Session 3

Materials for Design

Engineering Fundamentals

In This Session:

A) Properties of Materials (60 minutes)
- Student Handout
- Student Reading

B) Materials Applications (45 Minutes)
- Student Handout
- Student Reading

C) Materials Choice (45 Minutes)
- Student Handout
- Student Reading

Home Improvement
- Student Handout

Materials for Design introduces the principles behind materials selection. Like materials engineers, learn to differentiate and select materials based on their properties. In *3A: Properties of Materials*, test samples of metals, ceramics, polymers, and composites to compare their properties. Test for density, ductility, strength, fatigue, electrical and thermal conductivity, and optical properties. In *3B: Materials Application*, now apply your knowledge of material properties to solve real-world problems faced by materials engineers. When materials engineers select which materials to use, they also consider the cost of materials. In *3C: Materials Choice*, gain an understanding of the economics of material selection through a cost analysis of a beverage container made of different materials. Lastly, think innovatively about how to design a beverage container that can be put to another use.

In the Home Improvement activity, *Materials Scavenger Hunt*, look at objects and analyze what materials were used to make them.

Properties of Materials

Handout: Session 3, Activity A

Materials engineers design new materials and determine which materials are best used for certain structures and devices. They determine this by understanding the properties of materials so that they can select the most appropriate material or combination of materials for a particular use.

In this activity, you will test materials to learn about their properties. After each test, record your results. Charts can be made and completed in your design notebook. For each property, come up with examples of objects where each property is important.

Material Properties Definitions

Property	Definition
Density	How heavy objects are that occupy the same volume
Ductility	How easily a material stretches when force is applied
Strength	How much weight a material can hold without failing or breaking
Fatigue	How easily a material withstands repeated stresses
Electrical conductivity	Whether or not electricity passes through the material
Thermal conductivity	How easily heat passes through the material
Optical properties	How easily light passes through it (transparent, translucent, opaque)
Corrosion	If the material degrades easily because of the physical environment

Density Test
Question: Which materials are denser?
Materials: a clay brick, block of wood, and block of Styrofoam* (all the same size)

1. Demonstration: Compare the density of a brick, a block of wood, and a block of Styrofoam.

2. Rate materials: high, medium, and low density.

Rating *(highest to lowest density)*	Material Tested	Material Class

3A Handout: Properties of Materials (continued)

3. Discuss design issues: Think of examples of other objects where high density is important. Think of examples of objects where low density is important.

Ductility Test
Question: How easily does the material stretch when force is applied?
Materials: 1 wooden craft stick, 1 plastic cable tie, 1 paper clip

1. Test: Bend the wooden craft stick, a plastic cable tie, and a metal paper clip. What happens? Which one is most ductile? What about ceramic tile, what would happen if you bent a piece of tile?

2. Rate materials: from the most ductile to the least ductile.

Rating *(most ductile to least ductile)*	**Material Tested**	**Material Class**

3. Discuss design issues: Ductility is important in designing products which can only be allowed to bend by a certain amount or that need to be flexible when used and return to their original shape when not in use. What are examples of applications where ductile materials are needed?

Fatigue Test
Question: How much repeated stress can cause the material to fail or break?
Materials: wooden craft stick, plastic multipurpose cable tie, metal paper clips (same materials as used in the ductility test)

1. Test: Bend each item back and forth as you count how many times it takes to break. Record the times. Be sure to use the same amount of strength or stress when bending the material back and forth over and over.

2. Rate materials: high, medium, low fatigue resistant.

Rating *(most fatigue resistant to least)*	**Material Tested**	**Material Class**

3A Handout: Properties of Materials (continued)

3. Discuss design issues: For what objects is fatigue resistance important? For what objects is material fatigue not important?

Strength Test (Tensile Test)

Question: How much weight can the material hold without failing or breaking?
Materials: 8 inch x 1 inch (20 cm x 2.5 cm) strips of: heavy-duty aluminum foil, heavy plastic bag, and paper; 2 buckets (1 large and 1 small, such as 10 quart [9 liters] and 5 quart [4.7 liters]), 5 lbs. (2.2 kg) of sand, rice, or beans (as weights); 2 2-inch (5 cm) C-clamps

1. Test: Attach a bucket with a C-clamp to the material to be tested and attach the material with a C-clamp to a table. Be sure to have a larger bucket below to catch the weights. Fill the bucket slowly with weights. How much weight will it take until the material breaks? Record results and compare.

2. Rate materials: from strongest to weakest in strength.

Rating *(strongest to weakest)*	Material Tested	Material Class

3. Discuss design issues: Material strength is important in structural applications. What are examples of this? Material strength is also important in transportation applications. What are examples of this?

3A Handout: Properties of Materials (continued)

Electrical Conductivity Test
Question: Does electricity pass through the material easily?
Materials: battery, wire, bulb, aluminum foil, paper, plastic bag, and ceramic tile.

1. Test: Make an electrical circuit with each material and see if the bulb lights.

2. Rate materials: yes or no if the bulb lights.

Rating *(yes or no)*	Material Tested	Material Class

3. Discuss design issues: When is it important to use a material that conducts electricity? When is it important to use a material that does not conduct electricity?

Thermal Conductivity Test
Question: Does heat pass through the material easily?
Materials: candle, matches, same materials used in electrical conductivity test

1. Test: Investigate the ability of materials to transmit heat by holding each material a few inches (centimeters) from the candle flame for 15 seconds. Take the material away from the flame and compare how hot it is and how far the heat has traveled. A material that is very hot and where the heat has spread has high thermal conductivity. Record results and repeat.

2. Rate materials: high, medium, or low conductivity.

3A Handout: Properties of Materials (continued)

Rating *(highest to lowest thermal conductivity)*	Material Tested	Material Class

3. Discuss design issues: What are other examples of objects that need a material that is a thermal conductor? When is the use of insulation materials necessary?

Optical Properties Test
Question: Does light pass through the material easily? (Is the material transparent, translucent, or opaque?)
Materials: flashlight or bulb and battery, plastic bag, plastic cup, colored plastic bucket (Alternate materials may be used.)

1. Test: Compare materials by shining a light through them.
2. Rate materials: transparent, translucent, or opaque.

Rating *(transparent, translucent, opaque)*	Material Tested	Material Class

3. Discuss design issues: What are examples of objects made that are transparent, translucent, and opaque? When are these properties important?

What Are Things Made Of?

Reading: Session 3, Activity A

From the Stone Age to the Information Age, humans have made use of a wide array of materials to improve their lives. Stroll through the halls of a museum and you will see that major epochs have been shaped and even defined by certain materials. From iron and steel to textiles and microprocessors, materials have a seemingly infinite range of properties and applications.

Not surprisingly, the field of materials science covers a wide range of disciplines. Materials engineers contribute to the field by evaluating materials for how well they distribute stress, transfer heat, conduct electricity, and meet other design specifications.

New materials are constantly being invented, and new uses for existing materials continue to emerge. In recent years, for example, researchers from Nike have figured out how to grind up used athletic shoes and create a new material for resurfacing running tracks and basketball courts. Researchers from Patagonia have developed a method to reuse the plastic in soda bottles to make a synthetic fiber that is spun into soft fleece for making sportswear.

Let's take a look at four of the major classes of materials.

Metals

Metals are a class of materials that include metallic elements, such as iron or gold, and combinations of metals, known as alloys. Metals usually are good conductors of heat and electricity. They tend to be strong but can be shaped, and can be polished to a high gloss. Iron, for example, has been important as a building material ever since humans learned to change its properties by heating and cooling it.

Ceramics

Ceramics are compounds made of metallic and nonmetallic elements and include such compounds as oxides, nitrides, and carbides. The term *ceramic* comes from the Greek word *keramikos*, which means burnt stuff. The properties of ceramics are normally achieved through a high-temperature heat treatment process called firing. Ceramics tend to be good at insulating, highly durable, and resistant to high temperatures and harsh environments. For example, dentists have developed a way to use ceramics for fillings despite the special demands of materials used inside the mouth. In adapting ceramics for dental use, materials scientists had to develop ceramics that would not be affected by acids, would have low thermal conductivity, would be resistant to wear from chewing, would not expand or contract when exposed to heat or cold, and would be appealing cosmetically.

Plastics

Polymers occur when molecules combine chemically to produce larger molecules that contain repeating structural units. Plastics, for example, are a large group of organic, man-made compounds based upon carbon and hydrogen. The basic building block of a plastic is the polymer molecule, a long chain of covalent-bonded atoms. Plastics are processed by forming and molding into shape. Usually, they are low density and may have a low melting point. Polymers have a wide range of applications, from synthetic fibers like nylon and polyester to car parts and packaging materials like Styrofoam*. Velcro*, a synthetic fabric used for fasteners, is

3A Reading: What Are Things Made Of? (continued)

a well-known application of a polymer.

Composites
Composites can be synthetic or natural or biocomposites. Synthetic composites are manufactured whereas biocomposites are found in nature. Wood, silk, and cotton are examples of biocompsites. Composites consist of more than one material type, such as metal and ceramic. Fiberglass, a combination of glass and a polymer, is one example. Plywood, another composite, is made up of thin sheets of wood stacked and glued. The properties of composites depend on the amount and distribution of each type of material, but the idea is that the combination of materials will create a material with more desirable properties than possible with any individual material. One common use of composites is for sports equipment, such as golf clubs, tennis racquets, and bicycle frames.

References
Pizzo, Patrick P. *Exploring Materials Engineering*, Chemical and Engineering Department, San Jose State University, (September 15, 2003). www.engr.sjsu.edu/WofMatE*

The Minerals, Metals, and Materials Society. *Materials Science and Engineering Career Resource Center*. www.crc4mse.org*

Materials Applications

Handout: Session 3, Activity B

Using the materials properties test results from the previous activity, you will solve each problem to determine the best materials for particular uses.

For each problem, determine the following:

- Which properties are important to solving the problem?
- Which materials have the important properties?
- What types of materials would you use to make this product?

Make a sketch of the object for each problem and label the materials.

Problems

#1: Acme Foodstuffs has a problem. Acme started making a new product that requires using hot corn syrup. The corn syrup must be portioned out with a spoon into large bottles while it is still hot (350°F, 175°C). The operator will be using a big spoon that she will be holding for more than an hour a day. The company needs a new spoon to serve this purpose.

#2: A new golf club manufacturer would like to make lightweight, sturdy, and electrically nonconductive golf clubs but doesn't know where to start. The golf club heads should be hard and wear-resistant and must withstand repeated strokes of high force against the golf ball.

#3: Hang Dry Clothespin Manufacturers is undertaking an aggressive campaign to encourage people to conserve energy by hanging their clothes out to dry. They would like to come up with a new modern clothespin that will appeal to the masses.

#4: Phantom Phone Booths is trying to come up with a new public phone booth for the 21st century. Not only will the public phone booth contain pay phones, but will also be a private place for people to use their cell phones and plug in their laptop computers. The booth must be private, but allow for daylight to pass through and allow people to see if it is occupied.

Meet a Materials Engineer

Reading: Session 3, Activity B

Stephanie Kwolek: Developing a Miracle Fiber

Marketers call Kevlar* a miracle fiber. Police officers who wear vests reinforced with the stuff call it a lifesaver. And the chemist who developed the ultra-strong but lightweight synthetic material calls her famous invention "a case of serendipity."

Used in the manufacture of everything from bulletproof vests to puncture-resistant bicycle tires to flame barriers, Kevlar came about through a combination of scientific know-how, ingenuity, teamwork, persistence, and the willingness to follow a hunch.

Back in 1964, Stephanie Kwolek was working as a research chemist for DuPont. "I loved to solve problems, and it was a constant learning process. Each day there was something new, a challenge, and I loved that," Kwolek told the Smithsonian Institution in an interview after she had retired.

One of Kwolek's design challenges in the lab was to develop long chain molecules called polymers, used to make nylon and other synthetic fibers. Researchers saw a market for a new generation of materials that would be strong but lightweight and that would not melt, even at high temperatures.

An unexpected lab result led to the breakthrough that eventually yielded Kevlar. Ordinarily, a dissolved polymer solution looks like molasses—thick but translucent. When Kwolek dissolved certain polymers in a solvent, she wound up with a solution that looked watery and cloudy. When Kwolek stirred the solution, it separated into two layers. She tried filtering the solution and ruled out contamination as a factor. When she analyzed the flow and cohesive properties of the solution, she became more intrigued by her observations. "It had a lot of strange features," Kwolek later recalled. "I think someone who wasn't thinking very much, or just wasn't aware or took less interest in it, would have thrown it out."

Instead of tossing the mystery concoction, Kwolek set out to see what would happen if the solution was spun in a machine used to produce synthetic fibers. The coworker in charge of

3B Reading: Meet a Materials Engineer (continued)

the spinneret was skeptical and told her the solution was too watery to spin. She persisted, however, and he eventually agreed to run a test. "It spun beautifully," she recalled later. Researchers tested the spun fibers and found that they had remarkable strength and stiffness. Kwolek had revolutionized the polymers industry by developing the first liquid crystal polymer fiber.

It took a full decade of teamwork, testing, and product development before the first bulletproof vests made of Kevlar reached the market. By the time Kwolek was inducted into the National Inventor's Hall of Fame in 1995, the vests were credited with saving the lives of more than 3,000 law enforcement officers.

Kwolek retired from DuPont in 1986 with 17 patents to her name. She is a recipient of the Lifetime Achievement Award for innovation and invention given by the Lemelson-MIT Program. In 2003, at age 80, she was inducted in the National Women's Hall of Fame.

References

Brown, David E. *Inventing Modern America: From the Microwave to the Mouse*. Boston, MA: The MIT Press, 2001.

Howell, Caitlyn. "Kevlar®, The Wonder Fiber." *Innovative Lives*. Washington, DC: Smithsonian Institution, 1999. www.si.edu/lemelson/centerpieces/ilives/lecture05.html*

Materials Choice

Handout: Session 3, Activity C

Did you know that when you purchase a beverage, you pay more for the packaging than the beverage itself? So, what does it take to produce a beverage container and how are decisions made about what type of container to use?

The challenge: Your class has decided to go into the fruit juice business. You have already come up with delicious recipes and are now considering how you will package the drinks. As employees, you have been asked by the owner for your input on which type of beverage container to use. You are to do a cost analysis of aluminum, plastic, and glass, and make a case for one of these materials.

1. This chart shows the number of containers produced per pound of material, the raw material cost per pound, the average shipping cost per pound, and the production cost per container.

   Using this information, rank aluminum, glass, and plastic in the total cost to produce and deliver 1,000 containers. You will need to first determine how much one container weighs.

Material	Number of 12-oz./16-oz. Containers/lb.	Material Cost/lb.	Shipping Cost/lb.	Production Cost/Container
Aluminum	33.3/25.0	$0.70	$0.25	$0.10
Glass	2.3/1.8	$0.03	$0.25	$0.06
Plastic	14.3/11.1	$0.50	$0.25	$0.04

2. The next chart shows the total cost of returning the material to a state where it can be reused to make a new container instead of using raw materials. The chart also includes the cost of disposing the material into a landfill as an alternative to recycling.

   Calculate the cost to purchase scrap material and reprocess it and compare this amount to the cost of the raw material (in the previous chart plus the disposal cost.) Do this for 1,000 containers. For each material, is it more economically advantageous to recycle scrap material or dispose of it in a landfill?

Material	Scrap/lb.	Process Scrap/lb.	Disposal/lb.
Aluminum	$0.35	$0.15	$0.02
Glass	$0.01	$0.01	$0.02
Plastic	$0.10	$0.50	$0.02

3C Handout: Materials Choice (continued)

3. Global warming has been linked to the increase in carbon dioxide emissions to the atmosphere. Carbon dioxide is emitted by the burning of fossil fuels. Fossil fuels are burned to create energy that is used to manufacture and transport materials. Manufacturing beverage containers using recycled materials decreases the total carbon dioxide emissions because reprocessing consumes less energy than processing the raw material.

   The following chart summarizes the pounds of carbon dioxide emissions avoided by using recycled materials. From which material do you gain the most benefit by recycling?

Material	Lbs. of CO^2 Avoided Per Lb. of Material Recycled
Aluminum	4.5
Glass	0.2
Plastic	0.8

4. What type of beverage container do you think the juice company should use? Make a case for aluminum, glass, or plastic.

Extending the Life of the Container

Design challenge: You have been asked to design a beverage container that would not be considered waste after its use. Consider how the container might be recycled and reconstituted for another use or how the container might be redesigned to achieve a secondary use. Be innovative! Sketch your design idea.

Meet an Environmental Engineer

Reading: Session 3, Activity C

Cindy Butler
Project Manager, Energy, Environment, and Systems Division
CH2M Hill, Portland, Oregon

They might be called in to clean up an industrial site. Design a way to avoid groundwater contamination. Plan a new project so that it meets environmental regulations. Get the mold out of a tropical high-rise hotel ventilating system. These problem-solving activities, and many more, are all in a day's work for environmental engineers.

Cindy Butler is a project manager in the environmental division of a large engineering and consulting firm, CH2M Hill, in Portland, Oregon. The best part of her job? "On a weekly basis, sometimes daily, I learn something I didn't know before."

Laying the Foundation

When she was growing up in upstate New York, Butler had friends whose parents were doctors and lawyers. Her dad worked for Xerox. "He was the only engineer I knew," she says. "Otherwise, I wouldn't have had any idea what engineers do."

She took his advice and pursued engineering studies—with a vengeance. Within five years of finishing high school, she had earned dual bachelor's degrees (one in civil engineering and another in an interdisciplinary major called engineering and public policy) from Washington University in St. Louis, plus a master's in civil and environmental engineering from Carnegie Mellon in Pittsburgh, Pennsylvania.

During college, she also found time for an internship that gave her some practical experience and exposure to the field of environmental affairs. "The internship experience is key. It helps you find out what interests you, and what doesn't." Her days were jam-packed, she admits. "Between school and work, I became pretty good at time management."

Some of her favorite classes were in civil engineering, taught in the evenings by professors who spent their days actively working in the field. "I liked the real-world applications and discovered I was more interested in applications than theory," she says. Although she started in electrical engineering—her father's field—she eventually shifted her academic focus to civil and environmental engineering.

3C Reading: Meet an Environmental Engineer (continued)

Focus on People
On a typical day at CH2M Hill, where she has worked for three years, Butler might meet with clients. Scope out a project. Analyze a budget. Pull together a team of engineers and planners to work on a specific project. Talk with staff from a regulatory agency. "Lots of communicating and lots of problem solving," she says. "Interpersonal skills are a big part of the job. Even if you're doing research, you work on a team. There might be a few engineers who sit in a cubicle and crank numbers," she adds, "but not most of us. It's a people-oriented career."

The projects she manages might involve cleaning up the chemicals left behind at a former wood processing site, or solving groundwater contamination at a chemical plant. "We do a lot of site investigations, testing, and remediation," she explains. Sometimes, that means visiting a site to get a firsthand look. "It helps you see what you can't get from a map—the 3-D reality of the space."

Earlier in her career, Butler did more of the hands-on work. "You start by collecting soil and water samples, then move into analyzing data," she explains. Now she takes a longer view, keeping a big project on track and meeting the client's goals.

She appreciates the depth of resources found at a large firm like CH2M Hill. The company is involved in everything from building roads and designing transportation systems to cleaning up Superfund sites to industrial design projects. "People are eager to share what they know. I like to be challenged and keep learning something new. I think that's a common personality in the sciences," she says.

On the Cutting Edge
One of the most exciting aspects of engineering, Butler adds, "is being on the cutting edge. Engineering is always on the forefront, whether it's in designing new cars or coming up with the next biomedical breakthroughs."

For students considering the field, she shares an insight worth keeping in mind when the courses get challenging: "I think you work harder in college. It's grueling, and you can't afford to fall behind. You have to learn all the structural building blocks, and that means you do a lot of work manually so that you understand the concepts. Later, much of that work will be automated. But you have to learn the fundamentals first."

When the going gets tough, she adds, "remember that it's OK to ask for help." Peer tutoring programs and informal study groups are common practice at engineering programs, laying the groundwork for the teamwork of the real world.

Materials Scavenger Hunt

Handout: Session 3, Home Improvement

Walk through your home like a detective. Look for objects where the choice of material matters! Write about each item in your design notebook; its uses, the properties it requires, and how the materials meet those properties.

What is it?

What does it do?

What properties does it require?

How and why do the materials matter?