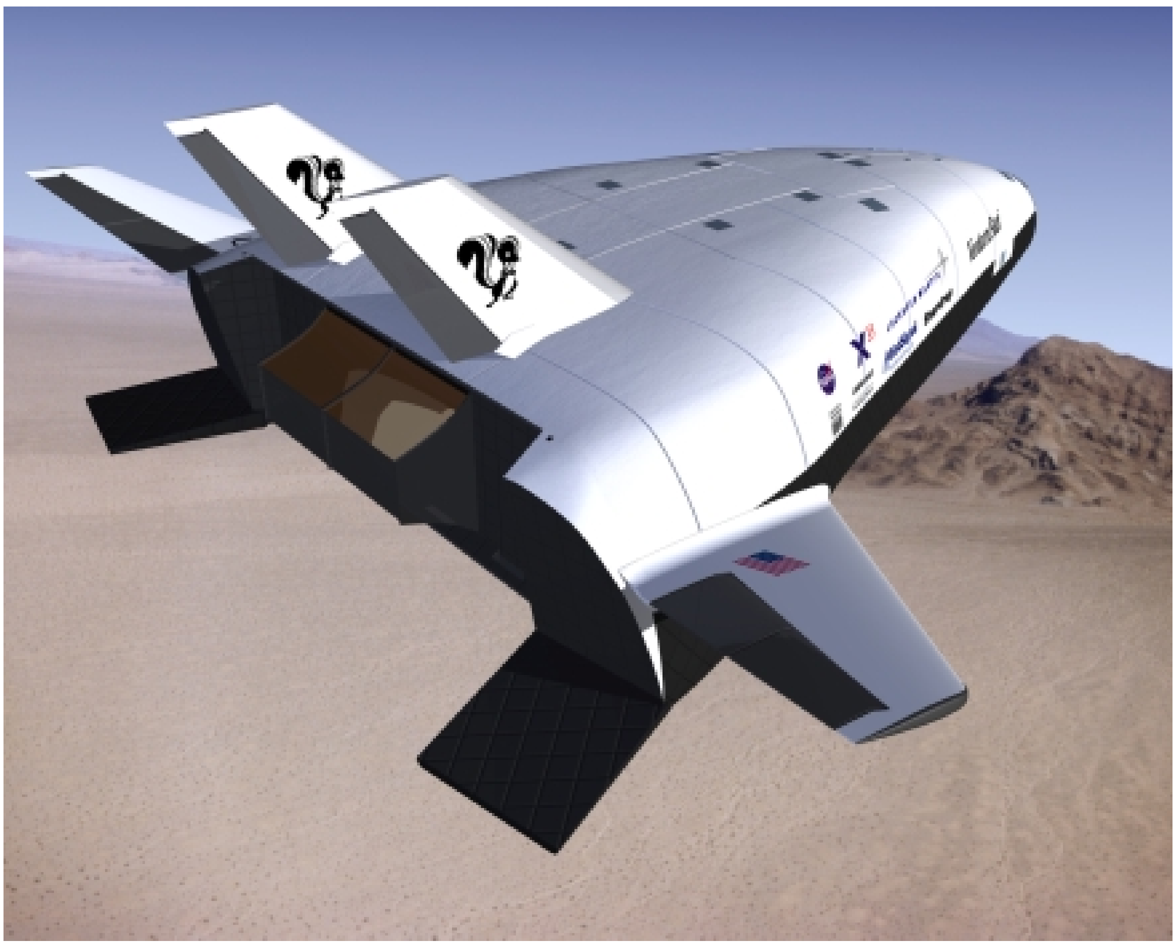
National Aeronautics and
Space Administration

Educational Product	
Educators	Grades 6-9

NASA Earth-to-Orbit Engineering Design Challenges

Thermal Protection Systems



Sponsored by

NASA Marshall Space Flight Center, Huntsville, AL

NASA Dryden Flight Research Center, Edwards, CA

Designed by

TERC, Cambridge, MA

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Overview

Space Transportation

NASA Engineers at Marshall Space Flight Center, Dryden Flight Research Center, and their partners at other NASA centers and in private industry are currently developing X-33, a prototype to test technologies for the next generation of space transportation. This single-stage-to-orbit reusable launch vehicle (SSTO RLV) may replace the Space Shuttle Orbiter and greatly reduce the cost of putting people, satellites, and scientific experiments into space.

Connect to Engineering and Science

The Earth-to-Orbit Engineering Design Challenges connect students with the work of NASA engineers by engaging them in related design challenges of their own. With some simple and inexpensive materials, you 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 structure from aluminum foil and copper screening that will protect a model of the X-33 from the heat of a propane torch for as long as possible. Students first measure the "protection time" of an unprotected model. Then they design, build, test, and revise their own thermal protection systems. 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.

Materials

You will need a few simple and inexpensive materials:

- A propane torch
- Some copper, aluminum, or brass screening
- Some aluminum foil
- Some wooden dowels
- A hot melt glue pot or glue gun and some glue (try a craft store)
- Some brass machine screws, nuts, and washers
- Some scraps of plywood
- Poster paper
- Markers
- Safety goggles
- A ring stand and clamps
- A fire extinguisher

Time Required

The design challenge can be carried out in seven 45-minute class periods, but you could easily extend it for twice that long. We give 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. The value of this activity to your students is 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. Students have many opportunities to learn about heat and heat transfer during the activities. 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 flyer to send home to inform parents about the activity and includes suggested activities students and parents can do at home together.

Safety

These activities meet accepted standards for laboratory science safety.

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
- Detailed materials list
- Extensions
- Resources
- Masters

National standards

If you have questions about how this activity supports the national science education standards, math connections, and thinking skills, read these sections that follow immediately. Otherwise, refer to those sections as you need them.

Suggested order of reading

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

Next, read through the Classroom Sessions that describe what happens in each of the seven sessions. Give special attention to the last part: "Linking Design Strategies and Observations to Science Concepts." This gives explicit suggestions on how to help students understand the science in their designs. Review this section once 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" and "Helping Students Understand the Design Process." 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: the thermal protection system (TPS). You will find information here about thermal protection systems in general, about the system used on the Space Shuttle, and about the new design for the X-33. An overview of the concepts of heat and heat transfer follows the section on thermal protection systems.

Further resources for you and your students can be found in the Resources section.

The reproducible masters you need are in the Masters section.

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.

National Science Education Standards

This Earth-to-Orbit 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.

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

All students should develop understandings about scientific inquiry.

Fundamental abilities and concepts

- Students should develop general abilities, such as systematic observation, making accurate measurements, and identifying and controlling variables
- 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

Physical science

All students should develop an understanding of transfer of energy.

Fundamental concepts and principles

- Energy is a property of many substances and is associated with heat and light
- Heat moves in predictable ways, flowing from warmer objects to cooler ones, until both reach the same temperature

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

Complete text of the National Science Education Standards http://books.nap.edu/html/nses/html/

Complete text of Benchmarks for Science Literacy http://watt.enc.org/online/ENC2299/2299.html

Science and technology

All students should develop abilities of technological design.

Fundamental concepts and principles

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

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

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 science ideas
- Involves construction that can be readily accomplished by students without lengthy learning of new physical skills or 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, provide benefits
- Perfectly designed solutions don’t exist; engineers build in back-up systems

Math Connections

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

Skillf	Application
Reading and writingf time measurements	Recording protection times
Performing operationsf with decimal numbersf	Protection time, size of TPS, quantities of materials
Roundingf	Rounding protection time to the second, tenth of a second, etc.
Calculating averagesf	Calculating average, mean, median, mode, or range for multiple tests of the same design, for all designs by one team, or for the entire class
Graphingf	Creating line graphs, bar graphs, circle graphs, or scatterplot of protection time Graphing protection time vs. mass of TPS Graphing protection time vs. size (width, length, diameter) of TPS
Measuring percentage improvementf	Comparing designs by one team, calculating improvement for the entire class
Calculating ratiosf	Determining the relationship between the quantity of materials used and protection time; between the flame length and protection time
Using a budgetf	See the extension activity: Designing on a Budget

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 students mastery of thinking skills.

Cognitive memory skills

1. Students accurately measure the protection time and compute the average time?
2. Students observe a design before testing and pick out the "key features"
3. Student 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., protection time, 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 heat transfer 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

Background

The X-33 Technology Demonstrator

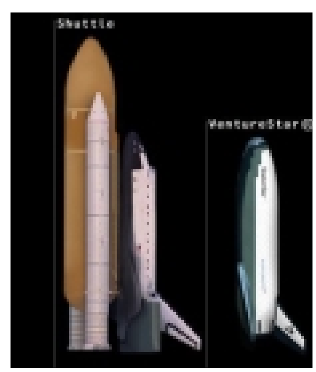
In 1972 NASA engineers began work on the first *reusable launch vehicle*. They wanted to build a rocket that would work like a plane. It would carry satellites and people into space, orbit the earth, reenter the atmosphere, and glide in for a runway landing. Nine years later the Space Shuttle Orbiter *Columbia* roared off the launch pad at Kennedy Space Center. Since 1972, the Space Shuttle has been carrying astronauts, satellites, and science experiments into space.

VentureStar and X-33
"The key to the next era of exploration and expansion, beyond globalization, is to make access to space reliable, affordable, and safe. We must do it. We are going to do it." Daniel Goldin, NASA Administrator

The Space Shuttle, is an engineering marvel, but it is expensive. It costs $10,000 to carry a pound of payload into space. If a space shuttle took 50 people for a flight, they would each have to pay $8,400,000 and that doesn't include souvenirs. Unpiloted rockets that only get used once cost about the same as the Space Shuttle to carry satellites into orbit. The Space Shuttle also takes a long time to get ready for its next launch. Technicians must inspect , repair, and re-waterproof all of the thermal protection tiles and blankets and that takes a long time.

With a less expensive and faster way of getting to orbit, we could do more in space. For example, NASA's largest project in 1999 is building the International Space Station. The Space Station will orbit the Earth and provide a place for scientific research and medical experiments. Missions to other planets may leave from the Space Station. We will need a better and less expensive way of getting to and from the Space Station. Just as lower airfares let more people fly, a less expensive launch vehicle could let more people work and even vacation in space.

The VentureStar Web Site
http://www.venturestar.com/



NASA engineers, along with engineers from private companies, are now working on *the* X-33, a vehicle to test and demonstrate technologies that could be used to build a vehicle to succeed the Space Shuttle. This vehicle would cost much less to operate, and be ready to launch much faster than the space shuttle. It might cost only $1000 to put a pound of payload into space, and while it takes several months to ready the space shuttle for launch, a new vehicle could be ready to launch again only a few days after it lands.

As the first step in building a new vehicle, NASA engineers (and their partners at Lockheed, B F Goodrich, Boeing, AlliedSignal, and Sverdrup) are building a model called the *X-33*. This vehicle is half the size of the new vehicle. The X-33 will launch but it won't carry people or a payload and it won't actually go into orbit. It is designed as a "technology demonstrator" so that engineers can test the many new materials and technologies they will use on the new vehicle, currently named *VentureStar*. One of the technologies being tested on the X-33 is a new thermal protection system.

Marshall Space Flight Center's X-33 Web Site
http://x33.msfc.nasa.gov

NASA Fact Sheet on the X-33
http://www1.msfc.nasa.gov/NEWSROOM/background/facts/x33.htm

Thermal Protection Systems

How thermal protection systems work

When a space vehicle re-enters the Earth's atmosphere, air friction can heat the surface of the vehicle as high as 3,000°F (1650°C). That is hot enough to melt steel. NASA engineers must design a way to protect the vehicle and the people and equipment inside. The system for protecting a spacecraft from high temperatures is called a Thermal Protection System or TPS.

A TPS is a covering on the spacecraft that can withstand the heat of re-entry and keep that heat from reaching the inside of the spacecraft. Think of other heat protection "systems" you may have seen or used—a potholder to pick up a pot from the stove, a thermal bottle to keep the soup inside hot, a fireman's special coat. These are doing the same job as the TPS on a spacecraft.

There are two ways that a TPS can keep heat from reaching the inside of the spacecraft. The first way is to absorb the heat that hits the spacecraft and hold that heat without letting it pass through to the inside of the vehicle. As the TPS absorbs heat it gets hotter. If the TPS absorbs too much heat, it will melt. Because there is so much heat when a spacecraft re-enters the atmosphere, only materials with very high melting temperatures can be used as a TPS.

Periodic Table of Elements
http://library.advanced.org/3659/pertable

The second way the TPS works is to send the heat back into space. All materials *radiate* heat when they get hot. You can feel this whenever you put your hand near something hot like a radiator or a hot stove, or the coals of a campfire. You can also see heat being emitted when you see something glow red-hot like a burner on an electric stove or the coils in a toaster. When the TPS radiates heat back into space, that heat does not reach the inside of the spacecraft. Some materials radiate more heat than others do.

Think about how different materials react to high heat. Some materials, like paper or wood, will burn up or vaporize because they can't absorb much heat and they can't radiate much heat. Some materials, like metals, can resist high temperatures without melting or burning, but even metals will eventually melt if they get too hot. The table below shows the melting temperatures of certain metals.

MaterialB	**Melting temperature**	
Aluminum	660°Cf	1220°F
Copperf	1083°Cf	1981°F
Nickelf	1453°Cf	2647°F
Ironf	1535°Cf	2795°F
Chromium	1857°Cf	3375°F
Tungstenf	3422°Cf	6192°F
(highest melting temperature of all metals)		

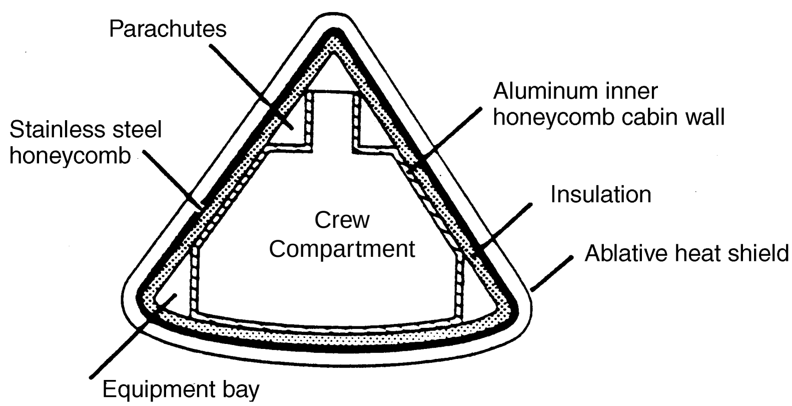
Some materials, such as the special ceramic tiles used on the Space Shuttle, can withstand high temperatures *and* radiate lots of heat. Engineers study materials carefully to find the best ones to use for a TPS.

Keeping the thermal protection lightweight

A launch vehicle's engines can lift a certain amount of weight into orbit. That weight is divided between two parts: the weight of the vehicle itself (including the fuel) and the weight of the passengers and the payload. If one part gets larger then the other part must get smaller (unless you build a larger engine). The more the structure of the vehicle weighs, the fewer passengers and smaller payload it can carry. Designers try to keep all the parts of the vehicle, including the Thermal Protection System, as light as possible so that more of the allowed weight can be used for passengers and payload.

The challenge for engineers designing a TPS is to select a material that will absorb and emit a lot of heat energy but still be very light weight. Throughout the history of space vehicles, engineers have used various strategies for thermal protection systems. You will read about some of them in the next section.

Apollo Entry Module Thermal Protection System



Thermal Protection Systems on early space vehicles

Early manned spacecraft, such as Mercury, Gemini and Apollo, re-entered the atmosphere tail end first. For thermal protection the tail end was covered with a heavy material that came off in tiny pieces when it got hot. The material would absorb heat and then vaporize a little bit at a time. This process is called *ablation* and the material used for the TPS is called *ablative material*. Each little bit of the thermal protection shield that came off of the spacecraft took some heat energy with it. This prevented the heat from getting into the vehicle, but It still got rather warm in the capsule during re-entry.

It didn't matter so much that the ablative TPS material was heavy because the engines used for those early rockets had more than enough thrust to carry the rocket out of the atmosphere. It also didn't matter that the thermal protection came off during re-entry because those spacecraft were only used once. They were *disposable* rather than *reusable*.

Thermal Protection System on the Space Shuttle

On-line information about the Space Shuttle Orbiter Thermal Protection System
NASA Facts On Line, John F. Kennedy Space Center
http://www-pao.ksc.nasa.gov/kscpao/nasafact/tps.htm

Introduction to the Space Shuttle: Shuttle Systems
http://163.206.3.4/processing/m1/s1-8a_tps.html

Space Shuttle News Reference Manual
http://www.ksc.nasa.gov/shuttle/technology/sts-newsref/sts_sys.html#sts-tps

The Space Shuttle orbiter was the first space vehicle designed to be used many times. A heavy thermal protection system that came off during re-entry wouldn't work. The Space Shuttle needed a Thermal Protection System that was lightweight to keep the weight of the entire vehicle low. The Thermal Protection System also needed to stay on the Space Shuttle so that it could be reused.

NASA selected four materials for the original Space Shuttle, *Columbia*. The materials were Reinforced Carbon-Carbon, two kinds of silica tiles, and felt blankets. Designers later replaced the original materials with better tiles and blankets made from new materials that were stronger and less expensive.

The orbiter's nose cone and the front edges of its wings heat up the most during re-entry. When the orbiter is at its hottest, about 20 minutes before touchdown, temperatures on these surfaces reach as high as 3,000˚F. Reinforced Carbon-Carbon (RCC) protects the orbiter's nose and wing leading edges from the highest temperatures. RCC is a combination of materials called a composite. To make RCC graphite cloth is saturated with a special resin then layers of the cloth are combined and allowed to harden. Finally they are heated to a very high temperature to convert the resin into carbon.

Most of the surface of the orbiter is protected from heat by silica fiber tiles. There are two kinds of tiles. The high temperature tiles protect areas where temperatures reach up to 2,300˚F. These tiles have a black surface coating. The low temperature tiles protect areas where temperatures stay below 1,200˚F. These tiles have a white surface coating. There are approximately 24,300 tiles on the outside of each orbiter. The tiles dissipate heat so quickly that you could hold a tile by its corners with your bare hand only seconds after taking it out of a 2,300˚F oven even while the center of the tile still glows red with heat. To make the tiles, engineers start with fibers of pure white silica made from common sand. They mix the fibers with water and other chemicals and pour the mixture into a mold where the excess liquid is squeezed out. This leaves damp blocks. The blocks are dried in the nation's largest microwave oven, then they are baked in another oven at 2,350˚F. Finally, the tiles are glazed, coated, and waterproofed.

RTV, room-temperature vulcanizing. An adhesive that cures at room temperature

Some of the upper surfaces on the Space Shuttle are protected by Flexible Insulation Blankets. There are 2,300 Flexible Insulation Blankets on the outside of each orbiter. These blankets look like thick quilts. They are made of silica felt between two layers of glass cloth sewn together with silica thread. The blankets are more durable and cost less to make and install than the tiles. The blankets protect areas where temperatures stay below 1,200˚F.

The tiles and insulation blankets are bonded to the orbiter with room-temperature vulcanizing (RTV) adhesive. The adhesive will withstand temperatures as high as 550˚F, and as low as -250˚F without losing its bond strength.

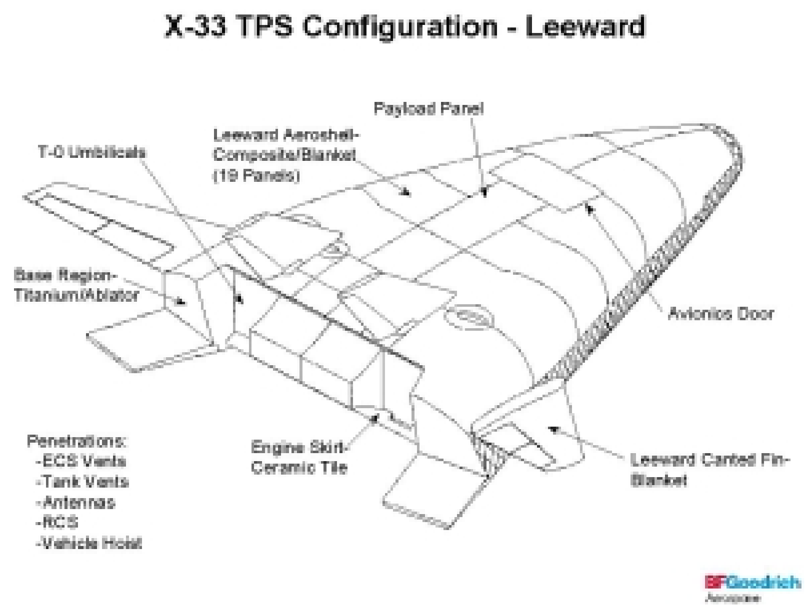
Drawbacks to the Space Shuttle TPS

The Space Shuttle TPS is not perfect. It has some problems that engineers would like to fix. First, it is heavy. Even though each tile is very light weight and the blankets do not weigh much either, there are so many tiles and insulation blankets and reinforced carbon-carbon that the weight of the TPS is a significant portion of the total weight of the Space Shuttle.

TPS tiles on the Space Shuttle are fragile. They are soft and are easily damaged by woodpeckers on Earth or meteorites in space. Sometimes they fall off when the Space Shuttle launches or re-enters the atmosphere. After each flight, scratches and gouges on the tiles must be repaired. Badly damaged and missing tiles must be replaced.

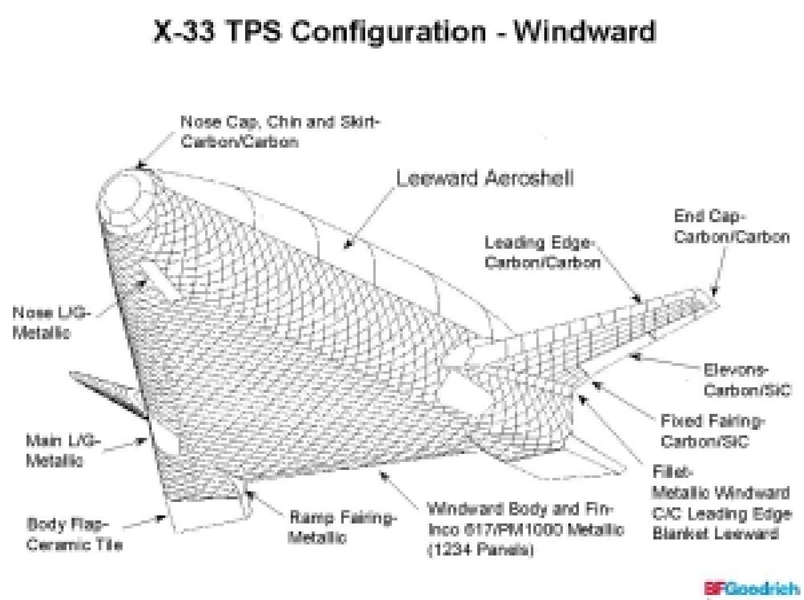
Because the uncoated tiles readily absorb water they are waterproofed. They must be re-waterproofed after each mission because the waterproofing burns up on re-entry. Repairing and waterproofing the TPS is time-consuming and expensive. If the Space Shuttle encounters rain during landing, the tiles could absorb water, which would make the vehicle much heavier and could damage the tiles.

Finally, the Shuttle TPS is expensive. A single coated tile can cost as much as $2,000. That's $48 million per Space Shuttle orbiter.



The X-33 TPS

The X-33 will be the first spacecraft that uses its skin as a thermal protection system. (The Space Shuttle's thermal protection is glued on top of the skin.) The X-33 thermal protection is not on top of the skin, it *is* the skin, which, on a spacecraft, is called the s*tructural shell*. Because the same material serves as both structural shell and thermal protection, the X-33 saves a lot of weight. Between the panels and the walls of the fuel tanks on the inside there is a small amount of space. This air space works like the space between double paned windows or between the two walls of a thermal bottle. It provides added insulation for the X-33.



The X-33 TPS is made of metal panels placed over insulating material. The metal panels consist of thin layers of the alloy Inconel. Inconel was, in fact, used as part of the TPS on the X-15, which flew during the 1959-1968 period. Inconel contains nickel, chromium, and iron. The two layers of Inconel are extremely thin, only .006 inch thick, about the thickness of a human hair. In between the two layers is a metallic honeycomb. Underneath each metal panel is a foil bag containing insulating material. About 1,200 panels will make up the external skin of the vehicle.

INCONEL

Nickel (Ni)B	**76%**
Chromium (Cr)B	**17%**
Iron (Fe)B	**7%**
Melting Point:B	**1370°C**
Density grams/cm³:B	**8.25**

The metal panels have many advantages over the tiles used on the Space Shuttle. Instead of being glued on, the metallic panels are attached with a bolt at each corner. This makes them much easier to put on and take off. The panels are also much more durable than the soft silica tiles and blankets. They will protect the vehicle from meteoroids, at least very small ones, called micrometeoroids. Metal panels only need to be waterproofed once. This saves a lot of time in between launches.

Two other parts of the X-33 TPS are very similar to the TPS of the Space Shuttle. On the upper surface of the X-33 where temperatures do not get as high during re-entry, insulation blankets will be used. And carbon-carbon will be used for the surfaces that get the hottest during re-entry, the nose and the edges of the fins.

See the Resources section in the back of the guide for further information on Thermal Protection Systems.

Review questions for class discussion or homework

1. What are the major parts of the Space Shuttle's thermal protection system?

2. What temperature do the tiles and blankets need to withstand?

3. What temperature can the cement that holds the tiles and blankets onto the Space Shuttle withstand?

4. What must be done to the Thermal Protection System in between Space Shuttle missions?

5. If you were a NASA engineer trying to improve on the design of the TPS for the Space Shuttle, what would you try to improve?

Answers to review questions

1. Reinforced Carbon-Carbon, silica fiber tiles, and Flexible Insulation Blankets.

2. High temperature tiles protect areas where temperatures reach up to 2,300˚F. Low temperature tiles and blankets protect areas where temperatures stay below 1,200˚F.

3. 550 degrees F

4. Damaged tiles must be replaced and the entire Thermal Protection System must be re-waterproofed.

5a. More durable materials

5b. Lighter weight materials

5c. Waterproof materials (for example, metal)

5d. Less expensive materials

5e. Make TPS easy to repair or replace

Heat and Heat Transfer

This unit provides an opportunity for you to introduce or reinforce concepts of heat and how heat moves. Students should be able to—

- Identify the direction in which heat flows
- Explain how conduction, convection, and radiation differ
- Identify factors that determine the conduction rate of heat through a solid
- Identify several materials that are good conductors and several materials that are good insulators
- Describe radiation, absorption, and reflection in terms of radiant heat

Heat is a form of energy. Heat always flows from a hotter place to a cooler place. The hotter place is sometimes called a heat source and the cooler place is sometimes called a heat sink. Heat transfer occurs in three ways:

Conduction

Heat moves by *conduction* when it flows through a solid substance or when heat flows between solid substances that are in direct contact. For example, when you touch your hand to a cold water pipe, heat flows from your hand to the pipe by conduction. Two solid surfaces at different temperatures are in contact. Heat is transferred by conduction.

Materials that conduct heat well are called *thermal conductors* while those that conduct heat poorly are called *thermal insulators*. Metals are good conductors while wood, glass, ceramic, and plastic foam are good insulators. Air is an insulator. Small pockets of air in wool, fur, and feathers keep heat from passing through, making these materials good insulators. Air spaces are also used to insulate buildings, for example between double pane windows.

Convection

Heat moves by *convection* when it flows through a liquid or gas because the liquid or gas particles move. In the winter when you feel a draft coming off a cold window, you are feeling a convection current of air. When a “warm front” of weather moves in, the warmth is brought by trillions of hot molecules of air traveling across the earth in a huge convective stream. When you see “heat” rising over a radiator or over any hot surface, you are seeing a convective current of warm air.

Radiation

Heat moves by *radiation* when it flows through empty space or a transparent medium without heating the space or the medium. Heat reaches earth from the sun by means of radiation. When you feel the heat of glowing coals or of a hot wood stove, you are feeling radiated heat. Radiated heat travels as electromagnetic waves. Most of the thermal energy is in the infrared portion of the spectrum, which is not visible.

Thermal conductivity and heat capacity

One of the things that students discover in this activity is that materials react differently to heat. Some materials readily *conduct* heat. They have high *thermal conductivity* and are good *thermal conductors*. *Thermal conductivity* refers to the ability of a material to transmit heat by conduction. Materials that have *low* thermal conductivity make good *thermal insulators*. In the TPS models, both copper and aluminum are good thermal conductors, though copper is almost twice as conductive as aluminum. (See first column in table below.)

Joule = amount of energy required to raise a 100g mass 1 meter

Watt = a measurement of power; 1 watt = 1 joule/second

If you hold your hand up to the sun, your hand will receive about 10 watts of energy on a clear, sunny day

A square meter of the Earth's surface receives 1000 watts from the sun.

Some materials *absorb* a lot of heat without heating up very much themselves. They have a high thermal capacity, or *specific heat*. Materials that have high specific heats make good heat sinks.

Thermal Conductivities and Specific Heats of Materials

Substancef	**Thermal ConductivityB** (Joules/s x m x ˚C)f	**Specific Heat** (kcal/g x ˚C)
Silverf	420f	56
Copperf	380f	93
Aluminumf	200f	220
Steelf	40	
Glassf	0.84f	200
Brick and concretef	0.84	
Waterf	0.56f	1000
Human tissue without bloodf	0.2f	830
Asbestosf	0.16	
Woodf	0.12f	400
Cork and glass woolf	0.042	
Downf	0.025	
Airf	0.023	

Source: *Principles with Applications*, 2nd edition, Douglas C. Giancoli Englewood Cliffs, NJ: Prentice Hall, 1994 p. 260

What's the difference?

These two ideas, thermal conductivity and heat capacity, are easily confused. However, it is important to understand the difference. One describes how readily a material transports heat internally; the other describes the heat-holding capacity of a material.

Students will sometimes think that a good conductor is also a good heat sink. This is not necessarily so. For example, consider water. Water has a very high specific heat, but only modest thermal conductivity. Similarly, compare silver and aluminum. Silver has more than double the thermal conductivity of aluminum, but has only 1/4 the specific heat. So, gram for gram, silver would make a better thermal conductor and aluminum would make a better heat sink.

Thermal conductivity and the TPS

In designing and testing their TPS models, students may talk about the TPS "absorbing heat," "conducting heat," and "storing heat." When they do so, you can lead the discussion in a more precise direction by introducing the ideas of thermal conductivity and specific heat and referring to this table.

Students also learn that they want to avoid conducting heat from the flame to the glue joint. They learn through experience that attaching copper or aluminum foil directly to the brass screw will provide a good conduction path for the heat to reach the glue. In contrast, if they introduce an air gap in the conduction path, air, which is a good insulator, will impede the flow of heat to the screw. The table shows how this makes sense: air, like down, has a very low thermal conductivity, while copper and aluminum have high conductivities.

Specific heat and the TPS

Students may speak of their TPS model functioning as a "heat sink." Whether it does so, in fact, depends on both the nature of the material and the mass of material involved. In fact, the mass of copper screen and aluminum foil used is so small that the ability of the materials themselves to absorb and hold heat is fairly minimal. Nonetheless, the idea of a heat sink provides an opportunity to discuss specific heat. Here is a more precise explanation of specific heat.

Specific heat refers to the quantity of thermal energy a given mass of material must absorb in order to increase its temperature a given amount. Typically, this is indicated as the number of kilocalories needed to raise the temperature of one kilogram of the material by one degree Celsius. (The table above, as noted, uses kilocalories/gram x ˚C.) For example, it takes one calorie (4.184 joules) of heat energy to raise the temperature of one gram of water 1˚C. The heat capacity of water is 1.0 cal/g˚C. The specific heat of a material is a measure of how well it will function as a "heat sink." The table shows that aluminum has about 2.5 times the heat-absorbing capacity of copper, and, therefore, would make a better heat sink. It must absorb nearly 2.5 times the heat energy as the same mass of copper before its temperature increases 1.0˚C.

As an exercise, you could have students measure the mass of the copper screen and the aluminum foil and, using their respective specific heats, calculate which would make the better heat sink. The "heat absorbing capacity" of a given mass is proportional to its mass times its specific heat, so

the heat absorbing capacity of a given amount of material = $m \times c$

Where m = the mass of material

c = the specific heat of the material

If a TPS contained 4 grams of copper, its heat absorbing capacity would be

$$4\ \text{g} \times 93\ \text{kcal/g} \times {}^\circ\text{C} = 372\ \text{kcal} / {}^\circ\text{C}$$

which means that the copper would absorb 372 kilocalories for each 1 degree C increase of temperature. If it rose in temperature by 10 degrees, it would absorb 3,720 kilocalories of energy.

Teacher Preparation

In order to prepare yourself and your classroom for this engineering design challenge, you should:

- Use the Background Information section of this guide, as well as the Earth-to-Orbit Engineering Design Challenge web site to familiarize yourself with Thermal Protection Systems 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 test stand
- Build the test assemblies
- Practice the test procedure with your own TPS 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 back of the guide

Required Materials

You can find complete details about sources, cost, and suitable replacements for materials in the Detailed Materials List later in this guide.

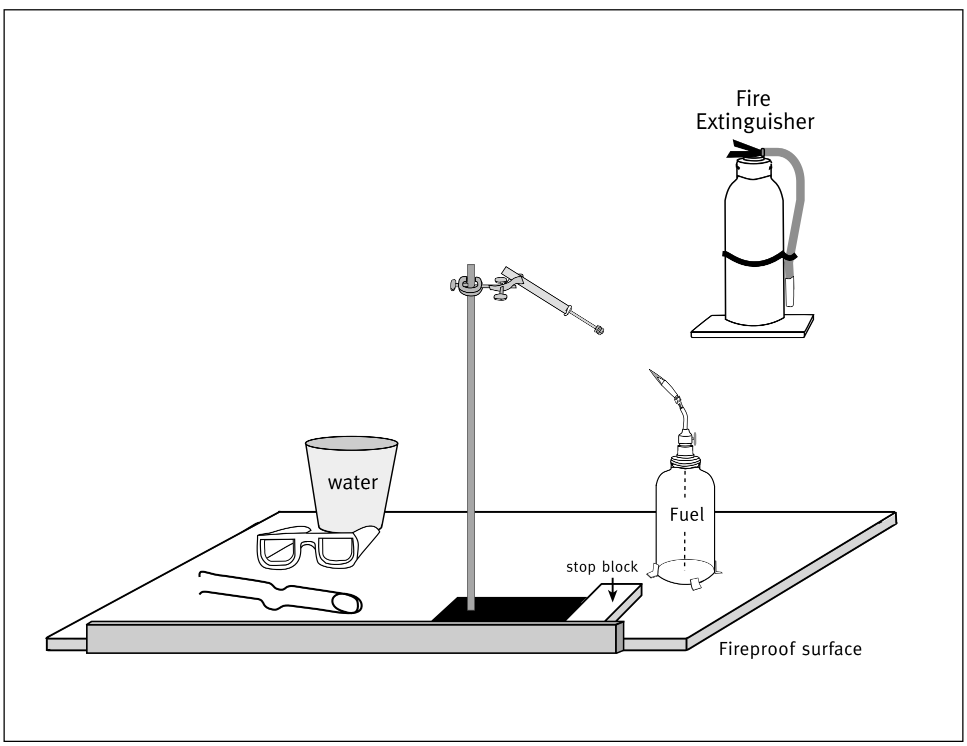
Required MaterialsB	**ApproximateB cost per unitB**	**Minimum quantityB for a few teamsB (60 test assemblies)**	**Recommended quantityB for 12–15 teamsB (120 test assemblies)B**	**Add for each additional team (10 test assemblies)**
Propane torchf	$11.00f	1f	1 (and a spare tank)f	0
Test stand (see instructions below)f		1f	1f	0
Hot-melt glue pot (or glue gun)f	$10.00f	1f	1 and a sparef	0
Hot-melt gluef	$0.15 - $0.50f	6 sticksf	12 sticksf	1 stick
Birch Dowels 1/4 inch diameter, 3 feet longf	$0.30f	4f	15f	1
Brass Pan Head Phillips Machine Screws (6-32 x 1 inch)f	$0.06f	100f	200f	10
Brass Hex Nuts (6-32)f	$0.03f	100f	300f	20
Brass Flat Washers (#6)f	$0.02f	100f	300f	20
Copper woven wire cloth (“screen wire”)f	$2.00-$4.00/sq. ft.f	3 sq.ft.f	6 sq. ft.f	1/2 sq. ft.
Aluminum foilf	$0.04/sq. ft.f	25 sq. ft.f	75 sq. ft.f	6 sq. ft.

Build the Test Stand

The Test Stand contributes to the safety and accuracy of the tests. It holds the torch fixed in position and makes it easy to position the model correctly by sliding a ring stand until it hits a stop. It also protects the table top against hot material falling from the model.

Materials needed

- A propane torch and a spare propane bottle
- A ring stand with a rectangular base and additional clamps to hold the test assembly in position
- A piece of 3/4 inch plywood anywhere from 14 by 22 inches to 20 by 36 inches (This is the base board. 16 by 28 inches is recommended.)
- Two pieces of 1 x 2 (actual dimension 3/4 x 1-1/2), one piece 18 to 24 inches long and another piece 2 to 6 inches long
- Two to four right-angle metal brackets approximately two inches long
- Screws for attaching the brackets and 1 x 2s to the base board
- Tape to attach the torch to the brackets
- Several 4 inch long pieces of 1/4 inch diameter wooden dowel
- Aluminum foil
- (Optional: a piece of insulating firebrick and some furnace cement)



A note on materials

3/4-inch plywood is generally easily available and makes a good material for the base board. 3/4-inch plywood is thick enough that screws can be driven into it without sticking out the bottom surface. Thinner plywood could be used, but different means would need to be used for attachment. For example, carefully countersunk flat head screws could go through the bottom of thinner plywood into the 1x2s, and wood blocks, attached the same way, could hold the torch.

How it works

To test a model you will load it onto the ring stand away from the flame. The model should be supported by the familiar ring-stand combination of clamps and rods. Then you will place the base of the ring-stand against a small board or other guide, and slide it toward the flame until the base hits a stop. This is a quick and safe way to move the model into the test position, and there is even an audible "thunk" that makes a good signal to begin timing. As soon as the test is completed, slide the ring-stand away from the flame and prepare it for the next test.

It's important for safety that the torch remains fixed in position. The teacher lights the torch and extinguishes it after testing, but it stays attached to a base board at all times. This also ensures that the flame is always in the same place, which simplifies placing the models in exactly the right position for each test—simply loosen the clamp, remove the tested model and insert the next one.

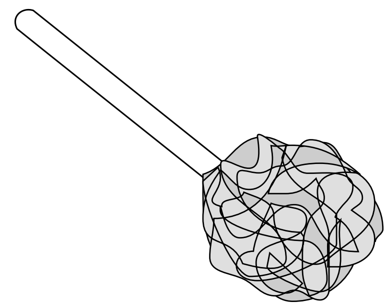
Simple construction

Begin by setting up the torch (don't light it yet) and the ring stand on the base board. Use ring-stand hardware to hold the four-inch dowel (simulating the length of the test assembly) so the tip is 10 cm from the torch nozzle. The angle of the dowel should match the angle of the torch nozzle. You'll want to be able to place each subsequent test assembly in the clamp just the same way. To make this easier, line up the top end of the dowel with some feature on the clamp that holds it. For example, you might want to make the end of the dowel flush with the top edge of the clamp. Tighten all the clamp screws securely (except the one holding the dowel) so they don't slip.

Next, consider where to place the guide for sliding the ring stand base. It should be attached to (or near) the long edge of the board, and a long side of the rectangular ring stand base should align with it. If you are using a tripod base, two feet of the tripod should rest against the guide. (You may need to rotate the test assembly holder around the vertical rod to line it up with the base.) Looking at the test stand as shown in the drawing, position the center of the torch fuel bottle about 6 inches from the right edge of the base board, and find the correct distance from the near edge so that the torch and the test assembly line up properly. Verify that you can slide the ring stand a foot or so away from the torch while keeping the base against the guide, and that the base slides smoothly back into position. Use a pencil to mark the position of the fuel bottle, the guide board, and the ring stand base.

Attach the guide board to the base board. Next use the brackets to locate the fuel bottle where it belongs. Simple right-angle brackets sold in hardware stores usually come with mounting screws short enough to screw into 3/4 thick wood.

In order to work out the final details of the test stand, including positioning the stop block, you'll need to light the torch and make sure the hottest part of the gas leaving the flame hits the test assembly directly. Use some aluminum foil to protect the end of the 4-inch long dowel from the flame. (You can just press a ball of crumpled foil onto the end of the dowel as long as you can tell from looking at the foil where the center line of the dowel would come through.) When you put this "alignment fixture" in the flame, the hottest part will glow red. You'll want to adjust the ring stand so that the dowel is directly in line with that hottest part. The foil won't withstand the flame for long, so slide the ring stand into place, take a look, slide it away, make an adjustment, and try again. (If you have a good supply of 4 inch long dowels, you could try using them without any protection, and look from different angles to see whether the hot gases from the flame are hitting them directly on the end. However, they will smoke and burn after only a few seconds of exposure.) When you have found the right alignment for the model, leave the ring stand in place, turn off the torch, and mark the location of the ring stand base. Tape the torch to the brackets so that it won't rotate. Attach the stop block so that you can easily slide the ring stand to the precise position you just found.



An aluminum foil ball on a dowel used to align the test stand

Build the Test Assemblies

With some experience, it's quick and easy to build test assemblies.

Materials needed

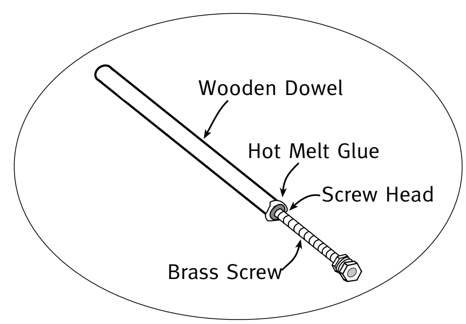
Screws, 6-32 machine screws, 1 inch long

3-inch long pieces of 1/4"-inch diameter wooden dowel

Low-temperature hot-melt glue (Dual-temperature glue may also be used, but low-temperature is preferred.)

Glue pot (a glue gun may also be used, but the pot is preferred.)

A way to hold the dowels vertical as the glue cools. (See below.)

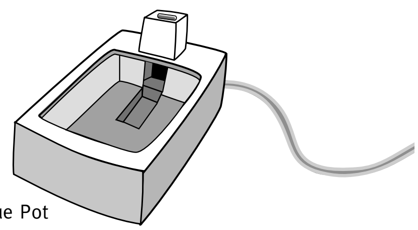


Using hot-melt glue

Hot-melt glue is widely used in classrooms, and it is fun to work with. Low temperature glue is preferred because it is less likely to cause burns, and it makes for a better Thermal Protection Challenge. In this activity, hot-melt glue is used only to build the test assemblies by attaching the metal screw to the wooden dowel. *It is not an appropriate material for use in the students' TPS designs because it melts easily and can burn when exposed to the flame.*

Attaching the screw to the dowel

The glue pot is recommended because it makes it easy to use hot-melt glue with the metal screw. When hot-melt glue is first applied to the screw, it does not stick, because the screw is relatively cold and very conductive, so it cools the glue, which then loses its stickiness. Hold the screw with the head slightly dipped into the glue pot for about 10 seconds. The screw will warm up, and the glue will stick. Then you can press the head of the screw (with the clinging glue) onto the dowel and hold it for a few more seconds as the glue hardens. It won't take long to learn how much to let the screw warm up before pressing it against the dowel. If you heat the screw too much, it will be too hot to handle comfortably, but satisfactory gluing will occur at lower temperatures.



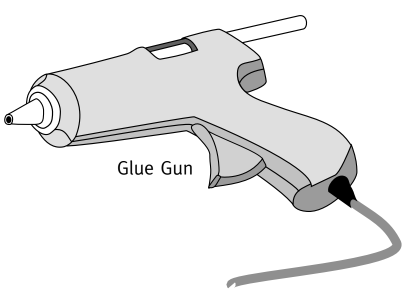
Glue Pot

It is helpful to have a way to put down the test assembly in a vertical position so the screw stays straight as the glue continues to cool. You might use a block of foam or wood with a dozen or more vertical holes, or a container of sand, or another arrangement.

The glue pot will work best with only a small amount of glue in it. It is fun to put more in, but you'll get the best results if the glue puddle is so shallow that you can touch the head of the screw on the bottom of the glue pot without glue running onto the back of the head.

After you have made a few test assemblies, let them cool thoroughly and check to see whether they are strong enough to withstand normal handling. They are not strong, but they should not fall apart easily. Students will learn how carefully to handle them by breaking a few as they begin to work with them, but those can easily be replaced. Students can also learn to make the test assemblies, and you will probably prefer to have a few students make more of them so that you always have plenty on hand. It is probably not a good idea to expect all of the students to make the test assemblies—there is a knack to making them, and once a few people have learned to do it right, they can keep everyone supplied.

Using a glue gun to attach the screws to the dowel



Glue Gun

It is a little more complicated to use a glue gun, but still practical. Depending on the design of your glue gun, you might find that it is satisfactory merely to hold the head of the screw against the tip of the glue gun to allow the screw to warm for a few seconds before squeezing a small amount of glue onto it. It may work better to hold the head of the screw over a candle flame for a few seconds before applying the glue. (Hold the screw just above the flame for best heating. This also avoids soot.) Still air will make the candle technique work better. For adult use, the propane torch could be set to a very low flame, and the screw head warmed very briefly. It would be easy to make the screw much too hot this way, so it is not recommended for student use.

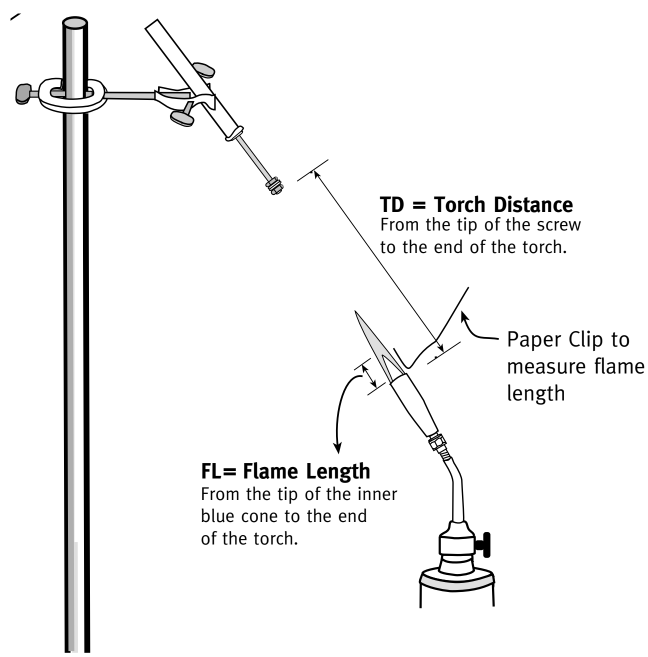
Practice the Test Procedure with Your Own TPS Designs

Once you have built the test stand, you will want to try some models yourself to become familiar with adjusting the stand and assuring consistent test conditions.

Adjust the torch

It is important to find a way to set the torch to the same flame size for each test. The exact way you choose to do this will depend on the torch you are using and the amount of heat from the flame that is appropriate for your students' models. Most propane torches produce flames that increase in length as the gas flow is increased, with a range of 10 to 15 mm for moderate sized flames. If your torch behaves this way, you can bend the end of a paper clip to the desired length and hold it in the flame as you adjust the fuel valve. (Of course you'll need to be careful not to hold the paper clip in the flame too long because it conducts heat to your fingers. Also, be careful where you put down the hot paper clip.)

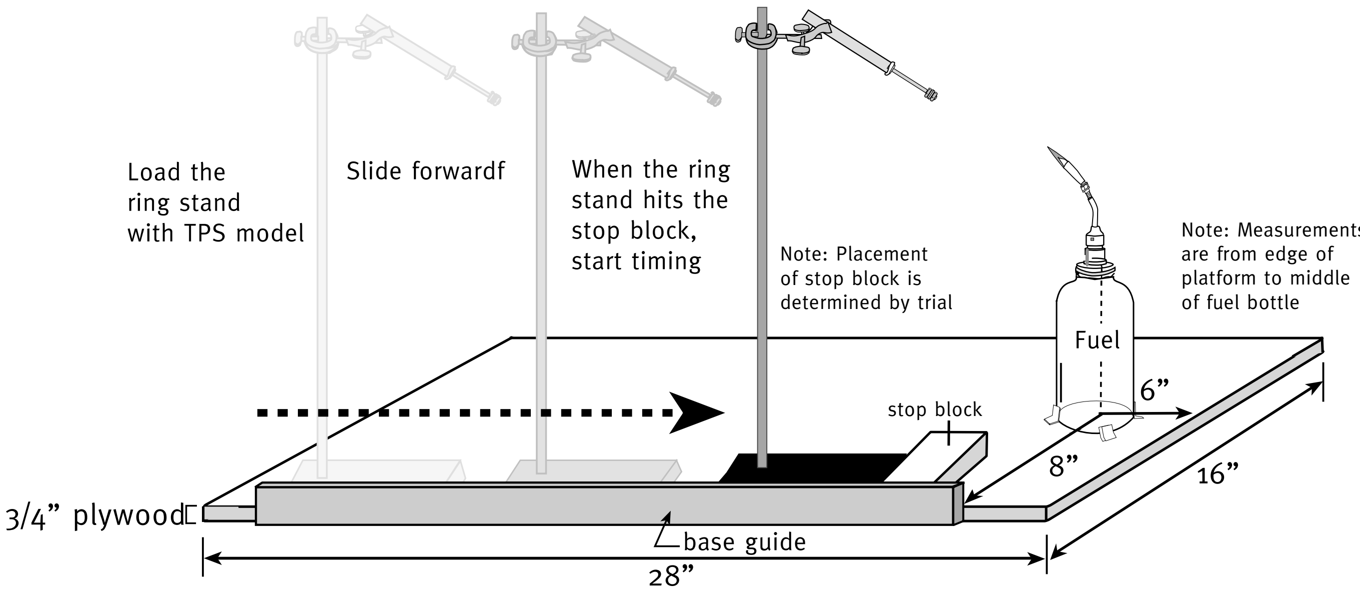
Other torches have flames that don't change much in length as the gas flow is adjusted. Some of them can be used with the valve "wide open." Others may need to be adjusted by sound or valve position or some other method that yields a repeatable setting. The next section tells how to check.



A larger version of this drawing is included in the Masters section at the end of this guide.

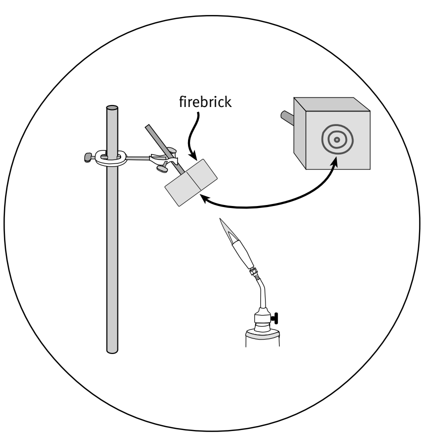
Test the stand to assure repeatable results

Once you have set up the test stand as described above, measure the time to failure of some unprotected test assemblies to determine whether the results are repeatable. ("Failure" means when the screw falls off.) Be sure to have all your safety supplies on hand for these first trials—it's important to establish safe habits from the beginning. A helper with a stop watch would make the work easier, but you should do these tests before class time in order to have a chance to correct any problems you might discover.



Install a test assembly in the clamp, light and adjust the torch, and slide the ring stand into place, starting the stopwatch at the sound of the base hitting the stop. Stop the watch when the screw falls away from the dowel. Record the time. Measure 3 or 4 times in this way, and then extinguish the torch, relight and adjust it, and try three or four more. Depending on the type of torch and the flame size (and the type of material used in the screws), times of 2 to 8 seconds are good, but they should cluster in fairly narrow range, for example, 3 to 4.5 seconds. Larger variations (a range of 2 to 1 or more) indicate that something is changing from test to test. The most likely cause is that the test stand is putting the test assembly at the edge of the hottest part of the flame, so small variations in position have a large effect on the heat to which the test assembly is exposed. Careful alignment should correct this. Also check the torch distance (TD), and the flame length (FL). If necessary, adjust the flame length until the average protection time falls in the 3–6 second range.

An improved alignment fixture



You can build an alignment fixture that is accurate and convenient to use if you have a piece of insulating firebrick and some furnace cement (both described in the Optional Materials list in the back of the guide). The firebrick is easy to cut and drill with normal metalworking tools, but it leaves an abrasive dust that you should not breathe. Use a hacksaw to cut a square piece about 2 inches by 2 inches by 1-1/2 inches. Using a drill press (or other means to drill perpendicular to the surface), drill a 1/4"-inch diameter hole 3/4 to 1 inch deep in the center of one square side. Using furnace cement, cement into the hole a 1/4"-inch diameter wooden dowel (or a 1/4"-inch diameter rod of another material that is rigid and heat-resistant). Start with a dowel longer than 4 inches and trim it after the cement has hardened so that the overall length of the firebrick and dowel is 4 inches +/- 1/4 inch. Next, mark the spot on the "front" side that is on the centerline of the dowel. One way to do this is to put the dowel in a drill and spin it. If you carefully hold a soft pencil or other soft marker near the block, you can mark a circle centered on the axis of the dowel. A safer way is to make a mark where you think the center is and then spin the dowel by hand to see if you got it right. When you've found the center, draw a circle the size of a dime or a nickel around it using a soft pencil.

To use the fixture, just mount it in the test stand as you would a test assembly, light the torch, and slide the ring stand into place. You should see an area on the block begin to glow red or orange. That is of course the area of maximum heat, and you can compare its location with the circle you drew earlier to determine whether your test stand is correctly aligned.

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 of this guide), assembling kits in advance will simplify tracking the budget.

Set up the classroom

Team work areas

Set up the classroom for student laboratory work in teams. Each pair of students should have a clear work area where they can organize their materials and build their designs. A classroom desk or table will do.

Glue station

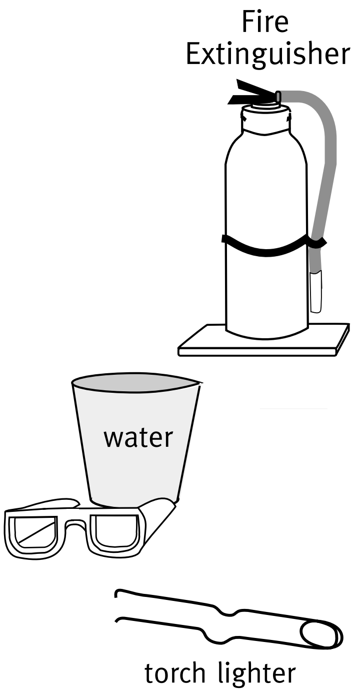
One or two glue pots or glue guns will serve adequately for a class of 24 students if you set up gluing stations. Students can go to the station to construct or repair testers. This will also make cleanup easier. Locate the glue station where you can easily observe it as you move around the classroom.

Test station

Set up the test station in a central location where students can gather around. Testing is best managed by the teacher, with students recording times and making observations.

Organize students in teams

For this activity, students working in pairs 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 actually manipulate the materials.



Review Safety Procedures

In the interest of maintaining the safety of the students and of yourself, you should be aware of several safety issues during this activity. We explicitly recommend that only the teacher should operate the torch at a single test station when the models are tested. Students should not operate the torch. The teacher should wear safety goggles while operating the torch in order to model good safety procedures for the students. Any students near the testing area should also wear safety goggles during the time the torch is operating.

As an additional safety precaution, we recommend that the propane tank be affixed solidly to the sliding wood base of the test stand using L-brackets and duct tape. This will prevent any accidental movement of the propane torch.

When all testing for the day has been completed, the propane canister should be stored in a safe place. When a canister is empty, it should be disposed of properly. These canisters are manufactured and sold for use in conditions much less well controlled and supervised than your classroom and are, in fact, quite safe when handled with common sense. You may want to consult your local and state school regulations regarding flames and pressurized gas in the classroom in order to make sure you are in compliance.

In addition to taking these safety precautions, you should review with the students what they should do in the event an accident does occur. Review your safety procedures for dealing with burns. You should have a fire extinguisher and a fire safety blanket nearby and should instruct students in their use. They should also know the location of a fire alarm and how to use it properly.

A second safety issue to be aware of is possible injury from touching a hot model that has just been tested. Hot objects should be picked up only with tongs or insulated mitts or be allowed to cool before being handled. If you wish, the models can be dunked in a container of water to cool them after testing. We recommend that only the teacher pick up the tested models until the teacher is satisfied that they have cooled so as not to pose any chance of a burn.

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 also can be painful but is unlikely to cause any serious burn. Nonetheless, students should be warned that the glue is hot.

Students also should be careful when cutting the copper screening. It is possible for small pieces of metal to fly off when scissors are used to cut the screen. Therefore, students should wear safety goggles with side screens when cutting this material. You may wish to set up a separate “cutting station ” at the side of the classroom in order to isolate this activity and be able to monitor it more closely.

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 the teacher 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 didn't 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've already done; compare their designs to previous ones they've tried. This will help them learn from the design-test-redesign approach.
- Encourage students to keep a running log or journal of their ideas, questions, and observations in a notebook. These notes will help them prepare their storyboard in Session 7.
- Steer students toward a more scientific approach. If they've changed multiple aspects of a design and observed changes in results, ask them which of the things they changed caused the difference in performance. If they aren't sure what caused the change, suggest they try changing only one feature at a time. 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 don't test a lot of models, they won't 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 "guiding" or "focusing" questions. For example: "How does the heat get from the flame to the glue?" or "What made this design last so long?" Keep coming back to these questions as the students try different designs.
- Require students to use specific language and be precise about what they are describing. Encourage them to refer to a specific element of the design (shield, air pocket, copper screen layer, 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.

- 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.
- Help students understand that designs that "fail" are part of the normal design process. Discuss how engineers and scientists learn from failures.

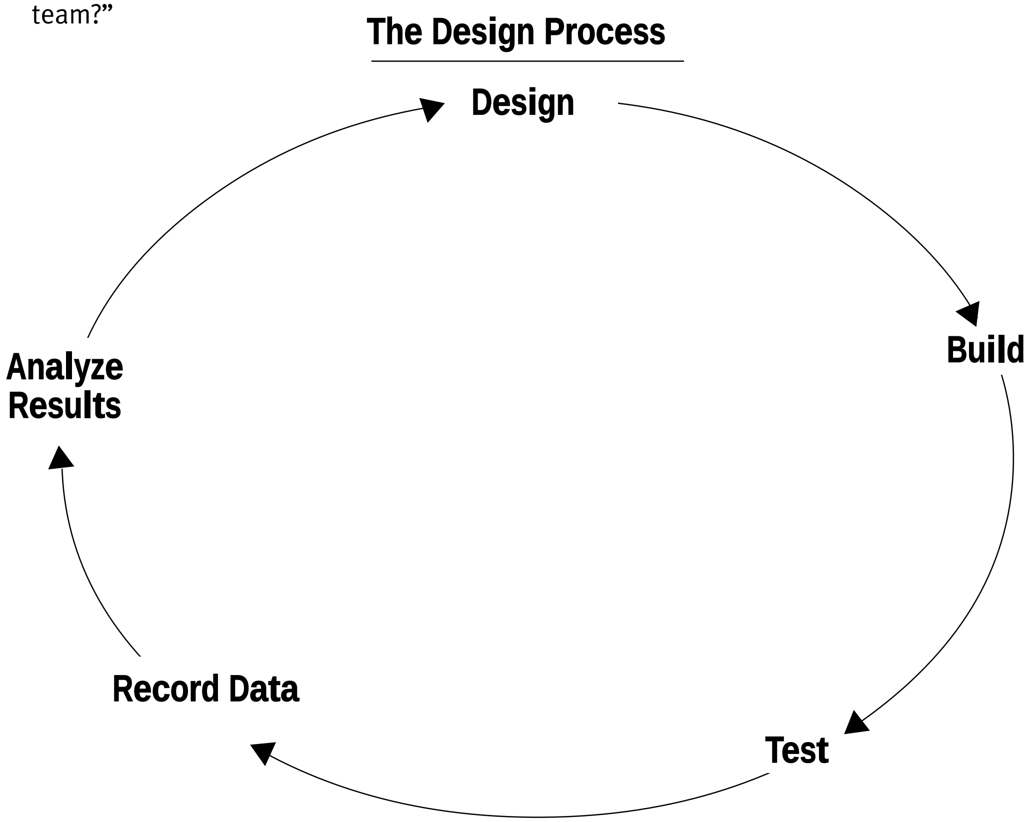
Helping Students Understand the Design Process

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.

In the Earth-to-Orbit Engineering Design Challenges, students experience this process. To help students visualize the cyclic nature of the design process, we have provided a 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" in the Master section 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 particular design as an example. It's useful to hold up the model and point out specific features that may be the result of studying the test data or 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, either done by you or by another team?"



Note: This chart appears as a black-line master in the back of the guide.

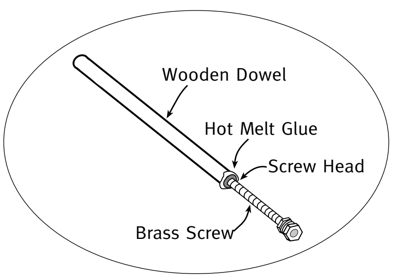
Session 1

Introducing the Challenge and Getting Started

In this first session, you will introduce the activity and provide students with background information about NASA, the X-33, and thermal protection systems. You will define the challenge and discuss how engineers approach a design problem. You'll conclude the session by testing several unprotected models to establish a baseline time upon which students will improve.

Learning goals

- Define thermal protection system
- Understand thermal protection systems
- Understand the requirements for a thermal protection system on a reusable launch vehicle
- Recognize the need for models
- Understand the relationship between a model and the actual object being studied
- Recognize the need for a baseline measurement
- Make observations and collect data
- Record data in a table
- Understand the need for averaging
- Calculate averages
- Begin developing ideas about heat transfer



TPS test assembly

Materials

- Transparencies for overhead projector (Masters can be found in the back of the guide.)
  –X-33
  –The Challenge
  –Relationship of TPS Model to Spacecraft
- Test station (see Preparation section)
- At least 6 prepared test assemblies
- At least 3 stopwatches
- Wall chart (or chalkboard) for recording times
- Design Specification and Test Results Sheet
- A poster of the X-33 (optional)
- Photos, video, or a model of the Space Shuttle (optional)

1. Introduce the unit

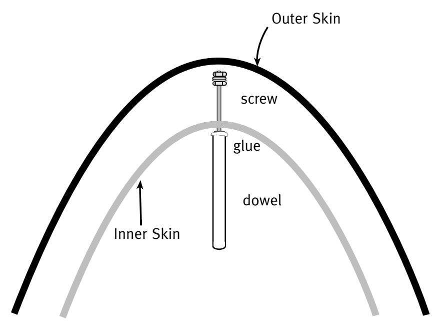
Explain to students that they will take on the role of engineers for this unit. They will attempt to solve a problem that NASA engineers are working on as they develop the "new" Space Shuttle. Use the background information in the previous section, the poster of the X-33, and pictures, video, or models of the Space Shuttle to introduce the concept of a reusable launch vehicle.

Introduce the term Thermal Protection System and ask students what they think it means. Ask students to think of examples of thermal protection in everyday items. Use the background information in the previous section, as well as other resources you might have, to introduce the concept.

2. Introduce the challenge

Explain to students that their challenge is to build the best possible thermal protection system for a model of the X-33 that you will test in the classroom. Pass around a prepared test assembly and explain that it will simulate a portion of the spacecraft. Use the transparency showing the relationship of the test assembly to the spacecraft. Ask students how the model simulates the thermal protection problem faced by designers of the X-33.

- How are the model and the spacecraft similar?
- What part of the model represents the inside of the spacecraft that must be protected? Students should recognize that the glue represents the inside of the spacecraft while the screw represents the outside.
- What part of the model represents the "skin" of the spacecraft?



This figure is reproduced as a large graphic in the Masters section.

Explain that the test assembly will be held over the flame of a propane torch until the glue melts and the screw falls off. Their goal is to keep the screw from falling off for as long as possible.

Explain the challenge goal and design constraints. Show the transparency that lists the challenge and the design constraints. For the remainder of the challenge, post this information prominently in the classroom.

Explain that engineers always face restrictions on their designs. Sometimes they are restricted by how much it would cost to build something. Sometimes they are restricted by how long it might take to build. There are many other possible restrictions. In this challenge, students will also face restrictions or constraints.

Discuss why the TPS cannot touch the dowel or the glue (because they represent parts *inside* the spacecraft). Post the challenge goal and design constraints in a prominent place in the classroom.

The Challenge:

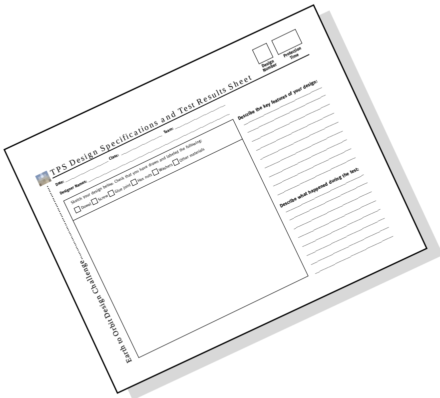
Build a thermal protection system (TPS), using the specified materials, that protects the model for the longest possible time.

Design Constraints:

- Use only the specified materials to construct the TPS.
- No glue may be used in the TPS itself
- No part of the TPS may touch the dowel.
- No part of the TPS may touch the glue.

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 TPS. Each team will then make a presentation to the class explaining the evolution of their design, using the storyboard.



The storyboard should contain at least three of the team's design spec 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 to final stages. Essentially, it should "tell the story" of the design process and explain why the design changes. It should conclude with a concise statement of "what we learned."

4. Establish a baseline protection time

Students will first test several unprotected assemblies in order to establish a starting point, which is also called a baseline. Refer to the Preparation section for instructions for setting up the test station. In order to get quickly to the testing itself, use test assemblies that have been constructed in advance.

Baseline: the initial measurement that will be improved.

Review safety procedures with students. Students standing near the test station should wear goggles. A container of water should be nearby for dousing hot models if necessary. Students should know the location of the fire extinguisher.

Align the flame and test several models. Check the flame length between tests and adjust if necessary. Have at least three students time the tests. Have one or more students calculate the average time for each test. Record the average test times on the easel pad or bulletin board as a public record. A sample recording table is included on the next page.

The screw should drop off within 3–6 seconds. If the average is outside this range, check the alignment of the screw with the flame, the torch distance (TD), and the flame length. If necessary, adjust the flame length (FL) until the average protection time falls in the 3–6 second range.

5. Discuss the results

After the test data has been recorded, calculate the average protection time for all the tests. Ask students what could be causing variation in the results? Possible answers include: different amounts of glue, a change in flame length between tests, observer error, etc.

Discuss with students the importance of standardizing test conditions (correctly aligning the test assembly and the flame, making sure the flame length is consistent for all tests), and of having several students time each test.

If students question the effect of differing amounts of glue, you may want to specifically compare test assemblies with different amounts of glue.

Begin thinking about heat transfer

Ask: "How does the heat from the flame reach the glue?"

You might choose to call the test assembly an "X-33" or a "tester."

This is an important question for students to begin thinking about because it will influence the way they design a thermal protection system. You may want to discuss convection, conduction, and radiation as methods of heat transfer. Do not plan to arrive at the definitive understanding of how the heat from the flame reaches the glue at this point. Students' understanding of the process will continue to evolve as they go through the design, build, and test process. Keep coming back to the question, however, as you and they discuss the results of each design.

Connect the simulation to the real spacecraft situation

"How does this model simulate the thermal protection problems faced by a spacecraft such as the space shuttle?"

- How are they similar? How are they different?
- The spacecraft has an "inside" that must be protected. What part of the model represents the "inside? What is it that must be protected on the model?
- What part of the model represents the "skin" of the spacecraft?

6. Wrap-up

Show students the copper screening and the nuts and washers they will use for their first design. Ask them to think about their designs before the next session.

Session 2

Design 1: A TPS Made of Copper Screen

In this session, students will design and build their first thermal protection system using nuts, washers, and a small piece of copper screen. The first design is kept simple in order to allow time to complete the entire design/build/test cycle within a single session. 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, accurate timing and reporting of results, and a post-test discussion.

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

Materials

- Extra dowels and screws
- Glue station
- Test station
- Chart paper to record test results
- Transparency of completed Design Specifications and Test Result Sheet (found in the Masters section)
- Each team receives:
  –A test assembly
  –2 hex nuts
  –2 washers
  –A 3-inch square piece of copper screen
  –A Design Specifications and Test Result Sheet

1. Review the design challenge and the design constraints.

2. Introduce the materials

Demonstrate how to construct a test assembly. Remind students that the assembly is somewhat fragile.

Depending upon the level of your students, you may wish to demonstrate how the nuts and washers can be used to fasten the copper screen to the screw. In general, however, the point is <u>not</u> to show students how to build the first design, but to allow them to exercise their creativity

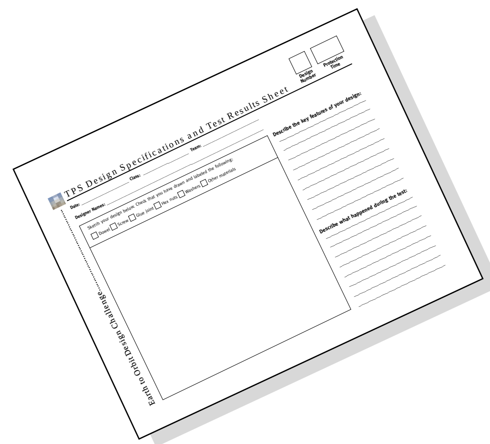
3. Review safety issues

Point out to students that the tip of the glue gun and the metal strip at the front of the glue pot are both hot and should be avoided. Review the procedure for burns. Remind students to wear safety goggles while cutting copper screening.

4. Introduce the recording sheet

Introduce the Design Specifications and Test Results Sheet. Tell students that this is 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 Spec” sheet.

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.

5. Explain the following test procedure to students:

- 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

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. Approve models for testing

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

- ❑ Model uses only allowable materials
- ❑ No glue was used in construction of the TPS itself
- ❑ No part of the TPS touches the glue
- ❑ No part of the TPS touches the dowel
- ❑ 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 - whole class

Begin testing when most of the teams’ designs have been approved. Have students stop working and gather around the test station. **The teacher should do all work involving the propane torch.**

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 test 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. For example, students have classified their TPS designs as mushroom, shield, cone, umbrella, battering ram, and burrito.

Before lighting the torch, 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 thermal protection, etc.)

Select three student observers to time the test with stopwatches. Assign a student to record the results of each test in a chart on the chalkboard or on a large sheet of paper. The chart should include the following columns:

Teamf	Design #f	Protection Time			
		Observer 1f	Observer 2f	Observer 3	Average

You may also want to include a column for “design strategy” if you choose to classify the designs.

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 question

> "How did the TPS keep the heat of the flame from reaching the glue?"

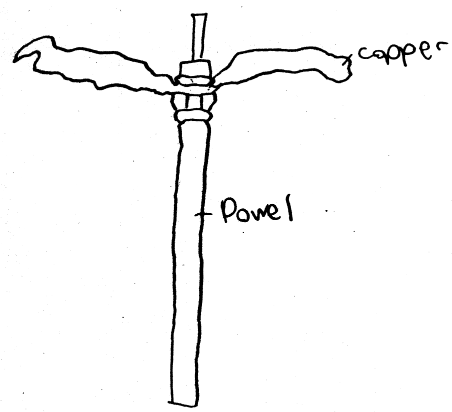
Other discussion questions might include:

- What happened to each part of the TPS during the testing?
- Did any parts of the design seem to heat up more than the rest? How could you tell?
- Which model designs were most effective? What made these designs effective?

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.

Session 3

Designs 2 and 3: TPS Made of Copper Screen



Student sketch

Using what they have learned from the first design, students will revise and redesign their TPS in two more design-build-test cycles using only copper screen, nuts, and washers.

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

Materials

- Extra dowels and screws
- Glue station
- Test station
- Chart to record test results
- Each team receives:
  –2 test assemblies
  –4 hex nuts
  –4 washers
  –2 3-inch square pieces of copper screen
  –2 recording sheets

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 the next two designs

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 TPS prevents the heat from getting to the glue. Refer to “Linking Design Strategies and Observations to Science Concepts” at the end of the Classroom Sessions section for connections that can be made between student observations and science concepts.

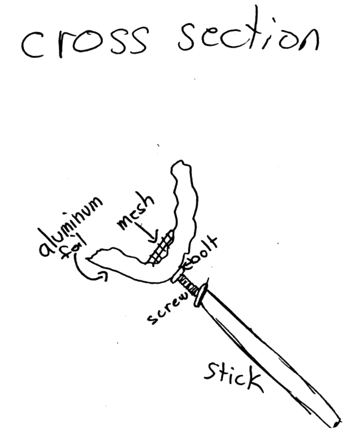
In the post-test discussion, lead students to make conclusions about the protection offered by a piece of copper screen.

Allow students approximately 15 minutes to design, build, and complete a recording sheet for each model.

Session 4

Design 4: TPS Made of Copper Screen and Aluminum Foil

Once students have designed and tested three models made from copper screen, introduce the next material they will use, aluminum foil. Lead a brief preliminary discussion about the properties of aluminum foil and how it might provide thermal protection. See step 2 below for suggestions of what to discuss about aluminum foil. Conduct the same design-build-test cycle described in the previous sessions.



Student sketch

Learning goals

- Distinguish between effective and ineffective design features
- Incorporate design strategies gleaned from experimentation and observation
- Refine observation skills
- Record test data
- Analyze test result data and draw conclusions
- Refine understanding of heat transfer, conductors, and insulators

Materials

- Extra dowels and screws
- Glue station
- Test station
- Chart to record test results
- Each team receives:
  –1 test assembly
  –2 hex nuts
  –2 washers
  –1 3-inch square piece of copper screen
  –1 3-inch square piece of aluminum foil
  –1 recording sheet

1. Review the previous session

If a day or longer has passed since the previous session, review the results. Review the successful and unsuccessful design features and any conclusions students were able to draw.

2. Introduce the materials

Lead a discussion about aluminum foil as a thermal protector. You may want to ask some of the following questions:

- What do the foil and copper screen have in common? How are they different? Refer to the Background section "Thermal conductivity and heat capacity."

- What are some familiar uses of aluminum foil?
- What can you conclude about the thermal properties of aluminum foil based on how it is used?
- What do you think will happen to the aluminum foil in the flame?

3. Design, build, and test a TPS using the copper screen and aluminum foil.

Follow the procedures from earlier test cycles.

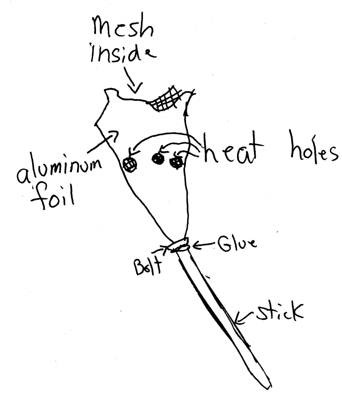
4. Discuss the results

Refer to “Linking Design Strategies and Observations to Science Concepts” at the end of the Classroom Sessions section for connections that can be made between student observations and science concepts.

Session 5

Designs 5 and 6: TPS Made of Copper Screen and Aluminum Foil

In this session , students will continue to revise and test their designs.



Student sketch

Learning goals

- Distinguish between effective and ineffective design features
- Incorporate design strategies gleaned from experimentation and observation
- Distinguish between thermal properties of copper screen and aluminum foil
- Refine observation skills
- Record test data
- Analyze test result data and draw conclusions
- Refine understanding of heat transfer, conductors, and insulators

Materials

- Extra dowels and screws
- Glue station
- Test station
- Chart paper to record test results
- Each team receives:
  –2 test assemblies
  –4 hex nuts
  –4 washers
  –2 3-inch square pieces of copper screen
  –2 3-inch pieces of aluminum foil
  –2 recording sheets

1. Review the previous session

If a day or longer has passed since the previous session, review the results. Review the successful and unsuccessful design features, as well as any conclusions students were able to make.

2. Design, build, and test a TPS using the copper screen and aluminum foil.

Follow the procedures from earlier test cycles.

3. Discuss the results

Refer to “Linking Design Strategies and Observations to Science Concepts” at the end of the Classroom Sessions section for connections that can be made between student observations and science concepts.

Session 6

Construct a Storyboard/Poster

As a culminating activity, each team creates a "storyboard" poster that documents the evolution of their TPS 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'x3', 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 developing TPS 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.

Students may attach their completed recording sheets or re-copy the information onto the storyboard. They should attach the actual tested models if possible. 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
- Explains the baseline model
- 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 test
- Includes conclusion about the most effective thermal protection system
- Uses scientific vocabulary
- Has an appealing layout with a title
- 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 resource list in the back of the guide for suggested starting points. Students could investigate:

- Thermal protection systems used in rockets
- Thermal protection systems used in other devices and vehicles
- Properties of materials
- Properties of a propane flame

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.

See the Math Connections section earlier in this guide for additional suggestions for graphing and analysis that could be included on the final posters.

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.

Optional extension:

Students may create their storyboards electronically using digital photographs of their models and may post their presentations on a school web site.

Session 7

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 science principles of heat energy and heat transfer. 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. The section is organized according to design strategies and observations made during pilot testing of this unit.

Observation: Changes in the foil and copper screen

Encourage students to watch carefully for changes in the TPS materials during and after testing. Careful observation of changes in the material can help determine how hot it got. When copper screen is exposed to high heat for a length of time, it first glows, then turns black, and eventually it disintegrates. If the copper screen is folded it will tend to unfold. Aluminum foil becomes faintly multihued, gets thinner, turns black, and eventually disintegrates.

The changes in the TPS materials exposed to heat are evidence of chemical activity. Many other good examples of chemical changes caused by heat occur in the cooking of food. For example, foods change color when they are cooked because there's chemical activity going on during cooking. The changes you see in the copper and aluminum are due to rapid oxidation driven by the high temperatures. Both copper and aluminum oxidize at room temperature, but the high temperatures caused by the torch increase the speed of these reactions. Students can think about how engineers must anticipate how TPS materials will react at high temperatures. Engineers also must think about the environment in which the TPS is operating. For example, at orbital altitudes there is almost no oxygen present; hence materials do not readily oxidize. But when high temperatures are encountered during reentry, oxygen is present, and oxidation reactions do occur.

Interestingly, the melting point of aluminum is higher than its combustion point. Therefore, aluminum will burn before it melts if there's oxygen present (not in space).

Observation: Glowing

Students may notice parts of the TPS, such as the copper screen and the aluminum foil, glowing. Materials glow because they are emitting electromagnetic radiation in the visible portion of the spectrum. This radiation carries away energy, so in the absence of further energy input, a glowing material gradually cools and stops glowing. Think about taking a glowing piece of hot metal from

Glowing metal is first absorbing and then radiating heat.

a furnace. At first, it may glow white hot, then yellow, then red, and finally stop glowing. The changes of color indicate a shift in the spectrum of light it is emitting. The spectral “signature” corresponds to the temperature of the metal. When it stops glowing, it is still warm, and still emitting radiation, but now the radiation is no longer in the visible portion of the spectrum. It is in the infrared.

Students may notice that only some parts of the TPS glow. The glowing parts are at a higher temperature than the non-glowing parts. The glowing can show students where heat is building up on the model, i.e. where the “hot spots” are. Students may notice that after a while, parts of the TPS that were glowing begin to deteriorate. Parts of the copper screen and the aluminum foil may vaporize. These “burn-throughs” destroy the structural integrity of the TPS and may allow the convective stream of hot gas from the torch to reach the glue joint. This is analogous to a “burn-through” on the TPS of a spacecraft and is to be avoided.

Compare the TPS test to what happens when you turn on the burner of an electric stove. If you put your hand above the burner, you can feel the heat radiating from it long before it starts to glow. As the coil gets hotter, it begins to glow. Where the TPS is glowing it is hottest. By observing where the model is glowing, you can tell where the largest amount of heat energy is going.

Why do hot metals glow? Metal atoms have free electrons that can be boosted into a higher energy state by an inflow of energy. When these electrons return to the lower energy state they emit photons as radiating energy. Atoms absorb heat energy and then give some of it back as electromagnetic radiation, some of which is visible light. As the material heats up, its atoms give off more and more radiating energy. As the temperature increases, more of the radiating energy is emitted as waves of shorter and shorter wavelengths. Still, most of the energy is emitted in the infrared spectrum. Only when the temperature gets high enough do the wavelengths become short enough to be visible as light.

If the TPS is glowing, then some of the heat energy it has absorbed is radiating into space rather than conducting to the screw. It’s not just conducting the heat back to the screw. Radiation actually cools the TPS.

Parts of the TPS that aren’t glowing are, obviously, not as hot, probably because they are not in the path of the hot air coming from the torch. This does not mean that those parts of the TPS are entirely ineffective; they may still be blocking some of the hot air and they may be radiating energy in the non-visible portion of the spectrum. Another possibility is that those parts of the TPS may be absorbing heat, but are conducting that heat on to something behind.

Observation: How the heat gets to the glue

Encourage students to compare the conduction paths of various TPS designs. Trace backward, from the glue to the flame. Find the path along which heat energy flows. Which model had a more direct path? Which model had a longer path? Which model had air gaps or other insulators in the path? How does this information compare to the test results for the TPS?

Design Strategy: Cover the tip of the screw

No matter what kind of shield you build, if the tip of the screw is exposed to the flame, the TPS will not be very successful. Shielding the screw against the hot blast of air flowing from the torch is an effective strategy. Students must come to the realization that they need to protect the tip of the screw rather than just the glue.

Many of the kids are wrapping the screw with copper screen or aluminum foil. Some are still leaving the screw tip exposed. When asked why they wrap the screw, they say that it forms a "heat sink."

Design Strategy: A long conduction path

Students should understand that they can increase protection time by creating the longest and most tenuous path of conduction. You can visualize this in terms of heat flowing like a river. Just as a broad deep river will carry a lot more water than a shallow narrow stream, a wide conduction path will allow more heat to flow along it.

In constructing a long conduction path, the cooler areas of the shield might suggest locations on the TPS where connections between materials should be made in order to reduce conduction. For example, if you will be layering two pieces of foil, it will be more effective to attach the two pieces to one another as far from the flame as possible, where they stay the coolest. See the section on glowing above.

One team created what they called "the battering ram," a tightly folded and coiled piece of aluminum foil attached to the front of the screw. They expected the thick wad of foil to take a long time to heat up.

Design Strategy: Wrap the screw

Students may have seen hot water pipes or tanks wrapped in a fiberglass blanket or foam sheath. The fiberglass blanket may have a backing that looks like aluminum foil. The fiberglass acts as an insulator while the aluminum foil serves to protect the fiberglass by keeping moisture out. (It also reflects some radiating energy.)

Wrapping the screw will prove a rather ineffective strategy because it ignores the issue of conduction. Because the aluminum foil or copper screen is in contact with the screw in so many places, heat energy absorbed by the wrapping will easily conduct into the screw.

Design Strategy: Large mass of material at the end of the screw

Like wrapping the screw, this strategy does not overcome the problem of conduction. A (relatively) large mass of material in front of the screw will take longer to heat up but eventually the heat will conduct through it. Even while it is heating it will conduct heat back to the screw that it is touching. The hotter the TPS gets, the more heat will be conducted back to the screw. If you put a mass of thermally conductive material in front of but touching the screw, it will take a while for it to heat up, but the heat will eventually be conducted back to the screw.

This provides an opportunity to discuss specific heat. Materials with a lower specific heat will conduct heat energy faster. Copper will conduct heat energy 2.5 times faster than aluminum. Ask students to put their hands on different materials in the classroom to tell which ones have a lower specific heat.

Observation: Do the holes in the copper screen matter?

Compare the performance of two similar shields, one made from copper screen and one made from aluminum foil. Because the aluminum foil is much more effective at blocking the hot air, it should protect the glue for much longer.

Design Strategy: Reflect the heat

Students may attach a mirror-like shield of aluminum foil designed to “reflect” the heat. This would be a more appropriate description if the heat energy was radiating. But the amount of radiating energy is a negligible amount in this situation compared to the amount of energy in the hot air flowing up and away from the area around the flame. The effectiveness of a “reflecting” shield is actually found in its ability to block the hot air from reaching the screw. If the torch was pointed *down* at the TPS, the protection time would be much longer because much of the hot air would flow upward because it is less dense.

You might ask students about using aluminum foil in baking. Does it make a difference if a dish in a conventional oven is covered with foil with the shiny side up or down? No, because the aluminum is *conducting* the heat from the air inside the oven into the food. Heat in an oven is not radiating energy and therefore the reflective side of the foil will have no different effect than the dull side. This contrasts with the silvered thermal bottle which reflects radiated heat. This heat comes from the contents if they are hot and from the outside of the bottle if the contents are cold.

Design Strategy: Deflect the heat

Students may design a flat or cone shaped heat shield to deflect the heat. It would be useful for students to think about the stream of hot gas emanating from the area around the torch. They could visualize it as a stream of water. Having in mind something like a stream will give them something to think about blocking. You might introduce the term “air convection.”

A convex shield will deflect the flow around the screw. Attaching the tip of the cone to the tip of the screw will provide a conduction path that defeats the purpose of the shield.

Some students may design a concave shield intended to deflect the heat that actually functions as a heat collector. You can compare this to a satellite dish or radar reflector. If you have a concave shape that blocks the air moving from the torch then it might cause the air to stay around the tip of the screw and heat it up even more.

Design Strategy: Multiple layers

A TPS made of many layers can be effective in at least two ways.

If students choose to construct a TPS using multiple layers, encourage them to experiment with the amount of space they leave between layers. Layers that are tightly packed will still allow heat transfer by conduction. Loosely packed layers will create a longer conduction path and will incorporate air pockets as insulating spaces.

Layers also block heat transfer by radiation. Each layer reflects some heat back so each successive layer back is at a lower temperature. The more layers, the longer it will take before the layer connected to the screw heats up enough to conduct heat back to the screw.

Design Strategy: Air pockets

An air pocket can serve as an effective insulator for the glue. Air pockets may be created by shaping the foil into a tube or bag shape. A loose layering of materials will trap air between the layers. Thinsulate, fiberglass insulation, down parkas, and double pane windows all use this strategy for insulation. In order to travel through an air space, heat energy must radiate from air molecule to air molecule which are much farther apart than atoms in a solid or liquid. This is why it takes much longer for heat to pass through an air space.

Design Strategy: Increasing surface area of shield

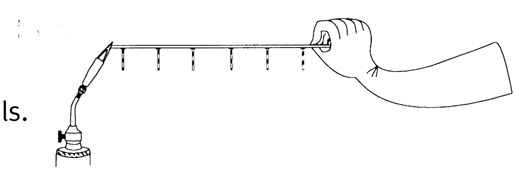
Increasing the surface area of the shield will increase the amount of heat transferred by conduction. The larger the surface area of the shield, the better it cools by conduction because more air comes into contact with the shield.

A larger surface area can be created simply by making the shield bigger, or by accordion pleating to get fins as in a radiator. Because of the materials constraints in this engineering design challenge, a large shield will need to be thinner. A smaller shield with finer fins can be just as effective as a larger flat one.

Conduction Demonstration

Use this demonstration to show how heat travels gradually through a solid. This may help students understand how heat conducts through the brass screw.

To do this demonstration, you will need:



- 6-8 brass screws glued to the rod at 2-inch intervals.
- A hot melt glue gun or glue pot
- A brass or steel rod about one foot long

Test station

Ask students to predict what will happen when you hold one end of the rod in the flame of the propane torch. If they suggest that the screws will fall off, ask them to be more specific. Will the screws drop off at equally spaced intervals of time? Will they drop off at an accelerating rate? Why or why not.

Light the torch and hold the rod by one end so that the other end is in the flame. Hold the rod in the flame until all the screws have dropped off or until the heat conducting up the rod reaches your hand.

Ask students what this demonstration can tell us about the way heat moves through the metal rod.

To illustrate different thermal conductivities, try the demonstration with rods made of different materials.

Extensions

You may find, especially with advanced students, that students achieve protection times of over 4 minutes. At this stage, you may want to add additional design constraints to increase the challenge.

Turning up the heat

The simplest way to make the challenge more difficult is to increase the flame length. You may also want to test the same design with different flame lengths and plot the data. Students can then find a relationship between flame length and protection time.

Limiting designs by mass

The X-33 TPS must weigh as little as possible. To achieve this, engineers use thin layers of metal combined with lightweight insulating material. Challenge students to build the lightest weight TPS that still achieves a minimum protection time. Have students plot mass versus protection time. You will want to determine in advance whether the washers and nuts are a mandatory or optional part of the TPS as removing them dramatically reduces the TPS mass.

Limiting designs by size

Students may find that a long thin TPS extending toward the flame will be very effective. However, it would be unrealistic for a spacecraft to employ a TPS that would significantly increase its size. You might add the challenge that the TPS be as small as possible. Alternatively, you may add the design constraint that the TPS must be "smaller than an egg" or "smaller than a lemon" or a similar object. You might also construct a box into which the TPS must fit before testing, similar to the box used for carry-on bags at the airport.

Limiting designs by cost

You can find information about the Space Shuttle at http://www.nasa.gov/qanda/space_shuttle.html

A primary goal of the X-33 project is to design a low cost way of getting to space. This means that cost must be a design constraint in every aspect of the design.

Ask students to brainstorm about what NASA engineers must do to reduce the cost of getting to space. Holding up a model of the space shuttle or referring to a poster will be useful in stimulating student ideas. You might want to discuss such facts about the Space Shuttle as how much fuel it uses, which parts are reusable and which are not, what needs to be done to the Space Shuttle to prepare it for launch, 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 don't 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 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 TPS. Compare designs from teams on the basis of protection time and cost. Have students find the ratio of cost to protection time for each design and plot the results on a graph. Create a scatterplot for the entire class.

Designing with additional materials

The brass screw, copper screen, and aluminum foil have been chosen for their high conductive ability. This keeps the protection time fairly low and avoids long waits during testing which can adversely affect students' engagement. You may wish to experiment with materials that are more heat resistant.

Vermiculite™ and Perlite™, available at gardening centers, are lightweight and highly heat resistant. These can be incorporated into a TPS by creating a bag of aluminum foil to hold the pellets or by affixing the pellets to the foil or copper screen using furnace cement. If you choose to use furnace cement, be especially careful with it, as it can be dangerous to the skin and eyes. We do not recommend using furnace cement unless your students are safety conscious.

Steel wire will allow students to design TPSs that stand away from the tip of the screw and dramatically increase the protection time. Wire provides an excellent opportunity to observe the effects of a long, thin conduction path.

If you are constraining designs by a budget, you will want to assign much higher costs to these materials.

Measuring where the heat is with a high temperature probe

If you have a high temperature probe, you can use it to show students where the hottest part of the flame is and how the heat travels from the flame.

Detailed Materials List

Propane torch

Hardware stores carry these torches for home use. The brass burner (with fuel valve) screws onto a small propane bottle. The propane bottles come in two shapes. The traditional tall shape is approximately 3 inches in diameter by 10 inches tall. A newer shape is approximately 4 inches in diameter by 7 inches tall. The shorter bottle has advantages for this activity, but either will work fine. Once you are set up to use one type it would be difficult to rearrange the test stand to use the other type. A single bottle is likely to be sufficient for the entire activity, but it is important to have a spare (of the same type) on hand. These propane bottles cost about $3.00 each.

Before you buy a torch, check to see whether you can borrow (or already own) one. The main characteristic that makes one better than another is the ease of setting the flame to an appropriate and repeatable level; most of them are easy to adjust. The burner nozzle of this kind of torch is angled about 15° away from vertical, and this is an important feature. It means that when the glue melts, the TPS can drop away without falling into the flame.

After the torch has burned for several minutes the burner will of course be hot. The correct way to extinguish the torch is to close the fuel valve, but take care that the valve is fully closed. It is possible for a very small flame to continue burning unnoticed. On the other hand, over-tightening the fuel valve will make it more difficult to adjust the flame level in the future. When you will not be using the torch for an hour or more, unscrew the torch from the propane bottle. If you have the dust cap that came with the propane bottle, keep it in place when the torch is not in use.

Hot-melt glue and glue pot (or glue gun)

A glue pot made for use with low-temperature hot-melt glue is a handy tool that works very well for building test assemblies. They are most widely used by people making arrangements of dried flowers. They are likely to be available at hardware and craft stores.

If you are not able to obtain a glue pot, you may use any kind of low-temperature glue gun and glue sticks that fit it, although extra attention is required. (See “Build the Test Assemblies.”)

Basic supplies

Dowels

Birch Dowels 1/4 inch Diameter 3 feet long
pkg. of 50 - about $13.00

These are just basic dowels that you might find at any hardware, lumber, or craft store. It is important to use 1/4”-inch diameter. Any kind of wood will do; birch is common and inexpensive. Most of the dowels will need to be cut to

3-inch lengths to make test assemblies (+/- 1/8 inch is a reasonable tolerance.) It is a good idea to have available some longer pieces for other uses.

Screws

6-32 x 1 inch Brass Pan Head Phillips Machine Screws
pkg. of 100 - about $6.00

It is important to use #6 screws 1 inch long. #6 is a very common size easily found in hardware stores, and 32 threads per inch is the normal thread for a #6 screw. Brass is the recommended material because of its excellent thermal conductivity. You may substitute steel or zinc-plated steel, which will be easier to find and less expensive, but the protection times you measure will not be directly comparable with measurements made using brass screws. Do not use cadmium plated screws (which are no longer generally available) because heating cadmium in a flame could give off toxic vapor. Basically any kind of head style will do, although it would be better if they are all the same.

Nuts and washers

You may use basically any type of nuts and washers, but here are some specifics:

6-32 Brass Hex Nuts, pkg of 100 - about $3.00

#6 Brass Flat Washers, pkg of 100 - about $2.00

Copper woven wire cloth ("screen wire")

A standard weave is 16 x 16 (wires per inch in each direction). Wire diameter of .011 inch is good. Copper screen wire is an excellent material because it retains a shape and is easier to mold than aluminum, brass, or bronze screen, but it may be difficult to find. If you substitute another material, be sure that it is not treated with a lacquer or other coating that would smoke when heated. Aluminum, brass and bronze may be available.

Copper Woven Wire Cloth 12" x 12" Sheets - about $4.00 each

Aluminum foil

Basic household aluminum foil is just right for this activity. You might also want to have on hand some heavy-duty foil.

Optional materials

Steel wire

Hardware stores sell small packages of steel wire, and 28 to 32 gauge wire is a handy size that may be useful.

Aluminum pie plates

The thicker aluminum foil used in disposable pie plates and roasting pans can be fun to work with, but extra caution is required, because it is thick enough to pose a hazard of cutting or puncturing skin.

Furnace cement

A yogurt-cup-sized package of furnace cement will cost about $2.00 at a hardware store. It is irritating to the skin, and slow to dry, but it has excellent resistance to high temperature and may come in handy.

Vermiculite and perlite

These are naturally occurring minerals with resistance to high temperature and insulating qualities. They are inexpensive and commonly used for gardening purposes. Because they are mainly available in granular form, they must be enclosed in an aluminum foil packet or bonded with furnace cement.

Resources

About the Space Shuttle

http://www.nasa.gov/qanda/space_shuttle.html

About the Space Shuttle Thermal Protection System

NASA Facts On Line, John F. Kennedy Space Center
http://www-pao.ksc.nasa.gov/kscpao/nasafact/tps.htm

Space Shuttle News Reference Manual, detailed information about every part of the Space Shuttle.
http://www.ksc.nasa.gov/shuttle/technology/sts-newsref/sts_sys.html#sts-tps

Introduction to the Space Shuttle: Shuttle Systems
http://163.206.3.4/processing/m1/s1-8a_tps.html

About the X-33 Thermal Protection System

Mission Update: X-33's Innovative Metallic Thermal Shield "Ready for Flight"
http://www.venturestar.com/pages/missupd/pressrel/1999/02049901.html

About Other Places You Find Thermal Protection Systems

NASCAR, http://www.bsrproducts.com/fp1.htm

SCUBA Diving, http://www.diveboulder.com/layerz.htm

Whales, http://pbs.org/oceanrealm/intheschool/school5.html

About Thermal Protection Materials

Thermal Protection Systems Expert and Material Properties Database (detailed description and contact person for every thermal protection material)
http://kauai.arc.nasa.gov/cgi-bin/tpsx/unrestrict/V2/tpsx-frame.pl

About New Space Vehicles

"The Way to Go in Space" by Tim Beardsley. *Scientific American*, February 1999, pp. 80-97. Further reading: www.sciam.com/1999/0299issue/0299beardsleybox1.html

http://www.venturestar.com/

At this web site you can follow the progress of the X-33 as it progresses through the stages of development.

About Engineering and Careers

www.discoverengineering.org

A new web site, Discover Engineering Online, lets adolescents investigate a host of engineering achievements. Aimed at inspiring interest in engineering among America's youth, the site is a vast resource. Among the many features of the site is information on what engineers do and how to become one. Designed specifically for students in grades six through nine, the site has links to games, downloadables, and powerful graphics, as well as to web sites of corporations, engineering societies, and other resources. One section, for example, lists several "cool" things tied to engineering, such as the mechanics of getting music from a compact disc to the ears of a teen, how to make a batch of plastic at home, or learning how to fold the world's greatest paper airplane.

CD-ROMs about Space Transportation

Space Transportation: Past, Present and Future
Available from NASA Marshall Space Flight Center

An Interactive Guide to the X-34 Program's History, Technology & Achievements
Available from NASA CORE

Venturestar: The Odyssey Begins
Available from Lockheed Martin

Some NASA Web Sites

http://spacelink.nasa.gov
An Aeronautics and Space Resource for Educators

http://core.nasa.gov
The worldwide distribution center for NASA-produced multimedia materials

http://education.nasa.gov
A link to the many education resources provided by NASA

http://www.nasa.gov
NASA home page

http://www.dfrc.nasa.gov/
Dryden Flight Research Center Home Page
Learn about the X-33 and other "X-planes." Includes a photo gallery of more than 1,000 digital images of research aircraft

http://www1.msfc.nasa.gov/
Marshall Space Flight Center Home Page

Career Information

http://spacelink.nasa.gov/Instructional.Materials/Curriculum.Support/Careers/.index.html

About 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" forthcoming.

Masters: NASA Earth-to-Orbit Engineering Design Challenges

Thermal Protection Systems

NASA Earth-to-Orbit Engineering Design Challenges

Dear Parent:

Your child is beginning an exciting unit in science class entitled the NASA Earth-to-Orbit 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.

Thermal Protection Systems

NASA is currently developing the X-33, a reusable spacecraft technology demonstrator that may one day replace the Space Shuttle as a low-cost way to put people and satellites into orbit. The X-33 is undergoing testing at Marshall Space Flight Center in Huntsville, AL, and at Dryden Flight Research Center in Edwards, CA. One challenge faced by designers of the X-33 is how to keep the vehicle from burning up when it re-enters the atmosphere. The tremendous heat caused by friction with the Earth's atmosphere must be kept from reaching the skin of the spacecraft. This is the purpose of a Thermal Protection System.

The Challenge

Your child's challenge in class is to build a thermal protection system for a model of the X-33. He/she will use such common materials as nuts, washers, screening, and aluminum foil to build a protective shield that will keep the model from melting. 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 improve the amount of time the model is protected. 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's 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 to:

- Explain the challenge and the design constraints.
- Describe the design and how it survived the testing.
- Explain why the design did or didn't 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 around home of thermal protection systems in action.

- Winter clothing, such as coats, mittens, and hats is designed to prevent the loss of body heat. Discuss whether the clothes create heat or just retain the body's heat.
- Cooking provides a way to examine the thermal properties of materials. Look for the following:
  - Pot holders: Cloth potholders contain a layer of insulating material.
  - Cooking utensils: When stirring hot food, what kind of utensil do you use? Wood is a poor conductor, so the heat from hot food does not easily travel up a wooden spoon to your hand. Metal is a good conductor, it heats up quickly when placed in hot food.
  - Pots and pans: What are your pots and pans made of? Do they have a different type of metal on the bottom? Is the bottom thicker than the sides? Aluminum and copper are popular materials for cooking pots because they are good conductors. Do the handles of your pots get as hot as the pots or do they stay cooler? What are the handles made from? How are they attached?
- Fans: Moving air carries heat away from hot objects by *conduction* and *convection*. When the air contacts the hot surface, heat moves from the hot surface to the air molecules by conduction. When the air moves away from the hot surface, it takes the heat with it. When heat is carried away by a moving gas or liquid it is called *convection*.
- Double or triple pane windows: air is a good insulator that can protect your house from hot weather in the summer and cold in the winter. The air pocket trapped between the two panes of glass (some windows have two air pockets and three panes) prevents heat from passing through the window in either direction. Air serves as an insulator.
- Deep eaves: Roofs with large overhangs serve to keep a house cooler because they shade the house and prevent the radiant heat energy from the sun from reaching the walls and windows of the house. Heat energy from the sun is called radiation or radiating heat. Radiating heat can pass through empty space, air, and other transparent media such as glass. But radiating heat can't pass through opaque materials such as the roof of a house. Instead the roof absorbs the heat energy. If the roof is a light color, it will reflect some of the radiation as well.
- Fiberglass blankets: check your hot water tank or your water pipes if they are visible. Wrapping a tank or pipe in a fiberglass blanket prevents heat from hot water pipes from escaping into the air. If you discover asbestos wrapping, do not disturb it.
- Insulation: The walls of your home probably have some type of insulation such as fiberglass batting, rigid foam boards, or blown-in insulation like cellulose. All of these materials are good insulators because they trap many air pockets in them to make it difficult for heat energy to pass through by conduction or convection.
- Thermal bottles: contain a double-walled container with a vacuum between the two walls. Heat does not travel easily through a vacuum. Another space between the bottle and the outer covering also prevents heat from passing through because air is a good insulator. The inner surface of the bottle is mirrored to reflect heat inward.

Resources for Further Exploration

About the Space Shuttle

http://www.nasa.gov/qanda/space_shuttle.html

About the Space Shuttle Thermal Protection System

NASA Facts On Line, John F. Kennedy Space Center
http://www-pao.ksc.nasa.gov/kscpao/nasafact/tps.htm

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Mission Update: X-33's Innovative Metallic Thermal Shield "Ready for Flight"
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About Other Places You Find Thermal Protection Systems

NASCAR, http://www.bsrproducts.com/fp1.htm

SCUBA Diving, http://www.diveboulder.com/layerz.htm

Whales, http://pbs.org/oceanrealm/intheschool/school5.html

About Thermal Protection Materials

Thermal Protection Systems Expert and Material Properties Database (detailed description and contact person for every thermal protection material)
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http://www.nasa.gov
NASA home page

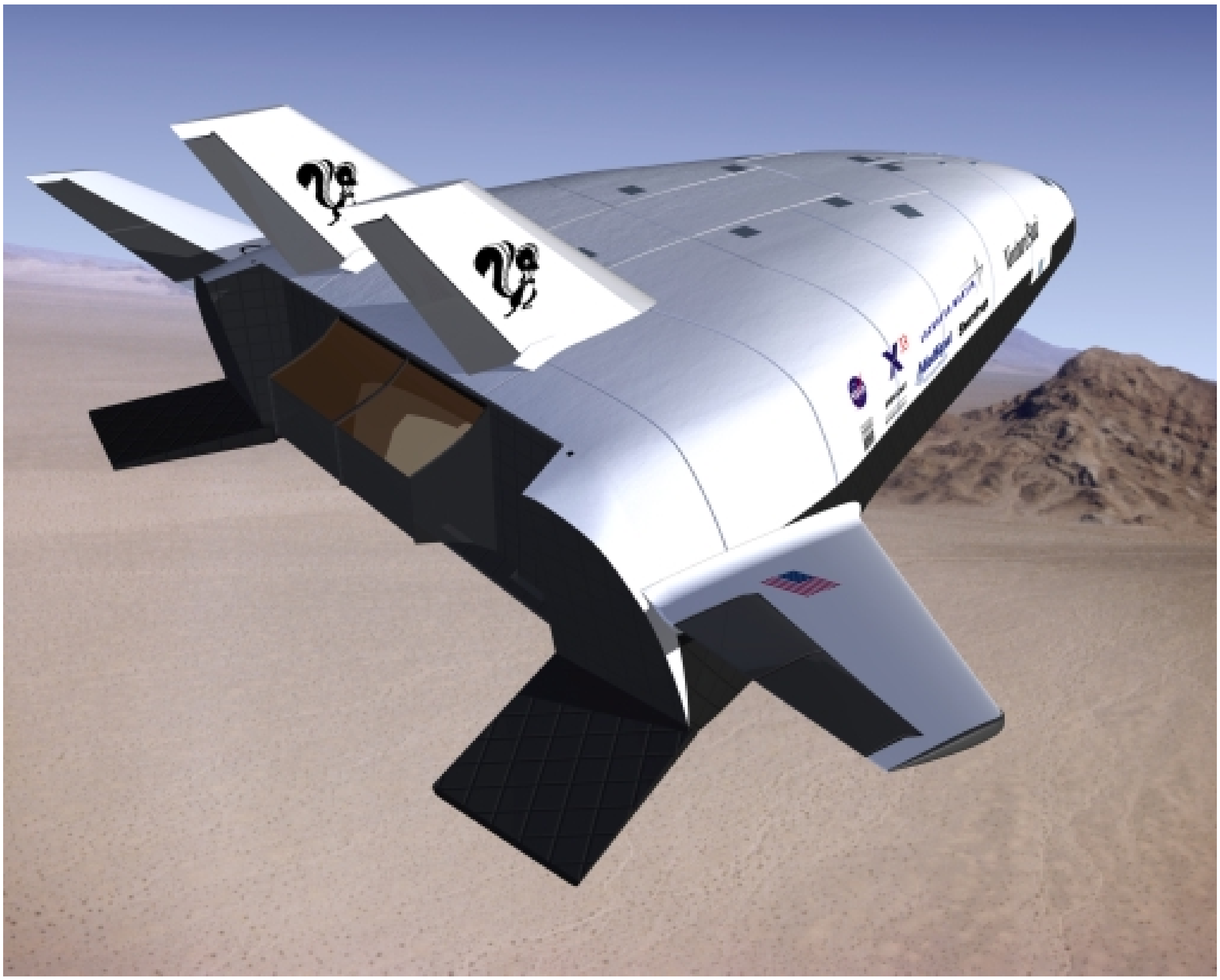
http://www.dfrc.nasa.gov/
Dryden Flight Research Center Home Page
Learn about the X-33 and other “X-planes.” Includes a photo gallery of more than 1,000 digital images of research aircraft

http://www1.msfc.nasa.gov/
Marshall Space Flight Center Home Page

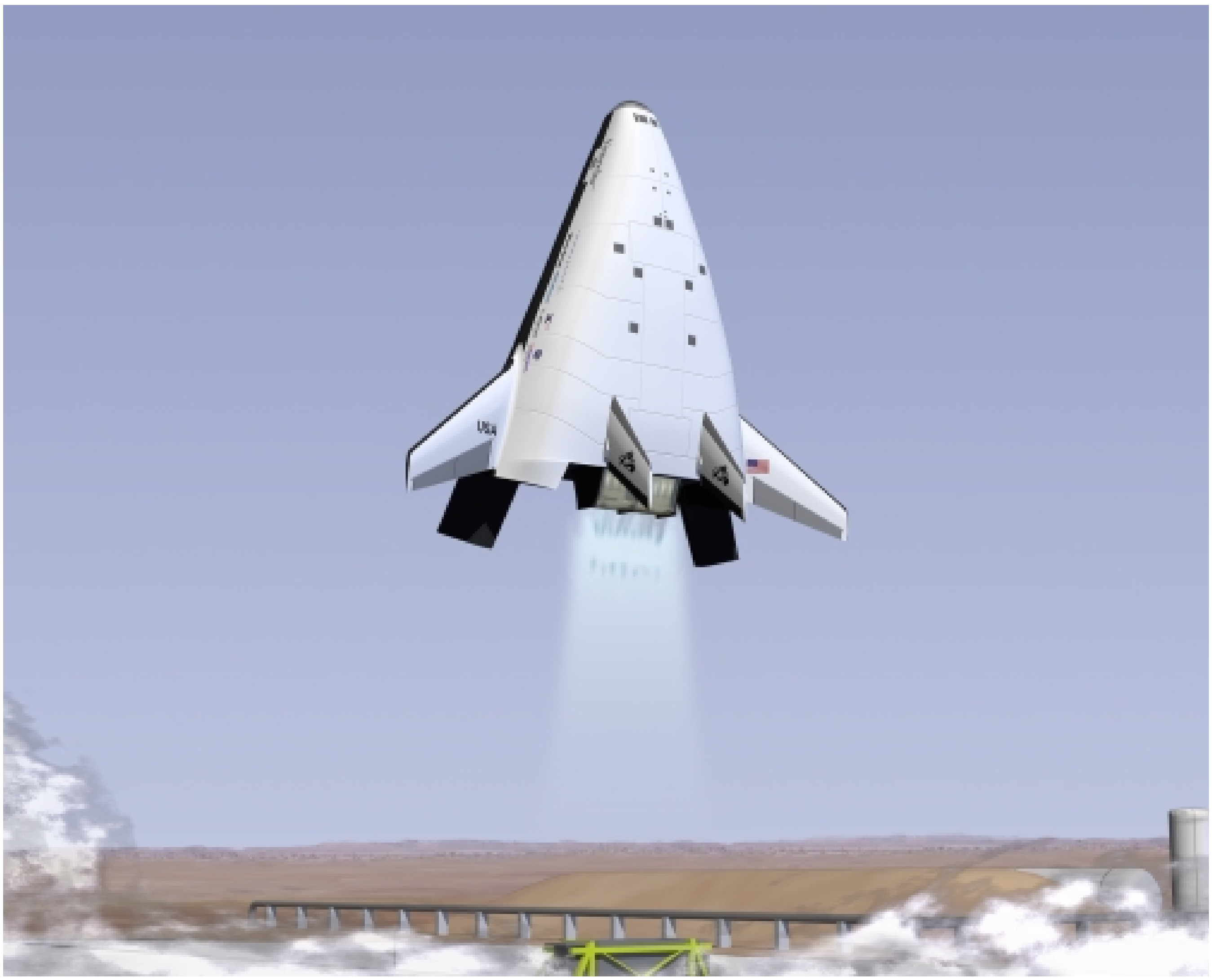
Career Information

http://spacelink.nasa.gov/Instructional.Materials/Curriculum.Support/Careers/.index.html

The X-33



X-33 Lift off



NASA Earth-to-Orbit Engineering Design Challenges

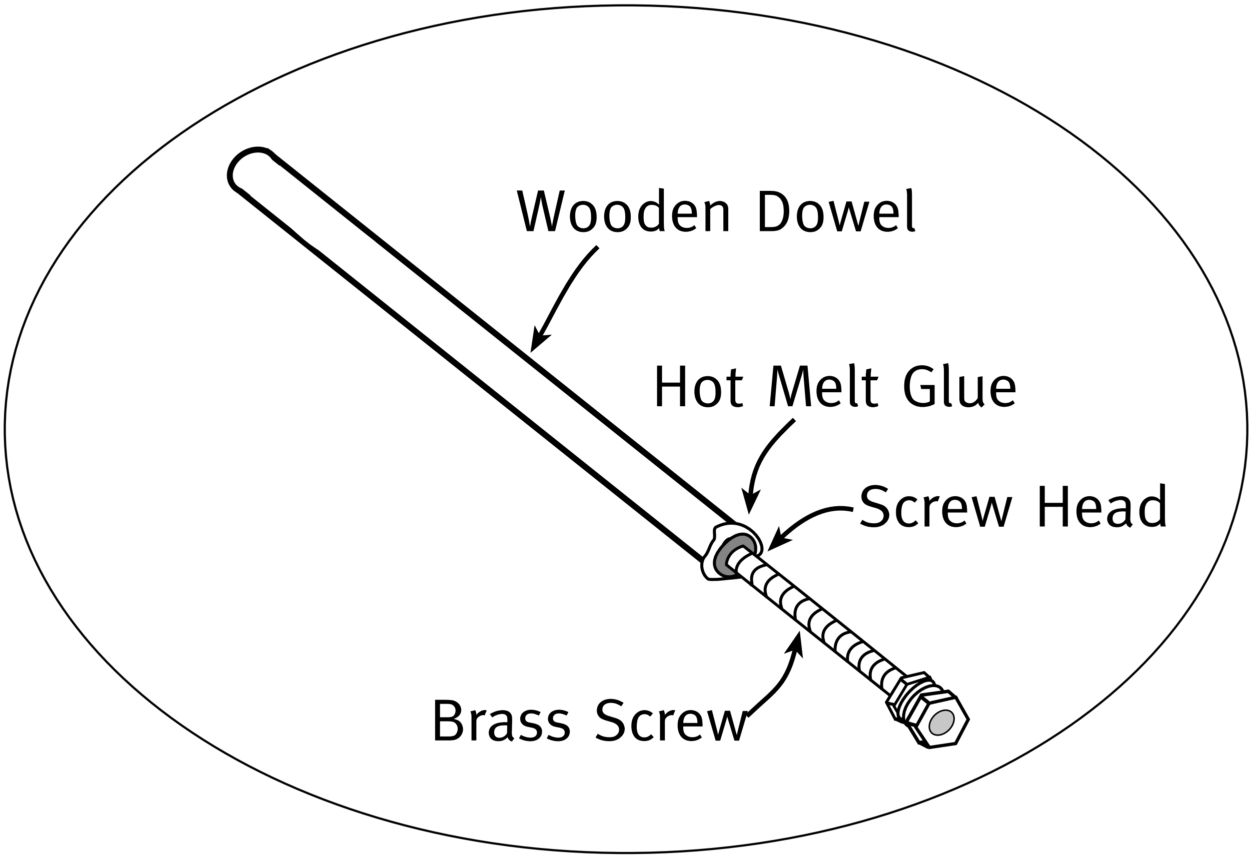
The Challenge:

Build a thermal protection system (TPS), using the specified materials, that protects the model for the longest possible time.

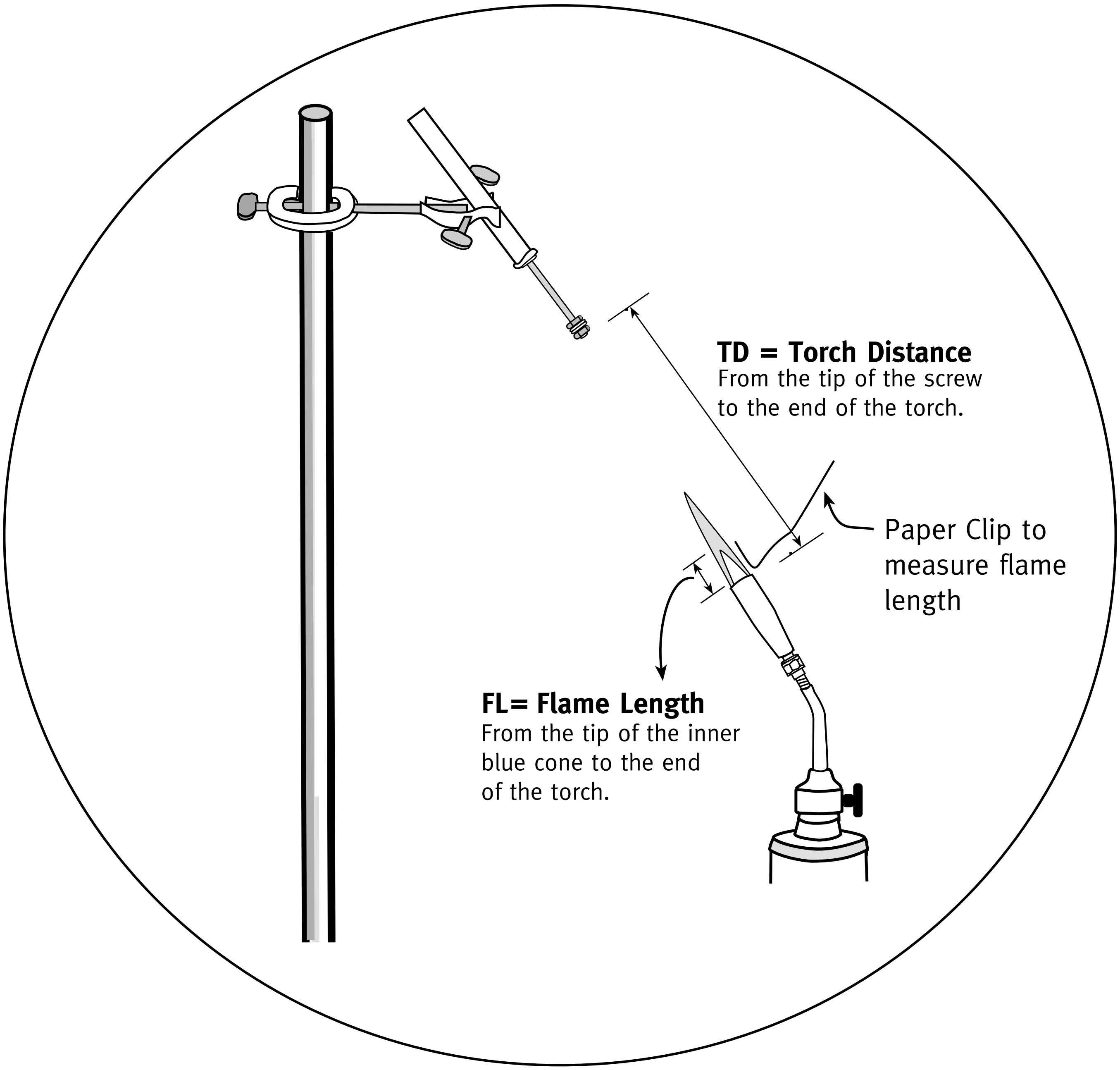
Design Constraints:

- Use only the specified materials to construct the TPS.
- No glue may be used in the TPS itself.
- No part of the TPS may touch the dowel.
- No part of the TPS may touch the glue.

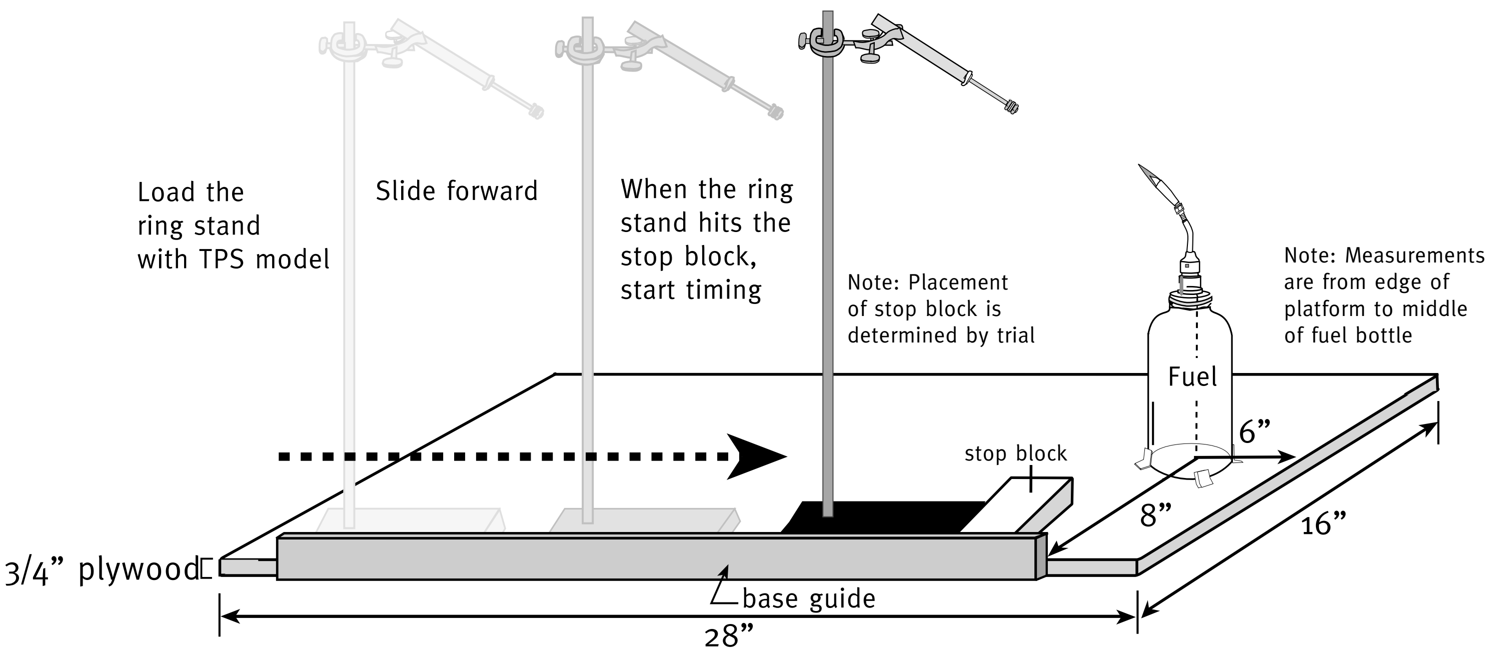
The TPS Test Assembly



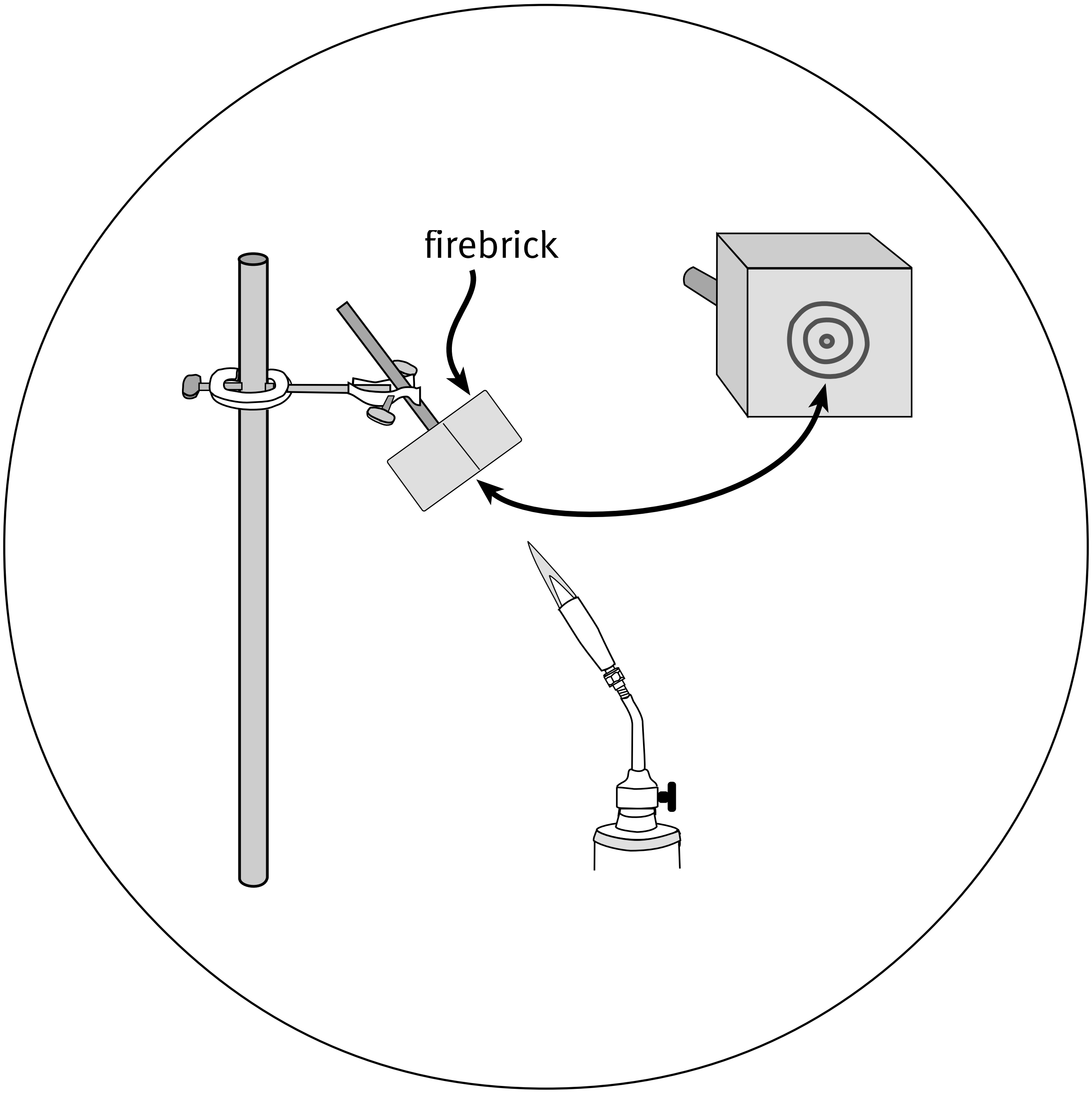
The TPS Test Stand



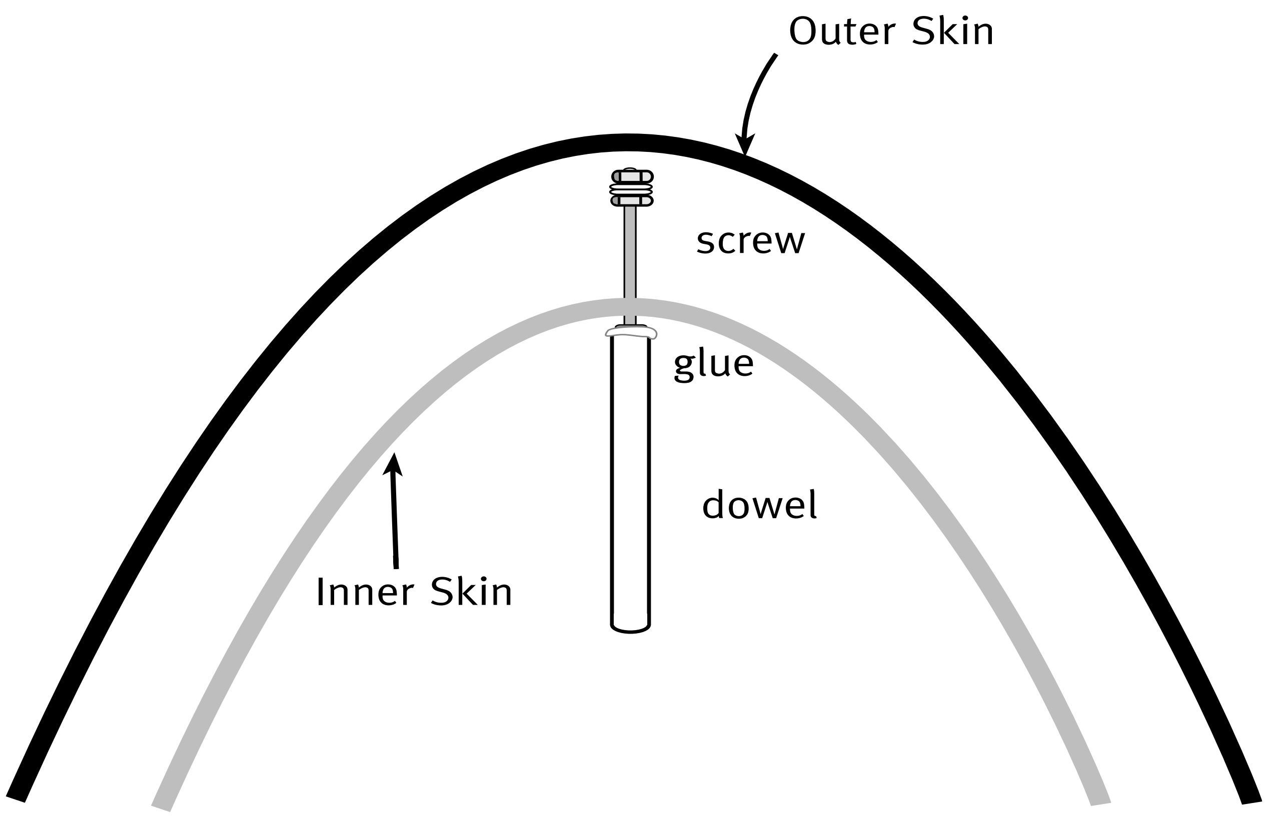
Using the TPS Test Stand



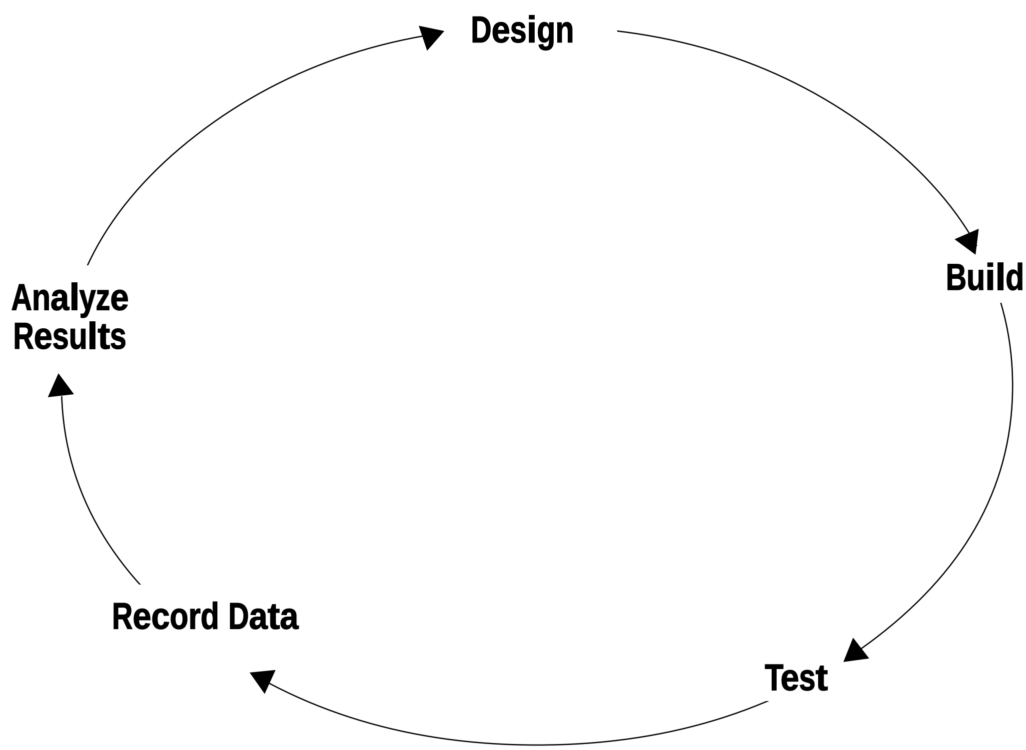
Alignment Fixture

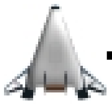


Relationship of the TPS Model to a Spacecraft



The Design Process





TPS Design Specifications and Test Results Sheet

Design Number: ____

Protection Time in seconds: ____

Date: ____________ Class: ________________ Team: ______________________________

Designer Names: ____

Sketch your design below. Check that you have drawn and labeled the following:

☐ Dowel ☐ Screw ☐ Glue joint ☐ Hex nuts ☐ Washers ☐ Other materials

Describe the key features of your design:

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Describe what happened during the test:

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