# Activity Four: Optimize a Water Rocket Engine

## Educator Notes

### Challenge

Students will work together as a team to build an air-powered water rocket from a 2-liter soda bottle to find the optimal amount of water volume to air pressure for producing maximum thrust.

### Suggested Time

120 minutes

### Learning Objectives

Students will

- Construct flightworthy water rockets.
- Find the optimal amount of water to compressed air within their water rockets to reach maximum performance (altitude).
- Demonstrate an understanding of Newton's second and third laws of motion and how they apply to rocket launches.

### Curriculum Connection

**Science and Engineering (NGSS)**

*Disciplinary Core Ideas*

- MS-PS2-2 Motion and Stability: Forces and Interactions: Plan an investigation to provide evidence that the change in an object's motion depends on the sum of the forces on the object and the mass of the object. PS2.A: Forces and Motion.
- MS-ETS1-1 Engineering Design: Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions.
  - ETS1.A: Defining and Delimiting Engineering Problems: The more precisely a design task's criteria and constraints can be defined, the more likely it is that the designed solution will be successful. Specification of constraints includes consideration of scientific principles and other relevant knowledge that are likely to limit possible solutions.
- MS-ETS1-2 Engineering Design: Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.
  - ETS1.B: Developing Possible Solutions: There are systematic processes for evaluating solutions with respect to how well they meet the criteria and constraints of a problem.
- MS-ETS1-3 Engineering Design: Analyze data from tests to determine similarities and differences among several design solutions to identify the best characteristics of each that can be combined into a new solution to better meet the criteria for success.
  - ETS1.B: Developing Possible Solutions: There are systematic processes for evaluating solutions with respect to how well they meet the criteria and constraints of a problem. Sometimes parts of different solutions can be combined to create a solution that is better than any of its predecessors.
  - ETS1.C: Optimizing the Design Solution: Although one design may not perform the best across all tests, identifying the characteristics of the design that performed the best in each test can provide useful information for the redesign process—that is, some of those characteristics may be incorporated into the new design.
- MS-ETS1-4 Engineering Design: Develop a model to generate data for iterative testing and modification of a proposed object, tool, or process such that an optimal design can be achieved.
  - ETS1.B: Developing Possible Solutions: A solution needs to be tested, and then modified on the basis of the test results, in order to improve it. Models of all kinds are important for testing solutions.
  - ETS1.C: Optimizing the Design Solution: The iterative process of testing the most promising solutions and modifying what is proposed on the basis of the test results leads to greater refinement and ultimately to an optimal solution.

*Crosscutting Concepts*

- Cause and Effect: Events have causes, sometimes simple, sometimes multifaceted. Deciphering causal relationships, and the mechanisms by which they are mediated, is a major activity of science and engineering.

*Crosscutting Concepts (continued)*

- System and System Models: Models can be used to represent systems and their interactions—such as inputs, processes, and outputs—and energy and matter flows within systems.
- Energy and Matter: Tracking energy and matter flows, into, out of, and within systems helps one understand their system's behavior.
- Interdependence of Science, Engineering, and Technology: Engineering advances have led to important discoveries in virtually every field of science, and scientific discoveries have led to the development of entire industries and engineered systems.

*Science and Engineering Practices*

- Asking Questions and Defining Problems: A practice of science is to ask and refine questions that lead to descriptions and explanations of how the natural and designed world works and which can be empirically tested.
- Developing and Using Models: A practice of both science and engineering is to use and construct models as helpful tools for representing ideas and explanations. These tools include diagrams, drawings, physical replicas, mathematical representations, analogies, and computer simulations.
- Planning and Carrying Out Investigations: Scientists and engineers plan and carry out investigations in the field or laboratory, working collaboratively as well as individually. Their investigations are systematic and require clarifying what counts as data and identifying variables or parameters.
- Analyzing and Interpreting Data: Scientific investigations produce data that must be analyzed in order to derive meaning. Because data patterns and trends are not always obvious, scientists use a range of tools—including tabulation, graphical interpretation, visualization, and statistical analysis—to identify the significant features and patterns in the data. Scientists identify sources of error in the investigations and calculate the degree of certainty in the results. Modern technology makes the collection of large data sets much easier, providing secondary sources for analysis.
- Using Math and Computational Thinking: In both science and engineering, mathematics and computation are fundamental tools for representing physical variables and their relationships. They are used for a range of tasks such as constructing simulations; statistically analyzing data; and recognizing, expressing, and applying quantitative relationships.
- Construct Explanations and Design Solutions: The products of science are explanations and the products of engineering are solutions.
- Obtaining, Evaluating, and Communicating Information: Scientists and engineers must be able to communicate clearly and persuasively the ideas and methods they generate. Critiquing and communicating ideas individually and in groups is a critical professional activity.

**Technology (ISTE)**

*Standards for Students*

- Global Collaborator: Students use digital tools to broaden their perspectives and enrich their learning by collaborating with others and working effectively in teams locally and globally.

*Standards for Students (continued)*

  - 7c: Students contribute constructively to project teams, assuming various roles and responsibilities to work effectively toward a common goal.

**Mathematics (CCSS)**

*Content Standards by Domain*

- CCSS.MATH.CONTENT.6.SP.B.5: Summarize numerical data sets in relation to their context, such as by:
  - CCSS.MATH.CONTENT.6.SP.B.5.A: Reporting the number of observations.
  - CCSS.MATH.CONTENT.6.SP.B.5.B: Describing the nature of the attribute under investigation, including how it was measured and its units of measurement.

*Mathematical Practices*

- CCSS.MATH.PRACTICE.MP1: Make sense of problems and persevere in solving them.
- CCSS.MATH.PRACTICE.MP3: Construct viable arguments and critique the reasoning of others.
- CCSS.MATH.PRACTICE.MP5: Use appropriate tools strategically.

## Preparation Time

### 2 to 3 hours for setup, but several weeks for collecting bottles

- Read the Introduction and Background, Educator Notes, and Student Handout to become familiar with the activity.
- Gather and prepare all supplies listed on the materials list.
- Note: This activity requires a water rocket launcher. This apparatus can be built in a few hours using basic tools and materials found at most hardware stores. The Water Rocket Launcher Directions in NASA's Rockets Educator Guide include a detailed supply list and building instructions for a water rocket launch stand. Commercial launchers are also available from many science education supply companies.
- Tip: Each team will also need an empty 2-liter soda bottle to complete this activity and several spare bottles to replace any with damage. It is recommended that you begin collecting 2-liter soda bottles a few weeks before you plan to perform the activity.
- If using a glue gun, even with cool-melt glue, set up a station for the glue gun to supervise safety and oversee proper use.
- Precut the PVC pipe for the launch lugs (one per team; instructions follow here).
- Optional: Construct the assembly stands for each team.
- Review the Water Rocket Introduction below for additional context and ties to the curriculum.
- If presenting videos or web-based resources, test the links and the classroom technology ahead of time.

**Water Rocket Introduction**

A water rocket is a chamber, usually a 2-liter soda bottle, partially filled with water. Air is forced inside the bottle with a pump. When the rocket is released, the pressurized air forces water out of the nozzle (pour spout). The bottle launches itself in the opposite direction. The bottle usually has a nose cone to reduce drag and fins for stability. Water rockets are easily capable of 100-m-high flights, but advanced hobbyists have combined bottles to create staged rockets for flights over 300 m high.

Water bottle rockets are ideal for teaching Newton's laws of motion. The launch of the rocket easily demonstrates Newton's third law. Students can see the water shooting out of the nozzle (action) and see the rocket streak into the sky (reaction). Students will experiment with different pressure levels inside the chamber and different amounts of water. The rocket will not fly very high if it is filled only with air. The air will quickly rush out during the launch, but its mass is very low. Consequently, the thrust produced is also low (Newton's second law). When there is water in the bottle, the air must force the water out first before the air can leave the bottle. The water increases the mass expelled by the rocket, thereby increasing its thrust.

Like all rockets, the flight performance of water bottle rockets is strongly influenced by the rocket's design and the care taken in its construction. Beveling the leading and trailing edges of fins allows them to slice through the air more cleanly. Straight-mounted fins produce little friction or drag with the air. A small amount of ballast weight inside the nose cone helps to balance the rocket. This moves the center of mass of the rocket forward while still leaving a large fin surface area at the rear.

## Share With Students

### Brain Booster

If heat energy from the SLS's solid rocket boosters (SRBs) could be converted to electric power, two SRBs firing for 2 minutes would produce 2.3 million kWh of power, enough to supply power to over 92,000 homes for a full day.

Learn more: https://www.nasa.gov/sites/default/files/atoms/files/sls_at_a_glance_10202015.pdf

### On Location

The 65-m- (212-ft-) tall core stage of the SLS will undergo testing on the B–2 test stand at NASA's Stennis Space Center near Bay St. Louis, Mississippi. The B–2 test stand is NASA's largest rocket engine test stand and was built in the 1960s to test the engines of the Saturn V, the first rocket to travel to the Moon. These "Green Run" tests ensure mission success by proving and certifying new hardware ready for flight.

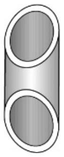
Learn more:

https://www.nasa.gov/feature/new-video-highlights-stennis-space-center-preparations-for-nasa-space-launch-system-testing

https://www.youtube.com/watch?v=6rSsMtRyV70&feature=youtu.be

### Launch Lug Construction

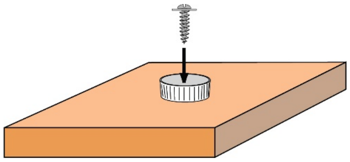
Precut the PVC segments using a saw or PVC cutter. The cuts can be slanted to make them more aerodynamic (see picture). The segments act as launch lugs to guide the rocket up the launch rod during the first moments of the rocket's skyward climb.



Launch lug with slanted cuts.

### Assembly Stand Construction (Optional)

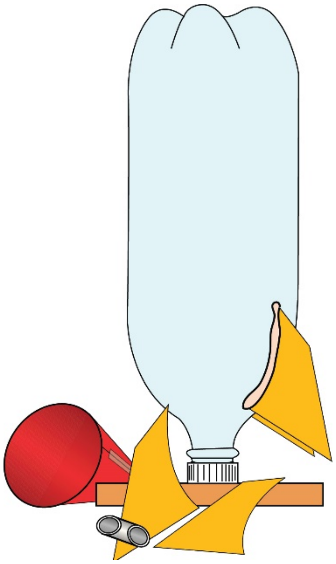
Construct assembly stands out of small blocks of wood. Attach a bottle cap to the middle of each board with a small screw and a washer through the cap. When students begin constructing their rockets, they can screw the bottleneck into the cap, and the board below will hold the rocket upright for gluing. The blocks are also a convenient way of storing the rockets upright when not being worked on.



Make mounting stand by screwing the plastic bottle caps to the board. Use a washer for added strength.

## Materials

- ☐ Safety glasses
- ☐ 2-liter soda bottles with caps (one per team plus spare bottles)
- ☐ Foam food trays, posterboard, and/or cardboard
- ☐ Masking tape
- ☐ Clear tape or low-temperature glue gun with cool-melt glue
- ☐ 4 oz. of clay
- ☐ Sandpaper or emery boards
- ☐ String, such as kite string
- ☐ Art supplies
- ☐ Copies of Student Handout and blank paper
- ☐ Metric measuring cups (mL)
- ☐ Water
- ☐ Rocket launcher and bicycle pump or air compressor with regulator (see note in Preparation Time)
- ☐ Launch lugs: 1/2-in.-diameter PVC pipe cut into pieces 1 to 2 in. long. (One launch lug per team)
- ☐ Optional: Altitude tracker (from Activity Two)
- ☐ Optional: Assembly stand
  - ☐ Board measuring 4×4×1 in. (one per team)
  - ☐ Small screw and washer



The Assembly Stand supports the rocket while it is being constructed.

## Introduce the Challenge

- Provide context for this activity using the Introduction and Background information in this guide and discuss how Newton's laws of motion apply to rocketry.
  - Optional: A balloon provides a simple example of how a rocket engine works. The air trapped inside the balloon pushes out the open end, causing the balloon to move forward. The force of the air escaping is the action; the movement of the balloon forward is the reaction.
  - Ask students to explain the phenomenon of the balloon rocket launch to assess prior knowledge and identify misconceptions.
  - Extend the concepts in the example of the balloon rocket to rockets for space travel. The combustion of fuel in a rocket engine produces great amounts of exhaust gas at high temperature and pressure. The hot exhaust passes through a nozzle, which accelerates the flow of gas. Thrust is produced according to Newton's third law of motion.
- Explain the role of engineers in designing technology to solve problems. Share the NASA for Kids video Intro to Engineering and introduce the engineering design process.
- Introduce any new terminology (e.g., pressure, propulsion, and Newton's laws of motion).
- Distribute the Student Handout and blank paper and explain the challenge and constraints. Ask students to make a hypothesis before starting this investigation.

### Safety

- Remind students of lab safety (e.g., wear eye protection and do not stand downrange during launch).
- Only use low-temperature glue guns or tape. High-temperature glue guns can melt and weaken the plastic bottles.
- Follow all safety instructions that accompany your water rocket launcher.
- Always wear eye protection when near the launch pad.
- Pump water rockets to a pressure no higher than 50 psi and NEVER allow a rocket to be pumped higher than 90 psi.
- Keep the launch area clear and do not stand over the launcher during pressurization and launch.
- Do not allow students to attempt to catch their falling rockets.

### Design Constraints

1. Each team will receive the same materials to construct an air-powered water rocket.
2. Each team must attach a launch lug to the side of the rocket between two fins and midway up the body of the rocket.
3. After the rocket has been qualified for launch and certified flightworthy, the only variable that teams will change during testing is the volume of water added to the rocket.

## Facilitate the Challenge

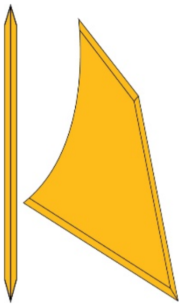
### Ask, Imagine, and Plan

Engage the students with the following discussion questions:

- What does it mean for a rocket engine to be efficient? What are the benefits of having an efficient engine?
- How do you think changing the amount of water and air inside the rocket will change its efficiency?
- When we test the water rockets, why do you think we keep the pressure constant for each launch?

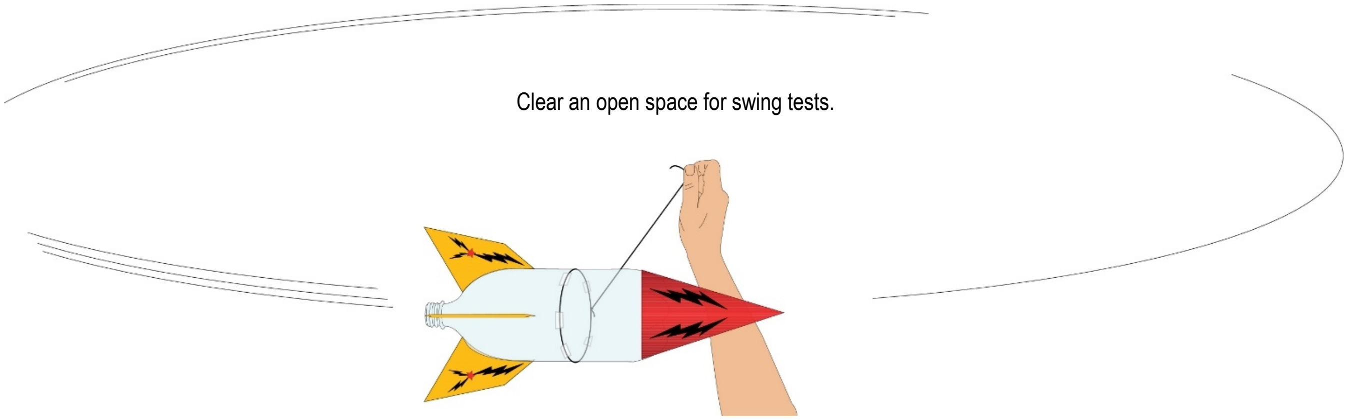
### Create

- Describe how fins can be smoothed with sandpaper to slice through the air with little drag.
- Remind teams to add clay to the inside of their nose cones. Trim fin edges with sandpaper to give them knife-blade shapes to slice through the air.
- Have teams glue a launch lug to the side of their rocket. The launch lug should be glued midway up the body of the rocket and positioned midway between two fins.



### Test and Improve

- Conduct a preflight inspection before launch to ensure that the nose cone, launch lug, and rocket fins are securely attached.
- When the rocket construction is complete, teams must qualify their rockets for flight by conducting swing tests.
- Review launch procedures and safety with the teams. The instructions are outlined in NASA's Rockets Educator Guide.
- Set up a tracking station for measuring the altitudes achieved by the rockets. (See Activity Two, Track the Altitude of a Rocket.)
- Follow all safety procedures and instructions when launching rockets.
- Each team will launch their rocket several times. After each launch, the team will record the water volume, pressure, and altitude attained by their rocket in tables like the example shown on the Student Handout. Based on the altitude achieved by their rocket, the team will adjust the volume of water in their rocket (increase or decrease) in an attempt to reach a higher altitude. When they can no longer gain an increase in altitude by changing the volume of water in their rocket, they have found the optimum volume of water for their rocket engine and have optimized its efficiency.



**Note:** No matter how much water is in the bottle, increasing the pressure within the bottle will always produce more thrust. The challenge in this activity is to find the optimal amount of water volume to pressurized air within the bottle for maximum thrust, not merely to increase the pressure. To eliminate variables in the challenge, it is recommended to select a constant pressure (e.g., 40 or 50 psi) to pressurize the bottles for every launch.

### Share

Engage the students with the following discussion questions:

- Did you try having your rocket nearly empty of water or nearly full of water for the launch? What was the result?
- What was the volume of water that your team found to be most efficient for your rocket? Was this the same or close to other teams? Why?
- If you were to increase the pressure in your rocket by 10 psi, do you think the volume of water you found would still be the most efficient? Why?

## Extensions

- Challenge teams to think of a way to add a parachute to their rockets for soft landings. Plastic grocery bags or lightweight fabric scraps can be used to make parachutes, and strings can be used to attach them. The nose cone must remain in place until the rocket reaches the top of its flight, then it should open and release the parachute.
- Collect class data and graph water volume versus altitude. Repeat the experiment for a different air pressure. Look for a correlation.

## Reference

Modified from Water Rocket Construction: https://www.nasa.gov/stem-ed-resources/water-rocket-construction.html

## Additional Resources

- Rockets Educator Guide. https://www.nasa.gov/stem-ed-resources/rockets.html
- Digital Badging: Online NASA STEM Learning. https://www.txstate-epdc.net/digital-badging/

# Activity Four: Optimize a Water Rocket Engine

## Student Handout

### Your Challenge

Build an air-powered water rocket from a 2-liter soda bottle to find the optimal amount of water volume to air pressure for producing maximum thrust.

### Design Constraints

1. You are only allowed to use the supplies provided by your teacher.
2. You must attach a launch lug to the side of the rocket between two fins and midway up the body of the rocket.
3. After your rocket has been qualified for launch and certified flightworthy, the only variable that your team will change during testing is the volume of water added to the rocket.

### Ask, Imagine, and Plan

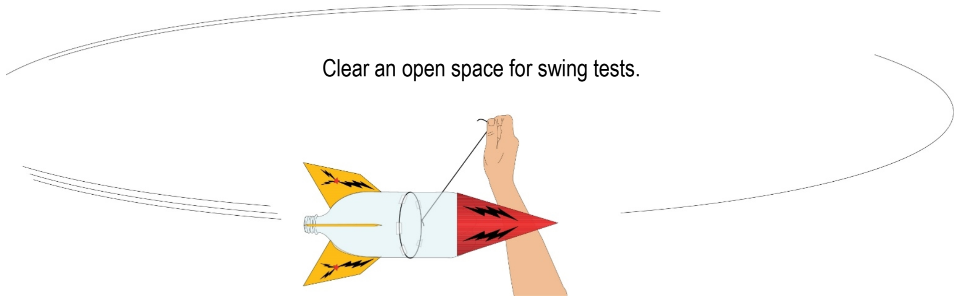
After receiving instructions from your teacher, ask any questions you may have about today's challenge and then sketch a diagram of the rocket you intend to build on the paper provided by your teacher.

### Create

1. Using the provided materials, construct a nose cone and fins for your rocket.
2. Add mass to the nose of your rocket to improve stability.
3. Attach a launch lug to the side of the rocket body.

### Test and Improve

1. Your teacher must conduct a preflight inspection of the nose cone, launch lug, and rocket fins to ensure they are secure. Qualify your rocket for launch by conducting a swing test.
2. **Swing Test:** Using several feet of string, tie the rocket around the middle so that it balances. Because of the nose cone weight, the balance point will be toward the nose. When the rocket hangs level, a small piece of tape should be temporarily fixed to the string and bottle to keep the string from slipping. The rocket is then swung in a circle. If the rocket tumbles while circling, it is not stable and needs more nose cone weight, bigger fins, or a combination of both. If the rocket circles with the nose always pointed forward, it is stable and ready for flight.



Clear an open space for swing tests.

3. Once your rocket is ready for launch, your team will find the optimum volume of water to place in your rocket in order to maximize its performance as measured by its altitude.
4. Be sure to follow all safety instructions for launch as given by your teacher.
5. For each launch trial, you must keep track of the volume of water in your rocket (measured in mL). Your 2-liter rocket will hold a maximum of 2,000 mL of water.

### Fun Fact

The RS–25 was the main engine of the space shuttle. If three RS–25 engines pumped water rather than fuel, they would drain a family-sized swimming pool in 25 seconds. The SLS rocket will use four RS–25s.

Learn more: https://www.youtube.com/watch?v=XP1CQtV8Qk8

### Career Corner

The lead systems engineer works with other engineers and analysts to ensure the SLS meets the unique requirements and constraints for each Artemis mission. Systems engineering is both an art and a science. The systems engineer is like the conductor of an orchestra, who knows what the music should sound like (the look and function of a design) and has the skills to lead a team in achieving the desired sound (meeting the system requirements).

Learn more: https://www.youtube.com/watch?v=VfmHda5e4Il&feature=youtu.be

6. Your teacher will provide the required air pressure (measured in pounds per square inch, or psi), and this will remain constant for all of your launches.
7. You will need to adjust the volume of water for each launch in order to determine the optimum water volume.
8. You will launch a maximum of five times.
9. Create a table like the example that follows here and record your data.

| Trial | Volume of water in rocket, mL | Pressure, psi | Altitude, m |
|---|---|---|---|
| 1 | | | |
| 2 | | | |
| 3 | | | |
| 4 | | | |
| 5 | | | |

### Share

- Did you try having your rocket nearly empty of water or nearly full of water for the launch? What was the result?
- What was the volume of water that your team found to be most efficient for your rocket? Was this the same or close to other teams? Why?
- If you were to increase or decrease the air pressure in your rocket by 10 psi, do you think the volume of water you found would still be the most efficient? Why?