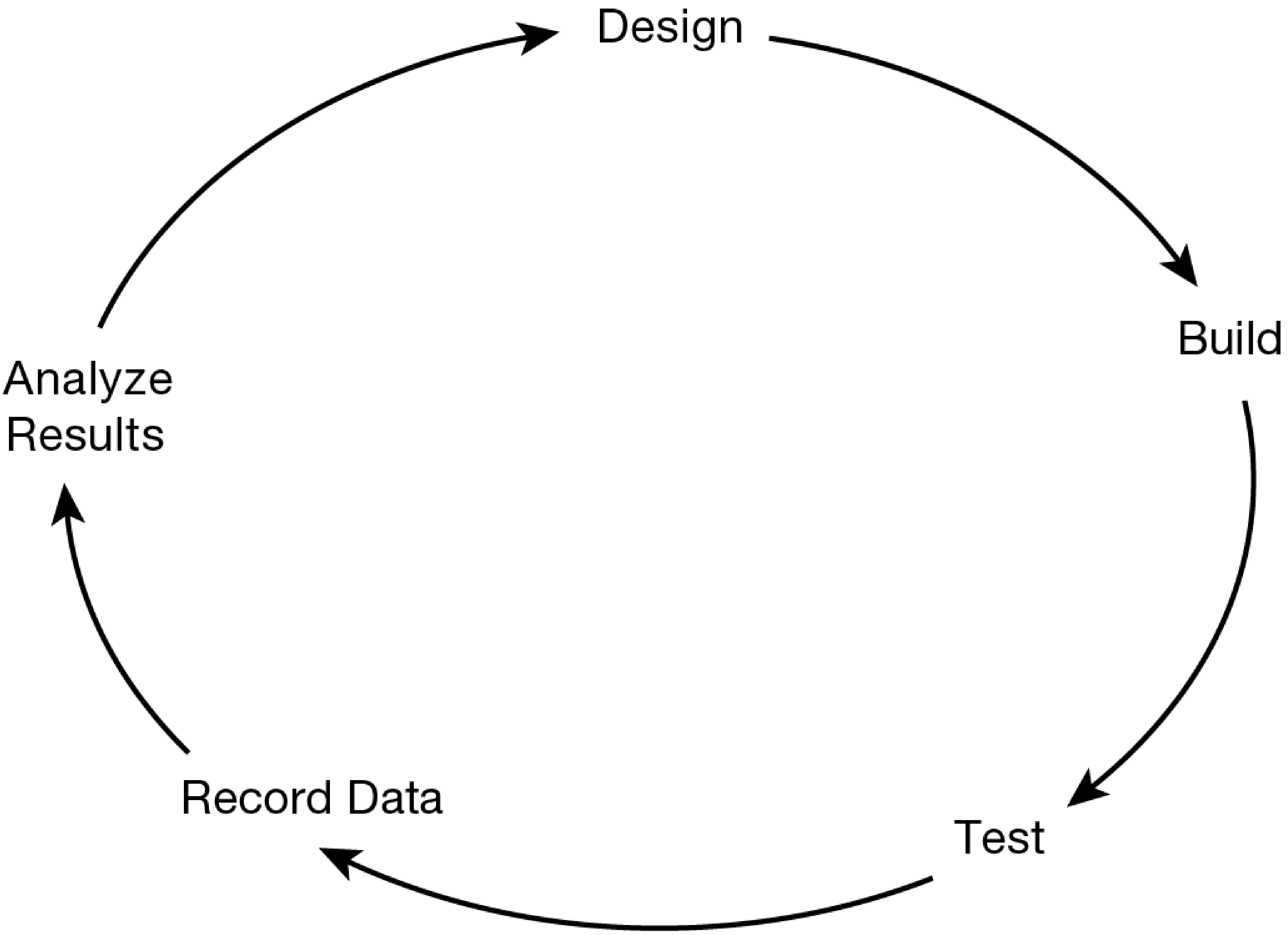
NASA STEM Engagement
https://www.nasa.gov/stem/

Appendix B: Handouts & Recording Sheets

The next few pages are images that might be helpful and the recording sheets for the challenge.

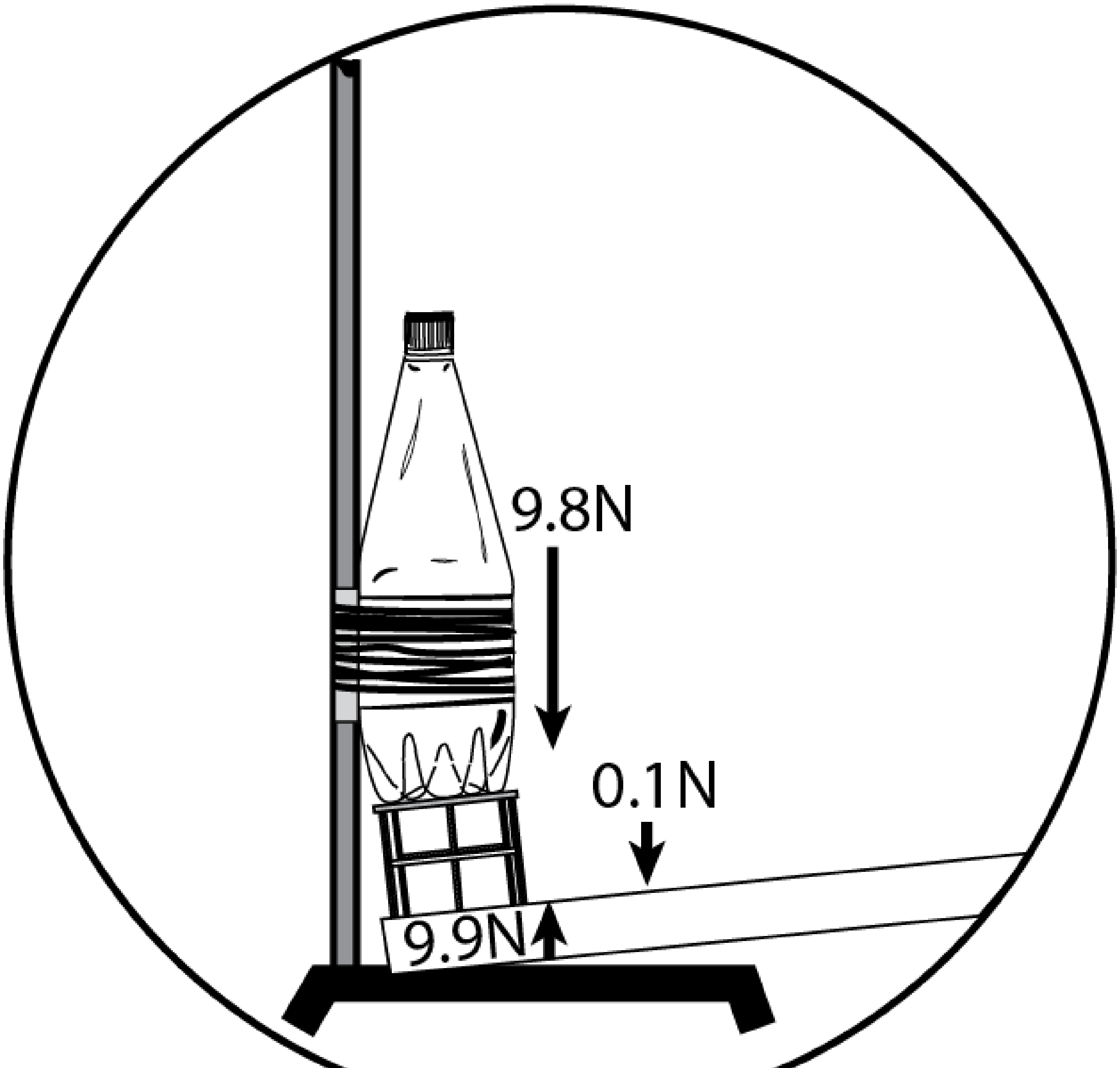


Space Launch System: Block 1 Expanded View

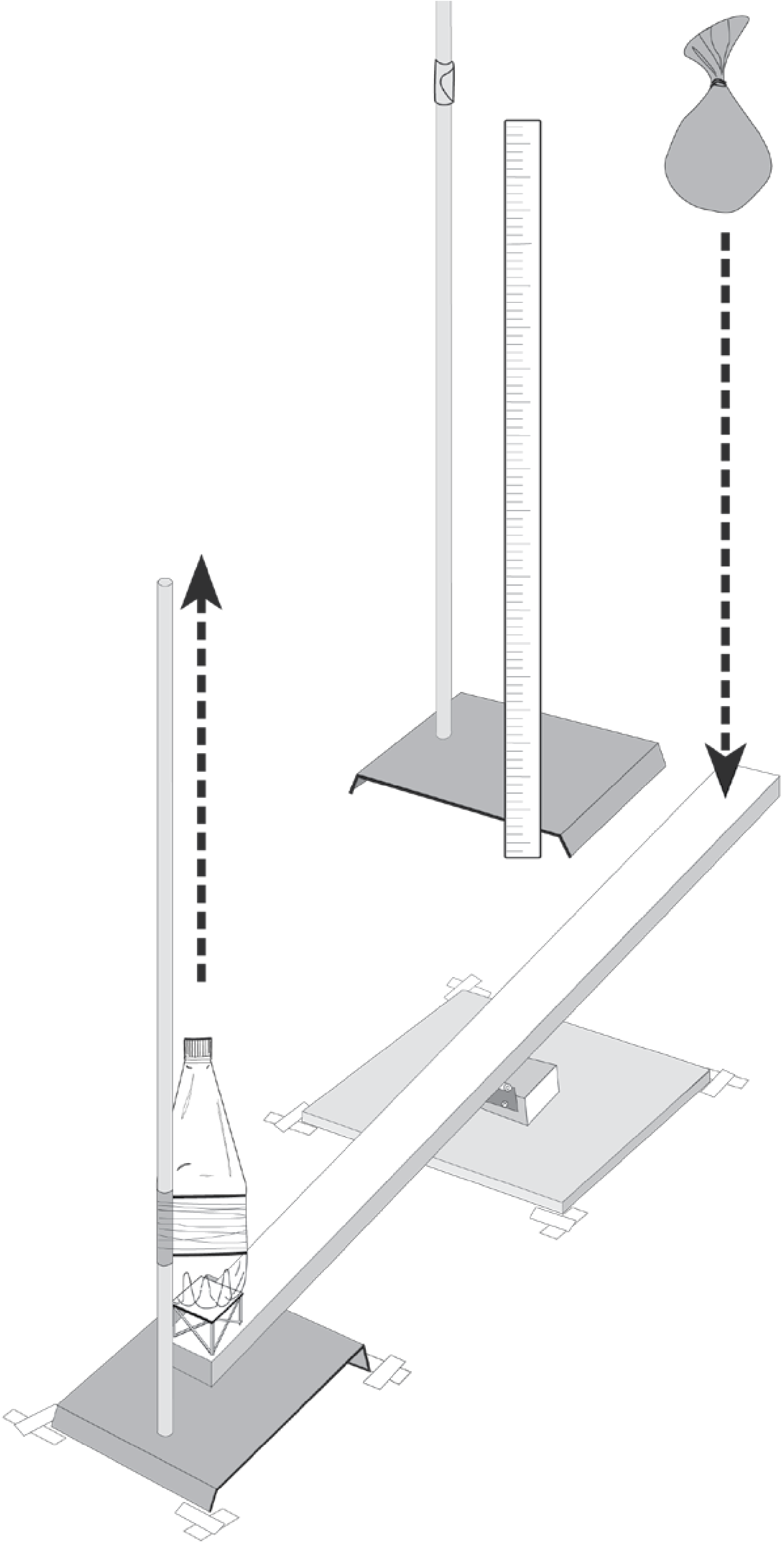


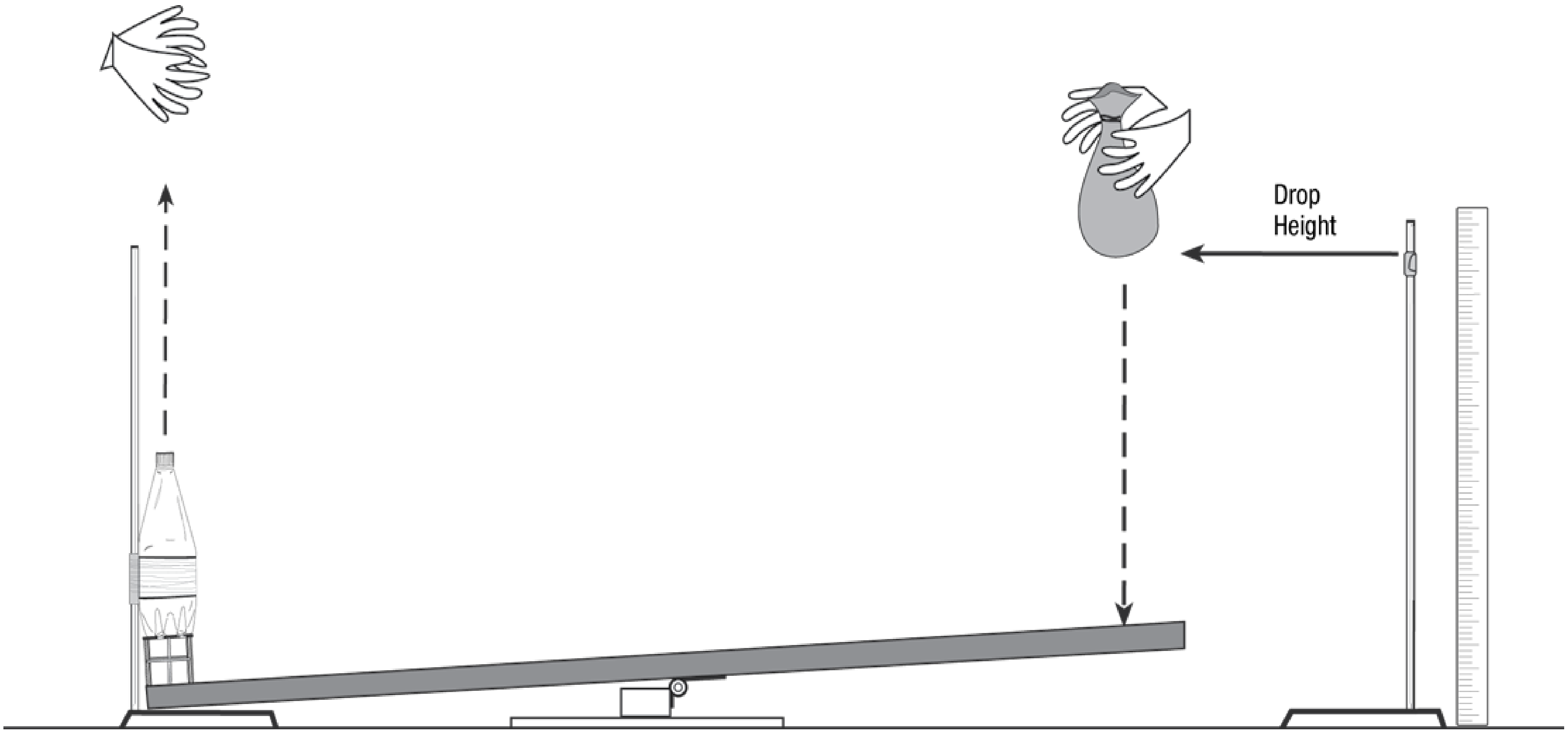
The Design Process

Forces Before Launch



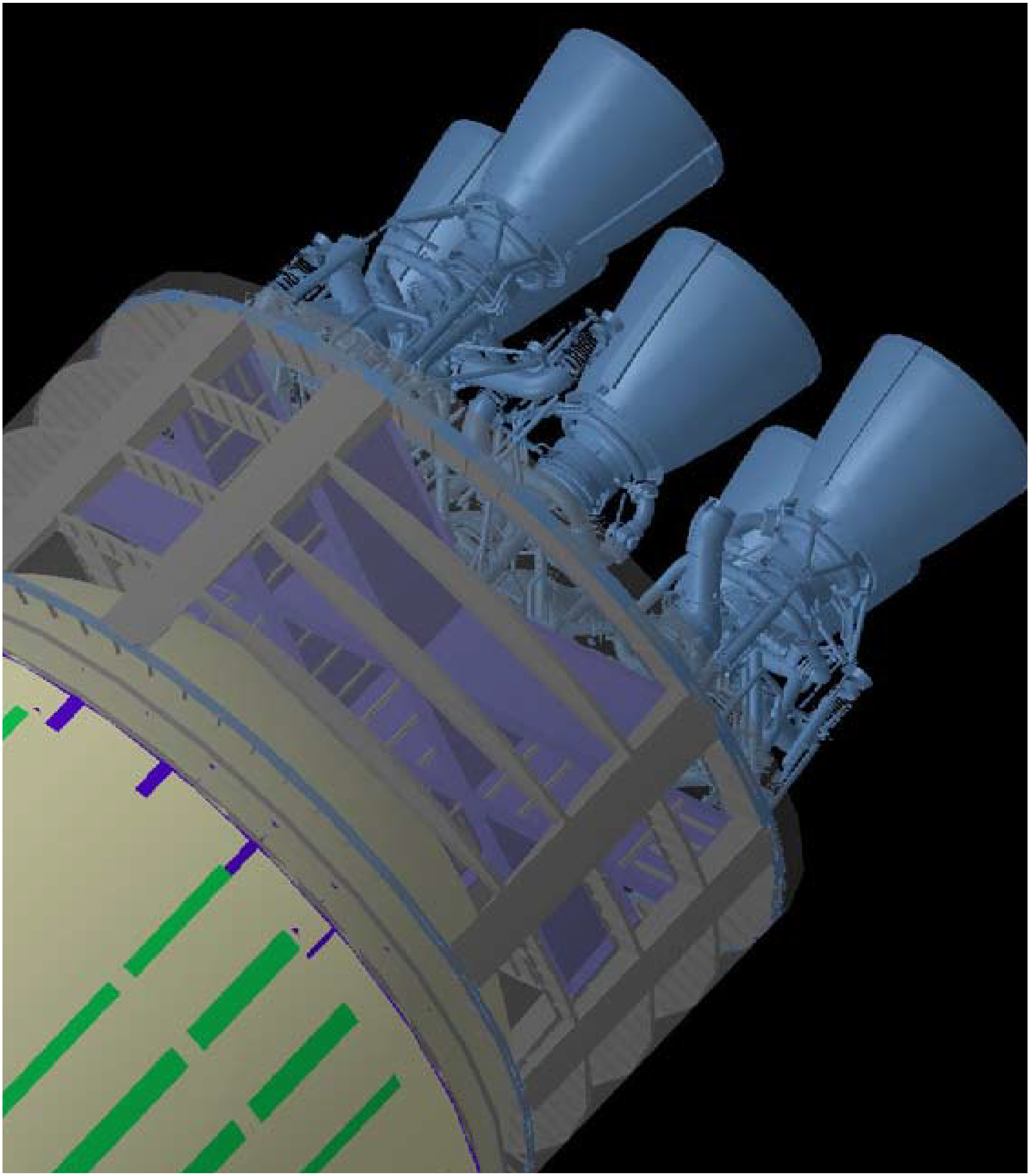
Launch Testing Station



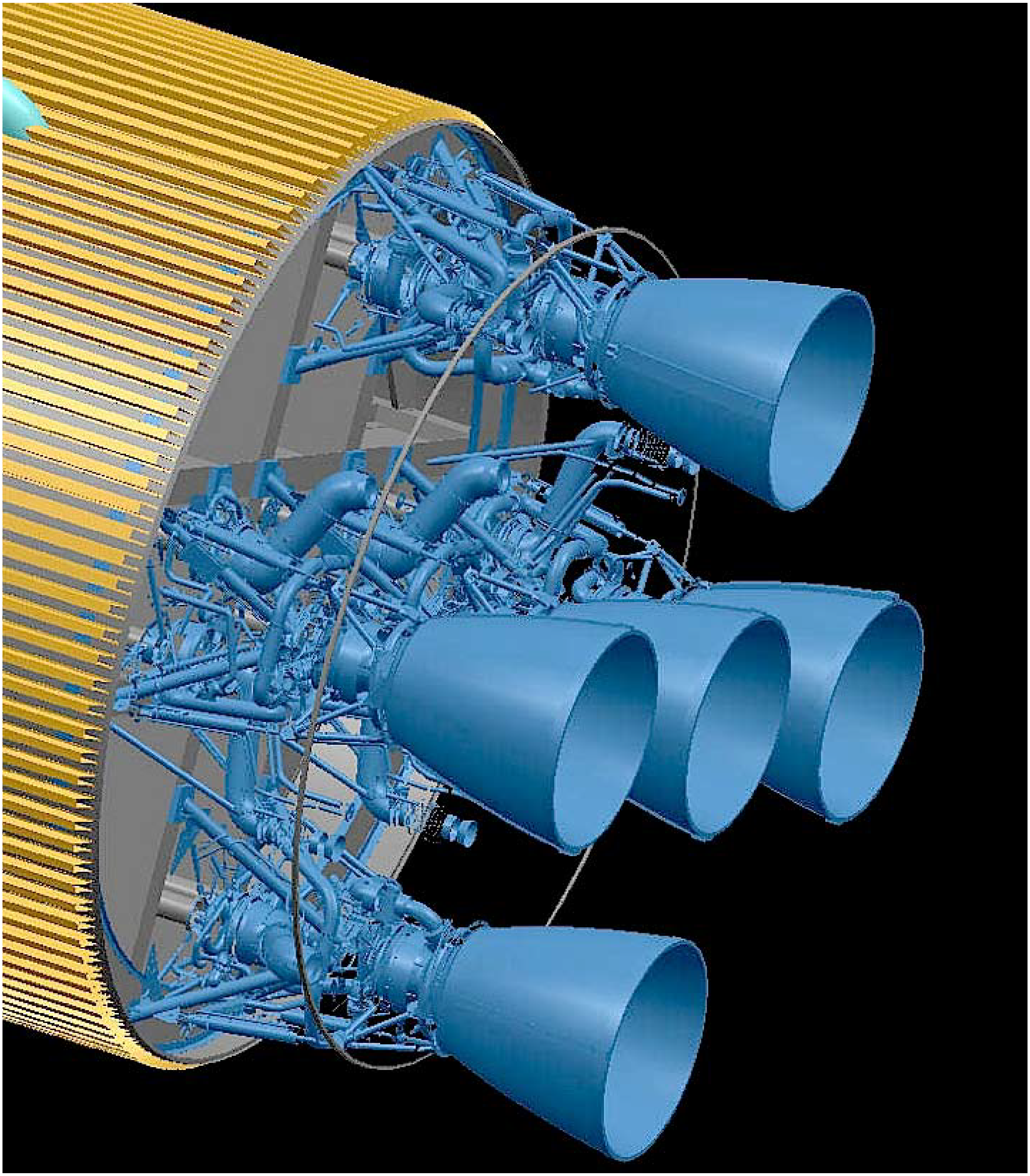


Testing a Thrust Structure

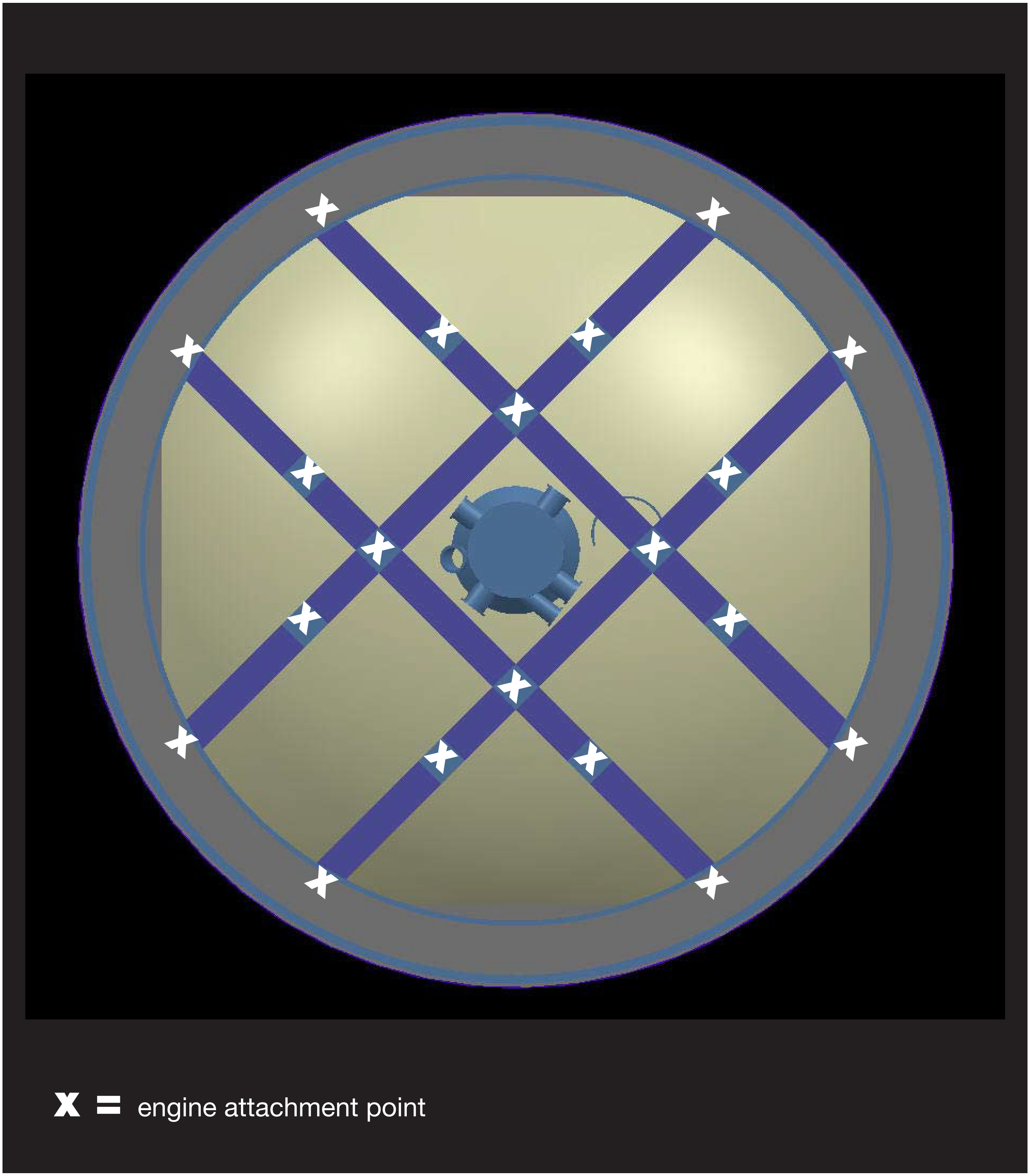
Sample Rocket Thrust Structure with 5 Engines – View 1



Sample Rocket Thrust Structure with 5 Engines – View 2



Sample Rocket Thrust Structure Showing Attachment Points for 5 Engines



Design Specifications Sheet

Design Number

Thrust Structure Weight

Date: ____________ Class: ____________ Team: ____________

Designer Names: ____________

Sketch your design below. Identify materials used. Show glue points.

Describe the key features of your design:

Test Results Sheet

Design Number ____

Thrust Structure Weight ____

Date: ____________ Class: ____________ Team: ____________

Designer Names: ________________________

After testing, sketch your model below. Show failure points if any.

Record the test results

Test ____________ Results ________

1 ________________________

2 ________________________

3 ________________________

Describe the results of the testing.
Explain which features seemed effective
and which did not.

National Aeronautics and Space Administration

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