TEACHER INSTRUCTIONS

Fun with Liquid Nitrogen

Objective: To demonstrate the effects of temperature on the mechanical properties of materials by observing that many objects which are soft and malleable at room temperature become brittle when they are very cold.

Background Information: There are many real-world applications that put our understanding of the effects of temperature on materials to good use. A very well-known example is that of the Liberty ships, a type of cargo ship produced in large numbers by the United States during World War II. Many of the early ships used a variety of steel which became brittle and could crack at lower temperatures. Unfortunately, the cold water of the North Atlantic Ocean was below the temperature at which the steel became brittle, and as a result, a number of ships literally cracked in half! Another application for which temperature is important to consider is in turbine blades of jet engines. Jet engines burn fuel at such high temperatures that most normal metals would melt or become soft during operation. Therefore, jet engines that run at the highest temperatures often use ceramic turbine blades because they can better withstand the high temperatures without becoming warped or flexible.

Demo Description: In this demonstration, students will learn the difference between how some common items act at room temperature versus how they act after having been submerged in liquid nitrogen for a short time.

Keywords:
- temperature: a quantity which indicates how hot or cold a material is
- brittle: a material that breaks with little deformation when subjected to stress
- ductility: a solid material’s ability to deform under tensile stress
- elasticity: the ability of a material to deform when loaded and then return to its original shape upon unloading
- plasticity: refers to the ability of a material to undergo permanent deformation without breaking

Materials List:
- liquid nitrogen
- styrofoam bowl (or some other well-insulating container)
- marshmallows
- rubber bands

· ping-pong balls
· sewing needle
· tongs
· insulating gloves
· safety glasses
· broom and dustpan
· hammer (OPTIONAL)

Safety Precautions: Liquid nitrogen is a hazardous substance. If misused, it may cause frostbite, eye damage, torn flesh, or asphyxiation. **ALWAYS FOLLOW THESE SAFETY RULES:**

- Keep liquid nitrogen away from students.
- Wear safety goggles at all times.
- Use tweezers to handle superconductors, magnets, or other small, cold objects. Plastic tweezers are desired but should be tested for embrittlement (see last caution) before use in the classroom.
- Wear insulating gloves when handling liquid nitrogen containers or large, cold objects.
- Use liquid nitrogen only in well-ventilated places.
- Do not allow liquid nitrogen to touch any part of your body.
- Items in contact with liquid nitrogen become **EXTREMELY COLD**. Do not touch any item that has been immersed in liquid nitrogen until it has warmed to room temperature.
- Do not store liquid nitrogen in any container with a tight-fitting lid. A tightly sealed container will build up pressure as the liquid boils and may **EXPLODE** after a short time.
- Many substances become brittle and may shatter when cold, sending pieces of the material flying. Avoid common glass and large, solid plastics.

Instructions:

1. While wearing gloves, pour some liquid nitrogen into the styrofoam bowl.
2. Submerge a rubber band in the liquid nitrogen for about one minute.
3. Remove the rubber band and hold it at one end with the tongs. Ask that a student put on a glove and attempt to stretch it. Observe that it snaps in a brittle manner.
4. Repeat step 2 with a marshmallow.
5. Remove the marshmallow. Drop it on the floor and observe it shatter.
6. Very carefully puncture a ping pong ball with the sewing needle and repeat step 2.
7. Remove the ping pong ball and place it on the floor or table. As the air inside warms back to room temperature, it expands and releases from the small hole, causing the ball to spin.

Demo Delivery Hints: The above items were chosen primarily due to their low cost and their ability to demonstrate some key mechanical property changes in materials. Feel free to augment the recommended items with others of your choice. Additional objects of interest might include fruit (such as grapes or bananas), flowers, or balloons inflated with air. The latter can be used to show the remarkable volume change experienced by a gas over a temperature range. You could also use the ideal gas law to quantify that volume change.

Troubleshooting: If the objects dropped to the floor do not shatter readily, a hammer can be used to shatter the objects. Place the objects on a hard surface that will not be damaged by the hammer and take extra precautions with finger and eye protection.

Cleanup/Replacement parts: Dispose of the liquid nitrogen by either letting it boil away completely, or for a bit more excitement, pour it carefully onto the floor where the liquid will form small spheres that will scatter and dissipate quickly. Make sure the shattered objects have warmed to room temperature, and then use the broom and dustpan to sweep up the pieces.

TEACHER DISCUSSION QUESTIONS

Fun with Liquid Nitrogen

Discussion Questions to Ask Before the Demo

1. Ask students to give examples of how materials deform when a force is applied to them.

   Discussion: Materials generally deform in one or both of two ways: in an elastic manner or a plastic manner. Perfectly elastic materials, like rubber bands at room temperature, can be deformed (stretched) by a force, but will return to their original shape when the force is removed. Perfectly plastic materials, like silly putty at room temperature, change shape when a force is applied and remain in that shape even after the force is removed. Most materials deform in a way that is a combination of the two. For example, squish a fresh marshmallow. It will flatten out because of the force applied by your fingers. When you stop applying the force, you may notice that the marshmallow tries to puff back to its original shape, but it doesn't quite get there. The marshmallow's attempt to puff back to its original shape is the elastic component of its deformation, while the leftover flattening is the plastic component of its deformation.

2. Ask students to give examples of how materials break.

   Discussion: Materials generally break in one or both of two ways as well: in a brittle manner or a ductile manner. In a 100% brittle material, such as a coffee mug, the constituents of the material (atoms in the case of a coffee mug) cannot rearrange themselves easily when a force is applied and therefore the bonds between them fracture. In a 100% ductile material, like silly putty, the constituents of the material (polymer chains in the case of silly putty) can easily slide over one another and eventually the material stretches so thin that no more material is left to slide over itself, and it becomes two pieces. As with deformation, most materials break in a way that is a combination of the two. If you pull a marshmallow fast enough at room temperature it will stretch some as the sugar molecules slide over one another, but it will then “snap” in two. The stretching is the tendency of the marshmallow to break in a ductile manner, while the “snap” is the tendency of the marshmallow to break in a brittle manner.

3. Ask students how they think changing temperature will affect how materials deform and break.

   Discussion: When discussing how materials break, it was noted that brittle materials are brittle because the constituents of the material cannot rearrange. What factor determines the ease of that rearrangement? Temperature is the answer in most cases. Temperature is a measure of thermal energy, which in turn is essentially how much and how fast atoms in the material vibrate back and forth. When a force is applied to a material, the material's thermal vibrations can let the material's constituents hop or slide over each other, allowing for plastic deformation and a tendency towards breaking in a ductile manner. For the same reason, a material with less thermal energy cannot as easily let its constituents hop or slide, so the material has a tendency towards breaking in a brittle manner. So, you would probably expect materials to become more brittle as the temperature decreases.

4. Ask students why it is important for engineers to think about temperature when selecting materials for specific purposes.

   Discussion: See the Background Information section in the Teacher Instructions for discussion of this question.

Discussion Questions to Ask During the Demo

1. Ask students to guess how each object will behave before subjecting the object to a test.

   Discussion: There is no right or wrong answer to this question. Encourage as much discussion as possible as this is the best way to get students interested in the demo.

2. Ask students to note how each object behaves or breaks after testing.

   Discussion: See the explanation of brittle/ductile and elastic/plastic and the influence of temperature discussed in Questions 1-3 above. Encourage students to make the connection about the change in material properties (e.g., moving from ductile to brittle when exposed to liquid nitrogen, elastic to plastic, etc.) that they observe when a material is subjected to liquid nitrogen.

Discussion Questions to Ask After the Demo

1. Ask students to compare the behaviors of the rubber band at room temperature versus at 77 K.

   Discussion: Both objects break in a very brittle manner because neither has enough thermal energy to plastically or elastically deform (only small atomic scale deformations occur). At room temperature, rubber bands can stretch because they are comprised of coiled polymer chains (like springs) that uncoil and recoil when a force is applied and removed. At 77 K, the polymer coils do not have enough thermal energy to uncoil themselves. Therefore, only the bonds between individual atoms in the polymer chains can stretch. The bonds between each polymer chain are much weaker than the bonds between atoms, resulting in the rubber band breaking as soon as the forces on the chains exceed the chain-chain bond strength. Interestingly, the rubber band still deforms elastically, but only the smallest amount on the atomic scale rather than on the larger chain scale. Ceramic materials behave similarly. Most people do not consider ceramics to be elastic, but in general, ceramics can ONLY deform elastically. The deformation from stretching atomic bonds in ceramics requires large forces and results in such little strain (overall lengthening or shortening of an object) that you cannot detect it without sophisticated measurement techniques.

2. Ask students to compare the behavior of the marshmallow and the other objects at room temperature versus at 77 K.

   Discussion: In a similar way to the rubber bands, the marshmallow breaks in a brittle manner at 77 K. It retains neither its elasticity nor plasticity.

3. Ask students to think about the fact that real engineering materials, like steel at room temperature, might be analogous to the marshmallow at 77 K. Ask them to hypothesize how a steel would behave if its temperature were raised to 2000°F (roughly 70% of a typical steel's melting point).

   Discussion: As you might expect, the steel will become softer and easier to deform at higher temperatures. Steel that might otherwise break in a mostly brittle manner may break in a highly ductile manner at 70% of its melting temperature. Eventually, at a high enough temperature, the steel will sag under its own weight, similar to silly putty. As mentioned in the Background Information section, steel is one of the most commonly used materials for engineering applications. If it is too cold, it will be too brittle, and if it is too hot, it may be too ductile. The key is to strike the right balance.

Student Question Handout

Fun with Liquid Nitrogen

1. How does the rubber band behave at room temperature?

2. How does it behave after being subjected to liquid nitrogen?

3. What caused this behavior?

4. How does the marshmallow behave at room temperature?

5. How does it behave after being subjected to liquid nitrogen?

6. What happened to the ping pong ball after it was removed from the liquid nitrogen?

7. Why do you think this happened?

The American Ceramic Society Materials Science Kits Warranty Disclaimer, Limitation of Liability and Safety Disclaimer

NO WARRANTY – DISCLAIMER OF WARRANTY

THE AMERICAN CERAMIC SOCIETY (ACerS), OFFERS THE MATERIALS SCIENCE KITS "AS-IS", WITH NO WARRANTIES WHATSOEVER, EXPRESS OR IMPLIED, INCLUDING, WITHOUT LIMITATION, WARRANTIES OF MERCHANTABILITY, SAFETY, FITNESS FOR ANY PARTICULAR PURPOSE OR NON-INFRINGEMENT OF PATENTS, COPYRIGHTS OR OTHER PROPRIETARY RIGHTS OF OTHERS. SOME STATES AND JURISDICTIONS DO NOT ALLOW LIMITATIONS ON IMPLIED WARRANTIES, SO THE ABOVE LIMITATIONS MAY NOT APPLY TO CUSTOMER. WHEN THE IMPLIED WARRANTIES ARE NOT ALLOWED TO BE EXCLUDED IN THEIR ENTIRETY, THEY WILL BE LIMITED TO THE SHORTEST DURATION PERMITTED UNDER APPLICABLE LAW. CUSTOMER MAY ALSO HAVE OTHER RIGHTS WHICH VARY FROM STATE TO STATE.

WITHOUT LIMITING THE GENERALITY OF THE FOREGOING, ACerS DOES NOT WARRANT THAT EACH MATERIALS SCIENCE KIT IS COMPLETELY ERROR FREE, WILL OPERATE WITHOUT INTERRUPTION, OR IS COMPATIBLE WITH ALL EQUIPMENT AND SOFTWARE CONFIGURATIONS. CUSTOMER EXPRESSLY ASSUMES ALL RISK FOR USE OF THE MATERIALS SCIENCE KITS.

LIMITATION OF LIABILITY

TO THE MAXIMUM EXTENT PERMITTED BY LAW, ACerS WILL NOT HAVE ANY LIABILITY OR RESPONSIBILITY TO CUSTOMER FOR DAMAGES OF ANY KIND, INCLUDING SPECIAL, INDIRECT OR CONSEQUENTIAL DAMAGES (INCLUDING, WITHOUT LIMITATION, DAMAGES FOR LOSS OF DATA), ARISING OUT OF OR RESULTING FROM THE MATERIALS SCIENCE KITS, ANY COMPONENT, DOCUMENTATION, SERVICES OR MATERIALS MADE AVAILABLE TO CUSTOMER IN CONNECTION WITH THE MATERIALS SCIENCE KITS OR THE USE OR MODIFICATION OF ANY OF THEM, EVEN IF ACerS HAS BEEN ADVISED OF THE POSSIBILITY OF THE DAMAGES. IN ANY CASE, ACerS AND ITS LICENSORS' ENTIRE LIABILITY UNDER ANY PROVISION OF THIS AGREEMENT WILL BE LIMITED TO THE AMOUNT ACTUALLY PAID BY CUSTOMER TO ACerS FOR THE PRODUCT OR TEN DOLLARS ($10.00), WHICHEVER IS GREATER. Some states do not allow the limitation or exclusion of liability for incidental or consequential damages, or have legislation which restricts the limitation or exclusion of liability, so the above limitation may not apply to Customer.

CALIFORNIA RESIDENTS

California Residents: I understand that I am waiving rights with respect to claims that are at this time unknown or unsuspected, and in accordance with such waiver, I acknowledge that I have read and understand, and I hereby expressly waive, the benefits of section 1542 of the civil code of California, and any similar law of any state, country or territory, which provides as follows: "A general release does not extend to claims which the creditor does not know or suspect to exist in his or her favor at the time of executing the release, which if known by him or her must have materially affected his or her settlement with the debtor."

MATERIALS SCIENCE SAFETY DISCLAIMER

The materials science kits contain lessons that are believed to be reliable regarding the safe use and handling of these materials in laboratories and student classrooms. ACerS, however, does not represent or warrant in this, or in any other publication, to specify minimum safety or legal standards or to address all of the compliance requirements, risks, or safety problems associated with the handling of hazardous materials, their use, or the methods prescribed for using them in laboratories or classrooms. This information is intended to serve only as a beginning point for information and should not be construed as containing all the necessary compliance, safety, or warning information, nor should it be construed as representing the policy of ACerS. The kits should be used by minors (under 18) only with adult supervision.

Without limiting the generality of the foregoing disclaimers, no warranty, guarantee, or other form of representation is made by ACerS as to the accuracy or sufficiency of the information and guidelines included with the materials science kits, and ACerS assumes no liability or responsibility concerning the use of such instructions and guidelines for any purpose. It is the responsibility of the users of these materials to consult and comply with pertinent local, state, and federal laws, regulations, and standards with respect to the handling of materials. Users of the materials science kits should consult with the school's legal counsel or other professional advisers about the applicable laws, safety issues, and compliance issues for the storage of materials and the methods for using the materials in school classrooms and laboratories.

THIS DISCLAIMER APPLIES TO ANY LIABILITY THAT IS, OR MAY BE INCURRED BY, OR ON BEHALF OF THE INSTITUTIONS THAT USE THE MATERIALS SCIENCE KITS; INCLUIDNG, WITHOUT LIMITATION, THE FACULTIES, STUDENTS, OR PROSPECTIVE STUDENTS OF THOSE INSTITUTIONS; AND ANY MEMBER OF THE PUBLIC AT LARGE; AND INCLUDES, BUT IS NOT LIMITED TO, A FULL DISCLAIMER OF ANY LIABILITY THAT MAY BE INCURRED WITH RESPECT TO POSSIBLE INADEQUATE SAFETY PROCEDURES TAKEN BY ANY USER.

TEACHER INSTRUCTIONS

Superconductivity

Objective: To demonstrate the basic properties of superconducting materials and to provide a basic understanding of superconductivity and some of its applications.

Background Information: Superconductivity was discovered in 1911 by Kamerlingh Onnes, after he became the first person to successfully liquefy helium (helium liquefies at a temperature of -269°C, a temperature difficult to attain with the scientific equipment available at the time). The ability to reach such low temperatures led him to explore the electrical properties of metals at temperatures close to absolute zero. It was well known that the resistivity of metals decreased with decreasing temperature in the higher temperature ranges (now known to be because the conducting electrons are less impeded by thermal vibrations of atoms). However, it was not clear what the resistance of a metal would do at extremely low temperatures. Three theories existed at the time: 1) the resistance would drop to zero at 0 K, 2) the resistance would flatten out to a constant value at 0 K, and 3) the resistance would increase to infinity at 0 K because the electrons themselves would "freeze". Upon testing mercury, Onnes discovered that its resistance suddenly dropped to an immeasurably low value at about 4.2 K. In fact, the resistance disappeared completely. This phenomenon, dubbed superconductivity because a zero-resistance material can conduct a current with no loss of energy to heat, results in a number of interesting and potentially useful behaviors.

The zero-resistance state of a superconductor is the result of a complex set of interactions between the electrons and the atoms of the material. However, on a conceptual level, the behavior can be explained as a resonance between pairs of electrons and vibrations in the material's lattice of atoms (called phonons when the vibrations have a regular frequency). There is an overall energy savings by allowing for electrons to pair up, and this electron coupling results in zero resistance. However, coupling can only happen when the electron-scattering effect of random thermal vibrations is reduced at very low temperatures.

Unlike conventional conductors whose current can be related to resistance through Ohm's law, current in superconductors is strongly tied to the magnetic field in the material. Materials in a Type-I superconducting state allow for no magnetic flux lines to pass through, channeling them to the outside like a boulder diverts current in a river (The material used in this demonstration, YCBO, is a Type-II superconductor which can remain superconducting while allowing some magnetic flux lines to pass through it. The theory for describing Type-II superconductivity is more complicated than the theory to describe Type-I superconductivity, but the basic principles remain the same). When a material transitions into the superconducting state upon reaching its critical temperature, the expulsion of magnetic field lines from the interior is called the Meissner effect. According to Maxwell's theory of electromagnetism, a complex arrangement of currents on the surface of the material, called screening currents, produces a magnetic field exactly equal and opposite to the external field. The resulting magnetic forces are often strong enough to exceed the force of gravity, allowing for the magnetic levitation which is highlighted in this demonstration.

Applications for superconductors are varied and take advantage of their different properties. The ability to produce magnetic levitation is used in Maglev trains to create frictionless bearings, which allow for very high speeds and a perfectly smooth ride. Coils of superconducting wire can produce large magnetic fields with relatively low power input. These super electromagnets are used in MRI medical instruments, among other places. Two other applications with huge potential are those of using superconductors to replace conventional power transmission lines and to create magnetic fields to contain the plasma developed in nuclear fusion reactors. The former application needs further research to be attractive for large-scale production due to the brittleness of most superconductor materials (making it difficult to draw them into wires), as well as the cost of refrigerating long expanses of transmission lines. If fusion reactor technology is to become a reality, the latter application will be a crucial component of successfully implementing this technology.

Description: A pellet of superconducting yttrium barium copper oxide (YBCO) will be submerged in liquid nitrogen and cooled below its critical temperature of 93 K (-180.2°C/-292.3°F). A permanent magnet will then be placed above the superconductor pellet, and the interaction between the two pieces' magnetic fields will allow the magnet to levitate.

Keywords:

Electric current: flow of electric charge

Electric field: a vector field which describes the electric influence of electrically charged particles or a time-varying magnetic field

Magnetic field: a vector field which describes the magnetic influence of an electric current or magnetic material

Flux: flow of a quantity (material, field, etc.) through a unit area

Critical temperature: temperature at which a superconducting material loses its resistance and exhibits superconducting behavior

Phonon: arrangement of atoms which have a regular vibration frequency

Meissner effect: expulsion of magnetic fields from a superconductor as it transitions to its superconducting state

Materials List:

- YBCO pellet
- Liquid nitrogen
- Small permanent magnet
- Petri dish (or a foam coffee cup bottom)
- Tongs (must be plastic)
- Insulating gloves
- Safety glasses

Safety Precautions: Liquid nitrogen is a hazardous substance. If misused, it may cause frostbite, eye damage, torn flesh, or asphyxiation. **ALWAYS FOLLOW THESE SAFETY RULES:**

- Keep liquid nitrogen away from students.
- Wear safety goggles at all times.
- Use tweezers to handle superconductors, magnets, or other small, cold objects. Plastic tweezers are desired but should be tested for embrittlement (see last caution) before use in the classroom.
- Wear insulating gloves when handling liquid nitrogen containers or large, cold objects.
- Use liquid nitrogen only in well ventilated places.
- Do not allow liquid nitrogen to touch any part of your body.
- Items in contact with liquid nitrogen become **EXTREMELY COLD**. Do not touch any item that has been immersed in liquid nitrogen until it has warmed to room temperature.
- Do not store liquid nitrogen in any container with a tight-fitting lid. A tightly sealed container will build up pressure as the liquid boils and may **EXPLODE** after a short time.
- Many substances become brittle and may shatter when cold, sending pieces of the material flying. Avoid common glass and large, solid plastics.

Instructions:

1. While wearing gloves, pour some liquid nitrogen into the petri dish.

2. Place the YBCO pellet in the liquid nitrogen and wait for it to reach its critical temperature, at which point it becomes superconducting (about a minute).

3. Move the permanent magnet to a short distance from the surface of the liquid nitrogen and directly above the YBCO. Release the magnet. When done properly, the magnet will levitate above the superconductor. If the magnet falls, use tongs to remove it from the liquid nitrogen and try again.

4. While keeping the magnet above the superconductor, move it to new positions and orientations. Spin the magnet in any position or orientation and observe it remain in that state.
5. If needed, add more liquid nitrogen to keep the YBCO below its critical temperature.

Demo Delivery Hints: Encourage students to safely approach the demo so they can see the superconducting behavior up close. For larger classes, have students approach in groups. Alternatively, if a video magnifier is available, the instructor may find it easiest to perform the demonstration under the camera and project the enlarged video feed on a screen.

Troubleshooting: Ensure that the YBCO has cooled to below its critical temperature, otherwise superconducting behavior will not be observed. The critical temperature of YBCO is 93 K (-180.2°C/-292.3°F), meaning that dry ice with a sublimation temperature of 194.7 K (-78.5 °C/-109.3 °F) is insufficiently cold to induce superconductivity in YBCO. Of readily available coolants, only liquid nitrogen will be cold enough.

Cleanup/Replacement parts: Remove the YBCO from the liquid nitrogen using tongs and allow it to warm to room temperature. Dispose of the liquid nitrogen by either letting it boil away completely, or for a bit more excitement, pour it carefully onto the floor where the liquid will form small spheres that will scatter and dissipate quickly. The YBCO and the permanent magnet can be reused indefinitely; to repeat the demonstration, obtain more liquid nitrogen. YBCO is a brittle ceramic. Dropping it on a hard surface, or dropping a magnet too large to levitate onto it may cause it to crack or shatter. In addition, prolonged exposure to moisture increases the susceptibility of YCBO to cracking; be sure to dry the pellet after it has warmed to room temperature to prevent water from condensing on its surface from the air. Storing the YBCO with desiccant is ideal.

TEACHER DISCUSSION QUESTIONS

Superconductivity

Discussion Questions to Ask Before the Demo

1. Take a moment to consider the question: how cold is 93 K, the critical temperature of YCBO?

   Discussion: Kelvin is a temperature scale that can be related to Celsius through the equation: K = C+273.15. Or to Fahrenheit using: K = (F+459.67)*(5/9). That means 93 K is -292°F! Zero Kelvin is called "absolute zero" and is the temperature at which the thermal motion of atoms stops. Try as we might, we cannot reach this temperature (the Third Law of Thermodynamics). Also, since 0 is placed at the bottom of the Kelvin scale, there are no negative temperatures. See Figure 1 for a comparison of the three most common temperature scales.

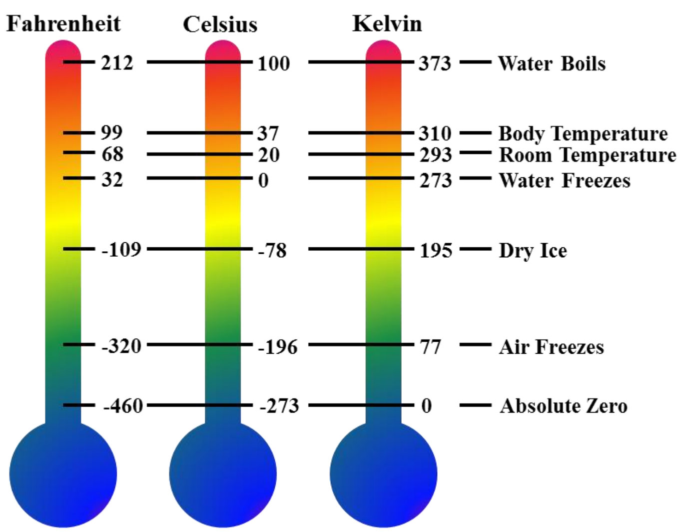

Figure 1. A visualization of how the three main temperature scales compare

2. How do normal magnets interact with one another?

   Discussion: Permanent magnets (such as those found on your fridge) each have a north and a south pole, connected by magnetic field lines. When two magnets are brought close to one another, the north and south poles of the two magnets will attract, while the north-north or south-south poles will repel. These repel because the field lines are pointing in opposite directions. They attract when the field lines are pointing in the same direction.

3. How does an electromagnet work?

   Discussion: An electromagnet is formed by coiling a wire and then running a current through it. The electric current flowing through the wire creates a magnetic field around the wire. Thus, when the current is turned off, the wire is no longer a magnet. These are often used in generators and motors and can also be found in your computer hard drive (it is the part that writes data to the hard drive).

Discussion Questions to Ask During the Demo

1. What is the liquid nitrogen doing to the YBCO?

   Discussion: The liquid nitrogen boils at 77.2K, so the liquid nitrogen we see is just below this temperature. Since heat passes from hot to cold, heat is leaving the YBCO and entering the LN2. This is cooling the YBCO down to such a low temperature that the atoms themselves are moving less, and this allows the superconducting nature of the material.

2. Why is the permanent magnet floating above the YBCO?

   Discussion: The permanent magnet is being repelled by the YBCO. The YBCO is so cold that it allows for no magnetic flux lines to pass through it; therefore, the magnetic lines of the permanent magnet are not allowed to interact with it, creating a repulsive force. The repulsion is actually stronger than gravity (one could calculate the force of gravity operating on the permanent magnet).

Discussion Questions to Ask After the Demo

1. What applications can you think of for superconductors?

   Discussion: See the Background Information section in the Teacher Instructions for a discussion of this question.

2. Why is it so much more difficult to get one permanent magnet to levitate over another, without using a superconductor?

   Discussion: These permanent magnets do not necessarily have exactly equal and opposite magnetic fields due to varying size, shape, and even the magnet's microstructure. Also, the magnets would have to be precisely positioned, centering their magnetic fields. Since the superconductor is not a magnet by itself, all of its magnetic field comes from the zero-loss current induced on the surface by the permanent magnet. Wherever the magnet is placed (if not over the edges), the superconductor will exactly balance the field of the magnet.

3. Can a superconductor carry an infinite current? Why or why not?

   Discussion: No, all superconductors have both a critical (magnetic) field and critical current density, which if exceeded, overloads the superconductor's capacity to remain superconducting. The superconducting behavior will subsequently break down.

4. Can a superconductor repel an infinitely strong magnetic field? Why or why not?

   Discussion: No, for the reason stated in the Question 3 discussion.

5. Each new superconductor material has a critical temperature. YBCO is an important material because it has a critical temperature of 93K, which means that liquid nitrogen can cool it below its transition temperature. The newest materials are superconducting at temperatures as high as 138K. What would be the next important critical temperature(s) to reach, so that the material could be cooled more cheaply?

   Discussion: The next important temperature would be 195K, where dry ice could be used (although the solid would not extract heat as efficiently as a liquid). Next, liquid water could be used above 273K, and obviously through room temperatures (~300K). Finding a room-temperature superconductor would drastically reduce the world's energy consumption by eliminating power transmission losses (this accomplishment would be a guaranteed Nobel Prize).

6. YBCO at room temperature has a resistance to the flow of current. So what causes YBCO to exhibit zero resistance at low temperatures?
   Hint: Electric current is the flow of electrons. Something is different about the flow of electrons in the superconducting state in that they pass unobstructed by the lattice. Because they bump into nothing and create no friction, they can transmit electricity with no loss in the current and no loss of energy.

Discussion: The understanding of superconductivity was advanced in 1957 by three American physicists – John Bardeen, Leon Cooper, and John Schrieffer, through their Theories of Superconductivity, known as the BCS Theory. Key points of BCS theory are (THE SCIENCE):

- The BCS theory successfully shows that electrons can be coupled to one another through interactions with the crystalline lattice of a material. This occurs despite the fact that electrons have the same charge.
- When the atoms of a material oscillate in conjunction with the motion of the electrons, the electron pairs are able to move without being scattered.
- The electron pairing is favorable because it has the effect of putting the material into a lower energy state.
- When electrons are linked together in pairs, they move through the superconductor in an orderly fashion.

At low temperatures, imagine each pair of electrons as a surfer catching a wave, except that the wave is in the material rather than in the ocean. If waves in the material have a regular frequency (making them phonons) like ocean waves, the electrons can surf through the material with no problem. This is similar to the YBCO at low temperature. At higher temperatures, the analogy is not so great, but imagine if the wind was always changing direction on the ocean. You might get sets of waves traveling in different directions, interacting with each other in crazy ways. The electron surfer would have a much harder time traveling smoothly in one direction. This is like the YBCO at room temperature.

STUDENT QUESTION HANDOUT

Superconductivity

1. What magnetic phenomenon occurs within a superconductor when it is cooled below its critical temperature?

2. Why does a superconductor need to be kept at low temperatures to maintain superconducting properties?

3. How does a superconductor levitate permanent magnets?

4. How is this levitation different than that caused by the interaction between two permanent magnets or a conventional electromagnet?

5. Why do metals, such as copper and gold (which are some of the best conventional conductors), not become superconductors? Hint: think about the energy savings associated with electron coupling in superconducting materials vs. non-superconducting materials.

6. Can a superconductor carry an infinite current? Why or why not?

7. Can a superconductor repel an infinitely strong magnetic field? Why or why not?

The American Ceramic Society Materials Science Kits

Warranty Disclaimer, Limitation of Liability and Safety Disclaimer

NO WARRANTY – DISCLAIMER OF WARRANTY

THE AMERICAN CERAMIC SOCIETY (ACerS), OFFERS THE MATERIALS SCIENCE KITS "AS-IS", WITH NO WARRANTIES WHATSOEVER, EXPRESS OR IMPLIED, INCLUDING, WITHOUT LIMITATION, WARRANTIES OF MERCHANTABILITY, SAFETY, FITNESS FOR ANY PARTICULAR PURPOSE OR NON-INFRINGEMENT OF PATENTS, COPYRIGHTS OR OTHER PROPRIETARY RIGHTS OF OTHERS. SOME STATES AND JURISDICTIONS DO NOT ALLOW LIMITATIONS ON IMPLIED WARRANTIES, SO THE ABOVE LIMITATIONS MAY NOT APPLY TO CUSTOMER. WHEN THE IMPLIED WARRANTIES ARE NOT ALLOWED TO BE EXCLUDED IN THEIR ENTIRETY, THEY WILL BE LIMITED TO THE SHORTEST DURATION PERMITTED UNDER APPLICABLE LAW. CUSTOMER MAY ALSO HAVE OTHER RIGHTS WHICH VARY FROM STATE TO STATE.

WITHOUT LIMITING THE GENERALITY OF THE FOREGOING, ACerS DOES NOT WARRANT THAT EACH MATERIALS SCIENCE KIT IS COMPLETELY ERROR FREE, WILL OPERATE WITHOUT INTERRUPTION, OR IS COMPATIBLE WITH ALL EQUIPMENT AND SOFTWARE CONFIGURATIONS. CUSTOMER EXPRESSLY ASSUMES ALL RISK FOR USE OF THE MATERIALS SCIENCE KITS.

LIMITATION OF LIABILITY

TO THE MAXIMUM EXTENT PERMITTED BY LAW, ACerS WILL NOT HAVE ANY LIABILITY OR RESPONSIBILITY TO CUSTOMER FOR DAMAGES OF ANY KIND, INCLUDING SPECIAL, INDIRECT OR CONSEQUENTIAL DAMAGES (INCLUDING, WITHOUT LIMITATION, DAMAGES FOR LOSS OF DATA), ARISING OUT OF OR RESULTING FROM THE MATERIALS SCIENCE KITS, ANY COMPONENT, DOCUMENTATION, SERVICES OR MATERIALS MADE AVAILABLE TO CUSTOMER IN CONNECTION WITH THE MATERIALS SCIENCE KITS OR THE USE OR MODIFICATION OF ANY OF THEM, EVEN IF ACerS HAS BEEN ADVISED OF THE POSSIBILITY OF THE DAMAGES. IN ANY CASE, ACerS AND ITS LICENSORS' ENTIRE LIABILITY UNDER ANY PROVISION OF THIS AGREEMENT WILL BE LIMITED TO THE AMOUNT ACTUALLY PAID BY CUSTOMER TO ACerS FOR THE PRODUCT OR TEN DOLLARS ($10.00), WHICHEVER IS GREATER. Some states do not allow the limitation or exclusion of liability for incidental or consequential damages, or have legislation which restricts the limitation or exclusion of liability, so the above limitation may not apply to Customer.

CALIFORNIA RESIDENTS

California Residents: I understand that I am waiving rights with respect to claims that are at this time unknown or unsuspected, and in accordance with such waiver, I acknowledge that I have read and understand, and I hereby expressly waive, the benefits of section 1542 of the civil code of California, and any similar law of any state, country or territory, which provides as follows: "A general release does not extend to claims which the creditor does not know or suspect to exist in his or her favor at the time of executing the release, which if known by him or her must have materially affected his or her settlement with the debtor."

MATERIALS SCIENCE SAFETY DISCLAIMER

The materials science kits contain lessons that are believed to be reliable regarding the safe use and handling of these materials in laboratories and student classrooms. ACerS, however, does not represent or warrant in this, or in any other publication, to specify minimum safety or legal standards or to address all of the compliance requirements, risks, or safety problems associated with the handling of hazardous materials, their use, or the methods prescribed for using them in laboratories or classrooms. This information is intended to serve only as a beginning point for information and should not be construed as containing all the necessary compliance, safety, or warning information, nor should it be construed as representing the policy of ACerS. The kits should be used by minors (under 18) only with adult supervision.

Without limiting the generality of the foregoing disclaimers, no warranty, guarantee, or other form of representation is made by ACerS as to the accuracy or sufficiency of the information and guidelines included with the materials science kits, and ACerS assumes no liability or responsibility concerning the use of such instructions and guidelines for any purpose. It is the responsibility of the users of these materials to consult and comply with pertinent local, state, and federal laws, regulations, and standards with respect to the handling of materials. Users of the materials science kits should consult with the school's legal counsel or other professional advisers about the applicable laws, safety issues, and compliance issues for the storage of materials and the methods for using the materials in school classrooms and laboratories.

THIS DISCLAIMER APPLIES TO ANY LIABILITY THAT IS, OR MAY BE INCURRED BY, OR ON BEHALF OF THE INSTITUTIONS THAT USE THE MATERIALS SCIENCE KITS; INCLUIDNG, WITHOUT LIMITATION, THE FACULTIES, STUDENTS, OR PROSPECTIVE STUDENTS OF THOSE INSTITUTIONS; AND ANY MEMBER OF THE PUBLIC AT LARGE; AND INCLUDES, BUT IS NOT LIMITED TO, A FULL DISCLAIMER OF ANY LIABILITY THAT MAY BE INCURRED WITH RESPECT TO POSSIBLE INADEQUATE SAFETY PROCEDURES TAKEN BY ANY USER.

TEACHER INSTRUCTIONS

Cold and Hot Processing of Materials

Objective: To demonstrate how increasing or decreasing temperature can affect the processing of materials.

Background Information: Atoms are in constant vibration at temperatures above 0 K (-273.15°C/-459.67°F). As the temperature is increased, the vibration of these atoms is increased, which encourages them to move from one place to another inside a material. Thus, by controlling the temperature, the extent to which various reactions take place can be controlled. This allows the processing of materials from one form to the other to also be controlled. Generally, as temperature is increased, a material goes from solid to liquid to gaseous state. Decreasing temperature usually has the opposite effect.

Ice cream is processed at temperatures lower than normal room temperature, which gives it a semi-solid texture. Sugar syrup is processed at temperatures higher than room temperature so that the sugar dissolves quickly in water to form a uniform liquid.

Description: In this demonstration, students will learn about the influence of lowering temperatures by processing ice cream using liquid nitrogen. They will then learn about the influence of increasing temperatures by processing sugar syrup.

Keywords:
Temperature: quantity which indicates how hot or cold a material is
Solid: fundamental state of matter that is characterized by structural rigidity
Liquid: fundamental state of matter that is characterized as having a definite volume, but no shape
Liquid Nitrogen: nitrogen that is in a liquid state at a very low temperature

Materials List:
- Liquid nitrogen
- Styrofoam bowl (or some other well-insulating container)
- Insulating gloves
- Wire whisk
- Half-and-half cream
- Stainless steel bowl

- Transparent glass cup/bowl that can be heated (e.g. a small Pyrex container or a beaker)
- Spoon
- Sugar
- Hot plate
- Vanilla/Chocolate ice cream syrup
- Safety glasses/goggles
- 1 teaspoon measuring spoon
- 1 cup measuring cup
- Wooden spatula

Safety Precautions: Liquid nitrogen is a hazardous substance. If misused, it may cause frostbite, eye damage, torn flesh, or asphyxiation. **ALWAYS FOLLOW THESE SAFETY RULES:**

- Keep liquid nitrogen away from students.
- Wear safety goggles at all times.
- Use tweezers to handle superconductors, magnets, or other small, cold objects. Plastic tweezers are desired but should be tested for embrittlement (see last caution) before use in the classroom.
- Wear insulating gloves when handling liquid nitrogen containers or large, cold objects.
- Use liquid nitrogen only in well ventilated places.
- Do not allow liquid nitrogen to touch any part of your body.
- Items in contact with liquid nitrogen become **EXTREMELY COLD**. Do not touch any item that has been immersed in liquid nitrogen until it has warmed to room temperature.
- Do not store liquid nitrogen in any container with a tight-fitting lid. A tightly sealed container will build up pressure as the liquid boils and may **EXPLODE** after a short time.
- Many substances become brittle and may shatter when cold, sending pieces of the material flying. Avoid common glass and large, solid plastics.

Instructions:

(a) For making ice cream

1. Mix 1 quart of half-and-half cream and ½ cup of sugar in the stainless steel bowl using the wire whisk. Continue mixing until the sugar has dissolved.
2. Add 2 teaspoons of vanilla or chocolate syrup to the cream and sugar mixture and whisk until well blended.
3. Put on insulating gloves and safety glasses. Using the Styrofoam bowl, pour a small amount of liquid nitrogen directly into the stainless steel bowl containing the ice cream

ingredients. Stir the mixture with a wooden spatula while slowly adding more liquid nitrogen until the ice cream starts to thicken.

4. Allow the remaining liquid nitrogen to boil off from the bowl. The ice cream will be left behind!
5. Serve or taste ice-cream only when all the liquid nitrogen vapors have gone away.

(b) For making sugar syrup

1. Add 2 cups of normal tap water to the clear/transparent glass cup.
2. Add 1 teaspoon of sugar to the glass of water and whisk using the spoon.
3. Continue adding teaspoons of sugar to the water until the sugar will no longer dissolve. Be sure to keep track of the number of teaspoons added to the water.
4. Empty the glass and again add 2 cups of water to it.
5. Put the glass on a hot plate and heat the water to 90 ºC. ***Note:*** the boiling point of water is 99.98°C, so the water should be almost to the boiling point.
6. Once this temperature has been attained, wear insulating gloves and safety glasses and repeat steps 2-3.

Demo Delivery Hints: At room temperature, the liquid nitrogen is already boiling and thus depletes very quickly. While making ice cream, be sure to whisk swiftly to minimize the use of the liquid nitrogen. While making the sugar syrup, the glass cup and hot plate can get very hot. Make sure to wear insulating gloves or use tongs to avoid accidentally burning your hands.

Troubleshooting: If the ice cream does not thicken after adding liquid nitrogen, then continue to add more liquid nitrogen. During the sugar syrup demonstration, if the sugar takes too much time to dissolve, do not hesitate to raise the temperature of the hot plate.

Cleanup/Replacement parts: Dispose of the liquid nitrogen by either letting it boil away completely, or for a bit more excitement, pour it carefully onto the floor where the liquid will form small spheres that will scatter and dissipate quickly. The half-and-half cream will also need to be replaced every time the ice cream is made.

TEACHER DISCUSSION QUESTIONS

Cold and Hot Processing of Materials

Discussion Questions to Ask Before the Demo

1. What is material processing?

   Discussion: Material processing is converting from one form of matter/material into another more useful or desired form.

Discussion Questions to Ask During the Demo

1. Why does the liquid half-and-half cream become semi-solid when the liquid nitrogen is added?

   Discussion: As liquid nitrogen is poured on the half-and-half cream, it cools it and thus reduces the vibrations of the atoms. This causes the half-and-half cream to change its state from liquid to semi-solid.

2. Ask students what they think will happen when sugar is poured in hot water as compared to cold water?

   Discussion: Sugar in hot water dissolves much faster as water molecules have lots of energy/vibrations due to the heat and want to move quickly. This creates more space between the water molecules, which allows more sugar particles to fill in this space.

Discussion Questions to Ask After the Demo

1. What other material processing requires increasing or decreasing temperature?

   Discussion: There are a variety of applications that students may mention. For example, frozen meals require heating to continue cooking the food and convert it to a semi-solid state appropriate for eating.

STUDENT QUESTION HANDOUT

Cold and Hot Processing of Materials

1. What happens to the half-and -half cream when the liquid nitrogen is added?

2. Why do you think this happens?

3. How many teaspoons of sugar were added to the room temperature water?

4. How many teaspoons of sugar were added to the hot water?

5. Was there a difference? Why or why not?

The American Ceramic Society Materials Science Kits

Warranty Disclaimer, Limitation of Liability and Safety Disclaimer

NO WARRANTY – DISCLAIMER OF WARRANTY

THE AMERICAN CERAMIC SOCIETY (ACerS), OFFERS THE MATERIALS SCIENCE KITS “AS-IS”, WITH NO WARRANTIES WHATSOEVER, EXPRESS OR IMPLIED, INCLUDING, WITHOUT LIMITATION, WARRANTIES OF MERCHANTABILITY, SAFETY, FITNESS FOR ANY PARTICULAR PURPOSE OR NON-INFRINGEMENT OF PATENTS, COPYRIGHTS OR OTHER PROPRIETARY RIGHTS OF OTHERS. SOME STATES AND JURISDICTIONS DO NOT ALLOW LIMITATIONS ON IMPLIED WARRANTIES, SO THE ABOVE LIMITATIONS MAY NOT APPLY TO CUSTOMER. WHEN THE IMPLIED WARRANTIES ARE NOT ALLOWED TO BE EXCLUDED IN THEIR ENTIRETY, THEY WILL BE LIMITED TO THE SHORTEST DURATION PERMITTED UNDER APPLICABLE LAW. CUSTOMER MAY ALSO HAVE OTHER RIGHTS WHICH VARY FROM STATE TO STATE.

WITHOUT LIMITING THE GENERALITY OF THE FOREGOING, ACerS DOES NOT WARRANT THAT EACH MATERIALS SCIENCE KIT IS COMPLETELY ERROR FREE, WILL OPERATE WITHOUT INTERRUPTION, OR IS COMPATIBLE WITH ALL EQUIPMENT AND SOFTWARE CONFIGURATIONS. CUSTOMER EXPRESSLY ASSUMES ALL RISK FOR USE OF THE MATERIALS SCIENCE KITS.

LIMITATION OF LIABILITY

TO THE MAXIMUM EXTENT PERMITTED BY LAW, ACerS WILL NOT HAVE ANY LIABILITY OR RESPONSIBILITY TO CUSTOMER FOR DAMAGES OF ANY KIND, INCLUDING SPECIAL, INDIRECT OR CONSEQUENTIAL DAMAGES (INCLUDING, WITHOUT LIMITATION, DAMAGES FOR LOSS OF DATA), ARISING OUT OF OR RESULTING FROM THE MATERIALS SCIENCE KITS, ANY COMPONENT, DOCUMENTATION, SERVICES OR MATERIALS MADE AVAILABLE TO CUSTOMER IN CONNECTION WITH THE MATERIALS SCIENCE KITS OR THE USE OR MODIFICATION OF ANY OF THEM, EVEN IF ACerS HAS BEEN ADVISED OF THE POSSIBILITY OF THE DAMAGES. IN ANY CASE, ACerS AND ITS LICENSORS’ ENTIRE LIABILITY UNDER ANY PROVISION OF THIS AGREEMENT WILL BE LIMITED TO THE AMOUNT ACTUALLY PAID BY CUSTOMER TO ACerS FOR THE PRODUCT OR TEN DOLLARS ($10.00), WHICHEVER IS GREATER. Some states do not allow the limitation or exclusion of liability for incidental or consequential damages, or have legislation which restricts the limitation or exclusion of liability, so the above limitation may not apply to Customer.

CALIFORNIA RESIDENTS

California Residents: I understand that I am waiving rights with respect to claims that are at this time unknown or unsuspected, and in accordance with such waiver, I acknowledge that I have read and understand, and I hereby expressly waive, the benefits of section 1542 of the civil code of California, and any similar law of any state, country or territory, which provides as follows: “A general release does not extend to claims which the creditor does not know or suspect to exist in his or her favor at the time of executing the release, which if known by him or her must have materially affected his or her settlement with the debtor.”

MATERIALS SCIENCE SAFETY DISCLAIMER

The materials science kits contain lessons that are believed to be reliable regarding the safe use and handling of these materials in laboratories and student classrooms. ACerS, however, does not represent or warrant in this, or in any other publication, to specify minimum safety or legal standards or to address all of the compliance requirements, risks, or safety problems associated with the handling of hazardous materials, their use, or the methods prescribed for using them in laboratories or classrooms. This information is intended to serve only as a beginning point for information and should not be construed as containing all the necessary compliance, safety, or warning information, nor should it be construed as representing the policy of ACerS. The kits should be used by minors (under 18) only with adult supervision.

Without limiting the generality of the foregoing disclaimers, no warranty, guarantee, or other form of representation is made by ACerS as to the accuracy or sufficiency of the information and guidelines included with the materials science kits, and ACerS assumes no liability or responsibility concerning the use of such instructions and guidelines for any purpose. It is the responsibility of the users of these materials to consult and comply with pertinent local, state, and federal laws, regulations, and standards with respect to the handling of materials. Users of the materials science kits should consult with the school’s legal counsel or other professional advisers about the applicable laws, safety issues, and compliance issues for the storage of materials and the methods for using the materials in school classrooms and laboratories.

THIS DISCLAIMER APPLIES TO ANY LIABILITY THAT IS, OR MAY BE INCURRED BY, OR ON BEHALF OF THE INSTITUTIONS THAT USE THE MATERIALS SCIENCE KITS; INCLUIDNG, WITHOUT LIMITATION, THE FACULTIES, STUDENTS, OR PROSPECTIVE STUDENTS OF THOSE INSTITUTIONS; AND ANY MEMBER OF THE PUBLIC AT LARGE; AND INCLUDES, BUT IS NOT LIMITED TO, A FULL DISCLAIMER OF ANY LIABILITY THAT MAY BE INCURRED WITH RESPECT TO POSSIBLE INADEQUATE SAFETY PROCEDURES TAKEN BY ANY USER.