

THE MATERIALS THAT MOVE US: DATA COLLECTION AND GRAPHING



Learn about the scientific method by selecting the best materials for use in a commercial jet engine. Then, learn how rigorous testing helps ensure the safety and performance of parts used in military fighter jets.

In this module students will be able to:

- Identify the steps of the scientific method
- Analyze data and create a graph to reveal trends in the data
- Use data and graphs as evidence to draw conclusions about the relationship between two variables
- Compare composites to raw materials and explain the advantages of using composites in various industries





TESTING THE LIMITS



Background

Have you ever noticed that scientists on television always seem to be taking measurements and gathering data? It's not just for dramatic effect.

Collecting data is an important part of the scientific method process. The scientific method is a logical or systematic approach to problem solving. The process is made up of a series of important steps: recording observations and developing questions; generating a hypothesis; experimenting; analyzing results; drawing conclusions; and reporting results. Access to accurate data enables researchers to test their hypotheses and draw scientifically sound conclusions.



The scientific method helps researches solve problems by guiding them through developing potential solutions and testing them. This chart shows the steps involved from the development of an idea to determining whether or not it will work.







This depiction of a jet engine shows the maximum temperature of various components when in use. (Photo courtesy of Arconic.)

If the steps of the scientific method sound too abstract, let's observe the method at work through a realworld example. Consider the image above which shows just how hot a jet engine can become when in use. When researchers are selecting the best material for a specific component, they can't just look up properties such as strength or elasticity because those qualities may be affected by other conditions such as the high temperatures the material must endure. Instead, they must employ the scientific method to ensure they are making the right choice.

Researchers must first *record observations* about the component and the conditions it will be exposed to. Then, they must develop questions that will guide their line of research such as, "what material can endure a great deal of stress above 500°F?" The team may then construct a *hypothesis* that specific materials might meet the identified need.

At this point, the team can begin testing their hypothesis through *experimentation* to see how the materials perform under different temperatures. After *analyzing* their results, and drawing a *conclusion* about the best material, the team can finally write a report which outlines their results and makes a suggestion for which material should be used.

How would you go about making your recommendations if you were a member of the research team? The following activity will show you.



Problem:

A new airplane manufacturer has hired your company to redesign their jet engine. You are the lead researcher tasked with determining the best materials for constructing various components.

Task:

Your team has conducted extensive testing on the properties of four alloys and presented their initial results to you. You must analyze their results to draw a conclusion about the best materials for building each component.

The tables below contain the results of your team's testing. They show how each alloy's **yield strength** and **Young's modulus** are affected by temperature.

Aluminum Alloy				Titanium Alloy				Nickel Alloy				Iron Alloy (e.g. Steel)			
Density = 0.100 lbs / in^3				Density = 0.160 lbs / in^3				Density = 0.315 lbs / in^3				Density = 0.285 lbs / in^3			
Max Use Temperature = 300 F				Max Use Temperature = 850 F				Max Use Temperature = 1275 F				Max Use Temperature = 900 F			
Price = \$1.62 / lb				Price = \$9.33 / lb				Price = \$7.15 / lb				Price = \$0.49 / lb			
Yield Stength		Modulus		Yield Stength		Modulus		Yield Stength		Modulus		Yield Stength		Modulus	
۴F	ksi	°F	10^6 psi	°F	ksi	۴F	10^6 psi	۴F	ksi	۴F	10^6 psi	۴F	ksi	۴F	10^6 psi
-374	57	-262	9	-318	242	83	15	-325	167	-285	29	-320	289	-113	26
-287	53	-198	9	-272	222	297	15	-245	161	-185	29	-203	259	71	25
-205	49	-120	9	-219	204	489	14	-165	156	-85	28	-75	246	363	24
-114	47	-27	9	-168	190	703	13	-85	151	15	28	72	236	567	24
-13	46	57	9	-107	178	797	13	-5	147	115	27	236	223	662	23
102	44	122	9	-33	167	869	13	75	144	215	27	375	214	795	22
165	44	181	9	58	155	933	12	155	141	315	27	509	203	915	21
210	42	260	9	136	145	996	11	235	139	415	26	648	193	980	20
246	39	341	8	207	135			315	137	515	26	778	183		
269	36	411	8	312	121			395	136	615	25	849	178		
296	28	481	7	424	107			475	136	715	25	904	169		
325	20	539	7	493	102			555	135	815	24	953	151		
363	14	588	6	565	99			635	135	915	24	983	130		
396	10	643	5	643	99			715	134	1015	23				
443	7			746	96			795	134	1115	23				
506	6			829	92			875	133	1215	22				
575	5			898	85			955	132	1315	21				
651	5			950	76			1035	131	1415	21				
				992	64			1115	128	1515	20				
								1195	121	1615	19				
								1275	114	1715	17				
								1355	97	1815	16				

Table 1: Data showing how the properties yield strength and Young's Modulus are affected by temperature for four different alloys. This table is available for download as an Excel file on the Materials Explorers[™] website in the Extra Resources section of the "Materials That Move Us" web page. (Courtesy of Arconic.)

1435

1515

73

57

1915

2015

14

13





Questions

- 1. Plot the following graphs in Excel, Google Sheets, or on graph paper. Make sure each graph TALKS (Title, Axes, Labels, Key, Spacing).
 - a. Temperature vs yield strength. Include the results for all four alloys on the same graph.
 - b. Temperature vs Young's modulus. Include the results for all four alloys on the same graph.
- 2. List the alloys from lowest to highest in terms of:
 - i. Density
 - ii. Maximum use temperature
 - iii. Price
- **3.** The compressor shaft operates at 850°F and needs a material with a very high yield strength at this temperature. Which alloy would be best for this part?
- **4.** The fan blade operates at 140°F and needs a material with modulus (stiffness) between 10-20 x106 psi at this temperature. Which alloy would be best for this part?
- 5. The fan case support is currently made from aluminum but a next generation design will need to operate at temperatures as high as 350°F. A new fan case support design would need to be as lightweight as possible and be at least as stiff (modulus) and as strong (yield) as aluminum. What is the next preferred alternative to aluminum? Explain your answer.
- 6. You are designing a turbine disk operating at 1115°F. List the yield strength and Young's Modulus for the alloys that work at this temperature.
- 7. The use of raw or pure materials is limited in the transportation industry because alloys or composites (materials made from two different materials with significantly different chemical and physical properties) often have more desirable properties. Research a composite material such as carbon fiber, glass fiber, or fiberglass reinforced plastic utilized in any industry and explain the properties of the composite and why it is more desirable than the raw or pure materials.

Definitions

Alloy

A mixture of two or more metals, or a metal and other elements.

Yield Strength

The magnitude of stress at the point at which a material ceases to be elastic and becomes plastic.

Young's Modulus

Also known as the elastic modulus, Young's modulus is a measure of the elasticity of a material. The higher the Young's modulus of a material, the more the material will resist stretching. It can be calculated by dividing stress by strain.



Teacher Resources & Answer Key

Standards: NGSS: HS-PS2-1

Notes:

- **1.** Materials needed:
 - Option 1: Computer with Microsoft Excel or Google Sheets
 - Option 2: Graphing Paper
- 2. Students should work with a partner or in small groups to complete this activity.
- **3. Optional Modification (No plotting of graphs)**: To simplify this activity, teachers may print the graphs provided below and ask students to interpret the data in order to answer the questions.

Answer Key:



2. List the alloys from lowest to highest in terms of:

Answer:

- i. Density: Aluminum, Titanium, Iron, Nickel
- ii. Maximum use temperature: Aluminum, Titanium, Iron, Nickel
- iii. Price: Iron, Aluminum, Nickel, Titanium
- **3.** The compressor shaft operates at 850°F and needs a material with a very high yield strength at this temperature. Which alloy would be best for this part?

Answer: Iron

4. The fan blade operates at 140°F and needs a material with modulus (stiffness) between 10-20 x106 psi at this temperature. Which alloy would be best for this part?

Answer: Titanium



Teacher Resources & Answer Key

5. The fan case support is currently made from aluminum but a next generation design will need to operate at temperatures as high as 350°F. A new fan case support design would need to be as lightweight as possible and be at least as stiff (modulus) and as strong (yield) as aluminum. What is the next preferred alternative to aluminum? Explain your answer.

Answer: Titanium. While titanium, nickel, and iron alloys are all stiffer and stronger than aluminum at 350°F, titanium is the lightest of the three.

6. You are designing a turbine disk operating at 1115°F. List the Yield Strength and Young's Modulus for the alloys that work at this temperature.

Answer: Nickel (Yield = 127.7 ksi and Modulus = 22.7 x 106 psi)

7. The use of raw or pure materials is limited in the transportation industry because alloys or composites (material made from two different materials with significantly different chemical and physical properties) often have more desirable properties. Research a composite material such as carbon fiber, glass fiber, or fiberglass reinforced plastic utilized in any industry and explain the properties of the composite and why it is more desirable than the raw or pure materials.

Answer: Student answers will vary. Examples include:

Carbon fiber: Used to produce lightweight motorcycle helmets to prevent neck fatigue (carbon fiber is better at deflecting impacts and increases safety)

Glass fiber: Glass fiber can be used in composite piles to support docks. The composite piles are corrosion resistant and designed to withstand extreme weather, temperature, and salt content in water. Composite piles were used to rebuild docks around the Statue of Liberty after Hurricane Sandy.

Fiberglass reinforced plastic: Used in a Miami art museum to create a vertical garden that grows down from the ceiling. The FRP tubes are designed to bend, but not break and hurricane force winds.

Websites such as http://compositeslab.com/ are helpful places for students to begin their research



Extension Activity



SOARING TO NEW HEIGHTS

Numerous industries rely on materials science and engineering innovations to help make tougher, lighter, and more efficient products.

Take the example of the Lockheed Martin F-35 Lightning II, also known as the Joint Strike Fighter (JSF). This advanced defense aircraft is made up of single-piece forged aluminum or titanium bulkheads that form the "backbone" of the aircraft structure. This design helps save up to 400 pounds per jet—this translates into further costs savings and greater fuel efficiency.



Aircraft such as the F-35 Lightning II rely on extensive testing to make them tough enough to protect the men and women using them.

The F-35 Lightning II uses bulkheads that are forged in a single piece. These bulkheads make up the "backbone" of the aircraft. (Image courtesy of Arconic.)

As you can imagine, a military aircraft such as the JSF needs to be able to tolerate some pretty extreme conditions and because the bulkheads are centrally located within the aircraft, they need to remain stable and intact. It must endure air-to-air or air-to-ground combat, be stealthy and agile, and reach speeds faster than the speed of sound!

The people operating or relying on this military aircraft need to be confident that it can handle all of these conditions. This is why researchers extensively test the materials used on the JSF to see how they will perform in real world conditions.

An example of this is seen in the rigorous **fracture toughness** testing that the JSF's bulkheads must undergo. Fracture toughness testing helps scientists quantify how well a material can resist fracturing once a sharp crack has been established. In other words, fracture toughness testing helps researchers know how quickly a crack will spread once it has formed. The pictures below will give you a better idea of how the test works.



Extension Activity





Figure 1: Testing starts by selecting the right specimen. Notice the notch in the specimen; as a load is repeatedly applied to the specimen, a small crack will begin to grow from the notched area. (Photo courtesy of Arconic.)



Figure 2: After a crack forms in the specimen, a measurement device is attached to the notch to measure how much the distance between the top and bottom of the notch grows as an increasing load is applied. (Photo courtesy of Arconic.)



Figure 3: At the end of the test, the specimen is broken open to look at the microstructure of the crack. Lastly the fracture toughness values are calculated, and the results are validated. (Photos courtesy of Arconic.)



Extension Activity

 The graph to the right shows the fracture toughness for the various section thicknesses required to compose the onepiece forgings for the main bulkheads in an F-35 Lightning II. Which section thickness actually had the highest fracture toughness?



2. The figure below shows the material thickness required to compose the one-piece forgings for the main bulkheads in a F-35 Lightning II. Which thickness would you expect to have the highest fracture toughness? Why?



3. Thinner materials are more susceptible to ductile fractures as opposed to brittle fractures. Research both ductile and brittle fractures and distinguish between each.

Definition

Fracture Toughness

The ability of a material to resist fracture.



Answers to Extension Activities



Questions and Answers

1. The graph below shows the fracture toughness for the various section thicknesses required to compose the one-piece forgings for the main bulkheads in a F-35 Lightning II. Which section thickness actually had the highest fracture toughness?

Answer: The 2.0"-4.0" section thickness had the highest fracture toughness.

2. The figure below shows the material thickness required to compose the one-piece forgings for the main bulkheads in a F-35 Lightning II. Which thickness would you expect to have the highest fracture toughness? Why?

Answer: Many students will likely predict the 10-12" section will have the highest fracture toughness since it is the thickest and should therefore be able to withstand a heavier load. However, the data shows that this is not the case and that the thinnest sections were most resistant to fracturing.

3. Thinner materials are more susceptible to ductile fractures as opposed to brittle fractures. Research both ductile and brittle fractures and distinguish between each.

Answer:

Ductile fractures:

- Occur with plastic deformation
- Physical warning before fracture
- Most common fractures are moderately ductile

Brittle fractures:

- Sudden, very rapid cracking of equipment under stress where the material exhibited little or no evidence of ductility or plastic degradation before the fracture occurred
- Typically caused by low temperatures



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Materials Explorers[™] is a STEM educational outreach initiative of The Minerals, Metals & Materials Society (TMS). TMS is non-profit, international professional society with a mission to promote the global science and engineering professions concerned with minerals, metals, and materials.

