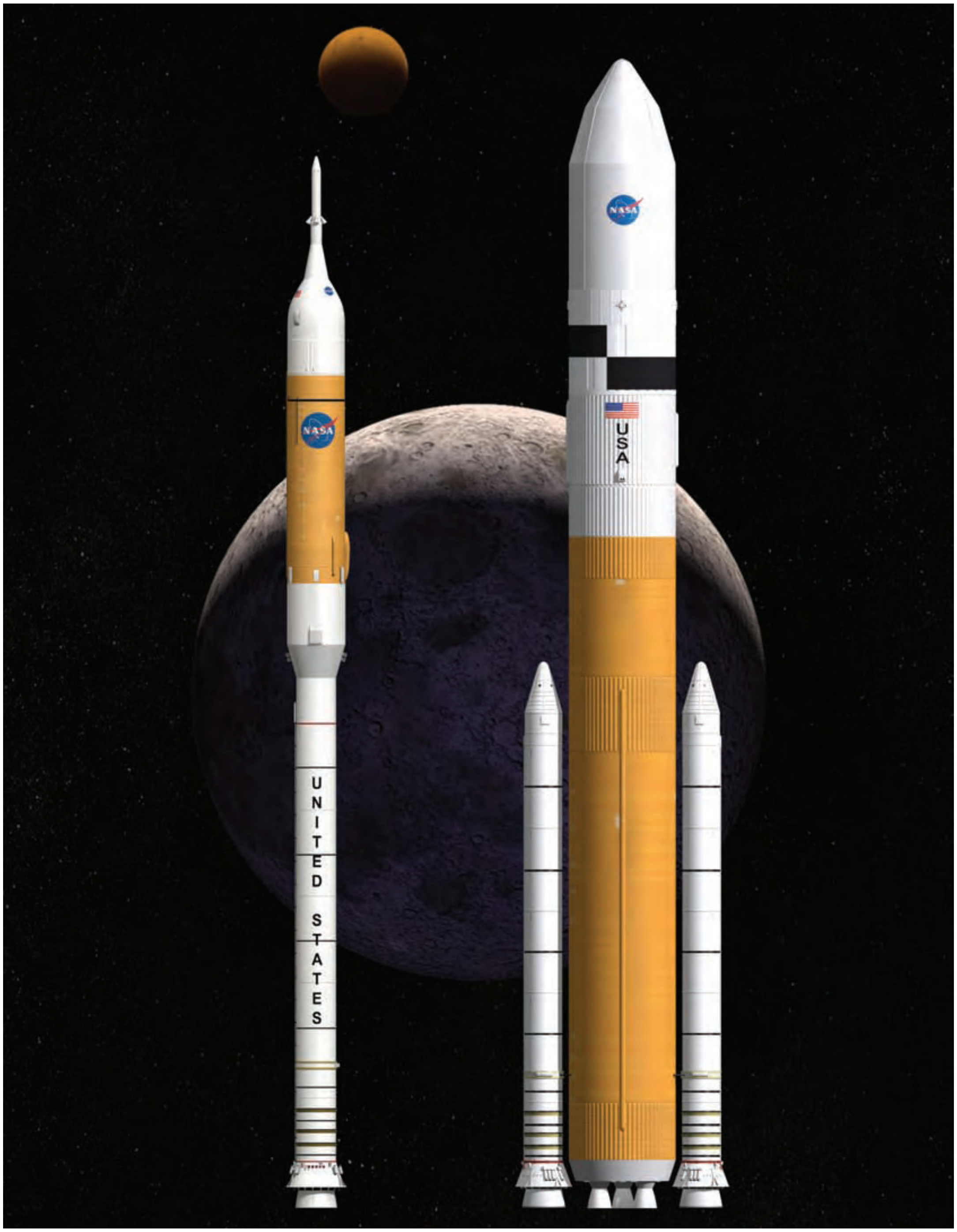
National Aeronautics and Space Administration

NASA Engineering Design Challenges

Spacecraft Structures



Educational Product	
Educators	Grades 6–9

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Cover Illustration:
NASA Ares I and Ares V Launch Vehicles
NASA artist conceptions.

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**The Ares Engineering Design Challenges use Traditional U.S. units of measure as the standard. Metric units follow in (parenthesis). In cases when a given formula is traditionally calculated in metric units, for mathematical correctness, it is presented in that manner.*

NOTE: The Ares vehicles are a very preliminary configuration and will be subject to change as the design progresses.

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Ares I and V
NASA artist conceptions

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Spacecraft Structures

1. Overview

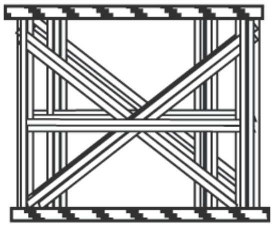


Figure 1.1. Thrust structure model.

Space Transportation

NASA Engineers at Marshall Space Flight Center, along with their partners at other NASA centers, and in private industry, are designing and beginning to develop the next generation of spacecraft to transport cargo, equipment, and human explorers to space. These vehicles are part of the Constellation Program, which is carrying out a bold vision of human space exploration. The program includes a crew exploration vehicle and the spacecraft to carry the crew to the Moon and later to Mars. The NASA Authorization Act of 2005 directs NASA to establish a program to develop a sustained human presence on the Moon, which will serve as a stepping stone to further exploration of Mars and other destinations. This design challenge focuses on the Ares family of rockets, which will replace the Space Shuttle in the task of putting people, satellites, and scientific experiments into space.

Connect to Engineering and Science

The Engineering Design Challenges connect 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

You will present students with a challenge: Build a model thrust structure (the portion of the structure that attaches the engine to the rest of the spacecraft) that is as light as possible, yet, strong enough to withstand the load of a "launch to orbit" three times. See Figure 1.1. Students first determine the amount of force needed to launch a model rocket to 3.3 feet (1 meter), 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.

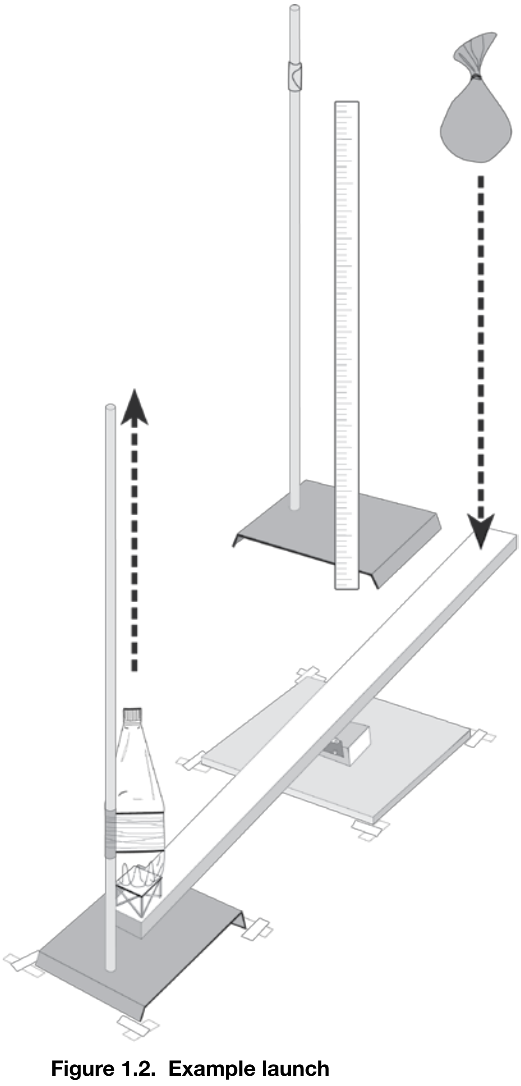


Figure 1.2. Example launch testing station.

Materials

You will need a few simple and inexpensive materials:

- Craft sticks.
- Dowels.
- Glue guns and hot-melt glue.
- Corrugated cardboard.
- 35 mm film canisters.
- 1-liter soda bottles.
- 2-liter soda bottles.
- 25-50 pounds (11-23 kilograms) of sand.
- A sturdy cloth bag to hold the sand.
- Brass tubing.
- Package sealing tape about 2 inches wide.
- 4-ounce paper cups.

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

These activities help students achieve national goals in science, math, and thinking skills. In the pilot testing of the design challenge, students embraced the design challenge with excitement. This activity will provide your students 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.

Student Research Opportunities

The "Resources" section of this guide includes many web sites where students can obtain additional information.

Parent Involvement

The "Masters" section of this guide includes a reproducible flier to send home to inform parents about the activity. It includes suggested activities students and parents can do at home together.

Safety

These activities meet accepted standards for laboratory science safety.

2. How to Use This guide

This guide is divided into several sections:

- National Science Education Standards.
- Math Connections.
- Thinking Skills.
- Background Material.
- Preparation for the Challenge.
- Day-by-day Procedures.
- Extensions.
- Resources.
- Masters.

National Standards

If you have questions about how this activity supports the National Science Education Standards, Math Connections, or Thinking Skills, read those sections first. Otherwise, refer to those sections only as you need them.

Suggested Order of Reading

First, skim through the entire guide to see what is included.

Next, read through the "Classroom Sessions." Give special attention to the last part, "Linking Design Strategies and Observations to Science Concepts," on Page 37. This gives explicit suggestions on how to help students understand the science in their designs. Review this section again after you start classroom work with your students.

Be sure to read the last two sections in the "Teacher Preparation" section: "Teaching Strategies for an Engineering Design Challenge," on Page 19, and "Helping Students Understand the Design Process," on Page 21. These will help you understand what is distinctive about an Engineering Design Challenge and how your students can get the most out of it.

When you understand the session-by-session flow and the pedagogical approach on which it is based, read the "Background" section. This will provide you with information you will want to have in mind to "set the stage" for students and to link their classroom work with the work of NASA engineers. It focuses on one of the challenges faced by NASA engineers in developing a reusable launch vehicle: Spacecraft Structures.

Further resources for you and your students can be found in the "Resources" section on Page 46.

The reproducible masters you need are in the "Masters" section at the end of the book.

Finally, read the remainder of "Teacher Preparation" to find out how to prepare your classroom and yourself to conduct the Engineering Design Challenge. It contains safety guidelines, lists of materials, suggestions for organizing the classroom, and teaching techniques.

3. National Science Education Standards

This Engineering Design Challenge supports the following Content Standards from the National Research Council's National Science Education Standards.

Science as Inquiry

All students should develop abilities necessary to do scientific inquiry.

Students respond positively to the practical, outcome orientation of design problems before they are able to engage in the abstract, theoretical nature of many scientific inquiries.

–National Science Education Standards, National Research Council

Fundamental Abilities and Concepts

- Students should develop general abilities, such as systematic observation, making accurate measurements, and identifying and controlling variables.
- Students should use appropriate tools and techniques, including mathematics, to gather, analyze, and interpret data.
- Students should base their explanation on what they observed, providing causes for effects and establishing relationships based on evidence.
- Students should think critically about evidence, deciding what evidence should be used, and accounting for anomalous data.
- Students should begin to state some explanations in terms of the relationship between two or more variables.
- Students should develop the ability to listen to and respect the explanations proposed by other students.
- Students should become competent at communicating experimental methods, following instructions, describing observations, summarizing the results of other groups, and telling other students about investigations and explanations.
- Students should use mathematics in all aspects of scientific inquiry.
- Mathematics is important in all aspects of scientific inquiry.
- Technology used to gather data enhances accuracy and allows scientists to analyze and quantify results of investigations.
- Scientific explanations emphasize evidence.
- Scientific investigations sometimes generate new procedures for investigation or develop new technologies to improve the collection of data.

Complete text of the National Science Education Standards
http://books.nap.edu/openbook.php?isbn=0309053269

Complete text of Benchmarks for Science Literacy
http://www.project2061.org/publications/bsl/online/bolintro.htm

Physical Science

All students should develop an understanding of motions and forces.

Fundamental Concepts and Principles, Grades 5-8

- An object that is not being subjected to a force will continue to move at a constant speed and in a straight line.
- If more than one force acts on an object along a straight line, then the forces will reinforce or cancel one another, depending on their direction and magnitude. Unbalanced forces will cause changes in the speed or direction of an object's motion.
- Energy is transferred in many ways.

Fundamental Concepts and Principles, Grades 9-12

- Objects change their motion only when a net force is applied. Laws of motion are used to precisely calculate the effects of forces on the motion of objects. The magnitude of the change in motion can be calculated using the relationship F=ma, which is independent of the nature of the force. Whenever one object exerts a force on another, a force equal in magnitude and opposite in direction is exerted on the first object.

Science and Technology

All students should develop abilities of technological design.

Fundamental Concepts and Principles

1. Design a solution or product.
   - Consider constraints.
   - Communicate ideas with drawings and simple models.
2. Implement a design.
   - Organize materials.
   - Plan work.
   - Work as collaborative group.
   - Use suitable tools and techniques.
   - Use appropriate measurement methods.
3. Evaluate the design.
   - Consider factors affecting acceptability and suitability.
   - Develop measures of quality.
   - Suggest improvements.
   - Try modifications.
   - Communicate the process of design.
   - Identify stages of problem identification, solution design, implementation, evaluation.

The challenge satisfies the following criteria for suitable design tasks:

- Well defined, not confusing.
- Based on contexts immediately familiar to students.
- Has only a few well-defined ways to solve the problem.
- Involves only one or two scientific concepts.
- Involves construction that can be readily accomplished by students, not involve lengthy learning of new physical skills, and not require time-consuming preparation or assembly.

All students should develop understandings about science and technology.

- Difference between scientific inquiry and technological design.
- Technological designs have constraints.
- Technologies cost, carry risks, and provide benefits.
- Perfectly designed solutions do not exist; engineers build in back-up systems.

Through design and technology projects, students can engage in problem-solving related to a wide range of real-world contexts. By undertaking design projects, students can encounter technology issues even though they cannot define technology. They should have their attention called to the use of tools and instruments in science and the use of practical knowledge to solve problems before the underlying concepts are understood.

–Benchmarks for Science Literacy, AAAS

4. Math Connections

This Engineering Design Challenge offers the opportunity to integrate a variety of math skills*, described in the following table. Some of the listed applications are part of extension activities.

Skill	Application
Performing operations with decimal numbers	Mass of structure, quantities of materials
Rounding	Rounding mass of structure to the gram, tenth of a gram, etc.
Calculating averages	Calculating average, mean, median, mode, or range for all designs by one team, or for the entire class
Graphing	Creating line graphs, bar graphs, circle graphs, or scatterplot of structure mass versus launch success
	Graphing number of successful launches vs. mass of the structure
	Graphing number of successful launches vs. size (width, length, diameter) of the structure
Measuring percentage improvement	Comparing designs by one team, calculating improvement for the entire class
Calculating ratios	Determining the relationship between the quantity of materials used and the number of successful launches; between the mass dropped and the launch height
Using formulas	Calculating gravitational potential energy, $PE = mgh$ and kinetic energy, $KE = 1/2 mv^2$
Using a budget	See the extension activity: Limiting designs by cost

*The Ares Engineering Design Challenges use Traditional U.S. units of measure as the standard. Metric units follow in (parenthesis). In cases when a given formula is traditionally calculated in metric units, for mathematical correctness, it is presented in that manner.

5. Thinking Skills

This Engineering Design Challenge provides an opportunity to assess students' development of critical thinking skills in a context in which these skills are applied throughout the task. Students are often asked to perform critical thinking tasks only after they have mastered such lower-level thinking skills as making simple inferences, organizing, and ranking. In this learning activity, various levels of thinking skills are integrated. The following rubric is designed to assist you in assessing student mastery of thinking skills.

Cognitive Memory Skills

1. Students accurately measure the drop height and compute the average height.
2. Students observe a design before testing and pick out the "key features."
3. Students observe a model during and after testing and document precisely what happens to the model.
4. Students record observations and organize data so that they can be exchanged with others and referred to later.

Structuring, Organizing, Relating Skills

5. Students can classify designs.
6. Students can rank designs according to various criteria, i.e., strength, mass.
7. Students can create diagrams, charts and graphs of the results.
8. Students can visualize relationships such as part-whole, cause-effect.
9. Students can interpret such information as test results and design documentation.
10. Students can compare and contrast different design solutions.

Convergent and Generalizing Skills

11. Students can demonstrate that they understand the challenge.
12. Students can draw conclusions and generalize.
13. Students can converge on a solution by choosing from alternatives.

Divergent Thinking Skills

14. Students can apply ideas and concepts of motions and forces to their designs.
15. Students can make inferences and predictions about the performance of a design.
16. Students can invent and synthesize a solution.
17. Students can devise an experiment to test a particular theory.
18. Students can balance trade-offs between cost, quality, safety, efficiency, appearance, and time.

Evaluation Skills

19. Students can evaluate designs based on given criteria.
20. Students value new knowledge.

6. Background

The Ares Launch Vehicles

On July 20, 1969, Neil Armstrong and Buzz Aldrin became the first humans to set foot on the Moon. They arrived there in a lunar lander, which had been propelled into orbit around the Moon as part of the Apollo 11 space flight. NASA now has plans to return humans to the Moon and eventually to Mars. NASA is designing new spacecraft to carry them there. These spacecraft are known as the Ares launch vehicles.

NASA Engineers at Marshall Space Flight Center are currently developing the launch vehicles for the next generation of space travel. The Ares I crew launch vehicle will deliver the Orion crew exploration vehicle into Earth orbit. Astronauts in Orion can then dock with the International Space Station, or rendezvous with the Altair lunar lander, put into orbit by the Ares V launch vehicle for transport to the Moon.

Ares I is a two-stage rocket. (See Figure 6.1.) The first stage is a reusable solid rocket booster (RSRB) similar to the boosters of the Space Shuttle. Its second stage is a liquid oxygen-liquid hydrogen engine similar to the upper stage engine of the Saturn V rocket, which propelled the Apollo missions to the Moon. Ares I will weigh 2 million pounds (907 metric tons) at liftoff, will stand about 325 feet tall (100 meters), more than a football field, and will deliver the Orion crew exploration vehicle to low Earth orbit (LEO).

Ares I will produce roughly 3.5 million pounds-force (15.6 meganewtons) of thrust at liftoff. The RSRB booster will burn for about 126 seconds. At the end of this burn, the rocket will be about 36 miles (58 kilometers) above Earth, traveling at a speed of 4,445 miles per hour (2,000 m/sec). The vehicle will have lost 69% of its weight by having burned up 1.4 million pounds (630 metric tons) of solid rocket fuel. The RSRB, no longer needed, will be jettisoned and will fall back to Earth, where it will be recovered to be used again. The liquid fuel J-2X engine of the Ares I upper stage will burn for about 464 seconds, producing 294,000 pounds (1.3 meganewtons) of thrust, to lift the crew module to a higher orbit at 185 miles (298 kilometers) above the Earth. In this orbit, the vehicle will be traveling at about 17,500 miles per hour (7,800 m/sec).

Ares V, shown in Figure 6.2, is NASA's heavy-lift cargo vehicle that will enable NASA to send more crew and more cargo to the Moon than the Apollo-era Saturn V. Ares V will weigh 7.4 million pounds (3,357 metric tons) at liftoff, will stand 360 feet (110 meters) tall, and can carry 287,000 pounds (130 metric tons) to LEO. The Saturn V was 4 feet (1.2 meters) taller but weighed nearly 1 million pounds (453,600 kilograms) less than Ares V and carried approximately 39,000 pounds (17,690 kilograms) less to the Moon. Ares V has a payload shroud more than 32 feet (10 meters) in diameter for carrying more massive payloads. It is this unmatched lift capability that will not only support extended exploration of most of the lunar surface, but will also support numerous human and robotic missions of exploration beyond the Moon.

Ares V has two stages. The first stage is powered by two solid rocket boosters similar to the Ares I first stage and a core stage powered by five commercial RS-68 liquid fuel engines working together. After the boosters burn out, they fall to Earth, and the core stage continues operating to an altitude of roughly 87 miles (140 kilometers). The stage falls to Earth, and the second stage, called the Earth departure stage (EDS), ignites to place the lunar lander, Altair, in Earth orbit. The EDS is powered by the same J-2X engine as the Ares I upper stage. After the astronauts in Orion rendezvous and dock with Altair, the EDS ignites again to send the Orion, Altair, and the crew to the Moon.

Figure 6.1.
Ares I.

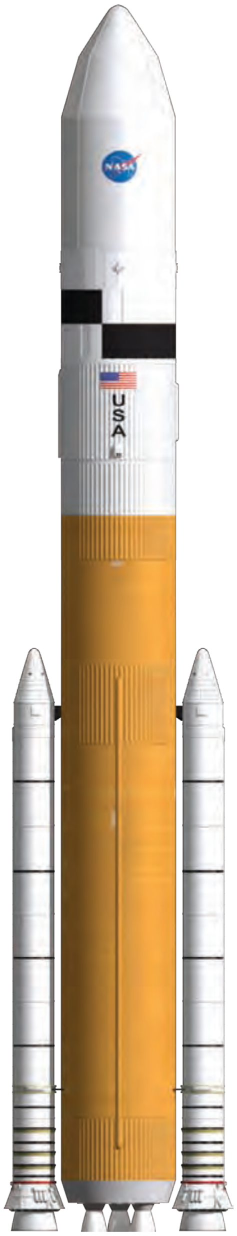


Figure 6.2.
Ares V.

Spacecraft Structures

Every pound that is carried to space requires fuel to do so, regardless of 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.

Students can calculate the "payload" to total weight ratios for (a) the family car and (b) a student riding a bicycle.

In order to make the Ares spacecraft as light as possible, NASA engineers are constructing them of lightweight, strong materials, such as Al-Li 2195, an aluminum-lithium alloy, which is less dense and stiffer than pure aluminum. NASA engineers also design structures that use as little material as possible to achieve the strength and rigidity they need. So, for example, they make use of a network of hollow tubular struts (called a truss) rather than use more compact, but heavier solid beams.

This engineering design challenge focuses on the Ares V thrust structure, which attaches the five liquid fuel engines of the Ares V to the body of the spacecraft. The thrust structure is an essential part of the spacecraft, which must be kept lightweight. As they burn, the five RS-68 engines of the Ares V produce about 3,510,275 pounds (1,592 metric tons) of thrust. This means that the thrust structure must bear a load equivalent to 3,510,275 pounds (1,592 metric tons) of weight pushing on it. The thrust structure must not only withstand this terrific force, it must transfer it to the vehicle in a balanced way, without damaging the vehicle.

Students may be familiar with design strategies used to make lightweight bicycles.

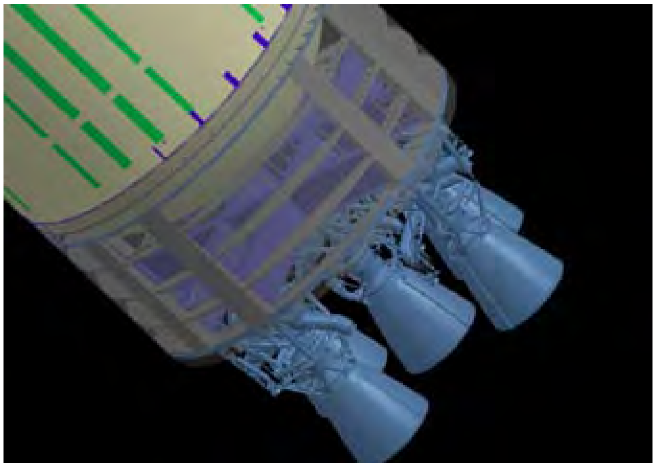


Figure 6.3. View of Ares V engines and thrust structure. This image appears in a larger version in the "Masters" section.

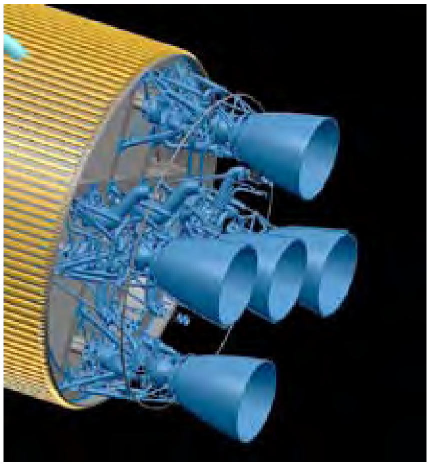


Figure 6.4. Ares V engines attached to thrust structure. This image appears in a larger version in the "Masters" section.

Figure 6.5. Ares I.

Ares I

Length: 325 feet (100 meters)

Width: 18 feet (5.5 meters)

Takeoff weight: 2 million pounds (907 metric tons)

Propellant fuel weight: 1.7 million pounds (764 metric tons)

Main propulsion: single RSRB

Take-off thrust: 3.5 million pounds-force (15.6 meganewtons)

Maximum speed: 17,500 miles/hr (7,800 m/sec)

Maximum speeds at end of staging:

Ares I First Stage: 6250 ft/sec (1,904 m/sec)

Ares I Upper Stage Orbit Injection: 25,582 ft/sec (7,798 m/sec)

Largest payload it can carry into orbit: 56,512 pounds (25.6 metric tons)

Figure 6.6. Ares V.

Ares V

Length: 360 feet (110 meters)

Core stage diameter: 33 feet (10 meters)

Takeoff weight: 7.4 million pounds (3,357 metric tons)

Core stage fuel weight: 3.16 million lbs (1,435.5 metric tons)

Main propulsion: 2 RSRBs plus 5 RS-68 liquid fuel engines

Take-off thrust: 10.65 million pounds (47.4 meganewtons)

Maximum speed: 24,462 mi/hr (10,935 m/sec)*

Maximum speeds at end of staging:

Ares V SRB separation: 3,958 ft/sec (1,206 m/sec)

Ares V Core stage cutoff: 16,227 ft/sec (14,946 m/sec)

Ares V Earth Departure Stage (orbital burn): 25,460 ft/sec (7,760 m/sec)

Largest payload it can carry into orbit: 287,000 pounds (130 metric tons)

**Trans-Lunar Injection (TLI)*

NOTE: The Ares vehicles are a very preliminary configuration and will be subject to change as the design progresses.

Figure 6.7. Space Shuttle.

Space Shuttle

Length Orbiter: 122 feet (37 meters),
Overall: 184 feet (56 meters).

Width Orbiter: 56.67 feet (17.3 meters),
Overall: 76.6 feet (23 meters)

Takeoff weight: 4.5 million pounds (2,041 metric tons)

Fuel weight: 4.3 million pounds, including Solid Rocket Boosters and external fuel tank (1,937 metric tons)

Main propulsion: 3 Main Engines,
2 Solid Rocket Boosters

Take-off thrust: 3.3 million pounds or (1,497 metric tons)

Maximum speed:
17,500 miles/hr (7,800 m/sec)

Largest payload it can carry into orbit:
50,000 pounds (22.7 metric tons)

Questions for class discussion or homework

1. Why is it important to make the launch vehicle as lightweight as possible?

2. What are the Ares launch vehicles?

3. What are some ways NASA engineers could make the Ares launch vehicles as lightweight as possible?

4. If it costs $10,000 to lift a pound (half a kilogram) of payload into orbit aboard the International Space Station, calculate the cost of sending yourself into space. How much would it cost to send yourself, your family and your pets into space?

Answers to questions for class discussion or homework

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

2. The Ares I and V are the next generation of space launch vehicles.

3. By making the vehicles of a lightweight composite material and by using a truss structure to support the engines.

4. Answers will vary.

7. Teacher Preparation

In order to prepare yourself and your classroom for this Engineering Design Challenge, you should:

- Use the Background Information section in this guide, and the Engineering Design Challenge web site at http://edc.nasa.gov to familiarize yourself both with the spacecraft structures used by NASA and the science and engineering concepts you will be introducing.
- Read through the day-by-day activities in the following section of this guide.
- Gather the required materials.
- Build the launcher.
- Build the test rockets.
- Practice the test procedure with your own designs.
- Prepare the materials for the classroom.
- Set up the classroom.
- Organize students in teams.
- Review safety procedures.
- Notify parents using the flier included in the "Masters" section.

Required Materials

Required Materials	**Approximate cost per unit**	**Minimum quantity for a few teams (60 structures)**	**Recommended quantity for 12–15 teams (120 structures)**	**Add for each additional team (10 structures)**
Craft Sticks	1/2¢	1500	3000	250
Dowels	15 to 50¢ for 3 ft.	5	5	0
Hot-melt Glue (low-temperature type)	5 to 50¢ per stick	12	20	2
Corrugated Cardboard	free	60	120	10
35 mm Film Cans	free	10	20	1
1-liter Soda Bottles	free or 5¢	8	20	1
2-liter Soda Bottles	free or 5¢	3	5	0
Weight	$2.35 for a 50-lb (23-kg) bag of sand	20 to 50 lbs total		
Brass Launch Tubes	80¢ for 4 inches	4	8	1
Package Tape	$2.00	1 roll	1 roll	0
Small Paper Cups 4-oz, waxed	2 or 3¢	12	36	3

Notes on Materials

Craft Sticks

Use a stick that is available in large quantity at a reasonable price in your area. Several kinds are suitable. Craft sticks the size of match sticks are excellent for this project. They are just under 3/32 inch (2 mm square) and are sold in craft stores. They are 2 5/8 inches (6.7 centimeters) long and come in a package of 500 for about $2.00. You might find toothpicks that have a square cross section in the middle portion. They would be a little more difficult to work with, but also very good.

Basswood and balsa sticks are available in craft and art-supply stores in a variety of sizes but they are likely to be excessively expensive. 3/32- or 1/8-inch square would be suitable for basswood; 1/8 or 3/16-inch square would be suitable for balsa. Round bamboo skewers for kitchen use could be used. They are about 3/32 inch (0.2 centimeter) in diameter and about 12 inches (30 centimeters) long. You may wish to cut off the sharp point before distributing them to students.

Dowels

Basic dowels that you might find at any hardware, lumber, or craft store are useful for making strong structures that are heavier than necessary. 1/8-, 3/16-, and 1/4-inch diameters would be handy. Any kind of wood will do; birch is common and inexpensive.

Corrugated Cardboard

This will be cut into 3 1/2 inch (9-centimeter) squares. Scrap from old boxes is suitable if it is flat and undamaged.

35 mm Film Cans

These are the plastic containers in which the roll of film comes. Usually photo stores can give you a big bag of them.

Weights

Static testing of structures requires weights that can be placed on the structure. One good approach is to fill some 1- or 2-liter bottles with sand. You will need to know how much your weights weigh.

Brass Launch Tubes

See the notes in the section, “Build the Rockets,” on Page 17.

Package Tape

Any sturdy tape 2-3 inches wide will do. Transparent is best.

Tools:

- Safety Glasses or Goggles.
- Glue Gun (low-temperature type is recommended).
- Cardboard Cutter (utility knife or box cutter for cutting 3 1/2 inch (9 centimeter) squares).
- Strong scissors (for cutting sticks or trimming cardboard).
- Rulers.
- Yard Stick (or meter stick).

Build the Launcher

Materials Needed

Ring Stand (Launch Rod)

A ring stand of the type used in chemistry labs with a vertical rod 1/2 inch in diameter and approximately 3 feet (1 meter) tall. (This is taller than most.) The kind with a large heavy base is best.

You can use any straight metal rod 1/2 inch in diameter and 3 to 4 feet (0.9 to 1.2 meters) 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.

Weight for Dropping

A sturdy cloth bag about the size of a loaf of bread containing about 15 to 20 pounds (7 to 9 kilograms) of sand or fine gravel will work well. If you plan to do calculations using the mass of the dropped weight, 22 pounds (10 kilograms) provides a convenient figure. Lead shot makes an excellent filler for the drop weight. Sturdy sewing of the bag is important.

Wooden 2 by 3

1 piece 50 inches (1.3 meters) long (for the launch lever)

1 piece 4 inches (10 centimeters) long (for the mounting block)

You can use a 2 by 4 in place of the 2 by 3. This works just fine. The 2 by 4 is heavier than necessary.

Plywood Base Board

3/4 or 1/2 inch thick, 10 by 14 inches (25.4 by 35.6 centimeters). Any size from 8 by 12 inches (20 by 30.5 centimeters) to 12 by 16 inches (30.5 by 40.6 centimeters) is fine.

Hinge

A “T” style hinge is ideal. A good size has one flap 3 1/2 inches (9 centimeters) wide (in the direction of the pivot pin) and about 1 inch (2.54 centimeters) long. The other flap is triangular, about 1 1/2 inches (3.8 centimeters) wide at the pin, and about 4 inches (10 centimeters) long. This kind of hinge costs about $3.00. 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. See Figure 7.1.

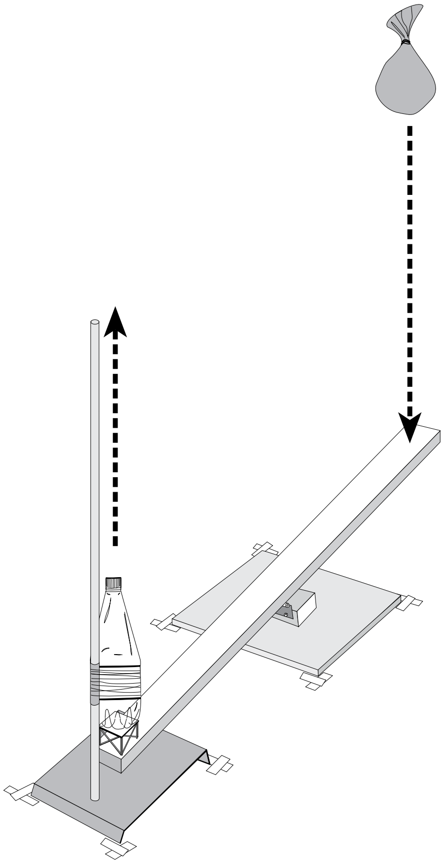


Figure 7.1. Example launch testing station.

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. See Figure 7.2. (If you want to be able to move the hinge to a different location as explained in “Alternate Hinge Location” below, this is the best time to mark the additional mounting holes.)
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 able to swing in both directions about 2 to 3 inches (5 to 8 centimeters) 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. See Figure 7.3. (This is the order of assembly that provides easiest access for the screwdriver.)

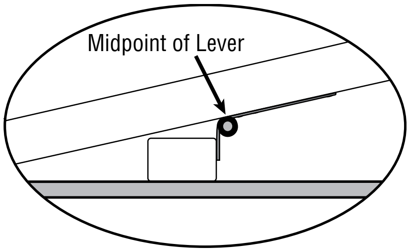


Figure 7.2. Side view of base, hinge, block, and lever.

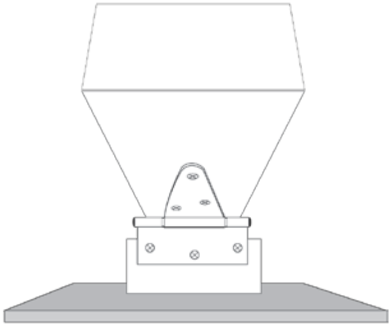


Figure 7.3. End view of base, block, hinge, and lever.

Optional Improvements

Alternate Hinge Location

You might want to experiment with moving the hinge point to a position 20 inches (0.5 meter) from one end, so that the ratio of the lengths of the ends of the lever is 2 to 3.

One Piece Launch Stand

If you mount the launch rod and the launch lever on the same base board they will stay correctly aligned.

Build the Rockets

Materials Needed

Soda Bottles (and Caps)

You will use the 1-liter size 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. See Figure 7.4.

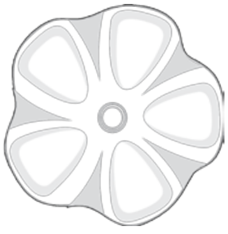


Figure 7.4. Bottle with a 5-lobe base.

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-inch lengths. 9/16 inch outside diameter is just right to fit easily over the launch rod (the ring stand). You will need to cut the tube into 4-inch (10-centimeter) lengths, 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. See Figure 7.5.

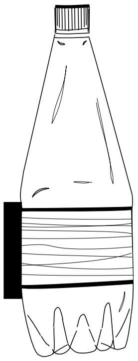


Figure 7.5. Brass tube attached to bottle with package tape.

Construction

Fill the bottle with water and cap it tightly. Tape a 4-inch (10-centimeter) length of tube to the flat cylindrical part of the bottle. Be sure the tube is vertical.

Practice Launching a Rocket

Once you have constructed the launcher and rockets, 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.

Slide the rocket tube onto the ring stand and center the bottle on the end of the launch lever. See Figure 7.6. 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. See Figure 7.7.

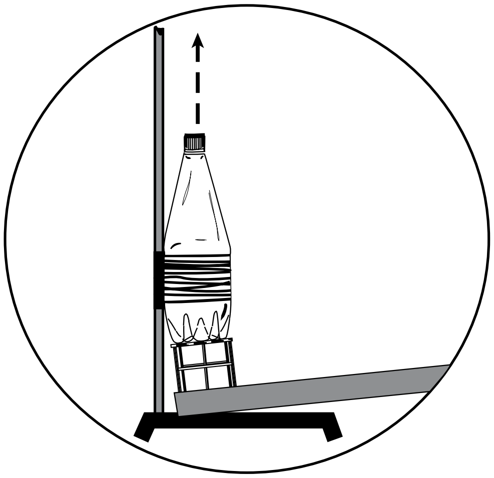


Figure 7.6. Forces before launch.

Notice that 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.

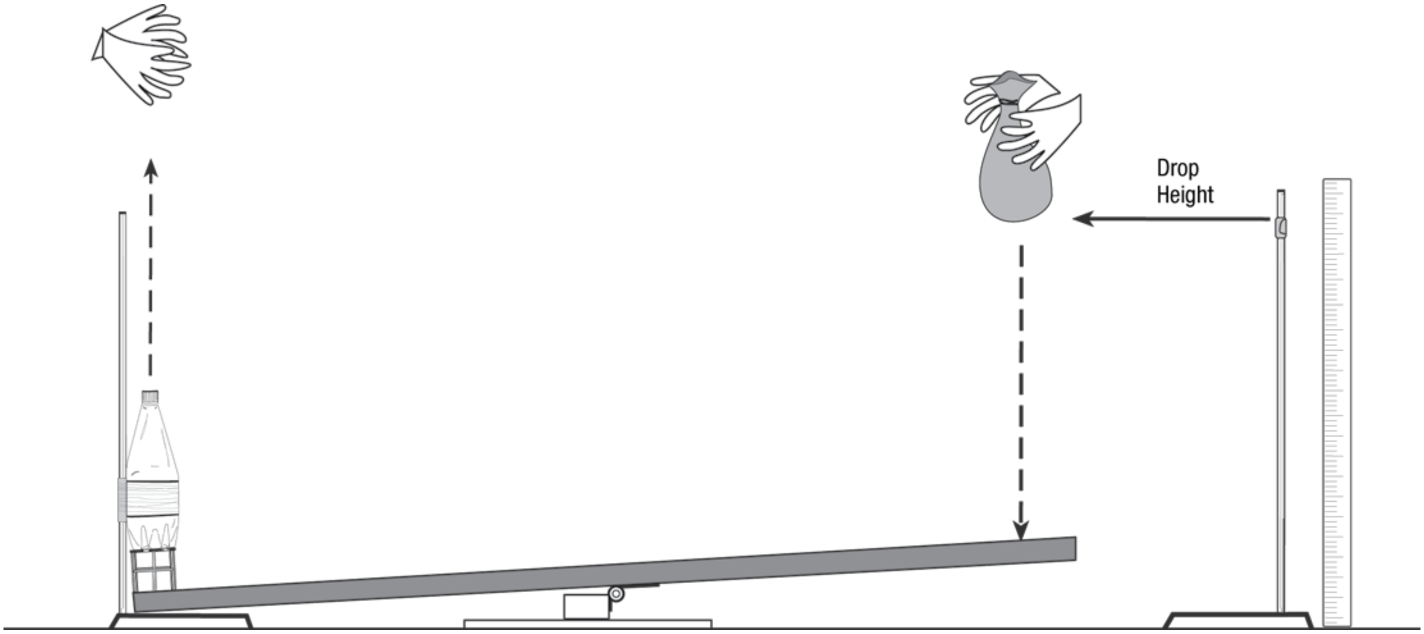


Figure 7.7. Testing a thrust structure.

Prepare the Materials for 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 on 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 "Extensions" section on Page 44 of this guide), assembling kits in advance will simplify tracking the budget.

Set up the Classroom

Team Work Area

Set up the classroom for laboratory work to be done in teams. Each pair 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.

Organize Students in Teams

If students work in pairs, they will all have the opportunity to engage in all aspects of the activity: design, construction, testing, and recording. You may find that larger teams make it difficult for all students to have a turn manipulating the materials.

Review Safety Procedures

In the interest of ensuring the safety of the students and of yourself, you should be aware of several safety issues 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.

Cutting a small slit in a tennis ball and then placing the ball onto the end of the launch rod will reduce the possibility of injury from the rod. The tennis ball “bumper” has several drawbacks: 1. It acts as a brake on the rocket and makes for a less exciting launch, 2. If the tennis ball is too secure, the rocket may bounce off of it making it difficult to catch.

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. Encourage students to address these questions in their journals.
- 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 ideas is given credit in documentation and in the pre-test presentation. Borrowing should also be documented in student journals.
- 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. See Figure 7.8.

In the Engineering Design Challenges, students experience this process. To help students visualize the cyclic nature of the design process, we have provided a reproducible chart that you can use in a class discussion.

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. Use the black-line master of "The Design Process" to make an overhead transparency. Project it on a screen. Then, using it as a guide, go through the process step-by-step, using a sample design as an illustration. It is useful to hold up the 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?"

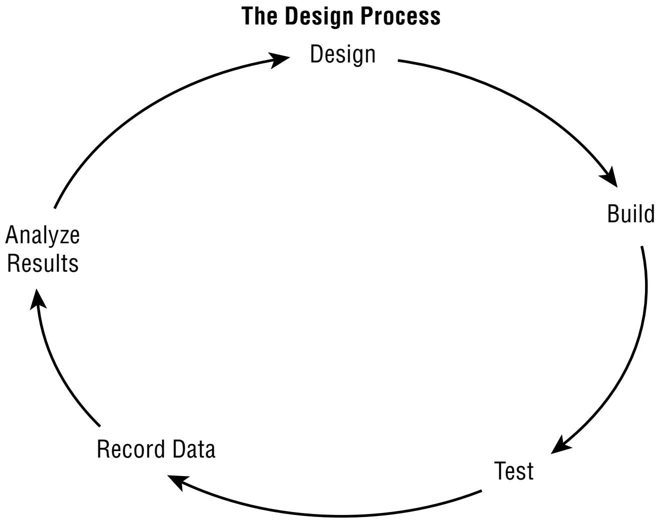


Figure 7.8. A larger version of this image is included in the "Masters" section at the end of this guide.

8. 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 Ares launch vehicles, 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

- Transparencies for overhead projector. (Masters can be found at the end of this guide.)
  - Ares Launch Vehicles.
  - Thrust Structures.
  - The Challenge.
- 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 section 6 later 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.

Optional:

- Additional ring stand.
- Third ring stand.
- String.

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, and pictures, video, or models of the Ares vehicles to introduce the concept of a reusable launch vehicle. Introduce the Ares launch vehicles, which are being designed to replace the Space Shuttle. Ask about what needs to be considered in designing a vehicle that must get into space and return to Earth. 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 are working on designing: A lightweight, but strong thrust structure for the vehicle.

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 spacecraft including the liquid fuel tanks.)

Explain to students that the thrust structure is the part of the spacecraft's skeleton that holds the engine on to the rest of the vehicle. Use the "Thrust Structure" masters to compare the Ares rocket thrust structure to the bottle rocket thrust structure. 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 Ares I and V must carry their engines with them. The push of the engine must travel through the thrust structure to the rest of the rocket.

Define the challenge. Either use a transparency made from the "Design Challenges" master at the end of this guide, post a copy prominently in the room, or hand out copies to each team of students.

Figure 8.1. Ares I and Ares V.

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 to the height of approximately 3 feet (1 meter) into the air.

Design constraints:

Use only the specified materials.

The thrust structure must be taller than 2 inches (5 centimeters) and must allow space in the center for fuel lines and valves represented by a 35mm-film canister without its lid.

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. Show students your heavy design, and tell them that you are sure they can do better!

3. Explain the “Culminating Activity”

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

The storyboard should contain at least three of the team’s recording sheets. If possible, students should attach three of the actual tested models. 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 journal or log. These journals will provide an excellent resource for documenting their experience when they need to make their storyboard.

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 or punch a small hole in a file card or piece of manila folder and slide it on a ring stand to mark the height. 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. 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. Mark a ring stand at that height with tape or tape the file card onto the ring stand. Optional: Use two ring stands and tie a string between them 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:

Trial #	Launch Mass pounds (kg)	Drop Mass pounds (kg)	Drop Height inches (cm)	Altitude inches (cm)	Orbit? (Y/N)
1					
2					
3					

If you graph the data in this table you may see some interesting relationships.

5. Discuss the Results

Ask students: How much mass are we launching to orbit? (2.2 pounds or a 1 kilogram bag of sand.) What's the source of the propulsive force? (22 pounds or a 10 kilogram bag of sand.) What forces are acting on the bag of sand when it is suspended in the air before the drop? (Gravity and the student's muscles.) What forces are acting on the bag when it is released? (Gravity.) Trace where the force goes. (Down on one side, up from the other end of the lever.) Optional: Discuss why it is important for the lever to be stiff rather than flexible.

Homework/Assessment. Sketch the test stand and identify the relevant parts. If you wanted to propel your 1-liter bottle rocket to a height of 1 yard, how much mass should you drop on the end of the lever and from what height?

It is instructive for students to think about how the model bottle rocket and an actual rocket, such as the Ares V, are the same and different. Here are typical "answers."

	Bottle Rocket	**Ares V**
Source of the thrust	The lever	2 solid rocket boosters plus 5 liquid fuel engines
Source of engine energy	Gravity on sandbag	Combustion of fuel creates it
Thrust duration	Fraction of a second	Minutes
Thrust magnitude	Small	10.65 million pounds (47.4 meganewtons)
Mass of rocket	2.2 pounds (1 kilogram)	7,400,000 pounds (3,356 metric tons)
Thrust depends on	Mass of sandbag Drop height Strength of gravity	Energy density of fuel Mass of fuel burned/sec Engine design

Use the master, "Comparing the Bottle Rocket and the Ares V," as an overhead and discuss how the "model" compares with the "real thing."

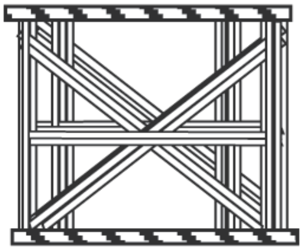


Figure 8.2. A heavy design.

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, Step 6.) In order to provide a baseline model for a thrust structure, you should build one that is truly a juggernaut. See Figure 8.2. For example, use 3-inch (7.6-centimeter) lengths of 1/4-inch 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 little more than 4 ounces (113 grams) 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.

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 pot or glue gun.
- 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, ring stand.
- Craft sticks.
- Glue guns and glue sticks.
- 3 1/2 by 3 1/2 inch square (9 by 9 centimeter) pieces of cardboard.
- Paper cups (optional).
- Transparency and handouts of recording sheets.
- Chart paper (or chalkboard) for recording launch results.
- A balance or scale accurate to a tenth of a gram.
- Overhead projector (optional).

1. Review the Design Challenge and the Design Constraints

Make sure students understand the challenge. Use the master to review it.

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 at the back of the book. One way is to make a transparency of each sheet and project it on the overhead. 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 record keeping is so important. Discuss each part of the “Design Specifications” and the “Test Results” 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 storyboard 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-through 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 section 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.

As an extension activity, have students try to reconstruct another team’s design using only the recording sheet. Assess the recording group on the quality of the sketch and the constructing group on their ability to interpret the sketch.

In addition to answering the questions on the design spec sheets, students should also keep running notes, diagrams, questions, research findings, data, etc., in a journal or log. These journals could be as simple as notes taken on the back of the design spec sheet. A journal will provide an excellent resource for documenting the experience when a student needs to make the storyboard.

5. Explain the Test Procedure

- When their design is completed, the team completes a recording sheet and brings the model and the recording sheet to the teacher.
- The teacher checks the recording 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.

6. Students Design and Build their Models

If you did not have time to complete the demonstration of a poorly designed model, do it now. See Steps 6 and 7 in Session 1.

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 inches (5 centimeters) 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 recording 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.

As an option, you may wish to classify the models once each team has presented. Students may come up with classifications based on design strategies.

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 include the following columns, which are shown in Figure 8.3.

Figure 8.3 shows a model of a table you may draw on the chalkboard to record the performance of each thrust structure during a series of three launches. The recommended column headings include Team name and Design number. There are also three columns for recording whether or not the rocket was launched successfully. A successful launch includes one in which the thrust structure was not damaged.

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

Figure 8.3. Chart test results.

If you choose to classify the designs, you may also want to include a column for "design strategy."

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 inches (5 centimeters) 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?"

Now is a good time to review the section "Linking design strategies and observations to science concepts."

If one side of the structure has collapsed, help students think about the importance of balanced loads.

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?

Have students trace the path of the force through the structural members. See further discussion of how to do this in the section, "Linking Design Strategies and Observations to Science Concepts," on Page 37.

Record (or have a student record) the most successful design features on a transparency or 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. See Figure 8.4.

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.)

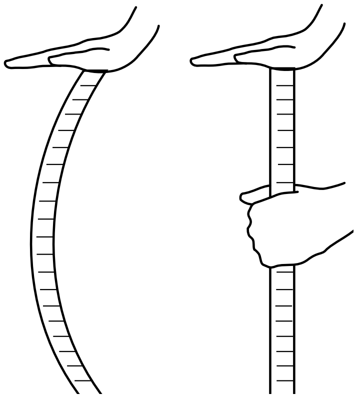


Figure 8.4. Bracing a ruler to prevent buckling.

Sessions 3 and 4

Designs 2, 3, 4 and 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 1/2 by 3 1/2 inch (9 by 9 centimeter) squares of cardboard.
- Ring stands to be used for static testing.

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 a transparency or 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. Refer to the science concept links following the session descriptions for connections that can be made between student observations and science concepts.

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 recording 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 that 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:

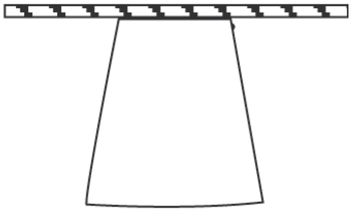


Figure 8.5. A paper cup used as a thrust structure.

(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. See Figure 8.5. Launch a bottle "to orbit" 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. See Figure 8.6.

	Number of launches to orbit	Weight required to crush in static test
Structure 1 (1 paper cup)		
Structure 2 (2 paper cups)		
(etc.)		

Figure 8.6. Static testing results chart.

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 that they should record the results of static testing directly on their “Test Results” sheet or in their journal for use in creating their storyboard.

You can lead from this introduction of static testing into a discussion of the similarities and differences between static and dynamic loads. Refer to the “Linking to Science Concepts” section on Page 37 for a more detailed description of the concepts involved.

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. If you need more weight than you can obtain using bottles of water, fill some bottles with sand. You can use bottles of different sizes, filled to different levels with 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 carry out. 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

Construct a Storyboard/Poster

As a culminating activity, each team creates a "storyboard" poster that documents the evolution of their thrust structure designs from initial to intermediate to final stage. The storyboard 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

- Posterboard or large sheets of paper approximately 2 by 3 feet (61.0 by 91.4 centimeters), one per team.
- Markers, crayons.
- Plastic sandwich bags for holding tested models.
- Glue or tape for attaching recording sheets and tested models to storyboard.

1. Explain the Assignment

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

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

Students may attach their completed recording sheets or re-copy the information onto the storyboard. If possible they should attach the actual tested models. 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 storyboards 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 on the storyboard. See the "Resources" section, on Page 46, 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 Storyboards

Give students an entire class session to create their storyboards. You might take this opportunity to encourage students to practice sketching detail and section views of the models as described in Session 2.

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 storyboards have been completed, 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 storyboard.

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 in 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, as you conduct the testing, and as you discuss 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. See Figure 8.7. 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.

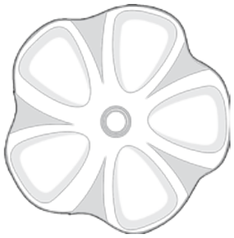


Figure 8.7. The base of the bottle has 5-fold axial symmetry.

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.

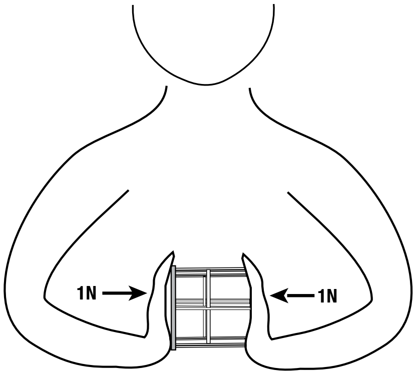


Figure 8.8. Balanced compressive forces.

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.”

Squeezing a Thrust Structure

If each hand in Figure 8.8 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 pound-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.

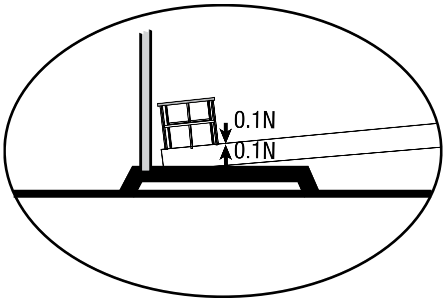


Figure 8.9. No compressive force on the thrust structure.

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 pound-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.

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.

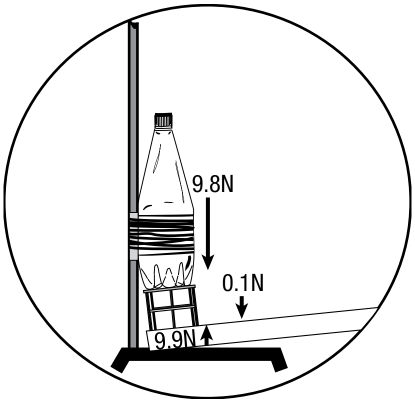


Figure 8.10. A compressive force of 9.8 N.

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.

When an object rests on a surface, there is no compressive force on the whole object. (We are not concerned with the internal compressive force due to the object's own weight.)

If a "rocket" presses down on a thrust structure with a force of 9.8 N (2.20 pounds-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 pound-force), so the total force the thrust structure exerts on the lever is 9.9 N. The lever pushes back with a force of 9.9 N (2.22 pounds-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 pound-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.

Forces 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. See Figure 8.11. 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).

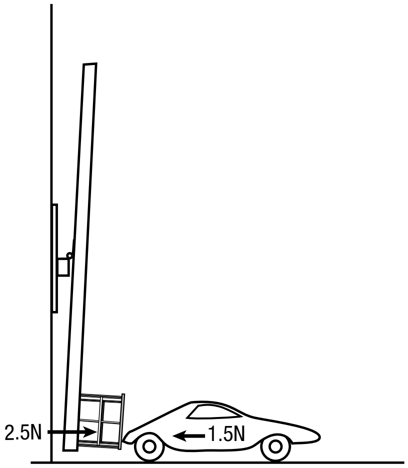


Figure 8.11. Forces during acceleration.

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).

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 following:

Pour sand into a jar on a scale and stop when the weight of the sand is 2.2 pounds (one kilogram). If the jar weighs 9 ounces (0.25 kilogram), the total static load on the scale is 2.75 pounds (1.25 kilograms). Now hold the filled jar just above the scale and release it suddenly. The scale hand will show a maximum of about 5.5 pounds (2.5 kilograms). 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.

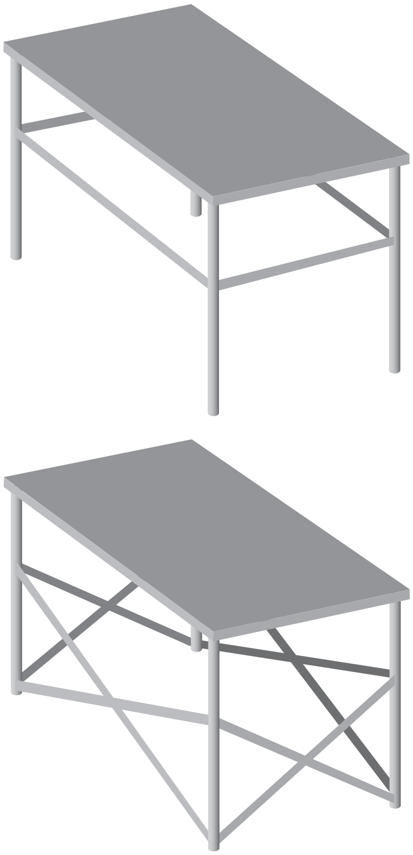


Figure 8.12. Crossbrace design strategies.

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 crossbrace. 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. See Figure 8.12.

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 an overhead transparency from the master page, "Testing a Thrust Structure," and project it where the entire class can see it.

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 overhead transparency, 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 inches (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.

$$PE = mgh$$

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 $PE = 10 \times 0.5 \times 10 = 50$ joules. [1 joule = $1 \text{ kg} \cdot \text{m}^2/\text{sec}^2$]

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

Its velocity, or speed, v

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

$KE = 1/2mv^2$

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

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,

$$KE = 1/2\ mv^2 = 50 \text{ joule}$$

$$1/2 \cdot 10 \text{ kg} \cdot v^2 = 50 \text{ kg} \cdot \text{m}^2/\text{sec}^2$$

$$5 \text{ kg} \cdot v^2 = 50 \text{ kg} \cdot \text{m}^2/\text{sec}^2$$

$$v^2 = 10 \text{ m}^2/\text{sec}^2$$

$$v = \sqrt{10 \text{ m}^2/\text{sec}^2}$$

$$v = 3.2 \text{ m/sec}$$

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.”

$KE = 1/2\ mv^2 = 10$ joules

$1/2 \cdot 1\ kg \cdot v^2 = 10\ kg \cdot m^2/sec^2$

$1/2\ kg \cdot v^2 = 10\ kg \cdot m^2/sec^2$

$v^2 = 20\ m^2/sec^2$

$v = \sqrt{20\ m^2/sec^2}$

$v = 4.5$ 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 going on. 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.

What percentage of the Ares V’s energy is in the form of KE while in orbit?

How do these energy transfers compare to those in launching the Ares V?

The Ares V is powered by the chemical energy of its rocket engines, not by a launch lever. Still, that chemical energy transfers into the kinetic energy of launch and then into the potential energy of the spacecraft’s position.

The Ares V can launch a payload of about 284,000 pounds (129,000 kilograms) to an orbit about 200 miles (322 kilometers) above the Earth, traveling at about 17,000 miles per hour (27,200 kilometers per hour). It has kinetic energy due to this motion and potential energy due to its position above the Earth. At an altitude of 200 miles (320 kilometers), the gravitational field is about 91% of its value at the surface of the Earth, so g = approximately 9 m/sec/sec. Therefore:

$PE_{\text{Ares V}} = mgh$ = about $129{,}000\ kg \times 9\ m/s/s \times 320{,}000\ m = 3.7 \times 10^{11}$ joules

Because the Ares V is also in orbit around the Earth, traveling at 17,000 miles per hour (27,200 kilometers per hour) it has kinetic energy as well. This kinetic energy is

$KE = 1/2mv^2$

$KE = 1/2 \times 129{,}000\ kg \times (27{,}200)^2$

$KE = 4.8 \times 10^{13}$ joules

Much more of the Ares V’s energy is in the form of kinetic energy than in the form of potential energy. This tells us that most of the work of putting the Ares V in orbit is taken up in accelerating it to its high speed rather than raising it to a height of 200 miles (320 kilometers).

9. Modifications and Extensions

Changing 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.

Allowing 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.

Increasing 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.

Limiting 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 Ares V or referring to a poster will be useful in stimulating student ideas. You might want to discuss such facts about the Ares V as how much fuel it uses, which parts are reusable, and which are not, etc. Possible answers include: Make sure all the parts can be reused, make the vehicle lighter so it uses less fuel, use less expensive materials, make it more durable so you do not need to do much to it to prepare for the next launch, 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.

Designing with Additional Materials

Some suggestions for alternative materials are included in the list of materials in the "Preparation" section of this guide. You may come up with your own ideas. If you are constraining designs by a budget, you will want to assign different costs to different materials.

10. Resources

Engineering Design Challenges Website
http://edc.nasa.gov/

The Ares Launch Vehicles
http://www.nasa.gov/mission_pages/constellation/ares/

The Space Shuttle
http://www.nasa.gov/mission_pages/shuttle/main/

The Space Shuttle Vehicle Structure
http://www.nasa.gov/mission_pages/shuttle/vehicle/

Space Vehicles
Isakowitz, Steven J. *International Reference Guide to Space Launch Systems*. AIAA Press, Washington, D.C., 1995.

Jenkins, Dennis R. *The History of Developing the National Space Transportation System*. Second Edition. Harbor Beach, FL. 1996.

Stine, G. Harry. *Halfway to Anywhere: Achieving America's Destiny in Space*. NY. M. Evans and Co. 1996.

Stine, G. Harry. *Handbook of Model Rocketry*. NY. Prentice Hall Press. 1987.

Engineering and Careers
NASA Careers

NASA Career Corner for Grades 5-8
http://www.nasa.gov/audience/forstudents/5-8/career/index.html

NASA Career Corner for Grades 9-12
http://www.nasa.gov/audience/forstudents/9-12/index.html

Discover Engineering Online
www.discoverengineering.org

Aimed at inspiring interest in engineering among America's youth, the site is a vast resource. Among the many features is information on what engineers do and how to become one. Designed for students in grades six through nine, the site has links to games, downloadables, graphics, engineering societies, and other resources. One section lists "cool" things tied to engineering, such as the mechanics of getting music from a compact disc to the ears, how to make a batch of plastic at home, and how to fold the world's greatest paper airplane.

Some Additional NASA Web Sites
Marshall Space Flight Center
http://www.nasa.gov/centers/marshall/home/

NASA CORE
http://education1.nasa.gov/edprograms/core/home

Worldwide distribution center for NASA's educational multimedia materials.

NASA Education Home Page
http://education.nasa.gov

Design Challenges

Dunn, Susan and Larson, Rob, *Design Technology: Children's Engineering*. 1990: Philadelphia, The Falmer Press.

Sadler, P., Coyle, H., and Schwartz, M., "Successful Engineering Competitions in the Middle School Classroom: Revealing Scientific Principles through Design Challenges," *The Journal of the Learning Sciences*, Vol 9, No. 3 (2000) 299-327.

Physics

Hewitt, Paul. *Conceptual Physics*.

Structures

Macaulay, David. Castle.

Macaulay, David. Cathedral, The Story of its Construction.

Macaulay, David. City: A Story of Roman Planning and Construction.

Macaulay, David. Mill.

Macaulay, David. Pyramid.

Macaulay, David. Unbuilding.

Pearce, Peter. *Structure in Nature is a Strategy for Design*. Chatsworth, CA. Synestructics. 1978.

Salvidori, Mario, and Michael Tempel. *Architecture and Engineering: An Illustrated Teacher's Manual on Why Buildings Stand Up*. New York. NY Academy of Sciences. 1983.

Salvidori, Mario. *Why Buildings Stand Up: The Strength of Architecture*. NY. Norton. 1980.

Salvidori, Mario. *The Art of Construction: Projects and Principles for Beginning Engineers and Architects*. Chicago. Chicago Review Press. 1990.

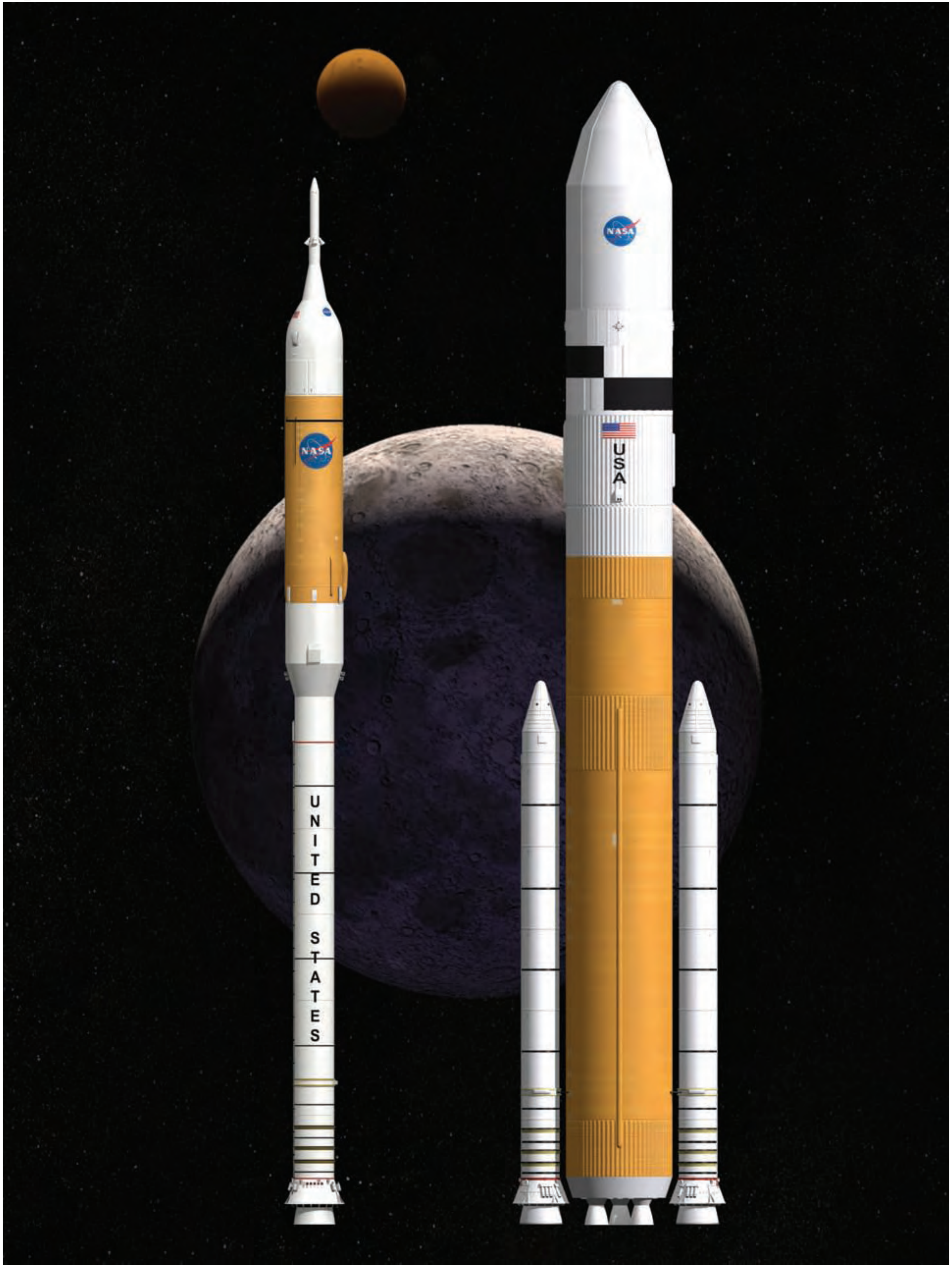
Sellers, Jerry Jon. *Understanding Space: An Introduction to Astronautics*. NY. McGraw-Hill. 1994.

Sloan, Eric. *An Age of Barns*. NY. Ballantine Books. 1967.

Zubrowski, Bernie. *Messing Around With Drinking Straw Construction*.

11. Masters: NASA Engineering Design Challenges

Spacecraft Structures



NASA Engineering Design Challenges

Ares I

Dear Parent:

Your child is beginning an exciting unit, in science class, entitled the NASA Engineering Design Challenge. This unit will connect students with the work of NASA engineers by engaging them in a related design challenge in their classroom. Students will design, build, and test their own solutions to a design problem similar to one faced by NASA engineers.

Spacecraft Structures

NASA is currently designing the Ares I and Ares V launch vehicles to replace the Space Shuttle as a way to put people and satellites into orbit. One challenge faced by designers of the Ares rockets is how to build a lightweight yet strong vehicle. For every pound lighter the engineers can make the structure, about eight pounds of fuel is saved on each launch. This adds up to huge savings for what might seem like insignificant weight reductions. At the same time, the structure has to be strong enough to withstand the tremendous thrust of the engines.

The Challenge

Your child's challenge in class is to build a thrust structure for a model rocket that can withstand the force of three launches. The structure will be built from such common materials as craft sticks, cardboard, and glue. The design will be tested and then the student will have the opportunity to revise the design based on the test results. Designs will go through a number of revisions to try to reduce the weight and increase the strength of the thrust structure. As a culminating activity, students will create posters documenting their design process and results.

Questions to Ask Your Child about the Project

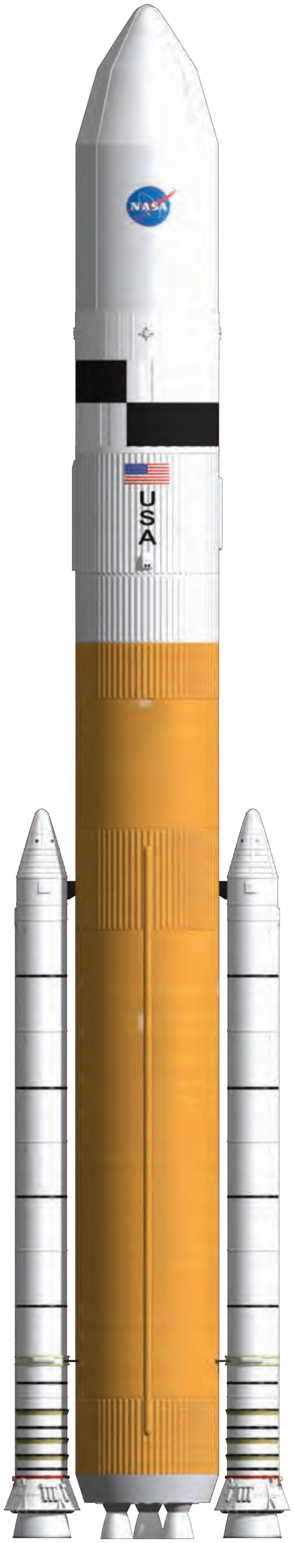
This is an inquiry-based activity. This means that much of your child's learning depends on hands-on experimentation. It is important, however, that your child reflects on the hands-on work and tries to understand why certain design features were or were not successful. You can encourage this reflection by asking your child about the activity. Ask your child to:

- Explain the challenge and the design constraints.
- Describe the design and how it survived the testing.
- Explain why the design did or did not work well.
- Explain whether other students in the class tried different designs and how those designs tested.
- Explain the next design and why it will be an improvement.

Some Activities to do at Home

There are many examples of structures in action around the home.

- The building you live in is held up by a structural skeleton. If you can, show your child some of the framing elements of your home. Perhaps by going to the basement or attic you can see some of the house framework more clearly. In the basement, you can probably see posts (columns), joists, flooring, and other members. You may well see diagonal braces fastening the floor joists to the subflooring. Discuss with your child how each of these elements contributes to the support of the house.
- Discuss with your child what kind of structural support is behind the walls, e.g., studs. Point out walls that are “load-bearing” vs. walls that are not. If you have done any remodeling lately, you may have had to address structural issues with the architect or carpenter. Discuss these with your child.
- The structure of a garage is often easier to see than that of a house because the studs, rafters, and other structural members are often left exposed. Perhaps you can measure the distance between studs and discuss why they are spaced as they are. If the garage has a gable roof, discuss the cross-ties that keep the roof from pushing out the walls that it sits on.
- Houses or buildings in the neighborhood that are under construction may reveal their structure more easily than an already-built house.
- The furniture in the house has a structure. Tables and chairs are supported by legs that are essentially columns. You can examine tables and chairs to see how the designer made them stronger by adding cross-braces and other supports.
- If there are any radio or TV towers nearby, point out how they are stabilized by the addition of guy wires (if they are). You may also see guy wires stabilizing home antennas. The guy wires are examples of structural elements that are strong while pulled taut. This is called “being in tension.” The antennas may also show how cross-bracing is used to make a structure stronger. The Eiffel Tower is a good example of a structure the designer tried to make lightweight but strong.



Ares V

Resources for Further Exploration

Engineering Design Challenges Website

http://edc.nasa.gov/

The Ares Launch Vehicles

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The Space Shuttle

http://www.nasa.gov/mission_pages/shuttle/main/

The Space Shuttle Vehicle Structure

http://www.nasa.gov/mission_pages/shuttle/vehicle/

Space Vehicles

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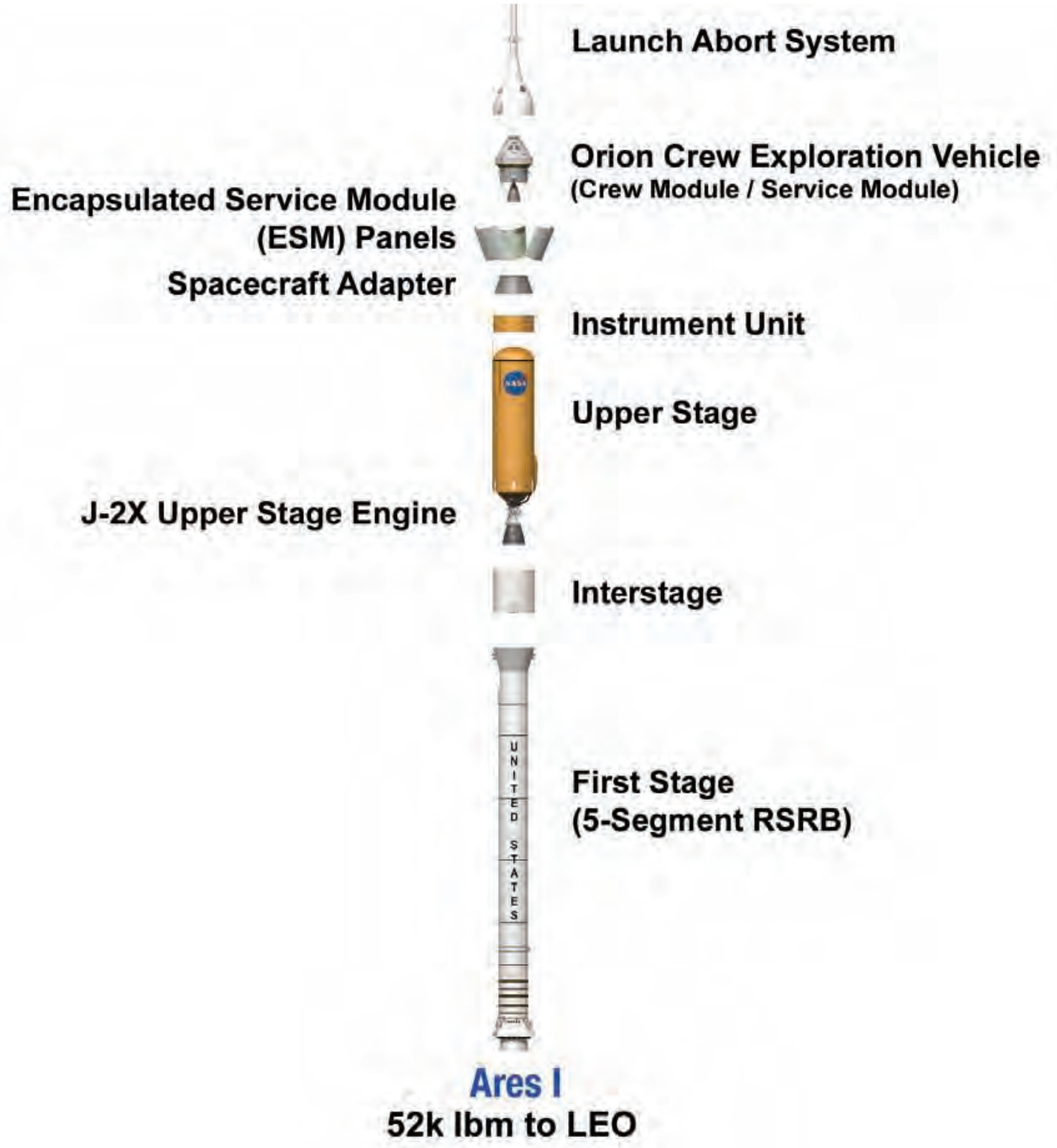
NASA CORE
http://education1.nasa.gov/edprograms/core/home

Worldwide distribution center for NASA's educational multimedia materials.

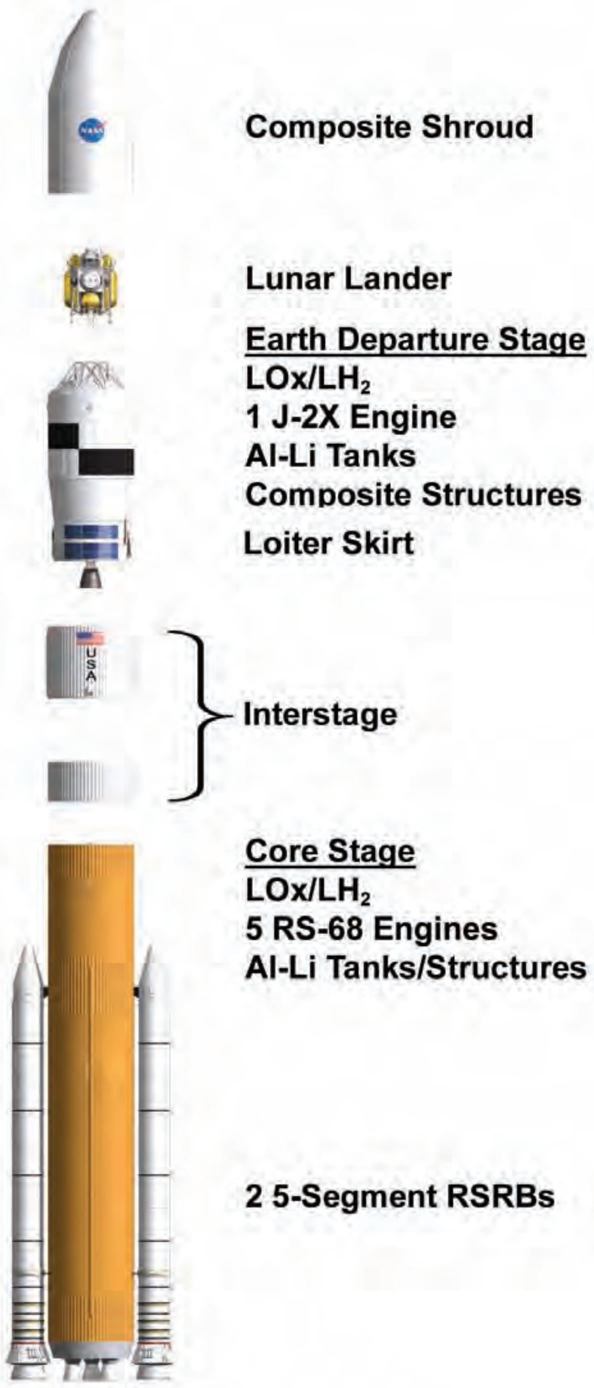
NASA Education Home Page
http://education.nasa.gov

Ares I and Ares V

Ares I


Launch Abort System
Orion Crew Exploration Vehicle
(Crew Module / Service Module)
Encapsulated Service Module
(ESM) Panels
Spacecraft Adapter
Instrument Unit
Upper Stage
J-2X Upper Stage Engine
Interstage
First Stage
(5-Segment RSRB)
UNITED STATES
Ares I
52k lbm to LEO

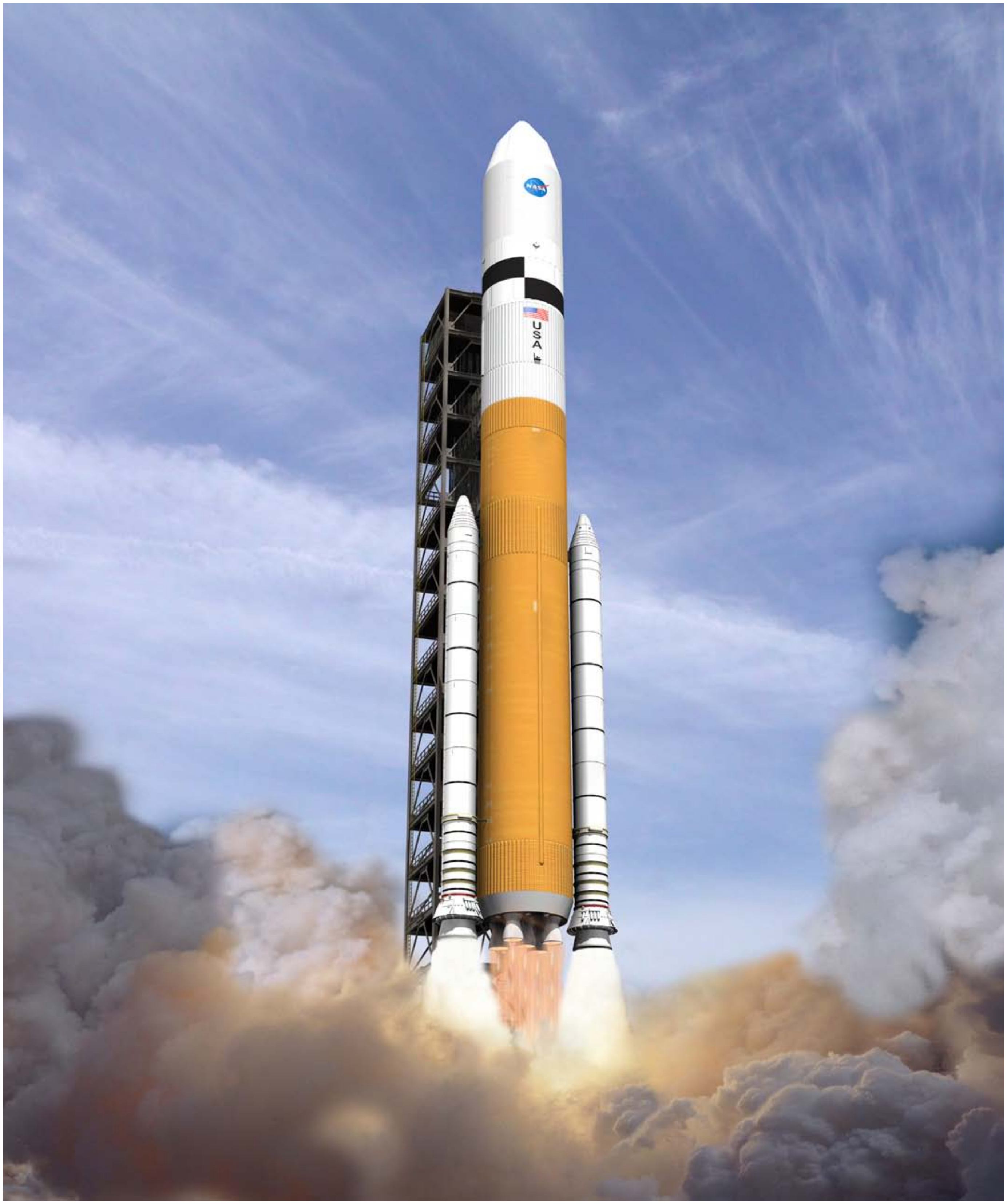
Ares V



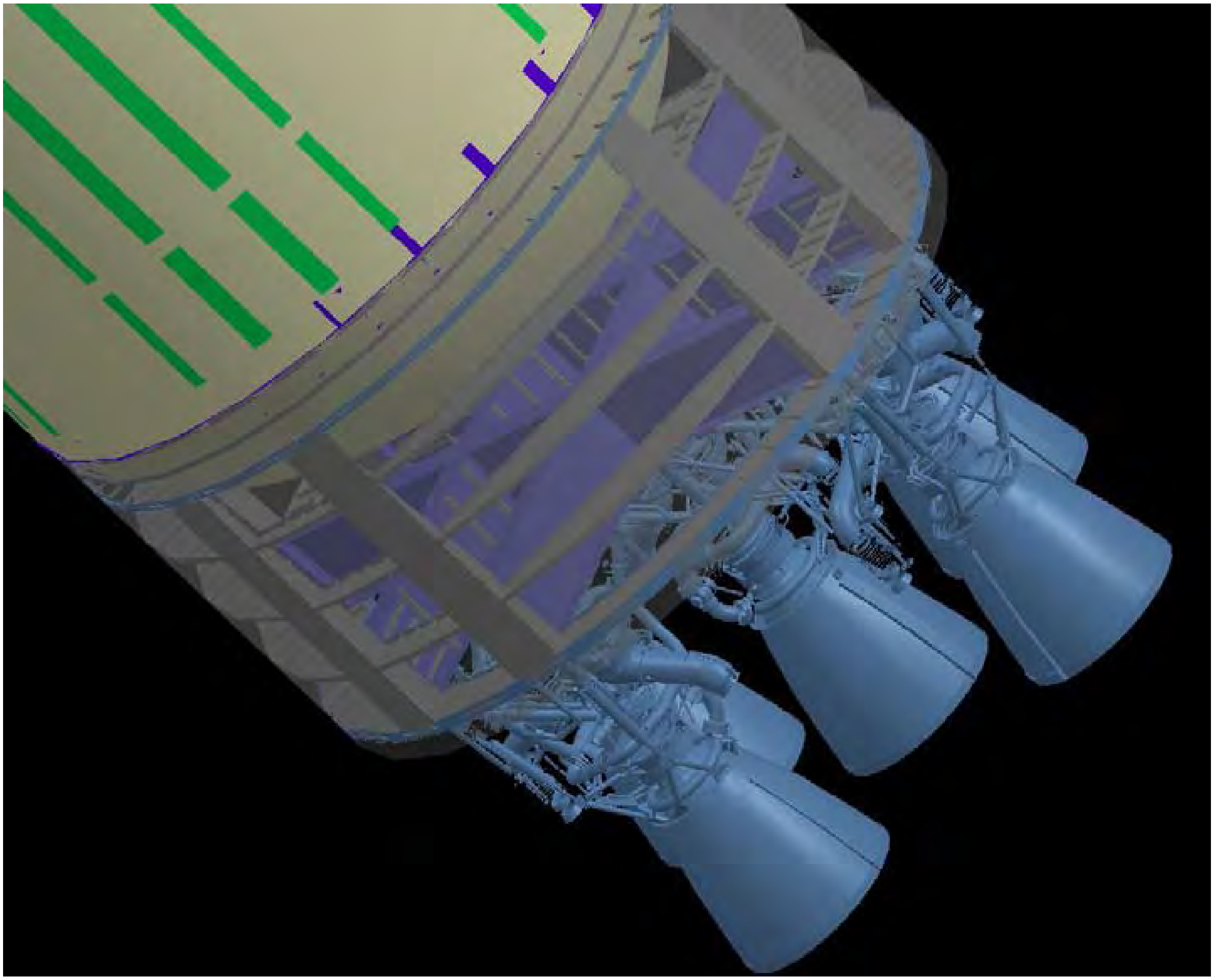
Ares V

143k lbm to TLI in
Dual-Launch Mode with Ares I
284 lbm to LEO

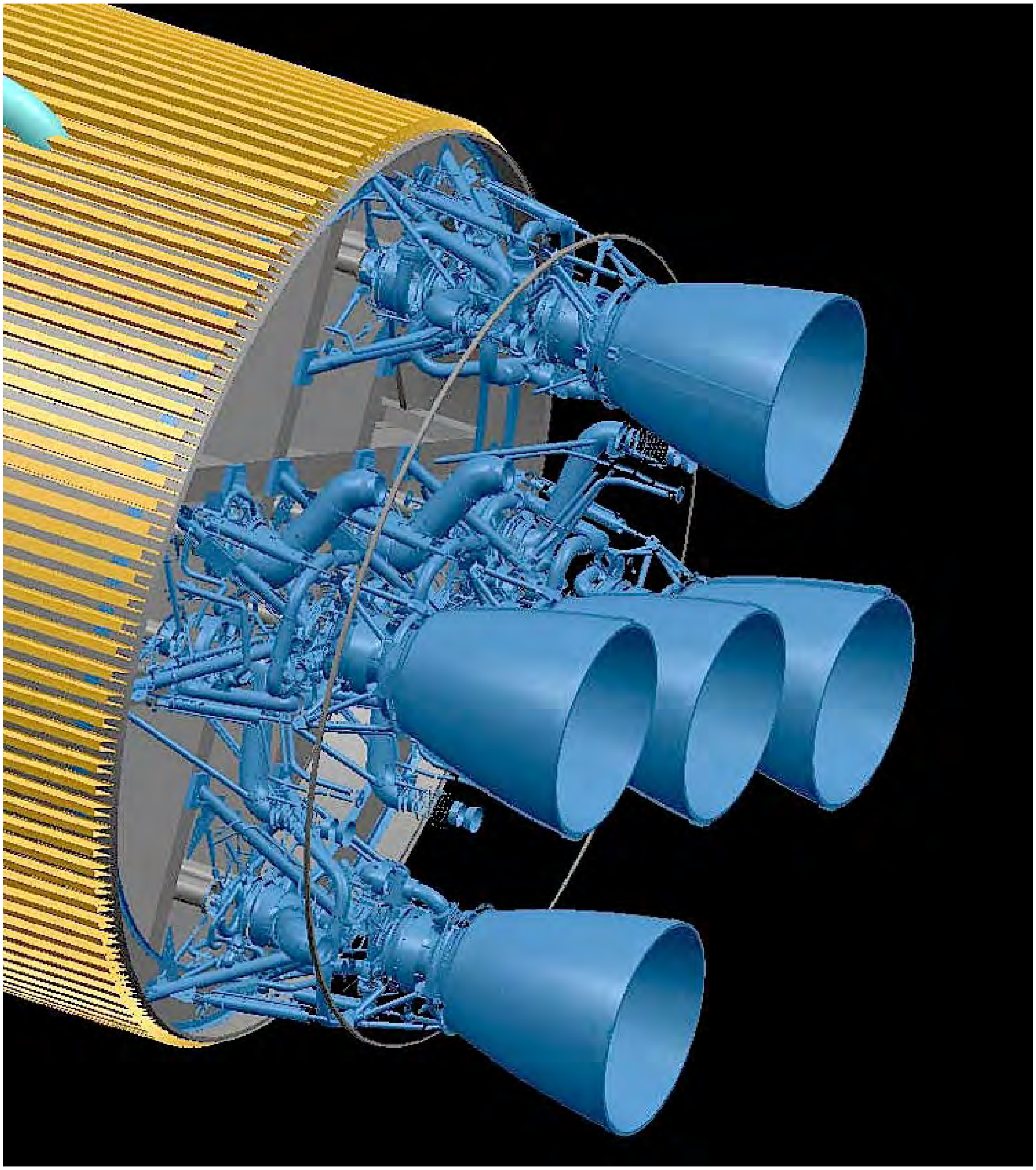
Artist's Rendering of the Ares V on the Launch Stand



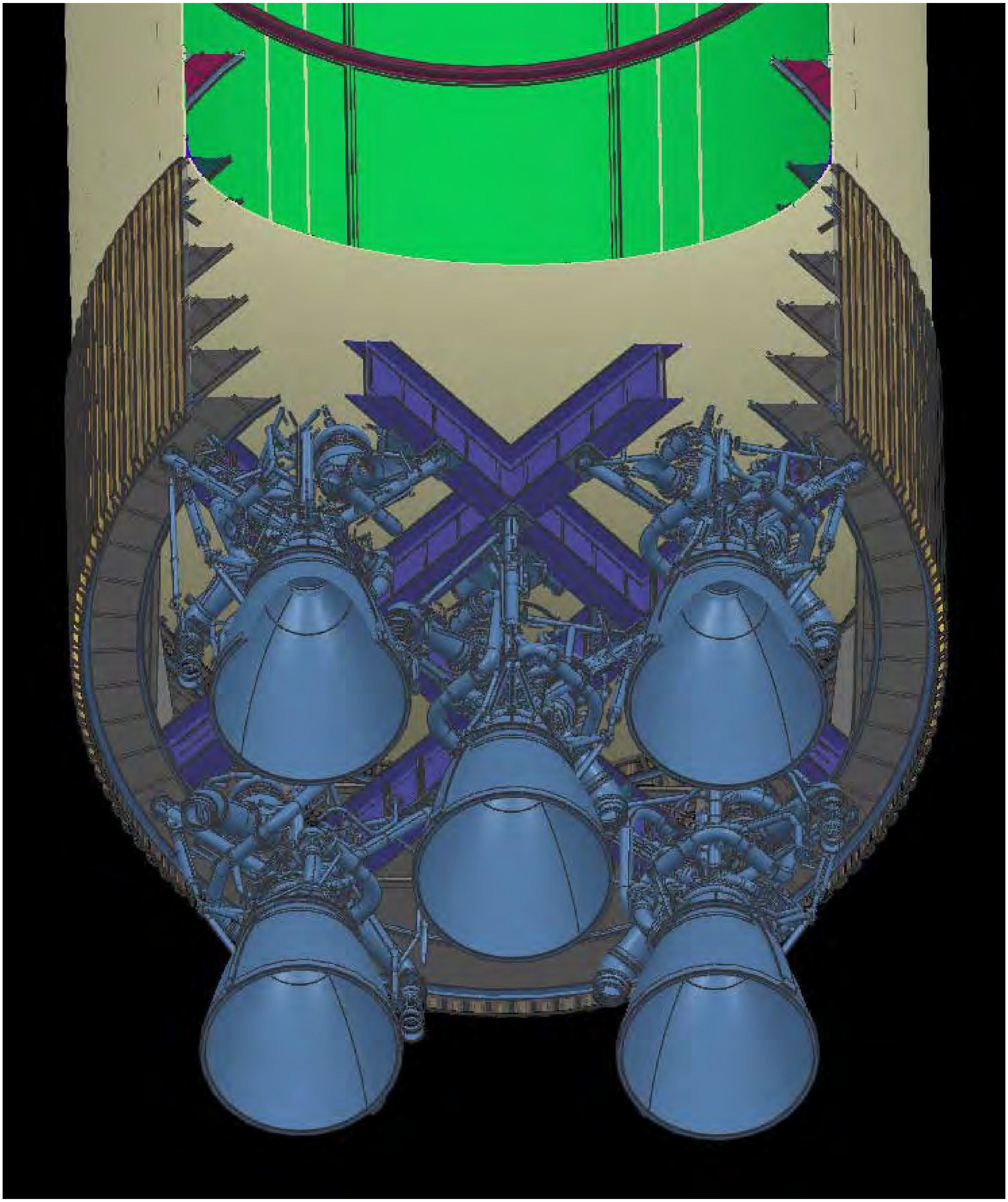
Ares V Engines and Thrust Structure: View 1



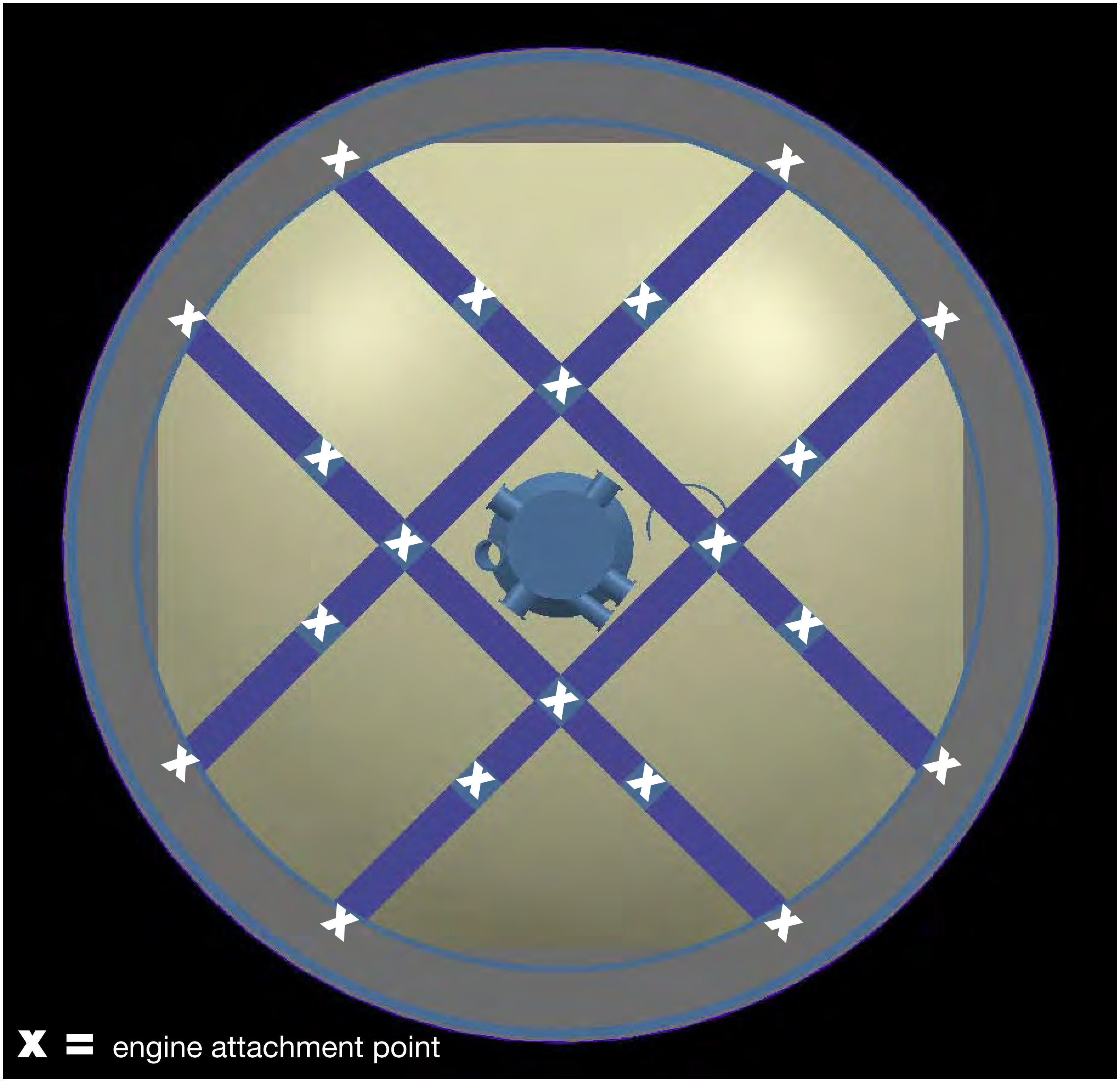
Ares V Engines and Thrust Structure: View 2



Ares V Engines and Thrust Structure: View 3

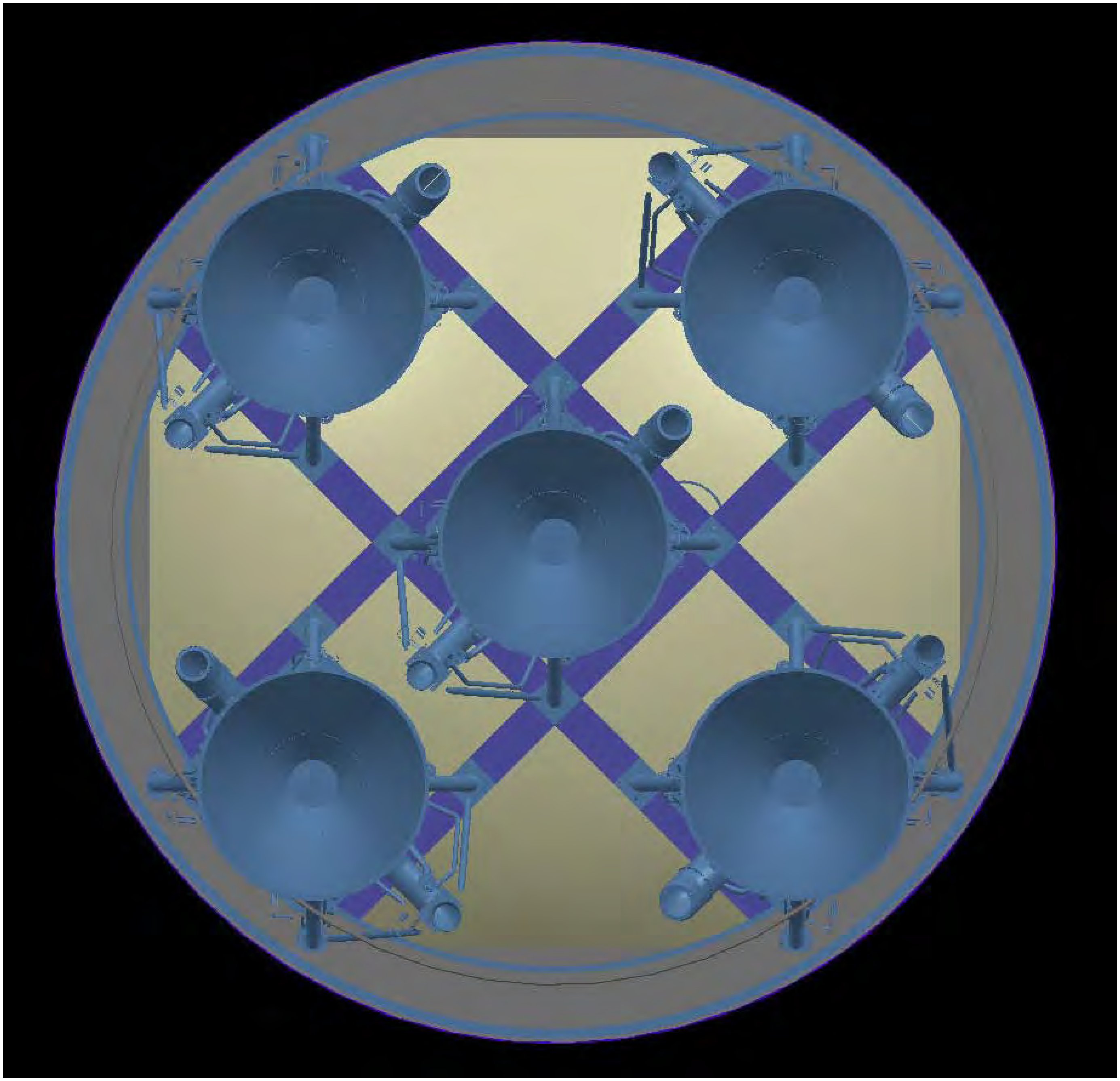


Ares V Thrust Structure Showing Attachment Points for 5 Engines



X = engine attachment point

Ares V Thrust Structure and Engines



RS-68 Liquid Fuel Engine for Ares V

Space Shuttle Launch

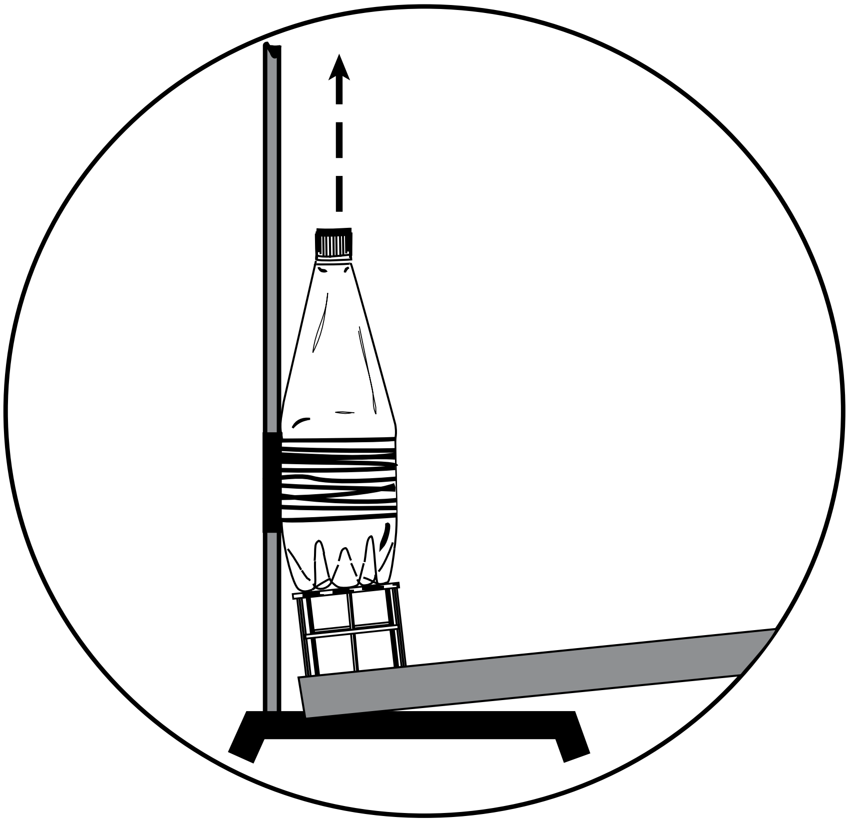
Thrust Structures

Actual

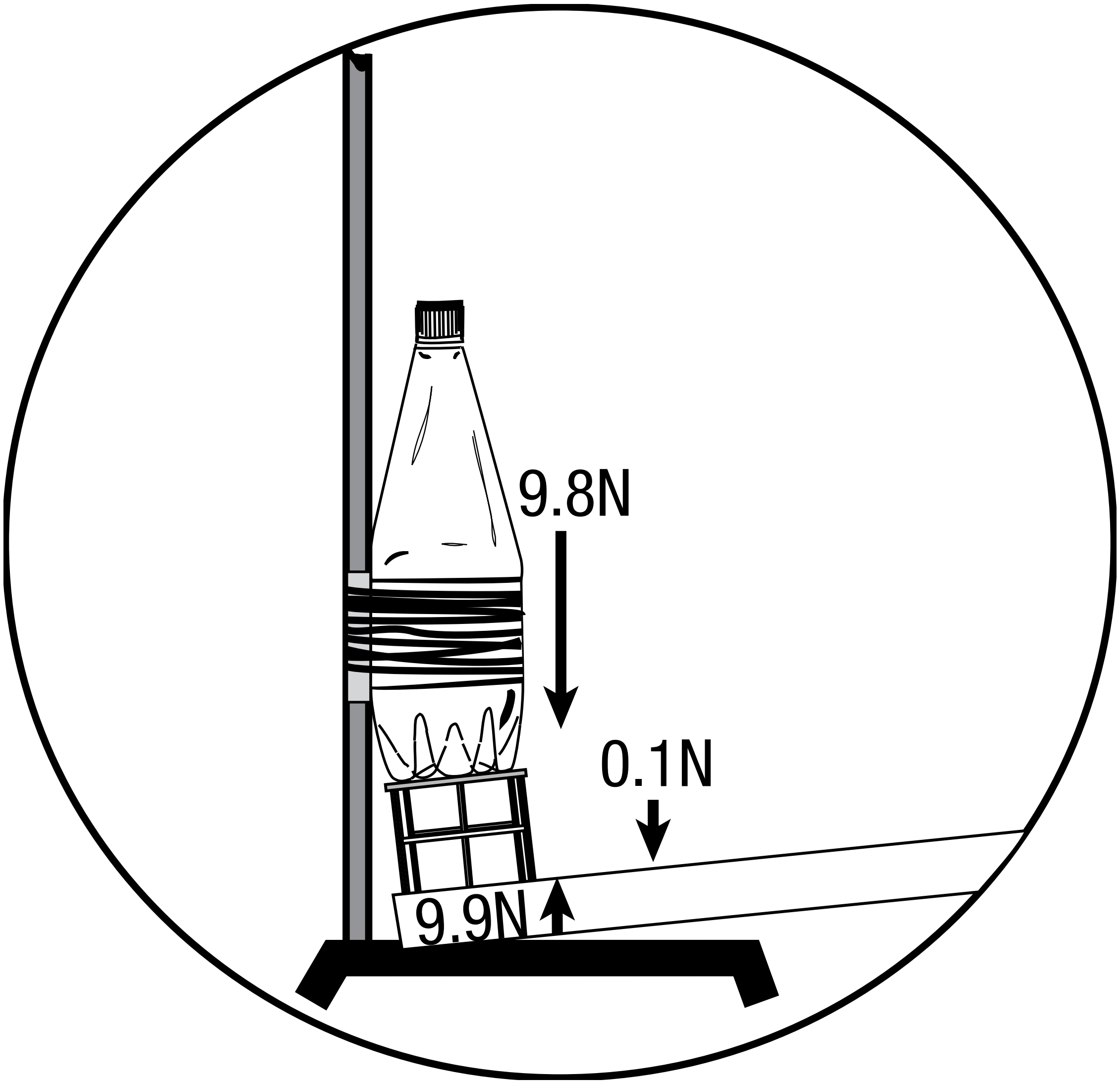
The Engine and Thrust Structure of a Titan Rocket

Model

The Launch Lever, Thrust Structure, and Bottle Rocket



Forces Before Launch



Comparing the Bottle Rocket and the Ares V

	Bottle Rocket	Ares V Vehicles
Source of the thrust		
Source of energy		
Thrust duration		
Thrust magnitude		
Mass of rocket		
Thrust depends on		

The Challenge.

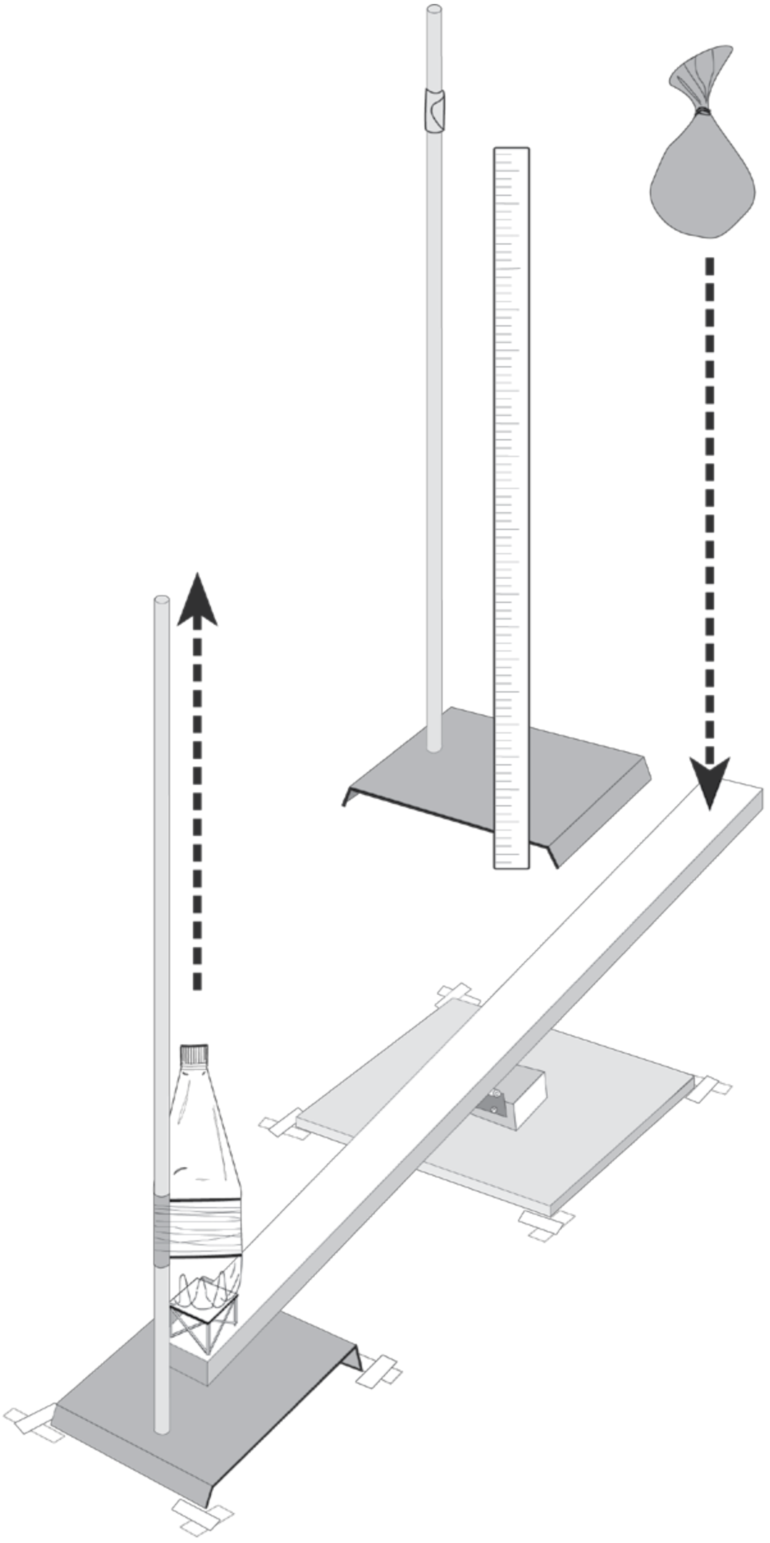
Build the lightest weight thrust structure that will withstand the force of launch to orbit at least three times.

Launch to orbit = propelling a 1-liter bottle of water approximately 3 feet (1 meter) into the air.

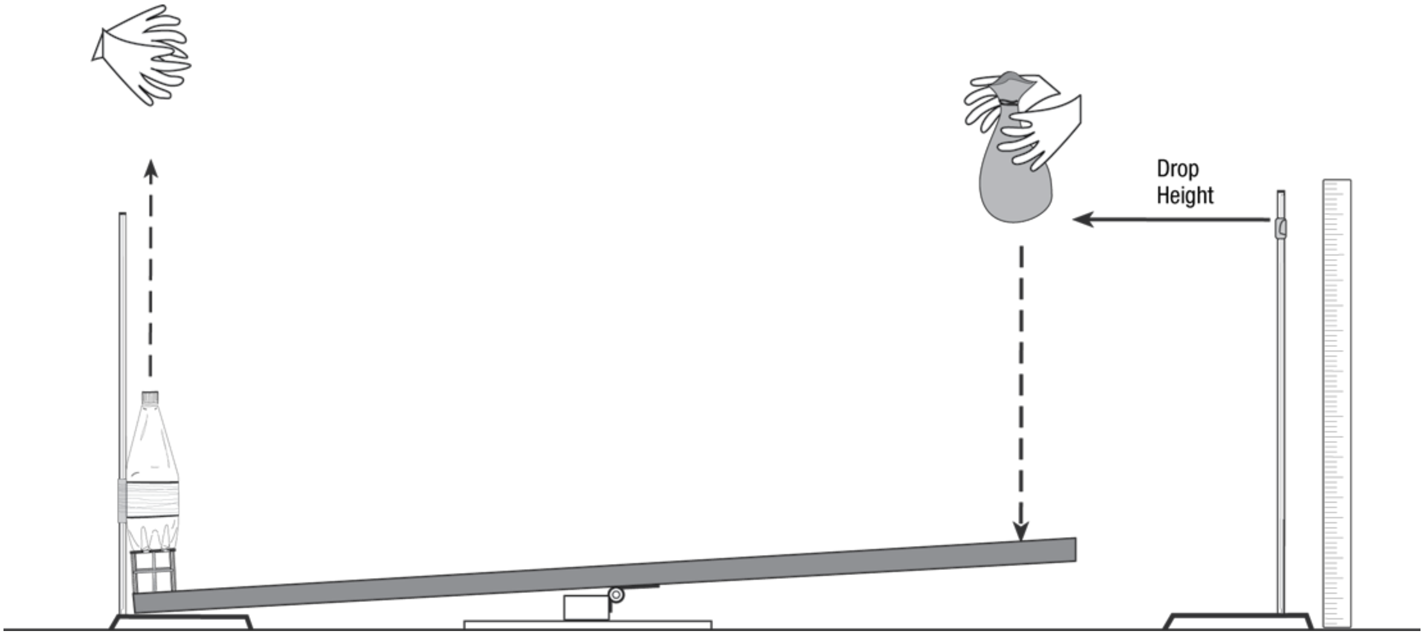
Design Constraints:

- Use only the specified materials.
- The thrust structure must be taller than 2 inches (5 centimeters) and must allow space in the center for fuel lines and valves represented by a 35mm-film canister without its lid.

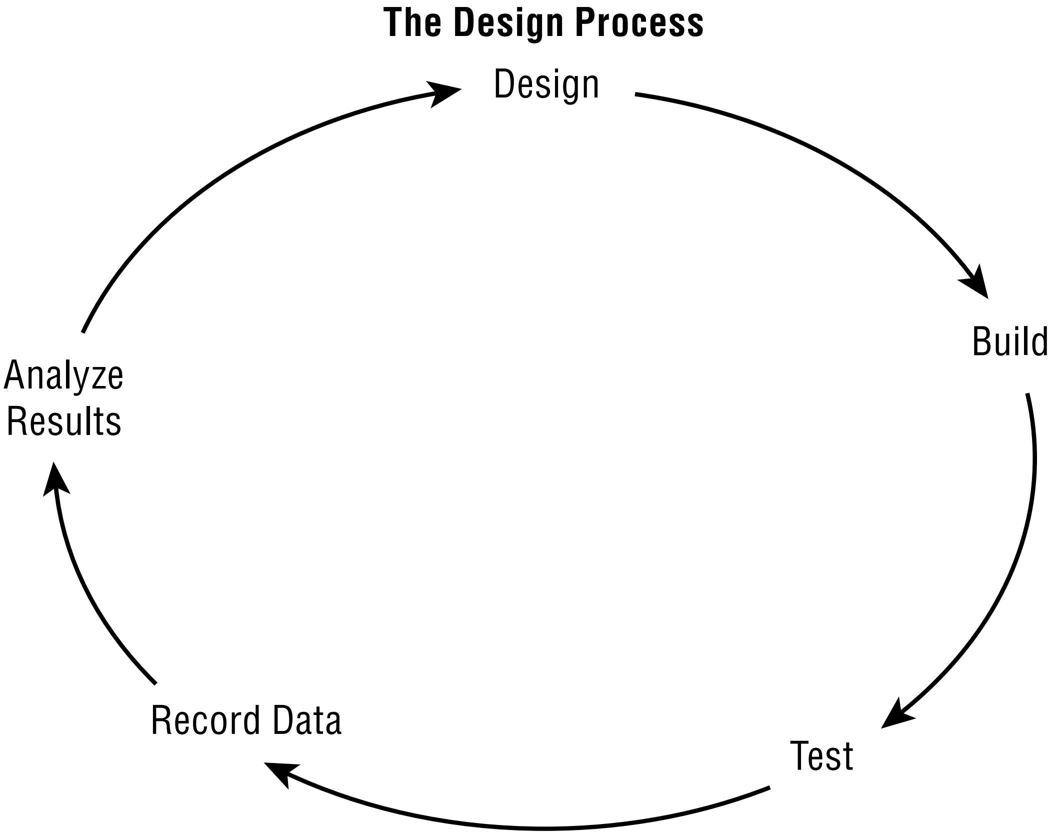
Launch Testing Station



Testing a Thrust Structure



The Design Process



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.

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National Aeronautics and Space Administration

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