FUTURE U.

Topology Optimization

Objectives

Students wil be able to:

- **Summarize** and **explain** how Newton's Second Law of Motion can be applied to spacecraft speed and efficiency.
- **Evaluate** how topology optimization can benefit aerospace vehicle construction.
- **Analyze t**he results of a spacecraft pressure test and **create** a 2D and 3D model of a topologically-optimized design.

Lesson Overview

As interns on Boeing's Additive Manufacturing team, students will be presented with the challenge of minimizing spacecraft weight in order to maximize flight capabilities.After investigating Newton's Second Law of Motion in order to consider the effects of this principal on rocket speed, students will gain an understanding of the concept of topological optimization.They will then interpret and apply the results of recent spacecraft pressure testing as they design and build a new model that removes unneeded materials and maximizes efficiency.

This lesson focuses on

Engineering Design Process

- Defining the Problem
- Designing Solutions
- Refine or Improve
- Communicating Results

21st Century Skills

- Communication
- Collaboration
- Critical thinking
- Creativity

Objectives

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- **Evaluate** how topology optimization can benefit aerospace vehicle construction.
- **Analyze** the results of a spacecraft pressure test and **create** a 2D and 3D model of a topologically-optimized design.

Timing

Three 45–60 minute class periods

Materials

All Days

- Computer or device with the ability to project, one for the instructor

Day 1

- Video to project: How Does A Rocket Escape Earth's Gravity
- Scrap paper, one piece per student
- F=MA handout, 10 copies
- F=MA experiment materials:
    - Painter's tape, a couple rolls for the class to share
    - Rulers, at least 5 for the class to share
    - Golf balls, 8
    - Ping pong balls, 8
    - Straws, 8
    - Stopwatches or timers that record time to the millisecond*, 8

*These can also be accessed online if stopwatches are not available

- Atlas V image, to project
- CST-100 Starliner interactive page, to project
- Rocket Model Handout, one per student

Day 2

- *Lightening the Load* Article Packet (4 pages, stapled), one per student

Day 3

- Pressure Testing Results image, to project
- Topology Optimization handout, one per every three students
- Modeling clay or play dough, a golf-ball sized piece for one-third of the class

Have you ever wondered…

What exactly is topology optimization?

The process of topology optimization helps manufacturers create the most efficient design for a product. Computer software programs achieve this by identifying areas of low pressure within a design and removing materials—so the resulting design is lightweight, but equally strong and durable. These programs are also able to take additional space or design constraints into consideration. Because a design that has undergone topology optimization tends to be untraditionally shaped, it can be more difficult to manufacture. For this reason, additive manufacturing (also called 3D printing) is often used. The combined ability of topology optimization and additive manufacturing to produce unique, lightweight designs make it a popular pairing in aerospace engineering.[1]

How is additive manufacturing different from traditional manufacturing?

Additive manufacturing produces 3D objects from a digital file of a 3D model. The name *additive manufacturing* comes from the additive way in which the object's construction occurs: It is created by adding layer after layer of material until the object is complete. More traditional manufacturing, on the other hand, can also be called subtractive manufacturing: It begins with a larger piece of material that is then cut and/or hallowed by a machine. The layer-by-layer approach of additive manufacturing allows for the creation of intricate geometric shapes and customizable parts.[2]

Make Connections

How does this connect to students?

While 3D printing's beginnings date back to the 1980s, it wasn't until recent years that the term became more mainstream. Today, 3D printing is used in a wide variety of fields that includes engineering, healthcare, architecture, fashion, the automotive industry, and aerospace. Many of these fields combine the process of topology optimization with additive manufacturing as they explore how to make the lightest and most efficient designs possible.[3]

With the ever-increasing scope of 3D printing and topology optimization, there is a strong likelihood that students will benefit from these processes in the future and/or enter a field that relies on them!

How does this connect to careers?

Space software engineers who specialize in topology optimization use a software tool to determine how to reduce the weight of a designated product. They also take factors such as materials and pressure testing results into account as they decide how to optimize aerospace designs.

Structural design engineers develop new methods, processes, and even materials that can be used to construct innovative designs. Some structural design engineers focus particularly on additive manufacturing.

Aircraft test technicians perform testing and trouble-shooting on all aircraft systems before, during, and after final assembly to ensure everything is functioning optimally—in addition to a variety of other aircraft-related responsibilities.

How does this connect to our world?

While Germany, Korea, the United States, and Japan currently lead the world in 3D printing, emerging markets like China and India are projected to see significant growth in this field as well.[4]

Around the world, the evolution of commercial topology optimization software and 3D printing are allowing engineers and manufacturers to create specialized, lighter, and stronger products.

The aviation and aerospace industries, for example, are now using both processes to create highly customized and lightweight parts for their products. The aerospace field even has their eyes on the power of 3D printing as they look toward building a lunar base.[4]

In the medical field, more doctors now have access to customized medical equipment and tools, from dental devices and transplant models to medical instruments designed uniquely for each patient.[5]

These innovations spread to defense, automotive and consumer good fields as well.

The software and processing tools for 3D printing and topology optimization are evolving rapidly, and global potential for these technologies is really just in its infancy!

Sources

1. Hale, Steven. "Engineering Advantage." CAE Associates. caeai.com/blog/what-topology-optimization-and-why-use-it.
2. "Additive versus Subtractive Manufacturing." Engineering Guides. formlabs.com/blog/additive-manufacturing-vs-subtractive-manufacturing/.
3. Goldberg, Dana. "History of 3D Printing." Autodesk. autodesk.com/redshift/history-of-3d-printing/.
4. Gadzala, Aleksandra. "3D Printing: Shaping Africa's Future." Atlantic Council. atlanticcouncil.org/images/publications/3D_Printing_Africa_WEB.pdf
5. Crutchfield, Brian. "3D Printing's Impact on Aerospace." Aerospace Manufacturing and Design. aerospacemanufacturinganddesign.com/article/3d-printings-impact-on-aerospace/.
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Blueprint for Discovery

DAY 1

1. Begin class with the following explanation:

   Let's flash forward a few years. You have successfully finished middle school and high school and each have an internship at Boeing, the largest aerospace company in the world.

   You have been placed on Boeing's Additive Manufacturing team, which is a team that explores how 3D printing can be used to benefit aerospace and aircrafts. Today is the very first day of your internship, and your team has just been tasked with the challenge of maximizing spaceflight capabilities. In other words, you will need to investigate: How can you make it easier for spacecrafts to travel long distances?

2. Explain that, since it is the interns' first day, it is important for them to begin with the basics. Tell students that you are going to play a segment of an introductory video about rockets, and instruct students to use scrap paper to jot down as least one key takeaway that could be important for them to keep in mind as they tackle this challenge.
3. Show the "How Does A Rocket Escape Earth's Gravity" video until 1 minute 48 seconds. Review students' key takeaways once the video is complete. Ensure that students understand that a rocket must accelerate at a speed of over 40,000 km/hour (just under 25,000 miles/hour) to overcome Earth's gravity and enter deep space.
4. Introduce and/or remind students of Newton's Second Law of Motion: Force = Mass x Acceleration. Write this equation on the board, and then ask the class to hypothesize and share how they think this equation may be related to rocket launches.
5. Divide students into groups of four students, and distribute one F=MA handout to each group. Also give each group a ruler, one golf ball, one ping pong ball, two pieces of painter's tape, and a stopwatch. Tell groups that they will have between 10 and 15 minutes to follow the step-by-step

instructions on the F=MA handout, which will guide them as they investigate Newton's Second Law and apply it to aerospace.

Note: This handout's directions are clear, and students should not need an instructor to review each step.

6. When about ten minutes have passed and/or once groups are mostly finished, bring the class back together and discuss the handout's discussion questions as a class:
    a. What happened to the ball's acceleration as the mass increased and the force stayed the same?
    b. What implications may this have for space exploration? What may aerospace engineers want to keep in mind as they try to design spacecrafts that can accelerate as fast as possible?

    Ensure students understand that in order to maximize the force during takeoff and accelerate as quickly as possible, it is important for the spacecraft to have as little mass as possible.
7. Next, project the [Atlas V rocket] connected to the CST-100 Starliner. Bring students' attention to the:
    - CST-100 Starliner capsule, which sits at the very top of the rocket.
        - Explain that this space capsule is being constructed at Boeing, and it is designed to hold passengers and bring them to the International Space Station.
        - Click over to this [interactive page] that explains some of the CST-100 Starliner's design details, and click through each of the five design feature explanations.
    - Atlas V rocket, which is everything below the CST-100 Starliner.
        - Tell students that it is the rocket's responsibility to launch the Starliner capsule into space, and it will eventually separate from the space capsule and fall back to Earth.
        - Pass out the Rocket Model Handout to each student, and review the different parts of the rocket. Explain that the majority of a rocket's weight comes from 3 factors: its propellent or fuel, its engine, and its payload (i.e. what the rocket is carrying).
8. Instruct students to use a think-pair-share strategy to discuss the question at the bottom of the Rocket Model Handout: How could a spacecraft's weight be reduced? Students should first study the handout and think about this question independently, then discuss their thoughts with a partner, and ultimately be ready to share their key discussion points with the class. As students share, remind them that there is no wrong answer to this question. They are just brainstorming!

DAY 2

1. Begin class by asking students to quickly recap some of the ideas they brainstormed during the last class period, especially in regards to how to lessen a spacecraft's weight. Then tell students that they are going to read an article called *Lightening the Load* that discusses how actual aerospace companies are trying to reduce the weight of spacecrafts.
2. Distribute one *Lightening the Load* Article Packet to each student, and read the intro segment aloud as a class. Together, use evidence from the first part of the article to discuss the guiding question: What was aircraft manufacturing like in the past, and how is it changing today?
3. Then split the class into four groups and assign each group one of the four remaining sections of the article. Instruct students in each group to work together to read the article segment and answer the accompanying guiding question. Tell the class that each group will be responsible for becoming an

expert on their section of the article, and they will later be responsible for sharing the answer to their guiding question with their peers.

Tip: If the four groups are large, it may be best to break each group into two smaller groups.

4. After about ten minutes have passed and/or most groups have finished, guide students in forming new groups of four throughout the classroom. One student who read each article segment should be represented in every group.

   Tip: If there are an odd number of students, it will be better for students to double-up in a group, rather than not having an article segment represented.

5. Turn the groups' attention to the last page of the article packet, and read the directions aloud. Then give groups about 20 minutes to share their answers and develop a response to the discussion questions.
6. Bring the class back together and talk about the last two discussion questions as a class. Encourage students to use evidence from the article to support their answers.
7. Wrap up by previewing that next session students will apply what they learned about topology optimization as they build something!

DAY 3

1. Begin by telling students that now that they are up to speed with current technologies, the Additive Manufacturing Management Team has results from a recent pressure test to share.
2. Project the Pressure Testing Results image.
3. Explain that pressure testing was recently performed on a newly-developed rocket fin. Image 1 shows the rocket fin as it was originally constructed. Image 2 shows the results of the pressure testing. Further explain that the purpose of the rocket fin's pressure test was to show which parts of the fin will experience the most pressure (i.e. have the most stress) throughout flight. In Image 2, red indicates high pressure and blue indicates low pressure.
4. Ask: Which parts of this fin are most crucial: the high-pressure areas or the low-pressure areas? Help students understand that the high-pressure areas are the most important. Without strength in these high-pressure areas, the fin would break or collapse!
5. Then bring students back to their initial challenge: to maximize spaceflight capabilities. Encourage students to think about what they learned over the past couple days, and discuss in groups of three: How can the results of this pressure testing be applied to make it easier for spacecrafts to fly long distances?
6. After students have a moment to discuss their thoughts with their peers, pass out one Topology Optimization handout to each small group. Explain that the directions will lead the pairs through creating a sketch and 3D model of a topology optimized rocket fin. Students will then briefly share their designs during the last 10–15 minutes of class.
7. Encourage students to read through the directions with their group and get started. As they work, distribute a ball of modeling clay to each pair so they have it when they begin Step 2.

8. Give students a five-minute warning when there are 10-15 minutes left in class. Then bring students back together and select a group to kick off the presentations to the Additive Manufacturing Management Team. As each group presents, be sure they explain their design choices and how the topology-optimized design will improve the spacecraft's flight.
9. Wrap up the student presentations with the following questions to ensure student comprehension:
    a. If we were to remove material from this fin to lighten the rocket's mass and increase acceleration, would it make sense to remove material from the high-pressure areas or the low-pressure areas?
    b. Out of the designs that were presented today, which do you think have the greatest chance of impacting space flight? Why?
10. Conclude by thanking the students for their hard work, and remind the class that internships and careers in additive manufacturing and topology optimization are rapidly expanding…So students should keep them in mind as they begin to consider their future careers!

Extend

While we know topology optimization can be used to help create structures on Earth, could they benefit extra-terrestrial projects too? Challenge students to research how 3D printing combined with topological optimization could benefit building bases on the moon . . . and beyond! Students can then apply their research to draft a memo for the Additive Manufacturing Division that details their findings and explains potential expansion opportunities.

National Standards

Next Generation Science Standards

Engineering Design

- MS-ETS1-1: Defining and Delineating 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.

Physical Science

- MS-PS2-2. Motion and Stability: Forces and Interactions
  The motion of an object is determined by the sum of the forces acting on it; if the total force on the object is not zero, its motion will change. The greater the mass of the object, the greater the force needed to achieve the same change in motion. For any given object, a larger force causes a larger change in motion.

Common Core English Language Arts Standards

Science & Technical Subjects, Grades 6–8

- RST.6-8.2 Determine the central ideas or conclusions of a text; provide an accurate summary of the text distinct from prior knowledge or opinions.
- RST.6-8.7. Integrate quantitative or technical information expressed in words in a text with a version of that information expressed visually (e.g., in a flowchart, diagram, model, graph, or table).

Common Core Mathematics Standards

Rations and Proportional Relationships

- 7.RP.A.2. Recognize and represent proportional relationships between quantities

F=MA

Instructions: Work with your group to investigate Newton's Second Law of Motion by following the steps below.

Step 1: Decide which group member will take the following roles:

- Assembler: You will be in charge of setting up the experiment.
- The Force: You will create the experiment's force by blowing into a straw.
- Timer: You will be in charge of operating the stopwatch.
- Recorder: You will be in charge of taking notes throughout the experiment.

Step 2: The **Assembler** should:

- Use the tape to create a starting line on a table or the floor.
- Measure 12 inches from the starting line and use the tape to mark the finish line.
- Place a ping pong ball on the starting line.

Step 3:

The Force should take a deep breath and practice exhaling steadily through one of the straws onto the ping pong ball, so that the ping pong ball is pushed from the starting line to the finish line. The **Timer** should keep track of how long this takes.

The Force should practice this several times until rolling between the two points takes about the same amount of time each time. It is important for **The Force** to be steady and consistent each time.

Step 4: Once your group has a steady force, begin the experiment:

1. Perform three trials to see how long it takes **The Force** to push the ping pong ball from the starting line to the finish line. **The Timer** should time how long each trial takes, and the **Recorder** should record it in the chart below. Be sure to record the time to the millisecond! (e.g. 1.003 seconds)
2. Repeat the experiment with the same steady **Force**—but this time the **Assembler** should replace the ping pong ball with the golf ball. The **Timer** and **Recorder** should continue to time and record each trial in the chart below.

	How long did it take to cross the finish line?			
	Trial 1	Trial 2	Trial 3	Average
Light Mass: Ping Pong Ball				
Heavy Mass: Golf Ball				

Step 5: When all trials are complete, work together to calculate the average time for each ball.

Step 6: Discuss the questions below as a group. The **Recorder** should jot notes as you discuss, so your group is ready to share your ideas with the class.

1. What effect did the increased mass have on acceleration (e.g. the trial times)?
2. What implications may this have for space exploration? In other words: What may aerospace engineers want to keep in mind as they try to design spacecrafts that can accelerate as quickly as possible?

Rocket Model

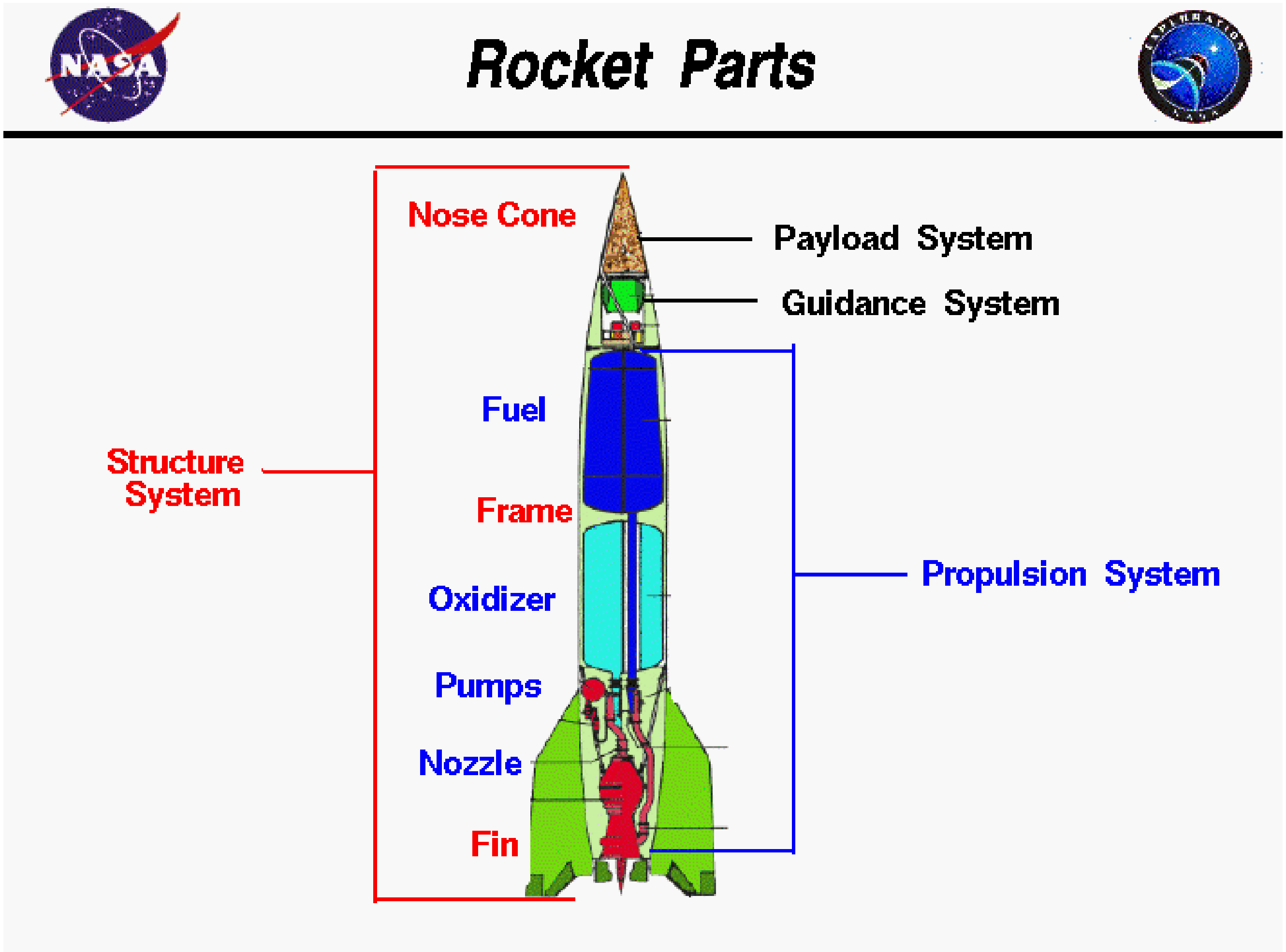


Image Source: https://www.grc.nasa.gov/WWW/K-12/rocket/rockpart.html

Brainstorm: How could a spacecraft's weight be reduced?

Lightening the Load Article Packet

Lightening the Load

by Emily Durham, Carnegie Mellon University Mechanical Engineering

Website: phys.org/news/2019-03-lightening-the-load.html

Intro:

The heavier an aircraft is, the more fuel it needs to stay in flight. Every single part adds to the total weight of the aircraft, from the wings to the engines to the bolts that hold everything together. The many parts that make up a vehicle are traditionally made using various machining processes in which raw materials are cut into their desired final shapes. However, traditional machining processes like milling or grinding are limited when it comes to optimizing shapes for the lowest weight. These traditional machining methods have led to manufacturers creating many separate parts that fit together—but this doesn't have to be the case.

Kate Whitefoot, an assistant professor of mechanical engineering and engineering & public policy, and Levent Burak Kara, a professor of mechanical engineering, are developing methods allowing manufacturers to consolidate discrete parts, by taking multiple different sized parts and redesigning them into a single part. This continuous part could then be 3-D printed in metal.

Guiding Question: What was aircraft manufacturing like in the past, and how is it changing today?

Text Segment 1

Additive manufacturing, also known as 3-D printing, allows for the production of new shapes that could not formerly be produced. As members of Carnegie Mellon's *NextManufacturing Center*, Whitefoot and Kara are using additive manufacturing to reimagine what's possible when creating component parts.

"What parts consolidation allows us to do is monolithically make components that would normally have to be assembled together," says Whitefoot. "This can substantially reduce the costs associated with making those parts, and also potentially allow us significant weight savings. So this is something that manufacturers are really interested in, particularly in industries like aerospace and automotive."

By consolidating multiple different sized parts into one part, Whitefoot can decrease the number of fasteners, remove mating surfaces associated with the parts, and monolithically print these parts. Under certain conditions, this can make them stronger than multiple parts that were, for example, welded together.

By redesigning the geometry of the parts to further reduce weight, Whitefoot's research could revolutionize many industrial sectors—particularly aerospace and automotive. When part consolidation is leveraged to bring down the production costs associated with the process, additive manufacturing becomes more cost competitive with more traditional manufacturing methods. By consolidating parts, Whitefoot and Kara are not only reducing production cost and weight savings, but also significantly decreasing the time spent printing the build.

Lightening the Load Article Packet

Guiding Question: What does 3D printing allow manufacturers to do? What are its benefits?

Text Segment 2

One reason why this [redesigning a product's parts so they weigh less] is so attractive in the aerospace sector is because pounds directly translate into fuel use throughout aircrafts' lifetimes. Every ounce saved by optimizing a part's size and weight can help offset that fuel use, thereby reducing costs and environmental impacts.

"If we can use these methods to significantly reduce production costs, then many more industries would be able to adopt additive and then take advantage of the performance benefits that it can bring," says Whitefoot, "which includes opening up the design space and potentially causing significant weight savings, having huge cost and environmental benefits when it comes to applications where we translate into fuel use."

Being able to merge parts and produce them as one single monolithic part is a giant leap for parts manufacturing, but the researchers want to take it a step further—towards automatic redesign. Whitefoot is working with Kara to automate the optimization of metal part shapes created through additive manufacturing—minimizing the weight of these parts, as well as the cost of production.

Guiding Questions: Why is this type of design beneficial to the aerospace industry? What else does the aerospace industry want to do?

Text Segment 3:

"With the advance of additive manufacturing, now we can manufacture more complex geometries," says Kara. "One thing that makes additive topology optimization attractive is that we can now manufacture parts that were only theoretically possible before. Within the parts, complex internal geometries can be produced to minimize the overall mass of the part, while making sure that the structure can withstand all the external forces applied to it as well as a traditionally machined part could."

Whitefoot and Kara are developing methods that allow for the automatic optimization of parts. With this research, a manufacturer could upload a CAD file of a set of parts, and these methods would automatically gauge the optimal way this set of parts should be consolidated.

Guiding Questions: This section describes a process called topology optimization. What is the main benefit of this process? When companies use topology optimization, what do they have to make sure of?

Lightening the Load Article Packet

Text Segment 4

"Taking several parts and automatically being able to synthesize them into one uniquely geometric part may not have been feasible before," Kara adds, "but with additive manufacturing, we can now not only optimize for the best combination of these parts, we can actually create the parts that were impossible to create with traditional machining methods."

Whitefoot and Kara are currently undergoing an initial one-year project with Boeing to demonstrate the feasibility of the methods they've developed. On the commercial market, it takes time to move from having a workable method in the research stage to actual commercial life ability—but the researchers forecast that this technology could be available commercially within a five-year time horizon.

"We're doing this to help additive manufacturing engineers and designers streamline the process of creating more automated tools," says Whitefoot, "so additive design can really move from an art to a science."

Guiding Question: What future goal(s) do Whitefoot and Kara have for topology optimization?

Lightening the Load Article Packet

Jigsaw Discussion Directions:

1. In the order of your article sections, each student expert should share their answers to their guiding question(s).
2. In the space below, jot notes as each expert shares.
3. Then work together to use the article, as well as what you have learned about space travel, to discuss and answer the discussion questions at the bottom of the page.

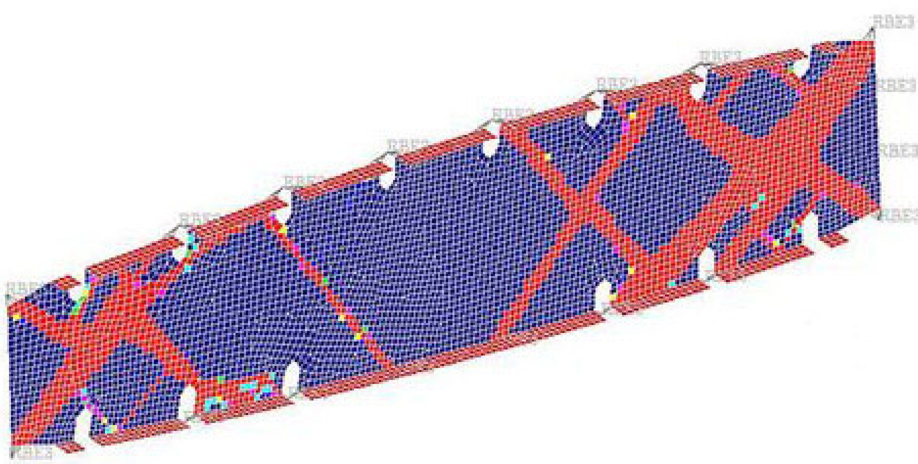
Notes:

Discussion Questions:

1. What is topology optimization?
2. Why are topology optimization and 3D printing often used together?
3. How could topology optimization help the aerospace industry?
4. What may aerospace companies have to consider when using topological optimization in aerospace vehicle construction?

Image #1
Original Rocket Fin

Image #2
Pressure Testing Results



Topology Optimization

Step 1: Plan

Your group's goal is to help spacecraft fly as easily and quickly as possible. Think about the pressure testing results and what you learned about topology optimization. Then in the blank square below titled *Image 3*, create a sketch of a topology-optimized rocket fin that could help you meet your goal!

Step 2: Model

Use Image #3 to create a 3D model of the topology-optimized rocket fin using modeling clay.

As you work with your group to create your model, follow the 3D printing process which **adds** material to create structures, rather than taking material way. To do this, start with a very small piece of clay and then add pieces little by little until you have a 3D model of the rocket fin you sketched above.

Step 3: Present and Justify

Prepare to share your design with the Additive Manufacturing Management team. Prepare a quick (less than one minute) presentation in which your group justifies your design choices and explains how this new design will improve the spacecraft's flight.

Pressure Testing Results Image

Image #1
Original Rocket Fin

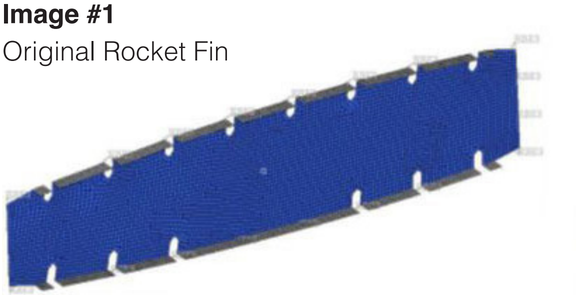


Image #2
Pressure Testing Results

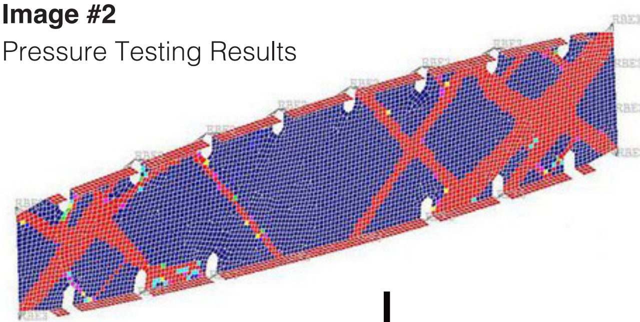


Image #3
Topology-Optimized Rocket Fin