NASA's BEST

SPACE SAILING

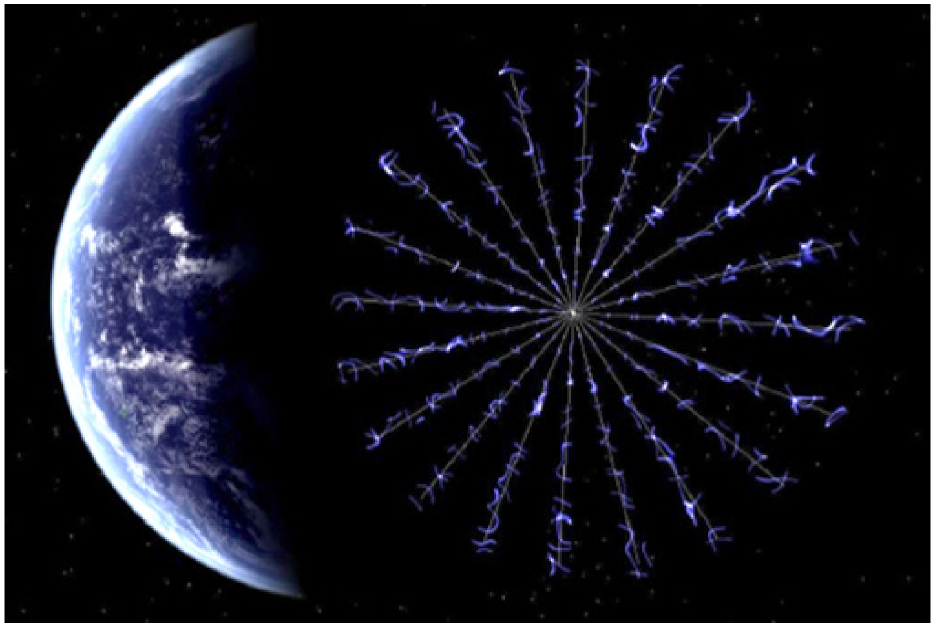
OBJECTIVES

After completing this design challenge, students will be better able to:

- Compare electric and solar sails for green space travel; and
- Use the Engineering Design Process to design, create, and test a prototype of a space sail that is able to self-deploy with minimal assistance.

VOCABULARY

acceleration
Astronomical Unit
deployment
design constraint
design requirement
electric sail
electrostatic
force
gravity assist
heliopause
heliosphere
interstellar medium
iteration
procedure
prototype
solar wind
surface area
solar sail
unfurl
verification



Long, very thin, bare wires construct this large, circular electric sail. The momentum exchange is produced as protons are repelled by the positively charged wires to create the spacecraft's thrust. Credits: NASA/MSFC.

INTRODUCTION

It takes a lot of rocket fuel to power spacecraft, but what if spacecraft could travel through space using no propellants at all? That is the goal behind two space sail technologies — electric sails and solar sails. Although one catches the solar wind while the other harnesses sunlight, both may be the answer to furthering NASA's exploration of deep space!

Electric Sails

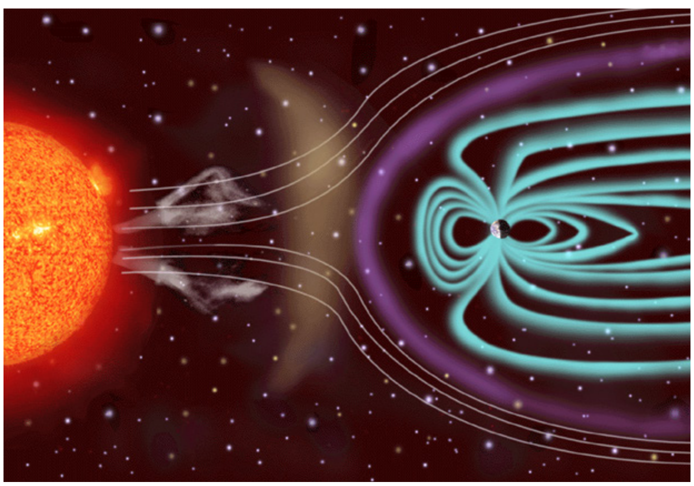
An electric sail, or e-sail, harnesses the solar wind for propulsion. The e-sail uses high-speed protons emitted from the sun to propel an attached spacecraft. These protons are emitted from the Sun at about 400 km/s, or about 1,000,000 mph!

E-sails use the force of repulsion (think opposites attract!) to make a spacecraft move. Electric sails consist of a network of very thin wires that form a positive electric field and repel solar wind protons. This repulsion results in momentum, which is transferred to the spacecraft.
The idea of e-sails has been around as long as liquid-fueled rockets, but they have only recently been made possible by technological innovations.

Solar Sails

Solar sails are an alternative to electric sails, and idea of solar sail dates back to the 1600s. Solar sails use the momentum produced from reflection (similar to light bounding off a mirror). Made of highly reflective material, solar sails reflect photons off the sail and transfer their momentum to propel an attached spacecraft.

The sails may be as large as soccer fields, but are 40-100 times thinner than paper. These giant, flat sheets of very thin, mirror-like material are able to reflect sunlight, which provides the force needed to push a spacecraft through space. When a photon from the sun hits the mirror-like surface, it bounces off the sail and transfers its momentum to the spacecraft—the same way that a cue ball transfers its momentum when it smacks into another ball in a game of pool.



The shape of Earth's magnetospere is caused by solar wind. Credit: NASA/SOHO (https://spaceplace.nasa.gov/review/solar-trickionary/)

What is the Solar Wind?

The solar wind is a constant stream of energized, charged particles, primarily electrons and protons, flowing outward from the Sun, through the solar system at speeds as high as 900 km/s and at a temperature of 1,000,000 degrees Celsius. The source of the solar wind is the Sun's hot corona. Learn more about the solar wind at The Solar Wind (https://solarscience.msfc.nasa.gov/SolarWind.shtml)

Space Sails and Wind-Borne Sails

E-sails and solar sails harness the energy of the sun in different ways, but both result in the propulsion of spacecraft. E-sails use repulsion and the power of the solar wind; solar sails use reflection and harness sunlight.

Which technology is the best? What are the advantages and disadvantages of each? And, how do these two technologies compare with wind-borne sails? This engineering design challenge is your opportunity to contribute to the research by designing a model of a space sail with based on characteristics of the electric sail, solar sail, or both!

View the following video to learn about one of NASA's newest electric sails:

Animation of Heliopause Electrostatic Rapid Transport System (HERTS)[1], 1:32 minutes

View the following video to learn about one of NASA's newest solar sails:

HELIOS advanced solar sail concept[2], 3:30 minutes

[1] *Animation of Heliopause Electrostatic Rapid Transport System (HERTS) - (https://youtu.be/8UpdnhOTIG4)*
[2] *HELIOS advanced solar sail concept - (https://youtu.be/4F97NdwvmUM)*

Solar sails are made of ultrathin, highly reflective material. When a photon from the sun hits the mirror-like surface, it bounces off the sail and transfers its momentum. Credit: NASA/MSFC.

ENGINEERING DESIGN CHALLENGE

Your challenge is to design, create, and test a prototype of a space sail that will self-deploy with minimal assistance.

Design Requirements:

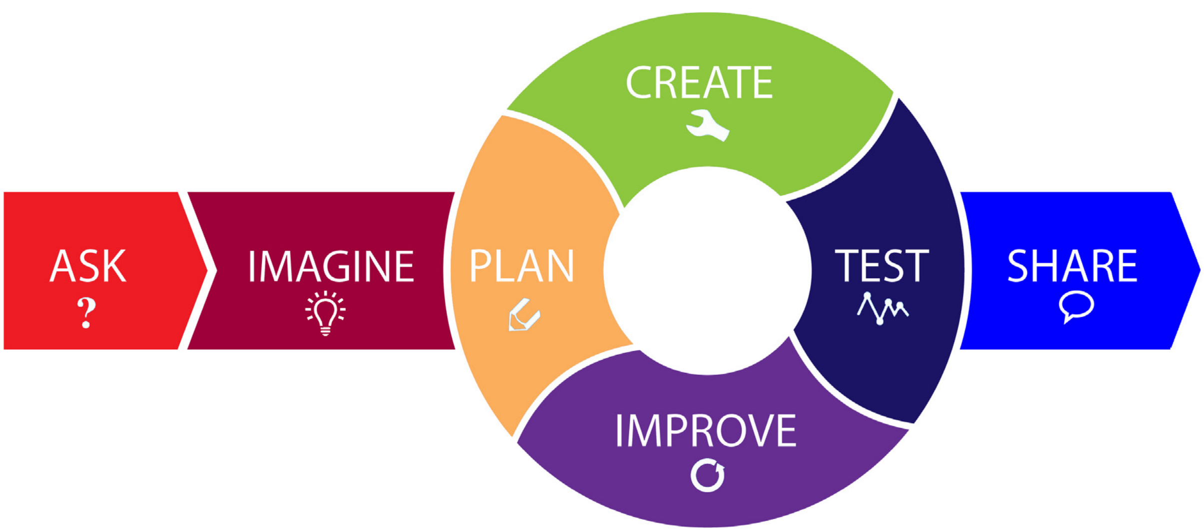
- The sail must be able to self-deploy from a launch vehicle and unfurl within 5 seconds.
- Once deployed, the sail must remain upright and open on the launch vehicle without assistance.

Design Constraints:

- The total mass of the sail must not exceed 20 grams.
- The total surface area of the sail must not exceed 2,500 cm2.
- Only materials provided can be used to create the sail.

REMINDERS!

- Be sure to address all design requirements and constraints.
- Document all designs and design revisions.
- Record all test results.



ENGINEERING DESIGN PROCESS

ASK

1. Identify the problem in this design challenge.
2. With your team, review the Engineering Design Challenge and highlight design requirements and constraints.
3. Identify questions and concerns you have about the challenge and discuss them with your team.

IMAGINE

1. Brainstorm possible solutions to the Engineering Design Challenge. What information do you need in order to create a sail that meets the design requirements and within constraints?
2. Brainstorm ideas about what materials will work best to allow the sail to self-deploy. What will you test first? What special features will you include?

PLAN

1. Draw and label your sail design on the Sail Design Plan.
2. Include dimensions and label all components. You should include at least two perspectives (e.g. top view, front view, or side views) of your device.
3. Submit your completed drawing and list of materials for teacher approval before continuing through the Engineering Design Process.Submit your completed drawing and list of materials to your teacher for approval before continuing through the Engineering Design Process.

CREATE

1. Create a prototype, or working model, of your sail.
2. Remember to consider design requirements and constraints as you build from your plan.
3. Record any revisions to your design on your Testing Data Table.

TEST

1. Verify that your prototype meets the design requirements by conducting tests.
2. For this design challenge, the tests require both numerical measurements (e.g. timing your sail's unfurling) as well as observations (e.g. did the sail remain upright and open?). What did you observe while conducting these tests? What do these observations tell you about the performance of your sail?
3. Complete the Testing Data Table.

IMPROVE

1. Consider how to optimize the design plan of your sail.
2. Continue through iteration(s) of the engineering design process (i.e. plan, create, test) to optimize your prototype.
3. Confirm your prototype meets the design requirements.
4. On the Final Design Summary, draw and label the final prototype, and define the final procedure for your sail.
5. Once completed, check with your teacher before asking another team to review your design.

TESTING AREA SAFETY CONCERNS

- No more than one team (no more than two team members) is allowed in each Testing Station at any time.
- Team members are required to clean up the Testing Stations before leaving.

SHARE

1. Meet with another team and present your sail. Be sure to review the Sail Quality Assurance Form and be ready to identify your device strengths and areas of additional improvement.
2. Complete the Quality Assurance Form for the other team.
3. As a class, review class data and complete Discussion Questions.
4. Compose a one-page Technical Report or a One-Paragraph Essay on your project.

MORE FUN WITH ENGINEERING

Extend Your Study of Sails

- Test different materials or shapes for the sail. Do materials affect stability? Speed of opening? Durability?
- Identify several tests to verify how effective your space sail can "catch the wind?"
- The solar wind is made of charged particles. Should this be important for the choice of material that NASA uses for e-sails?

Explore More About Space Sails

In your engineering design process today, you replicated NASA investigations of space sails. You did not have to worry about conditions in space like NASA engineers do when they are preparing their sails. In preparing for future missions, NASA engineers must continually improve existing technology to make sails more efficient and a viable means of to propel spacecraft.

- E-Sails - NASA Begins Testing of Revolutionary E-Sail Technology (https://www.nasa.gov/centers/marshall/news/news/releases/2016/nasa-begins-testing-of-revolutionary-e-sail-technology.html)
- Solar Sails - New NASA Spacecraft Will Be Propelled By Light (http://news.nationalgeographic.com/2016/02/160202-solar-sail-space-nasa-exploration/)

Use the links above to research the history of space sails and about their use in future NASA missions. Then answer the following questions:

1. When was the concept of a space sail first proposed? What was the context?
2. What kinds of materials are currently being used to make these sails? Why do you think those materials were chosen?
3. Why do these sails need to be folded at launch?
4. How are space sails being tested? What kinds of conditions are needed?
5. Which kind of sail (electric or solar) do you think holds most promise for space travel?
6. What changes might you need to make to your sail so that it could be used in space?

What does a Technical Report Include?

NASA engineers write technical reports for many reasons, including the documentation of experiments and designs. A typical technical report that documents the steps of the engineering design process includes the following sections:

- Statement of design challenge, requirements, and constraints.
- Solution proposed, including summary of design features, measurements, and capabilities.
- Summary of evaluation results, including improvements made and tested.
- Final outcome, lessons learned, and recommendations for next steps.

MORE FUN WITH ENGINEERING

Extend Your Study of Sails

- Test different materials or shapes for the sail. Do materials affect stability? Speed of opening? Durability?
- Identify several tests to verify how effective your space sail can “catch the wind?”
- The solar wind is made of charged particles. Should this be important for the choice of material that NASA uses for e-sails?

Explore More About Space Sails

In your engineering design process today, you replicated NASA investigations of space sails. You did not have to worry about conditions in space like NASA engineers do when they are preparing their sails. In preparing for future missions, NASA engineers must continually improve existing technology to make sails more efficient and a viable means of to propel spacecraft.

- E-Sails - NASA Begins Testing of Revolutionary E-Sail Technology (https://www.nasa.gov/centers/marshall/news/news/releases/2016/nasa-begins-testing-of-revolutionary-e-sail-technology.html)
- Solar Sails - New NASA Spacecraft Will Be Propelled By Light (http://news.nationalgeographic.com/2016/02/160202-solar-sail-space-nasa-exploration/)

Use the links above to research the history of space sails and about their use in future NASA missions. Then answer the following questions:

1. When was the concept of a space sail first proposed? What was the context?
2. What kinds of materials are currently being used to make these sails? Why do you think those materials were chosen?
3. Why do these sails need to be folded at launch?
4. How are space sails being tested? What kinds of conditions are needed?
5. Which kind of sail (electric or solar) do you think holds most promise for space travel?
6. What changes might you need to make to your sail so that it could be used in space?

DESIGN PLAN

Draw a detailed sketch of your design. Label all components, and include measurements (in cm.)	
Compose a step-by-step procedure on how to deploy your sail.	
Teacher Approval:	
Identify and define how your design plan meets the design requirements for this challenge.	

TESTING DATA TABLE

Record any revisions to your design as a result of creating your prototype. If none, leave blank.	
What is the surface area of your sail (in cm^2)?	
What is the mass of your sail (in g)?	
Describe how your sail deploys. Does it self-deploy? If not, what kind of assistance does it need?	
Describe how long it takes for your sail to deploy.	
Describe whether your sail, once deployed, is able to remain upright and open on the launch vehicle.	
Other Observations	
Based on your observations, determine whether your space sail meets the design requirements and explain why.	
☐ Meets design requirements ☐ Does not meet design requirements	
Complete the Final Design Summary.	

FINAL DESIGN SUMMARY

Drawing of FINAL Sail (with labels and measurements)	
Description of and procedure for FINAL Sail	
Summary of Design Process (what was initially proposed, test results, and revisions)	
Teacher Approval for Quality Review	

Student Worksheet

QUALITY ASSURANCE FORM

REVIEW OF DESIGN should be completed by a Review Team. Design Team should provide Review Team with the sail prototype and copies of Testing Data Table and Final Design Summary.

DESIGN TEAM NAME AND MEMBERS		
TEST CRITERIA		**RESULTS**
The sail self-deployed (with minimal assistance) from the launch vehicle	☐ Pass	☐ Fail
The sail unfurled within 5 seconds	☐ Pass	☐ Fail
The sail remained open and upright after it was deployed	☐ Pass	☐ Fail
The sail mass was less than 20 g	☐ Pass	☐ Fail
The sail surface area was less than 2,500 cm^2	☐ Pass	☐ Fail
DESIGN STRENGTHS		
SPECIFIC WEAKNESSES OR NEEDED IMPROVEMENTS		
JUDGMENT		
☐ Spacecraft meets all design requirements and constraints. ☐ Spacecraft meets some design requirements and constraints. ☐ Spacecraft does not meet design requirements and constraints.		
REVIEW TEAM NAME AND MEMBERS		

DISCUSSION QUESTIONS

1. How did your team verify that the prototype met or did not meet the design requirements?	
2. What are possible explanations for why some designs were more stable (i.e. remained upright and open) than others?	
3. Why were some designs able to self-deploy more effectively than others?	
4. How do you think your design would perform if the surface area limit were to be increased? Decreased?	
5. How would your design work in space? What kind of assistance might it need?	
6. How do you think your design would perform if the mass limit were to be increased? Decreased?	
7. What other uses might a space sail have?	
8. What challenges might a space sail mission encounter? How could engineers prepare for those challenges before the mission?	
9. What did you learn about your team's design while testing another group's design?	
10. Compare / contrast your space sail to a wind-borne sail. Is your sail more like an electric sail or a solar sail?	

Grades 6-8

DURATION: **45 Minutes**

STANDARDS

Next Generation

Engineering, Technology, and Applications of Science
MS-ETS1-1, MS-ETS1-2,
MS-ETS1-3, MS-ETS1-4

Common Core

Mathematics
CCSS.MATH.CONTENT.6.G.A.1,
CCSS.MATH.CONTENT.6.G.A.4,
CCSS.MATH.CONTENT.7.G.B.6

Language Arts
CCSS.ELA-LITERACY-RST.6-8.3,
CCSS.ELA-LITERACY.RST.6-8.10
CCSS.ELA.LITERACY.W.6.7,
CCSS.ELA.LITERACY.W.7.7,
CCSS.ELA.LITERACY.W.8.7

MATERIALS

Frame materials (e.g., pipe cleaner, bamboo skewers, straws, cardboard)

Sail materials (e.g., tissue paper, tin foil, plastic bags, wrapping paper)

Modeling clay or play dough

Scissors

Tape

Rulers

Stopwatch

Balance/scale

Cylindrical structure (e.g., paper towel tube, potato chip can, oatmeal canister) – one per team.

ENGINEERING DESIGN CHALLENGE

Students are challenged to design, create, and test a prototype of a space sail that will self-deploy with minimal assistance.

PRE-ACTIVITY SET-UP

Testing Station Set-Up

The deployment tests may be conducted anywhere there is at least 1-2 meters clearance above a flat surface.

For an additional challenge, you may wish to have students test their sails above a fan or heating unit to see how the "sails" catch the "wind."

ENGAGEMENT STRATEGIES

Discuss the difference between a design requirement and a design constraint. Mass and volume are also design constraints.

Use a KWL chart as an introductory activity to help students identify what they know, want to know, and learned about the engineering design process and the testing procedures for NASA spacecraft.

Learn more about NASA's space sails through the following resources:

- E-Sails - NASA Begins Testing of Revolutionary E-Sail Technology (https://www.nasa.gov/centers/marshall/news/news/releases/2016/nasa-begins-testing-of-revolutionary-e-sail-technology.html)
- Solar Sails - New NASA Spacecraft Will Be Propelled By Light (http://news.nationalgeographic.com/2016/02/160202-solar-sail-space-nasa-exploration/)

Have students propose tests that may be useful to determine the viability of sails.

COMMON MISCONCEPTIONS

The effects of solar wind at large distances away from the Sun can be confusing. The speed of the solar wind itself remains constant as it moves away from the Sun. However, there is very little force acting on the solar wind, so its velocity remains essentially constant. What changes is that the gas from the wind expands as it leaves the Sun, decreasing its density, and thus the pressure (force per unit area) available to propel e-sails diminishes at large distances from the Sun.

Students may believe that light can only be reflected from a shiny surface, and that an object cannot both reflect and absorb light. Clarify with students that all objects absorb and reflect light to different degrees, and so the trick of creating an effective solar sail is to use a surface that maximizes reflection while minimizing absorption.

You may need to remind students about conservation of energy; that is, energy from the solar wind is not "lost" but is instead transferred to other objects in the solar system.

Use of Technology

Students may use timing devices that send results to a computer, tablet, or smartphone. This can allow students to collect data continually over the testing period instead of taking discrete measurements, and supports more in-depth data analysis.

If you have access to 3D design software and/or 3D printing technology, you may wish to have students design their sails using the computer software, and if possible, create the frame of the sail using the 3D printer.

ASSESSMENTS

- Sail Design Plan
- Sail Testing Data Table
- Sail Final Design Summary
- Sail Quality Assurance Form
- Sail Discussion Questions

Questions for this activity primarily focus on observations made by students in the course of testing their projects; students should be prompted to be as thorough as possible in their responses.

Answers to Selected Questions:

3 & 5: Students should recognize that larger surface areas would allow sails to catch more wind, but that the trade-off is a larger mass, which is problematic for space flight.

7: Some reference should be made to the dissipation in solar wind over large distances.

ASSESSMENT TOOLS

- Technical Report Scoring Guide
- Engineering Design Process Rubric
- Engineering Design Process Teamwork Rubric
- Sail 1-Paragraph Essay Directions and Scoring Guide

Student Prompt: In this activity, you designed a sail that was required to be durable, accurate, and precise. You followed the steps of the Engineering Design Process to brainstorm solutions and research ideas, plan and sketch a design, build a model, evaluate the model, refine and optimize your model, and share your results. Choose one of the following questions and answer with a one-paragraph essay.

Compare and contrast wind-borne sails, solar sails, and electric sails.

How did what you learned through the engineering design process help you understand how NASA engineers might design a space sail for use in deep space?
Construct an argument for why space sails are viable spacecraft alternatives.

ENGINEERING DESIGN PROCESS

Review the Engineering Design Process with students. More information about the Engineering Design Process and its use at NASA can be found in the NASA's BEST Educator Guide Introduction. Instructional videos and more information about the Engineering Design Process (EDP) may be found at NASA's BEST Activity Guides (http://www.nasa.gov/audience/foreducators/best/edp.html) (six separate videos, about 2 minutes each).

ASK

Review Introduction and Student Pages, which provide additional detail and background information on the engineering design challenge.

Have student teams review the design challenge and identify design constraints and requirements. Use the NASA's BEST Glossary to review critical vocabulary prior to the activity. Help students answer any questions they have about the challenge.

IMAGINE

Brainstorm ideas about what material characteristics will work best to create a sail that is able to unfurl on its own and deploy upright and open.

Have students develop hypotheses for the performance of their sails.

You may wish to take students to the school library to conduct research. If a provided link is broken, students may easily search for information at the following sites:

- NASA Missions https://www.nasa.gov/missions
- NASA https://www.nasa.gov/

PLAN

Students should consider the various elements of a sail that is lightweight, yet able to unfurl and remain stable and upright on landing. They are asked to form hypotheses related to the aspects of their devices that will be tested. You may wish to suggest examples, such as: The ____ is the most important factor to consider for a lightweight sail, while ____ is the most important factor to consider for self-deployment. (Note: this may or may not be the same variable!)

Before allowing students to move to the next step, require design sketches and materials list to be submitted for your approval.

CREATE

Remind students to consider design requirements and constraints as they build their sails.

TEST

Students will check their designs by conducting drop tests that will demonstrate their sails' self-deploying capabilities, and confirm stability on landing.

Students will test and improve their sails.

After completing the challenge, teams will assess each other's sails.

IMPROVE

Students should redesign their sails to improve drop test, deployment, and landing results. Have students conduct a second round of testing and record all results. As time permits, students may revise and test a third time.

After testing, students will create their final model to share with a Review Team.

SHARE

Have students present their solutions and results by completing the Quality Assurance Form with a Review Team.

Engage students in class discussion using the questions in Discussion Questions.

Have students complete writing activities (i.e., Technical Report or One-Paragraph Essay). See scoring guides and writing prompts under Assessments.