Explorations in Materials Science

◆ METALS

STRUCTURE ◆

◆ PLASTICS

PROPERTIES ◆

◆ CERAMICS

PROCESSING ◆

Institute for Chemical Education

Explorations in Materials Science

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Preface

The General Atomics Sciences Education Foundation

Science and math education in grades K-12 directly affects our ability to meet tomorrow's challenges. In order to progress, more highly qualified scientists and engineers are needed working for our industry, government, and universities. Jobs of the future will require greater technical and mathematical literacy than jobs of the past.

Since 1992, General Atomics (GA) has received wide recognition for its Sciences Education Outreach Program, a volunteer effort of GA employees and San Diego science teachers. We work closely with the Science Coordinators for the San Diego Schools in order to bring the business and research side of science into the classroom. Our goal is both to improve the quality of science education and to encourage more students to pursue science careers. In addition, the teachers' interactions with the scientists and exposure to everyday uses of their disciplines help them to be better educators. In order to expand the program, the General Atomics Sciences Education Foundation was established in 1995.

The Foundation supports an annual day-long High School Science Day highlighted by laboratory tours and discussions on fusion, fission, and other advanced technologies being developed at GA. Classroom visits to GA and scientist/engineer visits to school sites also receive Foundation support.

The General Atomics Sciences Education Foundation (GASEF) is committed to playing a major role in enhancing pre-college education in science, engineering and new technologies. To attain this goal, four areas of core competency have been identified and converted into inquiry-based education modules and associated workshops. Scientist/teacher teams wrote these modules which fuse the content and methodology of industrial research and development with the teaching skills of experienced science teachers.

Since the program's inception, more than 500 teachers from over 175 junior and senior high schools have attended these workshops, many of them attending multiple workshops. Topics include:

- Explorations in Materials Science
- Fusion: Energy of the Stars
- Recombinant DNA Labs–Basic Tools for the Molecular Biologist
- Portrait of an Atom

In the spring of 1996, the Foundation launched a hands-on program for K-6 teachers resulting in a variety of K-6 modules and workshops.

These modules were meant to be enrichment activities that would provide a menu of novel activities that teachers could select for their students. However, some of these modules have attracted the interest of professional educational institutes, who are transforming them into educational modules that are being distributed nationally. The Line of Resistance module, part of the Explorations in Materials Science series of modules, was recently revised in collaboration with the Institute for Chemical Education (ICE) at the University of Wisconsin. ICE is currently distributing this module worldwide.

The development of these modules has served a number of unexpected purposes as well.

- It has invigorated the teacher members of the teams, as well as teachers who have attended the workshops, all of whom are excited to collaborate with working industrial scientists.
- It has reinvigorated the scientist members of the teams, who are excited to collaborate with teachers, learn about learning, and receive tremendous personal satisfaction helping to infuse the educational system with new ideas.
- It has demonstrated that teacher/scientist teams, who are not professional curriculum developers, can effectively participate in the continuous development of new content and approaches to learning.
- It has demonstrated that the business world is serious and committed to working with teachers and their students to improve the educational system.
- It can serve as a role model for a "Learning Society," where heretofore disparate groups collaborate and jointly work and learn together for the betterment of society.

For more information about GASEF contact:
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With Gratitude

- None of the efforts of the General Atomics (GA) Education Outreach Program would have been possible with out the vision, effort, and prodding of Patricia Winter, the GA Education Outreach Coordinator. We would also like to acknowledge the constant support and encouragement of Anne Blue. Patricia and Anne initiated the program at GA and quickly formed a partnership with the San Diego-area teachers through the efforts of Nancy Taylor, Science Coordinator at the San Diego County Office of Education. The support of GA management, particularly Neal Blue, is gratefully acknowledged. They all deserve much credit for trying to improve science education in San Diego, as well as across the nation.

  We would like to thank Kathleen Shanks for the excellent job she did in transforming our rather crude document into a visually appealing and educationally appropriate module. We would also like to acknowledge the able assistance of the entire ICE organization.

  The General Atomics/San Diego Teachers
  Materials Science Team
  Summer 1998

- Many thanks to all the people who provided support during the editing of this book, especially the authors. Their proofreading and clarifications were invalube. We would particulary like to acknowlegde the contributions of Dr. Dean Campbell of Bradley University, for his initial review of the manuscript; Celeste Kozlovsky, for her artistic expertise; and Patricia Winter, for her patience. The participants of ICE's 1998 Chemistry and Materials Science worskhop also deserve a word of thanks for their suggestions on the laboratory instructions.

  The ICE Staff
  Summer 1998

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Teacher's Guide

About This Booklet

The purpose of the ***Explorations in Materials Science*** module is to provide teachers with creative, inexpensive, hands-on/minds-on ideas that illustrate the physical, mechanical, and transport properties of three major classes of materials. These ideas include Exploration activities for the students, as well as some Extension activities for the advanced student. This module is directed to high school and college science teachers. It is intended to supplement and complement your regular curriculum materials. The information and activities may be used qualitatively in an introductory class, or quantitatively for an advanced group of students. Many teachers have found this module especially useful as an introduction to engineering materials.

The booklet begins with a listing of the American Association for the Advancement of Science (AAAS) Benchmarks that are relevant to the material in this module. The remainder of the booklet is arranged with the Teacher's Guide first, then the Student's Guide. The sections are arranged so that discussions of a particular set of properties (i.e. Physical Properties) precede the Exploration activities of those properties. You may choose to discuss all of the sets of properties and then proceed to all of the Exploration activities, or use the Explorations over the course of several weeks as your classroom discussion covers the different properties.

The Teacher's Guide covers many of the topics in more detail than the Student's Guide. Much of this is background material for you to share with the students and is not included in the descriptions in the Student's Guide. There are answers to selected questions which follow the Explorations in the Teacher's Guide. We recommend that students work on the Exploration activities in groups of 3, but groups of 2 or 4 will also work well. Single students may feel overwhelmed, and larger groups will not be able to work closely enough to benefit from the results of their Explorations. Each Exploration activity is intended to be performed with all three materials unless otherwise specified, which lends well to group work. Each student in a group might be responsible for a different material and write an individual report about that material. The students in each group could then communicate with one another to collaborate on a group report comparing the properties of the three materials.

General Atomics has set up a public forum on their web site for teachers to post comments, questions, and suggestions about Explorations in Materials Science. The web address is **http://www.sci-ed-ga.org/interaction$/forum/exploration**.

This booklet assumes the teacher has some advanced chemistry knowledge, and does not attempt to rewrite material easily found in college chemistry textbooks. In the Additional Resources section in the back of this booklet, a list of books has been included as a reference for teachers.

You will find that most of the materials and properties you discuss with your students will have relevance to their everyday lives. Use this familiarity to foster interest in further explorations. For example, many of your students are undoubtedly familiar with computers. Without the development of tiny semiconductor chips, the desktop and laptop computers of today could not exist. What properties of semiconductors make this possible? Questions like these and the Explorations in this booklet will help students develop an understanding of the importance of materials and their properties.

Benchmarks

Project 2061 is a program for long term systemic reform in science, math, and technology education in the United States. It is an initiative of the American Association for the Advancement of Science (AAAS). In 1989 *Science for All Americans* (SFAA) was published. SFAA was a statement of adult literacy in science, math, and technology. *Benchmarks for Science Literacy* states expectations of what students should know and be able to do in grades K-2, 3-5, 6-8, and 9-12 as they move toward developing adult literacy in science, math, and technology. This list is a suggestion of some benchmarks that might be addressed through a materials science unit. Only those benchmarks that directly relate to materials science have been included; additional benchmarks dealing for example with the Nature of Science, Habits of Mind, or Common Themes might also apply.

Grades 9-12

THE NATURE OF TECHNOLOGY: Technology and Science

- Technological problems often create a demand for new scientific knowledge, and new technologies make it possible for scientists to extend their research in new ways or to undertake entirely new lines of research. The very availability of new technology itself often sparks scientific advances.

THE PHYSICAL SETTING: Forces of Nature

- Different kinds of materials respond differently to electric forces. In conducting materials such as metals, electric charges flow easily, whereas in insulating materials such as glass, they can move hardly at all. At very low temperatures, some materials become superconductors and offer no resistance to the flow of current. In between these extremes, semiconducting materials differ greatly in how well they conduct, depending on their exact composition.

THE DESIGNED WORLD: Materials and Manufacturing

- Scientific research identifies new materials and new uses of known materials.
- Increased knowledge of the molecular structure of materials helps in the design and synthesis of new materials for special purposes.

Grades 6-8

THE NATURE OF TECHNOLOGY: Design and Systems

- Design usually requires taking constraints into account. Some constraints, such as gravity or the properties of the materials to be used, are unavoidable. Other constraints, including economic, political, social, ethical, and aesthetic ones, limit choices.

THE NATURE OF TECHNOLOGY: Issues in Technology

- The human ability to shape the future comes from the capacity for generating knowledge and developing new technologies — and for communicating ideas to others.

THE DESIGNED WORLD: Materials and Manufacturing

- The choice of materials for a job depends on their properties and on how they interact with other materials. Similarly, the usefulness of some manufactured parts of an object depends on how well they fit together with the other parts.
- Manufacturing usually involves a series of steps, such as designing a product, obtaining and preparing raw materials, processing the materials mechanically or chemically, and assembling, testing, inspecting, and packaging. The sequence of these steps is also often important.
- Modern technology reduces manufacturing costs, produces more uniform products, and creates new synthetic materials that can help reduce the depletion of some natural resources.

Grades 3-5

THE NATURE OF TECHNOLOGY: Issues in Technology

- Scientific laws, engineering principals, properties of materials, and construction techniques must be taken into account in designing engineering solutions to problems. Other factors, such as cost, safety, appearance, environmental impact, and what will happen if the solution fails also must be considered.

THE PHYSICAL SETTING: Structure of Matter

- When a new material is made by combining two or more materials, it has properties that are different from the original materials. For that reason, a lot of materials can be made from a small number of basic kinds of materials.

THE PHYSICAL SETTING: Energy Transformations

- Some materials conduct heat much better than others. Poor conductors can reduce heat loss.

THE DESIGNED WORLD: Materials and Manufacturing

- Naturally occurring materials such as wood, clay, cotton, and animal skins may be processed or combined with other materials to change their properties. Through science and technology, a wide variety of materials that do not appear in nature at all have become available, ranging from steel to nylon to liquid crystals.

HABITS OF MIND: Manipulation and Observation

- Choose appropriate common materials for making simple mechanical constructions and repairing things.

Grades K-2

THE NATURE OF SCIENCE: Scientific Inquiry

- People can often learn about things around them by just observing those things carefully, but sometimes they can learn more by doing something to the things and noting what happens.

THE PHYSICAL SETTING: The Structure of Matter

- Objects can be described in terms of the materials they are made of (clay, cloth, paper, etc.) and their physical properties (color, shape, weight, flexibility, etc.).

- Things can be done to materials to change some of their properties, but not all materials respond the same way to what is done to them.

THE DESIGNED WORLD: Materials and Manufacturing

- Some kinds of materials are better than others for making any particular thing. Materials that are better in some ways (such as stronger or cheaper) may be worse in other ways (heavier or harder to cut).

Supplies

Listed below are descriptions of the supplies that are needed to complete all of the Explorations in this booklet. Most will be readily available in a high school chemistry laboratory. The molds needed to form the test bars of each material are included with this booklet, as well as tin metal shot needed to make the metal sample. Since the Explorations are intended for hands-on/minds-on student learning, we also tell you how to obtain additional supplies for your students.

◆ **Bar Mold** (included)

This mold is made from a polymer which can withstand temperatures up to approximately 275°C. This is higher than the melting point of tin (232°C). Keep in mind that many hot plates can produce temperatures in excess of 500°C and caution your students to exercise care when using the molds on a hot plate to avoid melting them. Extra molds may be purchased from the Institute for Chemical Education (see contact information on page ii).

◆ **Anchor Cement**

Used to make the ceramic samples, this finely powdered mixture of portland cement and gypsum plaster can be obtained very inexpensively at hardware and home supply stores, under the brand names PourStone and Rockite, among others.

◆ **Epoxy**

Two-part epoxy, which is mixed to form the polymer samples, can be obtained at any hardware, home supply store, supermarket, or discount department stores. We recommend Duro Master Mend Epoxy #81501, but most brands will work. Whatever brand you buy, be sure that it takes at least 5 minutes to set, in order to give students enough time to mix and pour the epoxy into the molds.

◆ **Tin Metal** (included)

The tin shot included in this kit can be obtained from Belmont Metals. Request Grade A Tin Shot at (718)342-4900.
http://www.belmontmetals.com

Other Chemicals

- 6.0M HCl
- 6.0M NaOH
- saturated $KMnO_4$ solution
- reducing agent (e.g. $AgNO_3$) (optional)

Other Equipment and Supplies

- gloves
- safety goggles
- hot plate
- Bunsen burner
- balance
- tongs
- aluminum foil
- plastic wrap
- petroleum jelly
- cotton swabs
- test tubes
- test tube rack
- glass microscope slides
- dissecting microscope or magnifying glass
- metric ruler
- multimeter or ohmmeter
- paraffin wax or candles
- ring stands and clamps
- twine or heavy duty string
- plastic weigh boats or other disposable containers
- kilogram weights, lead sinkers or sealable containers filled with sand or water
- ceramic crucible or pyrex beaker
- paper cups
- hammer
- small glass beaker
- disposable glass pipettes

Introduction

The development of mankind is defined in terms of advances in materials: the Stone Age, the Bronze Age, and the Iron Age. The dramatic advances in architecture and building introduced by the Roman Empire were possible only because of the invention of a new material — concrete. The Industrial Revolution was to a large extent made possible by advances in the use of materials in industrial equipment, as was the rapid development of the railroads in the late nineteenth century, and the skyscrapers that began to define the skylines of American cities in the early twentieth century.

In the last half century, the growth of materials technology has been explosive, and its impact on our daily lives, pervasive. Beginning with the invention of the transistor in the 50's, the electronics revolution, enabled by advances in materials, has dramatically and irreversibly changed our lives. Some of us remember the sage career advice given to Dustin Hoffman in the 1960's film *The Graduate* — **"Plastics."** The use of plastics is now so widespread that it is difficult to imagine life without them. The double-edged sword inherent in the use of new technologies is apparent in today's concern with the disposal of non-biodegradable plastics.

If *The Graduate* were to be remade today, the career advice might well be **"Ceramics."** While ceramics were the first *Engineering Materials*, finding application as building materials and pottery in the Stone Age, recent technological advances combined with their unique electrical properties, hardness, durability, and heat resistance are making ceramics the material of the future. One of the most recent Nobel Prizes for Physics was awarded to J. Georg Bednorz and K. Alex Müller of IBM for the discovery that certain complex ceramic materials conduct electricity without resistive loss at temperatures substantially higher than those for conventional metallic **superconductors.**

superconductor: a material which offers no resistance to direct electrical current.

Artificial diamond is on the verge of having major impacts on fields as diverse as optics, wear coatings, and substrates for electronic circuits. In the near future, we can expect to find major advances in the use of ceramics in applications as diverse as microelectronics, superconductors, automotive and aircraft engines, prosthetic implants, and chemical process equipment.

Today's fundamental research activities in the universities and research laboratories give us confidence that we are seeing only the beginning of advances in materials science and technology that will profoundly affect the way we live our lives. We can expect to see:

biodegradable plastics produced by genetically engineered microbes;
structural materials that are analogs of naturally occurring materials such as shell or bone;

improved bioengineered materials to replace joints, bone, tendons, and skin;
super-hard materials with hardness greater than that of diamond;
aircraft skins that can detect and respond to changes in ambient conditions or to structural damage;
bridges made of strong, lightweight fiber-reinforced plastic composites; and
road surfaces that will last for a human lifetime.

We have just begun to see the impact of **The Materials Revolution.**

We have chosen Materials Science as the subject of this teaching module both because of its importance and pervasiveness in our lives, and because it brings together all of the major physical science disciplines and applies them to practical problems with which the student can identify. We have tried to bring in elements of chemistry, physics, mathematics, engineering and the use of computers. We have incorporated materials that represent all of the major classes of materials: metals, ceramics, and plastics.

The core of the module is the laboratory work. Here we have tried to keep things as "hands-on" as possible. The intent is for the students to become acquainted with the scientific method, with laboratory practice, with physical observation and data taking and analysis, and to get a feeling for the fundamental differences between the various classes of materials.

Materials Science involves the preparation and characterization of materials to ensure that they have the properties required for a particular application. Classes of materials include plastics, glass, ceramics, metals, and semiconductors. Key properties of materials include their mechanical behavior; electrical, magnetic, optical, and thermal characteristics; chemical stability; and other physical properties such as density and grain structure.

In this teaching module, students will be introduced to the preparation and characterization of a metal (tin), a plastic (polyamide), and a ceramic (anchor cement). They will first prepare the samples by either heating and melting the raw material, in the case of tin; or by a chemical curing process for the polyester resin and anchor cement. After the preparation of the test samples, the students will examine their optical and physical characteristics, determine their relative electrical and thermal properties, and investigate their mechanical behavior and chemical stability.

Metals

The general characteristics of metals are quite familiar. At room temperature they are opaque solids. (Mercury is an exception, being a liquid at room temperature.) Metals have a characteristic metallic luster. They are good conductors of heat and they conduct electricity both in the solid and liquid state. Metals are **ductile** — they can be drawn into wires; and they are **malleable** — they can be hammered into thin sheets. Metals generally have high densities and many have high melting points. In general, metals are insoluble except in other metals. Metals may appear to dissolve in some solutions, such as acids, but they actually undergo a chemical reaction; the substances found in the solution are ions rather than atoms of the metal.

ductile: the property of metals which allow them to be drawn into wires

malleable: the property of metals which allows them to be hammered into thin sheets

Although superficially metals look amorphous with little internal structure, they are crystalline solids with closely packed atomic structures. The tendency to form close-packed atomic structures accounts for the relatively high densities of metals. When a large number of metal atoms are brought together in a closely packed structure, the energies of the molecular orbitals become so closely spaced that they form a continuous "band" of energy levels. This **band structure** accounts for the electrical properties of metals.

The opaqueness and luster of metals are also explained in terms of the closely spaced energy levels of the band theory or "sea" of free electrons. A substance is transparent only if it does not absorb the light that is passed through it. In metals, the energy levels are so closely spaced that an electronic transition of almost any energy is possible, hence light of any wavelength is absorbed and the metal is opaque. The metallic luster is due to re-emission of the absorbed light by free electrons on the surface of the crystal. Hence a smooth or polished metal has a good reflecting surface. Metals are malleable or ductile because the atoms in the lattice structure can be easily displaced with respect to one another without weakening the bonding.

The tin provided in the laboratory kit is a fairly unusual metal in that it has a very low melting temperature: 232°C. This allows it to be melted and cast in a simple laboratory environment using a hot plate; whereas a more typical metal such as iron requires a temperature of 1535°C for similar processing. Room temperature is a high fraction of the absolute melting temperature of tin (273 + 232 = 505 Kelvin). At 300 K (27°C), the so-called **homologous temperature**, or fraction of absolute melting temperature, is ~0.6. Consequently, tin behaves at room temperature much like higher melting materials, such as iron, behave at red hot temperatures. For example, tin deforms very rapidly at room temperature and undergoes a time-dependent deformation process known as **creep** that is only observed in more conventional metals at quite high temperatures. One fairly unique aspect of tin, that of an audible **twinning**

homologous temperature: the ratio of a given temperature (in K) to the absolute melting temperature of that material (an atomic deformation process) phenomenon, is described in the Teacher's Guides for mechanical properties and for physical properties of metals.

Safety tip: Any air or water trapped within the structure of the metal expands rapidly during heating. This rapid expansion can lead to the ejection and splattering of hot metal from the vessel in which it is heated. An easy way to avoid this "popping" is to heat the entire mass of metal from room temperature, rather than adding metal to a preheated vessel or to molten metal.

Ceramics

Ceramic materials are **nonmetallic, inorganic compounds**, often consisting of metallic oxides, but also carbides, nitrides, borides, and silicides. Historically, "ceramics" referred to the art of pottery making, but now encompasses the science of manufacturing high temperature materials. Ceramic products are used not only for artistic objects and tableware, but also for such utilitarian items as bridges and building walls. Iron oxide particles are the active component in a variety of magnetic recording media, such as computer diskettes, and audio and video tapes. **Ceramic insulators** with a wide range of thermal and electrical properties have replaced conventional materials and made new applications possible such as ceramic packaging and heat sinks for integrated circuits. The electrical properties of a recently discovered family of copper-oxide-based ceramics allow them to become **superconductors** at temperatures much higher than those at which metals display this phenomenon. In nuclear reactors, the radioactive fuel is composed of a ceramic compound of uranium oxide. Ceramic materials are used to make nose cones, heat shield tiles, and many other components used in space applications.

By far the largest application of ceramics is in the construction industry where they are used in the form of concrete, bricks, and roofing materials. In the late 1980s, the US cement industry annually produced about 70 million metric tons, or about 6.6% of the world total. Cements are used for various purposes, such as binding sand and gravel together with **portland cement** to form concrete, for uniting the surfaces of various materials in the construction of walls or bridges, or for coating surfaces to protect them from thermal or chemical attack. Typical portland cements are mixtures of tricalcium silicate ($3CaO{\bullet}SiO_2$), tricalcium aluminate ($3CaO{\bullet}Al_2O_3$), and a dicalcium silicate ($2CaO{\bullet}SiO_2$), in varying proportions, together with small amounts of magnesium and iron compounds. By varying the percentages of its normal components or adding others, portland cement can be given various desirable characteristics, such as rapid hardening, minimal heating during hydration, and resistance to salt water or alkalis.

The anchor cement material used to prepare the ceramic sample in this module is a finely powdered mixture of portland cement and **gypsum** plaster that hardens and adheres after being mixed with water. The initial hardening of the cement is caused by the hydration of the tricalcium silicate, which forms interconnected hydrated silica and calcium hydroxide. The hydration of dicalcium silicate proceeds similarly, but far more slowly, hardening gradually over a period of days or even years. The process of hydration and setting of a cement mixture is known as **curing**; and heat is evolved during this period. (See page 47 for additional information on cement.)

Plastics

organic materials: compounds containing primarily carbon and hydrogen

polymer: an organic material comprised of repeating units called **monomers.**

Plastics are a class of **organic materials** consisting of large **polymeric** molecules. Thousands of tons of synthetic organic compounds, including fibers, sheets, pigments, and structural materials, are produced annually in chemical laboratories and industrial plants. Plastics can be formed into desired shapes by extruding, molding, casting, or spinning. The molecules can be either natural (e.g., cellulose, wax, natural rubber), or synthetic (e.g., polyethylene, nylon, polystyrene). The starting materials for forming processes can be in the form of resins, pellets, powders, or solutions.

The chemical nature of a plastic is defined by the repeating unit, or **monomer**, that reacts to form a long chain or network of polymeric material. For example, polyesters, such as dacron, are made up of monomer units of esters. Other examples are acrylics (polymethylmethacrylate), styrenes (polystyrene, styrofoam), vinyl halides (polyvinyl chloride, PVC), and polyamides (nylons). If the monomer molecule contains just two functional or reactive groups, growth can occur in only two directions and a linear polymer is obtained, such as nylon or dacron. If the reaction can occur at more than two positions in a monomer, then a highly cross-linked network polymer can form, such as in glyptal (shellac).

The fabrication of plastics involves procuring the raw materials, synthesizing the basic polymer, compounding the polymer into a material useful for fabrication, and molding or shaping the plastic into its final form. Although the production of nylon was originally based on coal, air, and water, most plastics today are derived from **petrochemicals**. The first stage in manufacturing plastic is polymerization, the joining together of many small molecules to form very large molecules, based on condensation and addition reactions.

Additives are frequently used to produce some desired characteristic. For example, **antioxidants** protect a polymer from chemical degradation by oxygen or ozone, ultraviolet **stabilizers** protect against weathering, **plasticizers** make a plastic more flexible, **lubricants** reduce problems with friction, and **pigments** add color.

The packaging industry is the leading user of plastics, accounting for about 30% of the US production. In the early 1990s, US sales of low-density polyethylene (LDPE) exceeded five billion kilograms per year. The major use of LDPE is in clear plastic wrap or film. High-density polyethylene (HDPE) is used for thicker films, such as those in plastic trash bags and containers.

The building industry is the second largest consumer of plastics, in the form of pipes, sheets, electrical insulation of cables and wires, and thermal insulation. Many industries, especially automobile and truck manufacturing, are also heavily dependent on plastics. Consumer goods range from sports equipment to small appliances, tools, luggage, and toys.

Most synthetic plastics are not environmentally degradable and do not break down over time, posing an environmental problem with their disposal. Recycling, where possible, has emerged as the most practical method to deal with this problem, although **biodegradable plastics** are also being actively developed for some applications.

Materials Preparation

This section describes the preparation of the metal, ceramic, and plastic test bars which will be used in the exploration experiments. Safety information is included, along with a list of necessary equipment. Each group will need 3 test bars of each material to complete all of the Explorations.

Safety

- Safety goggles are required for all laboratory activities.
- Use caution when handling molten tin. Be sure to use tongs to handle the crucible. Handle the hot bar mold with tongs or heat resistant gloves.
- Mix epoxy thoroughly on a disposable surface. Avoid contact with skin.

Materials

Anchor cement
2-part epoxy resin (Duro Master Mend Epoxy #81501 is recommended)
Plastic weigh boat or other disposable containers
Tin metal **(included in kit)**
Hot plate
Bunsen Burner
Balance
Tongs
Ceramic crucible
Aluminum foil
Petroleum jelly or vacuum grease
Cotton swabs
Bar mold **(included in kit)**
Mold release spray (optional)

Preparation

Metal sample

1. Use caution, melting point of tin is 232°C!
2. Warm the bar mold on a hot plate. The exact temperature is not important; the lowest setting or two on a hot plate works well. Be careful not to melt the plastic mold!
3. Weigh approximately 50 g of tin into a ceramic crucible or pyrex beaker.
4. Heat metal in the crucible or beaker over a Bunsen burner or on a hot plate until the tin is melted.
5. As soon as the tin is melted, use tongs or heat resistant gloves to pour molten metal into the trough of bar mold.
6. After all troughs are filled, carefully remove bar mold from hot plate.
7. After bar mold has cooled to near room temperature, invert to remove samples. You may have to tap the mold on the bench top to loosen the tin bars.

Plastic sample

1. Use in well-ventilated area.

2. Coat inside of troughs on bar mold with petroleum jelly using a cotton swab or spray with mold release agent and line with aluminum foil. (Use the eraser end of a pencil, a previously prepared metal test bar, or your fingers to press a thin layer of aluminum foil into the troughs as shown in the figure below). Try not to puncture the foil. If the foil punctures, remove the foil, line the troughs with plastic wrap, and then re-line the troughs with foil.

3. Follow all recommended safety instructions on epoxy package.

4. Mix epoxy carefully to avoid the formation of bubbles. Mix the resin in a plastic weigh boat or small paper cup.

5. Pour epoxy into troughs.

6. Cure according to instructions. It will take quite a bit longer to harden than is indicated on the package, as the bar is considerably thicker than a typical epoxy application. Generally, hardening overnight is recommended.

7. Lift foil carefully at one end to remove bars. Peel the foil from the hardened bar.

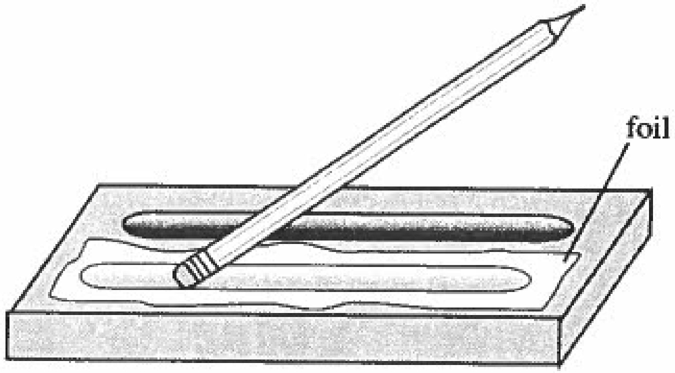


Figure 1. Preparation of molds for casting plastic and ceramic samples

Ceramic sample

1. Line the inside of the troughs of bar molds with a thin strip of aluminum foil by pressing the foil into the trough with the eraser end of a pencil or with a previously prepared metal test bar.
2. Mix anchor cement in paper cup with sufficient water to create a slurry with the consistency of honey.
3. Pour anchoring cement slurry into troughs.
4. Leave to air dry at room temperature at least 12 hours.
5. Remove sample by lifting foil carefully from one end. Peel the foil from the hardened bar.

Physical Properties

The properties and characteristics of materials figure prominently in almost every modern engineering design, providing opportunities for new inventions and setting limits for many technological advances. During the last generation, we have witnessed and benefited from many technological advances enabled by the development of new technological systems. Examples are nuclear power plants to produce electricity and high speed jet aircraft capable of carrying hundreds of passengers at speeds over 700 mph. We have sent spacecraft into the far reaches of our solar system and beyond, and have put men onto the surface of the moon. Closer to home, high speed computers control many aspects of our daily routines, from balancing our bank accounts to controlling the speed of traffic on our freeways. Advances in electronics have brought us satellite communications, color television, and the use of lasers in complicated surgical operations. Each of these technologies has advanced because of the discovery or development of materials with new and exotic properties. **Physical properties** might best be described to the student as "those features a material possesses that we can recognize through the use of our senses." By looking at a material, we make conclusions about the appearance. Is the material shiny or dull; is it transparent or opaque; what is the color? By touching the material, does it feel smooth or rough, and does it feel heavier or lighter than the other materials? These are but a few of the many physical properties that all materials possess. It might be of interest to have the students make predictions about the characteristics of a material after they have been allowed to look at it without touching, or after feeling the material while blindfolded.

Extension:
Make predictions about the properties of a material after
a) looking at the material without touching it, or
b) feeling the material while blindfolded.

Metals

Metal Oxide	Color
Ag_2O	black
Fe_xO_y	red-brown to black
SnO_2	gold

There is much that can be learned from the appearance of materials. Many materials are identifiable based, in part, on their color (gold, silver, copper, etc.). The appearance of the tin sample can be described as **shiny, silvery, and metallic**. There is also some history of a material that is revealed by its appearance. Many metals, for example, are observed to have regions of different colors when heated. The colored area is the **metal oxide** that is formed when the piece is heated in the presence of oxygen. The formation of the oxide layer is actually a natural occurrence, but is accelerated by heating above ambient temperatures. We encounter this phenomenon frequently in our everyday lives: the pan that was left on the stove too long, the tarnished silverware, the chrome plated exhaust pipes that turn blue or purple. After making the tin specimens you may notice a yellow-gold color on the surface. This is tin oxide. Can you think of some other oxides? What color are they? The tin oxide is removed when lightly brushed with a cotton swab dipped in 6M HCl. For extra credit, some students might want to look into the **anodizing** process, which is a controlled oxidation to protect metals like aluminum.

Extension:
Research the anodizing process.

It is also a means of visually coloring a metal that is widely used in consumer and industrial products.

Metals are excellent conductors of both heat and of electricity. Metals and soluble mixtures of metals (called **alloys**) are able to withstand a wide range of temperatures, ranging from absolute zero up to the melting point of tungsten at 3410°C. Tin melts at 232°C.

When the tin sample is bent, it stays bent. This is because most metals undergo what is termed **plastic deformation**. Plastic deformation describes a material that remains in the shape into which it has been deformed upon removal of the load. In crystalline solids (such as tin) there are two dominant modes of deformation. These are **slip deformation** and **twin deformation**. Figure 2 will help to illustrate these two different modes.

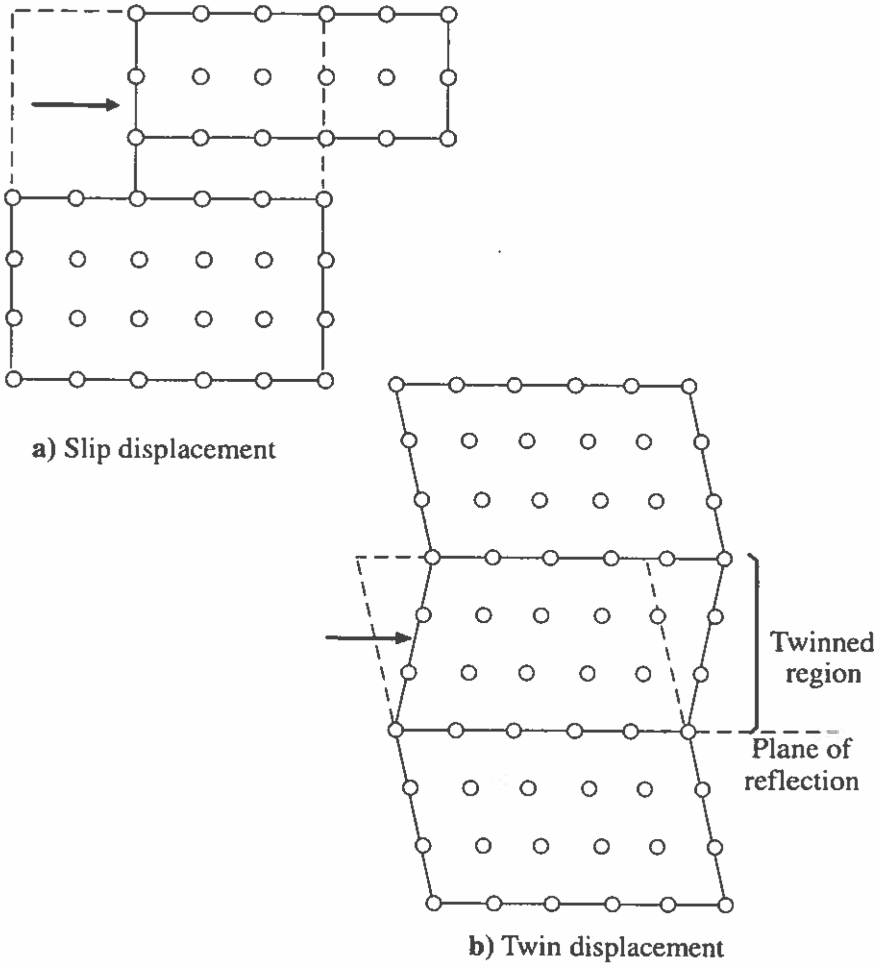


Figure 2. Shape change in a solid caused by plastic deformation. (a) solid with slip displacement; (b) solid with twin displacement. Displacements are proportional to distance from twin plane.

Slip deformation involves a simple translation across a slip plane such that one rigid portion of the solid slides relative to the other; and the registry of the atoms across the "slip plane" remains unchanged. Slip typically occurs on several atomic planes simultaneously. In **twinning,** the deformation occurs by shear across the "twin plane" such that the atoms on either side of the twin plane are in mirror image positions. In both cases, the sample undergoes a shape change. In tin, twinning can be heard as a crunching sound as the tin sample is bent back and forth (the **tin "cry"**). Twinning is often observed as a growth pattern in crystalline minerals such as quartz, calcite, and galena. The twin boundaries can be readily observed on the surface of the crystals; often the shifts in the positions of atoms can be inferred from the crystal growth patterns.

Ceramics

Ceramics, which are now being eyed as the material of the 21st century, are in fact the oldest of the materials examined here. Earthenware dates back as far as 5000 BC. The first forming machine, which was probably the potter's wheel, was used earlier than 3500 BC. Ceramics are so exciting because of the many compounds that have been formulated and the ever increasing quality of properties that can be obtained by relatively simple changes in chemistry and processing.

The surface appearance of the ceramic sample can be described as **opaque, dull,** and **non-reflective**. This appearance is due to the porosity of the material, which scatters light rather than reflects it. Ceramics are mostly white, gray, or brown. However, they can be made in any color by the addition of pigments during the fabrication. Sapphire and ruby are the same basic ceramic material (aluminum oxide), differing only in the presence of trace amounts titanium oxide that gives sapphire its characteristic blue color, and chromium oxide that imparts a deep red color to ruby. They are also transparent due to the absence of porosity and crystallite boundaries that would scatter light. Ceramics are able to withstand high temperatures for extended periods of time. They are generally poor conductors of heat and electricity. For these reasons ceramics are often used as electrical or thermal **insulators**. However, as research in the field of ceramics continues, more and more custom ceramics are being developed with very specific properties that allow ceramics to be designed as either an insulator or a conductor. Ceramics are typified as **hard, brittle, non-flexible** materials.

Plastics

Plastics generally are **organic polymers** (that is, they consist of long chain-like molecules containing carbon) which are formed in a plastic state either during or after their transition from a small-molecule chemical to a solid material. Stated very simply, the large chain-like molecules are formed by hooking together short-chain molecules (**monomers**) in a reaction known as **polymerization**. In the broad classification of plastics, there are two generally accepted categories: **thermoplastic and thermosetting**. Thermoplastic resins are softened by heating, and for that reason can be reformed again and again. Thermoset resins are of the type that is cured by crosslinking induced by heating or by the addition of catalysts and cure promoters that result in a room temperature curing system.

The plastic provided with the laboratory module is a thermoset. The sample is smooth and glassy in appearance, transparent and relatively colorless. This is due to the structure of the plastic. The plastic is formed by long chain molecules that allow the light to pass through with little interaction.

Extension:
Students can qualitatively demonstrate temperature dependence of mechanical properties of their plastic test bars by bending bars that have been heated or cooled to different temperatures.

Plastics are not able to withstand temperatures above a few hundred degrees Celsius. Plastics are also poor conductors of both heat and electricity, and have found widespread use as an electrically insulating covering for electrical wire. However, because of their temperature limitations they are seldom used as thermal insulators except in cold chests. Plastics are relatively flexible; but thermoplastics do undergo extreme changes in flexibility as a function of temperature. As might be expected, as plastic is warmed it becomes more pliable and as the temperature is reduced, the plastic becomes more brittle. This is easily demonstrated in the polyamide samples made in this teaching module by immersing the samples in beakers of water at various temperatures and bending them to failure.

◆ Explorations: Physical Properties

The following activities allow the students to explore the physical properties of metals, ceramics and plastics. Answers are provided to selected questions.

Safety

- ◆ Wear safety goggles and gloves when working with strong acids.
- ◆ Use caution when melting tin. The glass slide will also be hot—be sure to let it cool before handling.

Materials

6.0M HCl
Cotton swabs
Dissecting scope/magnifying glass
Glass microscope slide
Tin shot
Hot plate or Bunsen burner
Hammer
Test bars of metal, ceramic, and plastic

Experiments

1. Describe the following characteristics for your material:
   - Color
   - Transparency/Opacity/Texture
   - Reflectivity/Luster
2. Wipe the surfaces of the samples with 6.0 M HCl solutions using a cotton swab (etching) and examine with a low power microscope or magnifying glass. Follow safety procedures for using acids.
3. Melt a drop of tin on a glass microscope slide on a hot plate or over a Bunsen burner. Let it cool and then examine the surface of the tin drop under a microscope.
4. Record observations in data table. You may wish to draw what you see.

Questions & Answers

1. Based on your observations, indicate what best describes the materials samples - metallic, opaque, or transparent?

   The tin has a metallic luster due to unbound electrons absorbing and re-emitting light energy; the cement is opaque due to the presence of extensive fine porosity that scatters light; and the plastic is transparent due to the absence of any interaction with light.

2. Does wiping the surfaces of the samples with 6.0M HCl solution reveal any structure? Describe what you see!

   The metal reveals a typical structure with individual "grains," each of which is a single crystal, tightly bound together with little or no porosity. The cement (ceramic) has a complex structure with a lot of fine porosity. The plastic is featureless as is typical of a polymer which is made up of intertwined molecular chains of carbon and hydrogen atoms.

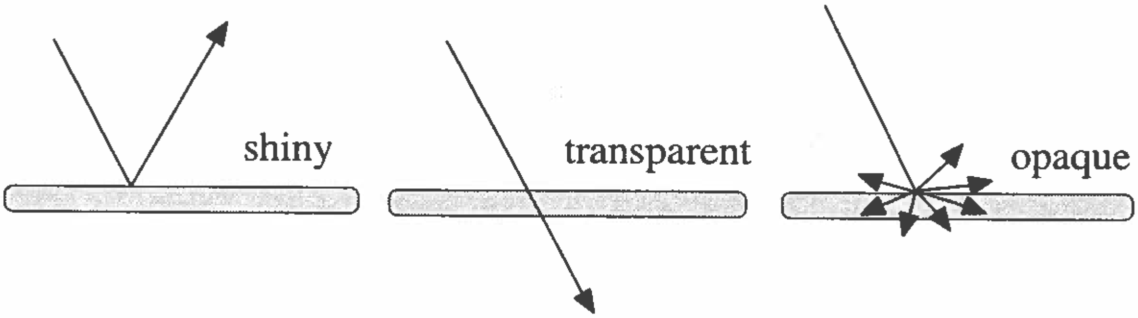
3. Describe the material's **hardness**—how readily is it scratched?

4. Describe the material's **malleability**—can it be deformed by pounding with a hammer?

5. Are there any other physical properties you would like to mention or test (magnetism, porosity, etc.)? How would you devise an experiment to test or observe these properties?

6. Why are some materials shiny (they show metallic luster), opaque, or transparent?

   Interaction of light with the material can produce a lustrous, opaque or transparent appearance. The tin has a metallic luster due to unbound electrons absorbing and then re-emitting light. Absorption of light by bound electrons can produce color, and materials that don't absorb or scatter light are colorless and transparent. The scattering of light by pores and interfaces produces opaque material. The transparent polyamide is featureless, as is typical of a polymer which is made of intertwined molecular chains of carbon and hydrogen atoms. The opaque cement (ceramic) has a complex structure with much porosity. The figure below depicts how the light interacts with shiny, transparent, and opaque materials.



Mechanical Properties

The mechanical properties of materials are described by terms such as **strength, stiffness, toughness, and brittleness**. To a large extent, these properties determine how materials are used in structures. For example, we are all aware that suspension bridges are made out of steel and Gothic churches are made of stone. Airplanes have been made from aluminum, but more and more they are being constructed of plastics reinforced with high strength glass or graphite fibers. Gaining an understanding of the properties of materials, particularly the mechanical properties, helps us to understand why these choices have been and are being made. **Metals, ceramics, and plastics** represent three broad classes of materials with fundamentally different mechanical properties. In the following paragraphs, the mechanical behavior of these materials is described to provide a guide for the teacher or the more advanced student in performing the laboratory portion of the teaching module *Explorations in Materials Science.*

Metals

Metals were first used in a historical context in the form of gold for ornamental purposes. This was because gold can be found in elemental form in nature. Its **ductile** or **malleable** nature allowed it to be readily beaten and shaped into ornaments. However, for the same reason, its use as a structural material was limited. It was too soft and not durable enough to be really useful.

Alloy:
An intimate mixture of two or more metals.

In time, early man learned to refine metals from ores and to mix or **alloy** metals to obtain superior properties. Thus in the Bronze Age, useful metal tools, utensils, and weapons began to appear. Continued improvements in metallurgy during the Iron Age led to the development of the "Damascus sword," an alloyed steel, which is unmatched even today in terms of toughness, durability, and ability to hold a sharp edge.

Deterministic behavior:
Behavior that is determined by the fundamental properties of a material.

The ductility of metals means that they are much more forgiving materials than ceramics. High local stress concentrations can be relieved by plastic deformation rather than by catastrophic failure. This means that metals are much less sensitive to the presence of flaws and defects than are ceramics. The flaws are blunted by plastic deformation and consequently do not propagate. The mechanical behavior of metals is also much more **deterministic** than that of ceramics; the behavior is determined by the fundamental (intrinsic) properties of the metal rather than by extrinsic cracks or flaws as is the case with brittle materials like ceramics. Thus we can talk of an absolute strength rather than a probability of failure. As a result, metals are generally used in applications where tensile loads are important. This includes the bulk of structural applications, including suspension bridges, rebar for reinforcing concrete, airplane wings, and pressure vessels.

The mechanical behavior of a typical metal can be described as **elastic/ plastic** as illustrated in Figure 3. As a load is applied, an initial elastic or Hookean region is observed, followed by a region in which nonrecoverable **plastic deformation** occurs. This behavior can also be observed in a three point bend test (see Figure 8). As the load is increased very gradually, the point at which measureable permanent deformation is first observed is the **yield point**. On removal of the load, the elastic deformation is recovered, but the plastic deformation is not.

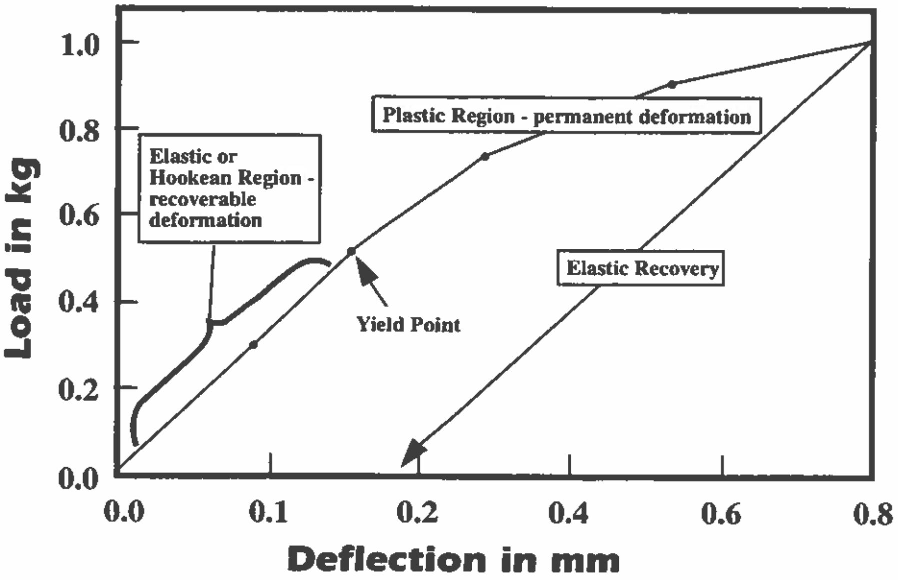


Figure 3. Elastic and plastic deformation in metals.

Another important characteristic of the mechanical properties of metals is a phenomenon known as **creep**. Creep is the time-dependent deformation of the material under a constant load. While creep is generally a high temperature phenomenon, in a metal with a very low melting point, such as tin, it can be readily observed at room temperature. If the tin sample in the Mechanical Properties section is loaded near the yield point and observed over time, the behavior illustrated in Figure 4 will be observed. The sample will exhibit a transient stage of gradually decreasing deformation rate, followed by a steady state region in which the deformation is linear with time. The creep process is highly dependent on both temperature, following an Arrhenius relationship (see Extension on page 19), and on load, following a power law relationship. The advanced student could devise experiments to study these relationships.

Extension:
Devise an experiment to study the relationship between creep and load.

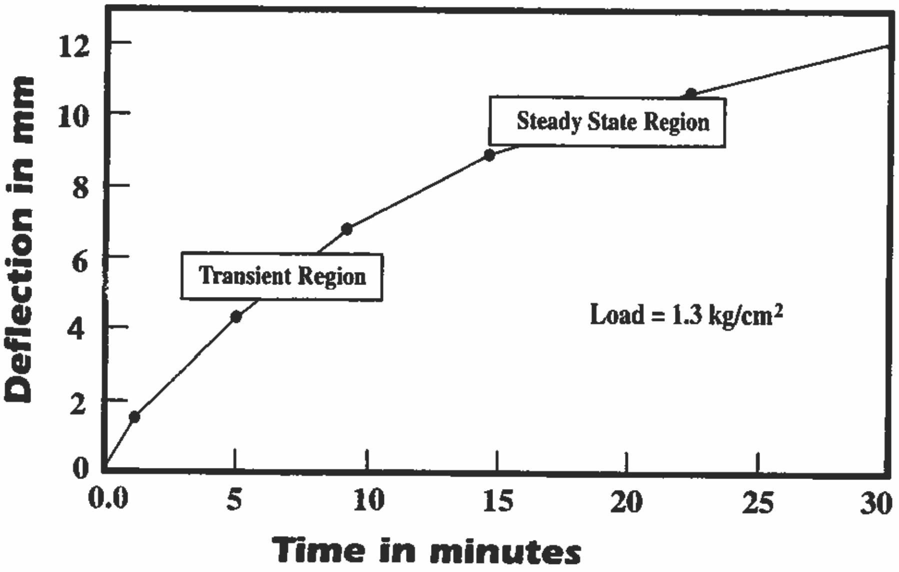


Figure 4. Creep behavior of a metal bar.

Extension: Bend an extra tin bar to hear the plastic deformation propagating through the metal.

The plastic deformation of metals occurs by the shear displacement of planes of atoms past each other. This occurs at atomic level defects that are present in all metals. The attached excerpt from *Teaching General Chemistry: A Materials Science Companion* by Ellis, *et al* describes how in some metals such as tin, this atomic motion results in a readily discernible cracking sound. This is apparent on flexing the tin samples that are produced in the laboratory module.

> "In some metals, the motion of atoms during plastic deformation occurs at the speed of sound in the solid, which is typically on the order of several thousand meters per second or about an order of magnitude faster than the speed of sound in air. Three metals, zinc, indium, and tin, exhibit a snapping sound when rods of the metals are bent at room temperature, due to the dislocation-assisted motion of their atoms. Because the rate at which the atoms move exceeds the speed of sound in air ('Mach 1'), an audible click results."

Ceramics

Extension:
Make ceramic bars of various materials (plaster of paris, portland cement, etc.) and compare the mechanical properties to those of the anchor cement test bar.

Ceramics, particularly brick, stone and concrete, have been the standard materials of construction for durable structures for millennia. Their durability is attested to by the survival of structures or parts of structures from the early Mediterranean civilizations for thousands of years, and by many European castles and Cathedrals that have been in continuous use for nearly 1000 years. The key to this success has been the design of structures that are loaded almost totally in compression. Ceramic materials are very strong in **compression**, but because of the presence of defects such as cracks, are generally relatively weak in **tension**.

In modern times, high technology ceramics are being used in situations where the loading is much more complex; for example, in radomes (used in the nose of aircraft and missiles for the transmission of radar signals), rocket nozzles, electronic packaging, and increasingly in automotive engine parts. This requires a much more sophisticated understanding of the properties of ceramics. This understanding is continuing to be developed in research programs throughout the world.

brittle: describes a material which fails catastrophically with little or no deformation.

Ceramics are classically **brittle** solids. Their loading behavior is characterized by a linear increase of deformation (strain) with increasing load (stress). This behavior was first described about 300 years ago by Robert Hooke, and is known as **Hooke's Law**. On removal of the load the deformation is totally recovered. There is no permanent deformation. This is known as **elastic behavior**. Ceramics behave in a purely elastic manner. Failure occurs suddenly and catastrophically, much as the behavior of a coffee mug dropped on a hard floor.

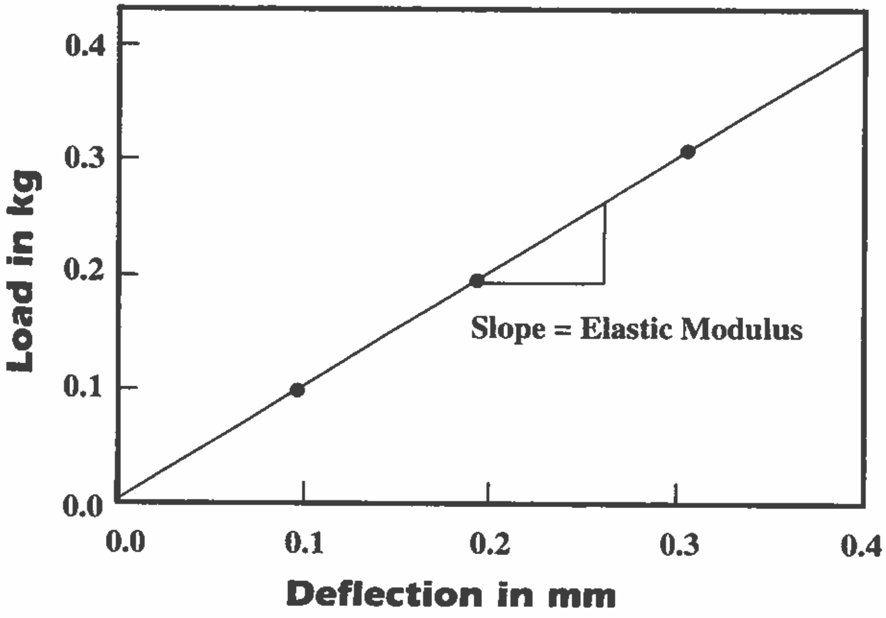


Figure 5. Elastic behavior of ceramics.

The loading behavior of a ceramic is illustrated schematically in Figure 5. Hooke's Law is followed to the failure load. This behavior can be illustrated by loading the ceramic beam produced in the laboratory module by suspending it at two points and by applying a concentrated load at the midpoint. In this case the thickness of the beam and the **elastic modulus** (slope of the load/deflection curve) are such that the elastic deformation prior to failure cannot be visually detected. With a much thinner beam, the elastic deflection is detectable even with a very stiff material such as ceramic. The elastic modulus is a measure of the **stiffness** of a material, which is also an important factor in engineering design (why is this?). The higher the elastic modulus, the higher the stiffness of a material. Ceramics typically have a very high stiffness.

Extension:
Test approximately 10 "identical" ceramic test bars for the failure load. Calculate the mean, median, and standard deviation for the failure load.

Another key aspect of the mechanical behavior of ceramics is that, because of the presence of a random distribution of flaws, the largest of which causes failure, the failure load or failure stress of a ceramic is determined by a **probability function**. There is no uniquely predictable failure load for a ceramic test bar. The advanced student could learn about statistics by testing approximately 10 nominally identical ceramic test bars and performing the standard analysis for mean, median, and standard deviation of the failure load.

Plastics

Plastics are composed of **polymers** or long chain molecules. They are an invention of the second half of the twentieth century. However, in their short history they have made such enormous inroads into the engineering and consumer industries that it is difficult to imagine life without them. Packaging, textiles, airplane interiors, automobile bumpers, missile bodies, and sporting goods are just a few of the widespread applications of plastics.

Plastics have tremendous diversity; however, they can be generally characterized as **tough, strong, lightweight,** and **durable**. Their durability is a double edged sword in this era of sensitivity to the environmental aspects of recycling and disposal of materials.

Plastics can be described as **viscoelastic** materials. That is, their deformation is recoverable over time. This property explains why textiles made from polyester are wrinkle-free. The mechanical behavior of a typical plastic is illustrated in Figures 6 and 7.

The deformation of plastics occurs by the sliding of the long chain molecules past each other. This sliding is opposed by frictional forces that result in the generation of internal stresses that subsequently cause the relaxation of the part back to its original shape. Since this sliding process involves the motion of atoms past one another, it is very temperature dependent. At high temperatures, the increased thermal agitation of the atoms makes the sliding process easier.

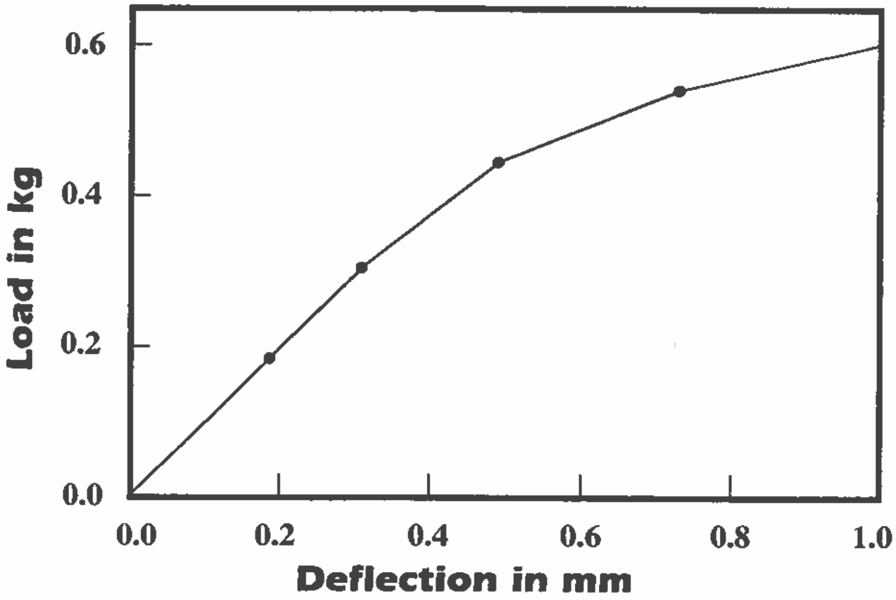


Figure 6. Viscoelastic behavior of plastics.

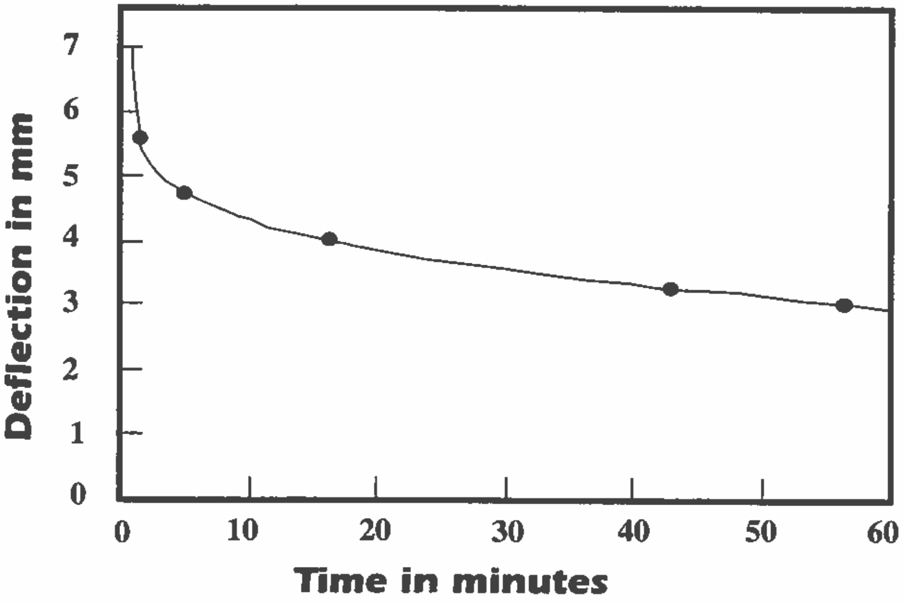
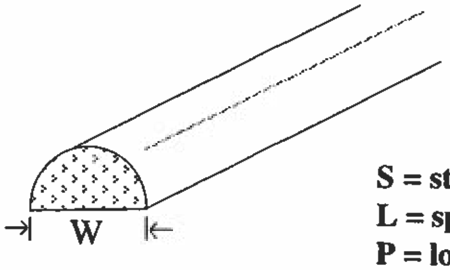


Figure 7. Viscorelaxation behavior of plastics.

2. Use the maximum load from the previous test to calculate the strength of your material as shown below. For the tin bar, how do you define the maximum load?



$$S = \frac{3PL}{W^3}$$

S = strength (kg/cm^2)
L = span (cm)
P = load (kg)
W = width (cm)

Figure 9. Strength calculation.

3. Perform a creep test on a tin bar. Apply a constant load in a three-point bend configuration, as illustrated in Figure 10, sufficient to cause the bar to slowly deform. You can determine the appropriate load from the previous bend test experiment. A load that causes the tin bar to slightly bend is appropriate. Observe and record the motion of a pointer attached to the tin bar versus time. Plot deformation versus time. You should see an initial region of gradually decreasing rate of deformation followed by a roughly straight line region of constant **rate** of deformation (see Figure 4). The slope of the curve in the linear region is referred to as the **creep rate.** Try different loads and observe the effect on the creep rate. Try chilling the bar with ice water and observe the effect on the creep rate. Try it again with cold water. (**Experimental note:** masking tape can be used to suspend or support the ruler between the ring stands.)

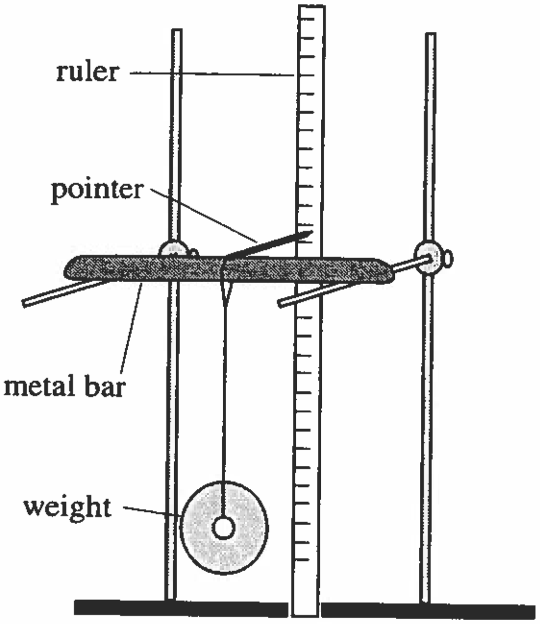


Figure 10. Set-up for creep test.

Questions

1. Why are some test bars of the same material weaker than others? (Hint: look for flaws in the fracture surface.)

2. Are some of the materials ductile (deform extensively under load) and some brittle (fracture with little or no deformation)?

   The metal is ductile and the ceramic is brittle.

3. Is any of the deformation recoverable on removal of the load? Is the recovery instantaneous or time dependent?

   The plastic will recover over a period of time.

4. Describe the characteristics of the mechanical properties of metals, ceramics, and plastics in terms of ductility, brittleness, strength, and ability to recover from deformation.

	Ductile	Brittle	Deformation Recovery	Strength
Metal	Yes	No	not measurable	Low, but deforms plastically rather than breaking
Ceramic	No	Yes	not measurable	Weakest
Plastic	Yes	Yes	Yes	Strongest

5. What did you learn from the deformation measurements?

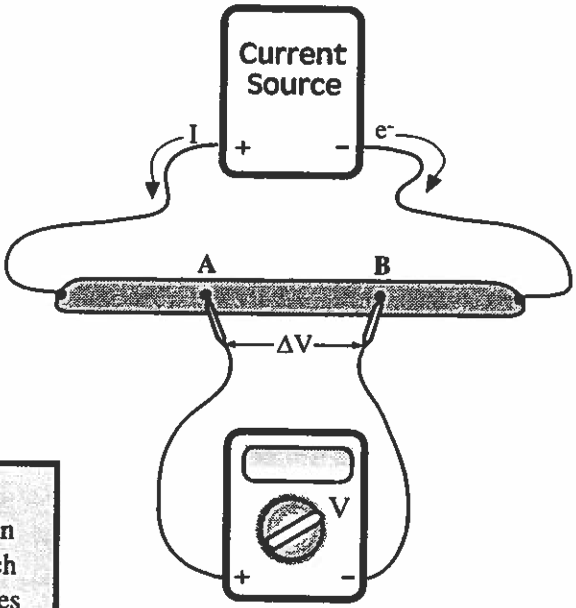
   The metal undergoes extensive non-recoverable deformation. The ceramic fails under load without perceptible deformation (brittle). The plastic deforms extensively, but slowly recovers its shape. Recovery of the original shape of the plastic can be accelerated by heating the sample in warm water.

6. Which material is the strongest and which is the weakest?

   The plastic held the most mass and slowly deformed, the metal held less and slowly deformed, and the ceramic held least and fractured.

7. Describe the nature of the creep curve. Is there a "transient" region? A "steady state" region? (See Figure 4).

8. How is the creep rate affected by load? By temperature?



The **four probe** method is used to measure electrical resistance between points A and B of a material of low resistance. The resistance is determined using $R=\Delta V/I$.

By convention, current (I) flows in the direction which the *positive* charges move. This means that current is shown flowing from the positive terminal to the negative terminal, even though the electrons (e^-) actually flow from the negative terminal to the positive one.

When many metallic elements, alloys, and compounds are cooled below a certain temperature, called the superconducting critical temperature T_C, their conduction electrons undergo a phase transition into the superconducting state. In the superconducting state, the material is a perfect conductor of dc electrical current — it has truly zero electrical resistance. It also displays a unique magnetic behavior called the **Meissner Effect**, where a magnetic field is expelled from a superconductor as it is cooled down below T_C (see Figure 11). The unique magnetic characteristics of superconductors result in their ability to magnetically levitate a permanent magnet in a stable configuration.

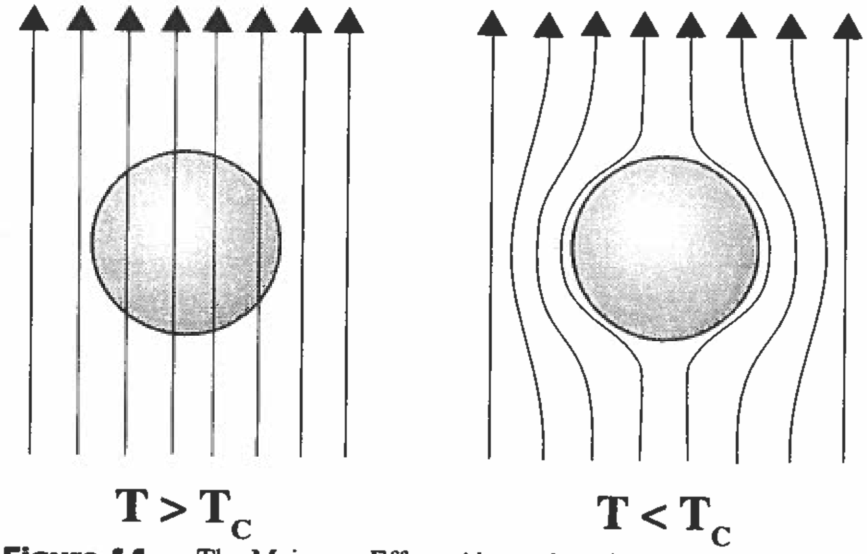
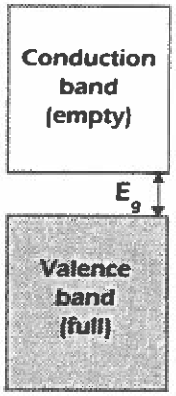


Figure 11. The Meissner Effect. Above the critical temperature (left) the magnetic field lines pass through the superconducting sphere. Below T_C (right) the magnetic field is expelled from the sphere.

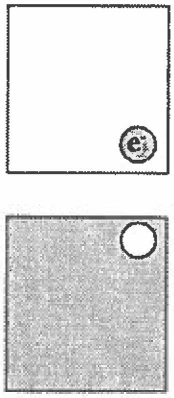
Prior to 1986, many superconductors had been discovered (Nb: T_C=9.2K; Sn: T_C=3.7K; Pb: T_C=7.2K; NbTi: T_C=9.8K; Nb_3Ge: T_C=23K), but none with a T_C above 23K. Since then, many ceramic oxide superconductors have been discovered with T_C values of up to 160K. These materials can be cooled using inexpensive liquid nitrogen (77K boiling point) instead of the more expensive and difficult to handle liquid helium (4K boiling point). The ceramic oxide superconductor materials that are the focus of much current research are YBa_2Cu_3 oxide (T_C=93K) and $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3$ oxide (T_C=110K).

For a more thorough discussion of energy bands, consult a college general chemistry text or *Teaching General Chemistry: A Materials Science Companion.*

When individual atoms are placed in a crystal lattice, their discrete electron energy levels widen into electronic energy bands. When the highest occupied energy band is partially filled, the material is a metal. Since the free electrons in this band are responsible for the electrical conductivity of the material, this band is called the conduction band. In a metal such as copper, the electrical resistivity at room temperature is low, ~2 microohm-cm, and the density of conduction electrons is high, ~$10^{22}/cm^3$. The high electrical conductivity of copper is the main reason that it is used for household wiring.



a) semiconductor bands



b) electron in conduction band, hole in valence band

In a semiconductor at a temperature of absolute zero, there are no electrons in the conduction band and the next band lower in energy, the valence band, is filled (see diagram a) at left). The valence and conduction bands are separated by a small energy gap (E_g). The energy gap for the material that is the basis for the semiconductor age, Si, is 1.1 eV. At room temperature, however, some of the electrons in the valence band are thermally excited into the conduction band, leaving an absence of an electron, called a hole, in the valence band (see diagram b) at left). Both the mobile electrons in the conduction band and mobile holes in the valence band contribute to the electrical conductivity of a semiconductor. Doping silicon (Si) with a donor atom, such as phosphorus (P), which contributes as electron to the conduction band, or with an acceptor atom, such as boron (B), which contributes a hole to the valence band, also leads to mobile electrons and holes that result in a higher electrical conductivity. A typical room temperature concentration of mobile charge carriers in a semiconductor is $10^{15}/cm^3$ to $10^{19}/cm^3$, corresponding to an electrical resistivity of 10 ohm-cm to 10 milliohm-cm. In general, the electrical conductivity of a semiconductor increases with increasing temperature due to the higher density of thermally excited mobile charge carriers.

If the conduction and valence bands just overlap slightly or are very close, then a semimetal results. In this case, the density of mobile charge carriers is ~$10^{19}/cm^3$ and is somewhat temperature dependent. The temperature dependence of the electrical conductivity is complex. Graphite is an example of a semimetal, with a room temperature electrical resistivity of ~60 microohm-cm.

Ceramics and Plastics

For insulators, the density of free electrons is many orders of magnitude smaller than that of metals, since most of the electrons are bound to the atoms. This leads to the very low electrical conductivity of insulators, such as most ceramics and plastics.

In an electrical insulator, the energy band gap between the valence band and the conduction band is very large, typically greater than 5 eV. The density of free electrons is very low, less than $10^{10}/cm^3$, which arise primarily from impurities in the insulator. The electrical resistivity of an electrical insulator at room temperature is very high, typically greater than 10^{14} ohm-cm.

Figure 12 shows that the electrical resistivity of materials can vary over many orders of magnitude, as shown on the right hand side of the figure. The left hand side indicates that the many forms of carbon — from polyethylene to graphite — also have enormous differences in electrical resistivity.

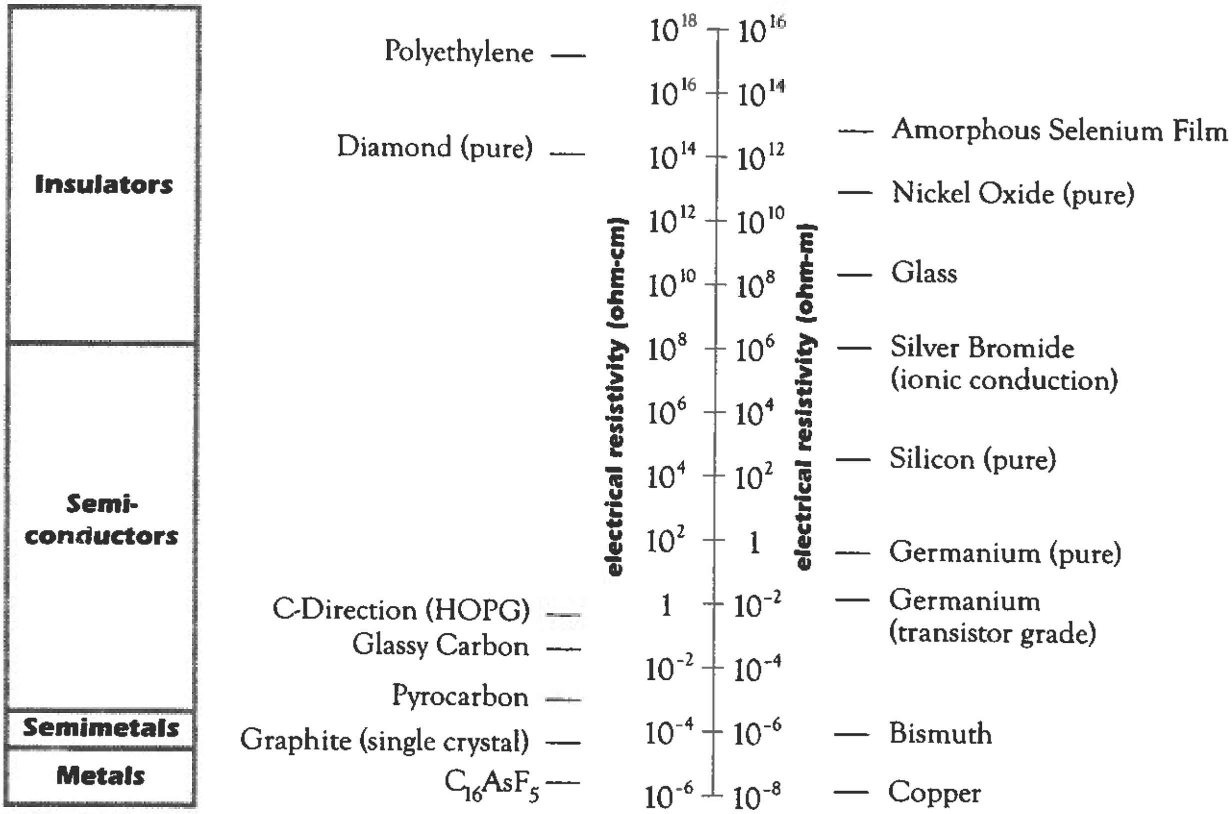


Figure 12. Room temperature electrical resistivities of Carbon (left) and Other Materials (right).

II. Thermal Transport

The high thermal conductivity of metals is closely related to their high electrical conductivity. A relation called the Wiedemann-Franz Law states that for a metal (a good conductor of electricity), the thermal conductivity is proportional to the electrical conductivity times the temperature.

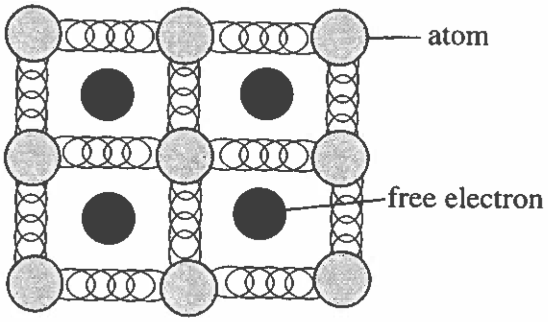
If a metal is placed between a hot source and a cold sink, then one end of the metal will become hot and one will become cold. In the hot end, the free electrons have a higher average speed than the electrons in the cold end. In addition, the amplitude of the vibration of the coupled lattice of atoms is larger at the hot end than at the cold end. In a metal such as tin, heat is transported predominantly by the electrons colliding with the vibrating ions in the crystal lattice. As a result of these collisions, energy is transported from the hot end to the cold end.

For an electrical insulator, heat is not transported by free electrons because the electron density is so low. However, because the atoms in a solid are closely coupled together, like balls attached by springs, an increase in vibrational energy in the hot part of the crystal lattice will still be transmitted to the colder parts.

Thus, heat can be transmitted both by free electrons and by vibrations of the coupled lattice of atoms, which are also called **phonons**. For metals, heat is conducted by both free electrons and lattice vibrations, whereas for electrical insulators, heat is conducted by lattice vibrations alone. In general, the thermal conductivity arising from the free electrons is much higher than that from the lattice vibrations. However, there are exceptions. For example, the thermal conductivity of diamond, an electrical insulator, is much better than that of copper, an electrical conductor.

The thermal conductivity of metals can be modeled by using a two dimensional array of balls coupled by springs (the crystal lattice of atoms) with a ball that is free to move in the center of each square (the free electrons). For the electrical insulator, there is no ball in the center of each square.

Extension:
Design a network of styrofoam balls and springs to represent a crystal lattice. Use additional balls as electrons and model how electrical conductors and insulators work.



In the model, heat is applied by rapidly moving the "crystal lattice" (and free electrons in the case of the metal) at one end of the grid — the hot side — while keeping the grid fixed at the other end — the cold side. Heat conduction can be determined by observing how rapidly the balls and springs are moving between the ends. Depending on the size and weight of the atoms, density of the free electrons, stiffness of the "springs," and spacing between the atoms, the heat transport may be dominated by either the free electrons or the vibrations of the atoms.

The measurement and definitions of thermal conductivity parallel that of electrical conductivity. To measure the thermal conductivity, power is applied to a heater on one end of a bar shaped sample and the heat travels through the sample to a cold sink. The temperature is measured by two temperature probes situated between the heater and the cold sink. The thermal resistance equals the temperature measured between the two temperature probes divided by the power put into the heater. The inverse of the thermal conductance is the thermal resistance. For a bar shaped material, the thermal resistance is equal to the product of the thermal resistivity and the length divided by the cross sectional area. The thermal conductivity is equal to the inverse of the thermal resistivity.

Also, in analogy to the electrical resistance R, for 2 thermal resistors (TR) in series, the total thermal resistance is equal to the sum of the individual thermal resistances:

$$\mathbf{TR_{total} = TR_1 + TR_2}$$

For 2 thermal resistors in parallel:

$$\mathbf{TR_{total} = \frac{TR_1 \times TR_2}{TR_1 + TR_2}} .$$

◆ Explorations: Transport Properties

Be sure that the students use a warm, not hot, hot plate. They do not want to melt the test bars, only the wax drops. The lowest setting on the hot plate should work well.

Safety ◆ Hot wax can burn. Avoid getting it on your skin.

Materials

Test bars of metal, ceramic, and plastic
Multimeter or ohmmeter
Paraffin wax or candles
Hot plate
Ring stand and clamp
Beaker
Disposable glass pipette

Experiments

1. Measure the electrical resistance of the metal, ceramic, and plastic bars using a multimeter, ohmmeter, or other resistance measuring apparatus, such as an LED conductivity tester. Determine whether your material is an electrical conductor or an electrical insulator. Recall that an electrical conductor has a low electrical resistivity and hence a low electrical resistance and an electrical insulator has a high electrical resistivity and hence a high electrical resistance.

2. Measure the relative thermal conductance of your material using the method shown in Figures 13 and 14. First, melt the wax by placing some paraffin in a glass beaker and then placing the beaker on a warm hot plate. Using a glass pipette, pick up some melted wax from the beaker and drop a bead of wax every centimeter on a test bar of each material.

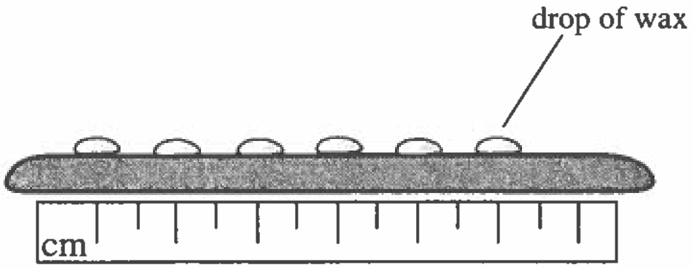


Figure 13. Preparation of test bar for thermal conductance testing.

Using the hot plate as a heat source, set up an apparatus like the one in Figure 14. The hot plate must be set hot enough to melt at least some of the wax drops. In a data table, record the time elapsed for each drop to melt and become clear.

drop	distance (cm)	time (sec)
1	0	
2	1	
3	2	
4	3	
5	4	
etc.	etc.	

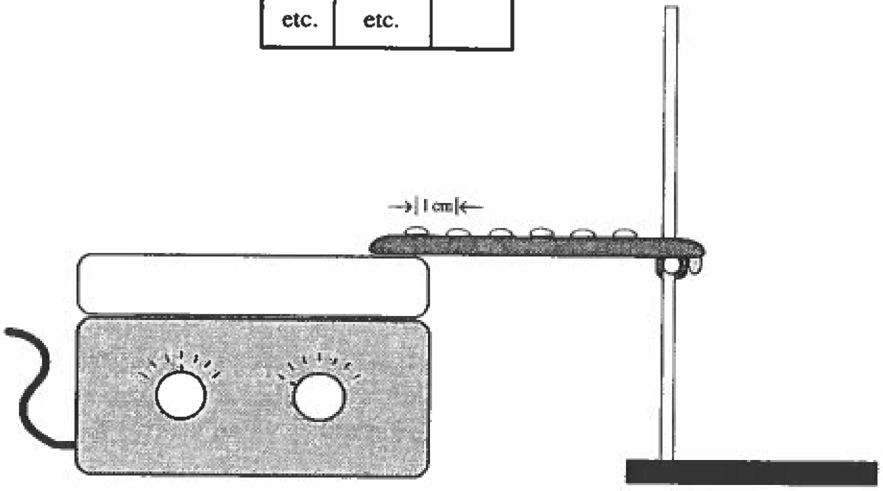


Figure 14. Set-up for thermal conductivity testing.

3. Construct a graph of the distance at which the wax drops melt versus time. This will help you to see the difference in thermal conductance of the three materials. Measure each sample for no more than 5 minutes.

Questions & Answers

1. Calculate the average rate of heat transfer for each of the materials in cm/sec.
2. By analyzing the graph, determine which material has the highest thermal conductivity and which material has the lowest. Suggest a reason why.

The metal has the highest thermal conductivity. Metals have "free" (unbound) electrons that conduct heat and electricity.

3. Describe the characteristics of the electrical and thermal conductivity of metals, ceramics, and plastics.

	Electrical Conductivity	Thermal Conductivity
Metal	High	High
Ceramic	Low	Low
Plastic	Low	Low

◆ Explorations: Density

Broken ceramic test bars from a previous Exploration will be needed for this experiment.

Safety

- Use care when handling the broken pieces of ceramic test bar. The edges can be sharp.

Materials

Graduated cylinder
Balance
Test bar pieces of ceramic
Test bars of metal and plastic

Experiment

Measure the mass first and then the volume of your material and calculate the density by using the following formula.

$$\textbf{Density}(\text{g/cm}^3) = \frac{\textbf{mass (g)}}{\textbf{volume (cm}^3\textbf{)}}$$

The mass is measured by using a balance and the volume can be measured by direct volume measurement, or Archimedes principle/displacement. Use broken pieces of ceramic (from previous experiments) to measure density. Do not use your ceramic test bar. Why shouldn't you use your ceramic test bar?

Questions & Answers

1. Compare your measured density for tin with the literature value. Discuss the reasons for observed discrepancies if any.

   The literature density of tin is 7.28 g/cm³. Discrepancies could occur due to the presence of any porosity in the samples and from any errors in measurement, especially the volume.

2. What are some reasons that materials might vary in density? (Consider such factors as atomic weight, atomic bond length or atomic packing, and porosity.)

   The greater the atomic weight of the particles that make up the material, the greater the mass. If the particles are packed in a tight arrangement, then the density will be greater. If there are pores in the material, then the material will be less dense.

◆ Explorations: Chemical Properties

Broken or damaged test bars of each material can be used for these experiments. Tin shot can be used in lieu of breaking the tin bar.

Safety

- Wear safety goggles.
- Use caution when handling strong acids and bases. Wear gloves.
- Use caution when handling strong oxidizers and reducers. Wear gloves.

Materials

Test tubes
Test tube rack
Test bar pieces
6.0M HCl
6.0M NaOH
$KMnO_4$ solution, saturated
reducing reagent such as $AgNO_3$ (optional)

Experiments

1. Reaction with strong acid — place a small piece of material (about the size of a pea) into a small test tube and fill half way with 6 M HCl (hydrochloric acid).
2. Reaction with strong base — place a small piece of material (about the size of a pea) into a small test tube and fill half way with 6 M NaOH (sodium hydroxide).
3. Reaction with strong oxidizing agent — place a small piece of material (about the size of a pea) into a small test tube and fill half way with saturated $KMnO_4$ (potassium permanganate).
4. Reaction with strong reducing agent. Wait two days before recording observation.

Question & Answer

Which material is the most reactive? Which is the least reactive?

The metal was most reactive, then the ceramic, and the plastic was the least reactive.

◆ Explorations: High Temperature Behavior

The plastic test bar can potentially give off hazardous fumes when heated. Be sure that students avoid breathing the fumes. Also beware of molten tin, which can burn skin, clothes and surfaces.

Safety

- Perform this experiment in a hood to avoid breathing hazardous fumes and smoke.
- Use care when heating the material in the Bunsen burner. Use tongs to hold the material. Be careful when heating the tin sample, as molten tin can burn.

Materials

Test bars of metal, ceramic, and plastic
Bunsen burner
Tongs

Experiment

Observe and record the high temperature behavior of your material in the flame of a Bunsen burner. Perform this experiment in hood or well ventilated area.

Question & Answer

Which material is most changed by high temperature? The least changed?

The plastic was the most changed due to the breaking of the carbon-hydrogen bonds. The metal melts at 232°C. The ceramic cannot be melted with a Bunsen burner or hot plate and shows little effect from heating.

◆ Explorations: Summary and Conclusions

- Summarize the characteristics of ceramics, metals and plastics. How do these characteristics determine the way the three materials are used?
- Name five applications of each type of material from your personal experience and relate the use to the properties you measured [e.g. copper (metal) wire for conducting electricity, wire insulation (plastic), and dishes (ceramic)}. Also consider how materials' properties affect the choice of materials for furniture, pots and pans, stoves, barbeques, silverware, light bulbs, lamps, fans, etc.

Student Explorations

Properties and Characteristics of Tin

Tin is a relatively unreactive metal found in group IV-A of the periodic table. It has an atomic number of 50 and an atomic weight of 118.69. Tin has a number of naturally occurring isotopes with the most abundant one having a mass of 120. Its chemical symbol is Sn from stannum, the Latin word for tin. **Bronze**, an alloy of copper and tin, has been known since about 3000 BC when it formed the basis for tools, weapons, and jewelery in the Bronze Age. Bronze was known long before tin itself was identified, as a result of the co-occurrence of tin and copper ores.

Tin is relatively rare (about 0.001% in the Earth's crust) and is generally obtained from its chief ore, cassiterite, by various refining methods, including carbon reduction. Important cassiterite deposits are found in Central Africa, South America, and Southeast Asia. More than 200,000 metric tons of tin are produced annually in the world.

Allotrope:
Different forms of the same element that exist in the same state (i.e. solid) under the same temperature and pressure conditions.

Tin exists in several **allotropic** forms, the most common being white tin. White tin is a silvery-white, soft, **ductile** metal with a pronounced metallic lustre. It has a melting temperature of 232°C and a boiling temperature of 2,270°C. Its density is 7.28 gm/cm^3. Below 13.2°C, pure metallic tin slowly converts to powdery gray tin that lacks the metallic properties of white tin. Tin is highly **malleable**, permitting it to be hammered into thin sheets of tin foil, although aluminum foil is more common today.

Tin exhibits two common oxidation states, +2 and +4. Tin dissolves in hydrochloric acid, reacting to yield stannous dichloride ($SnCl_2$) and hydrogen gas. Concentrated nitric acid oxidizes tin to the +4 oxidation state, forming stannic oxide (SnO_2). Strong bases, such as sodium hydroxide, dissolve tin to form stannate salts. Tin forms a gold-colored protective oxide that resists further corrosion when heated in air. Stannous fluoride, SnF_2, is a white, water-soluble compound that is added to toothpaste to help prevent tooth decay.

Because of its resistance to corrosion, tin is used as a protective coating for other metals that corrode easily. Tin cans are actually steel cans with a thin coating of metallic tin to prevent the organic acids contained in many foods from reacting with the steel. Once a portion of the tin coating is removed and steel is exposed to the atmosphere and moisture, rapid corrosion occurs.

Tin is a major component in many useful **alloys**. Copper is mixed with tin to form bronze, which is easy to cast and has superior mechanical properties. Pewter, an alloy of tin and lead hardened with antimony and copper, was commonly used for tableware in the 18th and 19th centuries. Tin alloys, often with lead, are used in solder, bearings, and type.

Properties and Characteristics of Cement

Cement is a mixture of minerals possessesing unique adhesive and cohesive properties that make it capable of bonding mineral fragments into a compact whole. The cement most commonly used in civil engineering and building is portland cement. Concrete is the aggregate material achieved by bonding fine and coarse aggregate particles with cured cement.

The use of cementing materials was critical to the architecture of the ancient Egyptians and Romans; but modern portland cement was invented relatively recently in the early 19th century. Currently, the annual world production of portland cement is around 700 million metric tons. Portland cement is usually made from calcium-containing minerals, such as limestone or chalk, and from alumina- and silica-bearing material, such as clay or shale. The manufacturing process consists of grinding the raw materials, mixing them intimately in specified proportions, and heating in air in a large rotary kiln at a temperature of approximately 1350°C. The resulting partially sintered agglomeration or "clinker" is cooled and ground to a fine powder, and gypsum is added to control the speed of setting when the cement is mixed with water.

The main compounds in portland cement are calcium silicates, with lesser amounts of calcium aluminate and tetracalcium aluminoferrite. The characteristic gray color of portland cement arises from the presence of the aluminoferrite. When white cement is desired, other additives are utilized. The chemical reaction of the silicates with water produces calcium silicate hydrates and calcium hydroxide, which make the largest contribution to the strength of the cement. Gypsum (calcium sulfate) is added to control the rate of the hydration reaction.

Concrete is produced by intimately mixing cement, water, fine aggregate (sand), and coarse aggregate (gravel). The mixture is then placed in forms, compacted thoroughly, and allowed to harden. Typically, three-quarters of the volume of hardened concrete is occupied by the aggregate. Compaction of the fresh concrete is essential because the strength of hardened concrete depends on the volume of air-voids within it as well as on the water-cement ratio of the cement paste.

The tensile strength of concrete is relatively low, so concrete structures are designed to exploit the good compressive strength properties of the material, and steel reinforcement is placed where it is necessary for structural members to resist tensile forces. This is called **reinforced concrete**. The steel reinforcement is bonded to the surrounding concrete so that stress is transferred between the two materials. The steel is often stretched, or prestressed before the bond develops between it and the surrounding concrete. When the force that produces the stretch is released, the concrete becomes precompressed in the part of the structural member that is normally under tensile load. The application of loads to the concrete structure in service reduces the precompression; but generally tensile cracking can be avoided. Such concrete is known as **prestressed concrete**.

Some concrete structures have survived for many centuries. Examples are to be found in Rome and elsewhere today. However, portland cement is attacked by acids, sulfates, and some other salts, which commonly occur as pollutants today. Frost can also damage concrete, but this can be prevented by adding an air-entraining agent to the mix that entraps fine air bubbles and improves the thermal insulating characteristics of the concrete.

Properties and Characteristics of Polymers

There are a wide variety of plastics derived from such raw materials as polyethylene, polypropylene, polyvinyl chloride, polystyrene, polyester, polyamides, polyurethane, polycarbonate, nylon, and phenolics. All plastic materials are formed by joining of small molecules to make very large molecules in a process known as **polymerization.** The small molecules are known as **monomers**. The polymerization process can occur via a chain-reaction or a step-reaction mechanism and both require some type of initiator. The initiator can be either a compound that forms free radicals or an organic ion. When a free radical adds to a monomer, it generates another free radical, which then adds to another monomer to generate a larger molecule, and a very large polymer results. This chain propagation continues until there are no more free radicals.

There are two basic types of molecular structures for plastics. One consists of large molecules that are either linear or branched. These include the fibrous materials, such as nylon, polyester, polystyrene, and polyvinyl chloride. These polymers may be more or less crystalline and are **thermoplastic**. They soften when heated and can be molded or extruded into complex shapes.

The other type of polymer consists of space-network polymers or resins, which are highly cross-linked to form a solid structure. These include phenol-formaldehyde, some polyurethanes, and urea-formaldehyde resins. These highly cross-linked materials do not soften with heating, because that would require breaking covalent bonds. These materials are therefore known as **thermoset** plastics. These materials are amorphous and can be thought of as one giant molecule.

Certain linear, thermoplastic polymers do not form crystalline structures, but remain amorphous by forming strong dipole bonds with adjacent molecular chains. Because they do not develop distinct crystalline planes that reflect light, they remain transparent like glass. Polymethyl methacrylate, commonly known as Lucite or Plexiglas, is an example of such a material. The brittle space-network structure does not deflect or "give" when struck hard, therefore it breaks or shatters just like glass.

Materials Preparation

This section describes the preparation of the metal, ceramic, and plastic test bars which will be used in the exploration experiments. Each group will need 3 test bars of each material to complete all of the Explorations.

Safety

- Safety goggles are required for all laboratory activities.
- Use caution when handling molten tin. Be sure to use tongs to handle the crucible. Handle the hot bar mold with tongs or heat resistant gloves.
- Mix epoxy thoroughly on a disposable surface. Avoid contact with skin.

Materials

Anchor cement
2-part epoxy resin
Plastic weigh boat or other disposable containers
Tin metal **(included in kit)**
Hot plate
Bunsen Burner
Balance
Tongs
Ceramic crucible
Aluminum foil
Petroleum jelly or vacuum grease
Cotton swabs
Bar mold **(included in kit)**

Preparation

Metal sample

1. Use caution, melting point of tin is 232°C!
2. Warm the bar mold on a hot plate. The exact temperature is not important; the lowest setting or two on a hot plate works well. Be careful not to melt the plastic mold!
3. Weigh approximately 50 g of tin into a ceramic crucible or pyrex beaker.
4. Heat metal in the crucible or beaker over a Bunsen burner or on a hot plate until the tin is melted.
5. As soon as the tin in melted, use tongs or heat resistant gloves to pour molten metal into the trough of bar mold.
6. After all troughs are filled, carefully remove bar mold from hot plate.
7. After bar mold has cooled to near room temperature, invert to remove samples. You may have to tap the mold on the bench top to loosen the tin bars.

Plastic sample

1. Use in well-ventilated area.

2. Coat inside of troughs on bar mold with petroleum jelly using a cotton swab and line with aluminum foil. (Use the eraser end of a pencil, a previously prepared metal test bar, or your fingers to press a thin layer of aluminum foil into the troughs as shown in the figure below). Try not to puncture the foil. If the foil punctures, remove the foil, line the troughs with plastic wrap, and then re-line the troughs with foil.

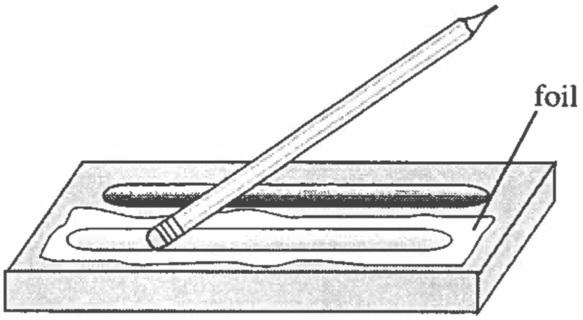
3. Follow all recommended safety instructions on epoxy package.

4. Mix epoxy carefully to avoid the formation of bubbles. Mix the resin in a plastic weigh boat or small paper cup.

5. Pour epoxy into troughs.

6. Cure according to instructions. It will take quite a bit longer to harden than is indicated on the package, as the bar is considerably thicker than a typical epoxy application. Generally, hardening overnight is recommended.

7. Lift foil carefully at one end to remove bars. Peel the foil from the hardened bar.



Ceramic sample

1. Line the inside of the troughs of bar molds with a thin strip of aluminum foil by pressing the foil into the trough with the eraser end of a pencil or with a previously prepared metal test bar.

2. Mix anchor cement in paper cup with sufficient water to create a slurry with the consistency of honey.

3. Pour anchoring cement slurry into troughs.

4. Leave to air dry at room temperature at least 12 hours.

5. Remove sample by lifting foil carefully from one end. Peel the foil from the hardened bar.

Student Activities

I. Physical Properties

Safety

- Wear safety goggles and gloves when working with strong acids and when using a hammer.
- Use caution when melting tin. The glass slide will also be hot—be sure to let it cool before handling.

Materials

6.0M HCl
Cotton swabs
Dissecting scope/magnifying glass
Glass microscope slide
Tin shot
Hot plate or Bunsen burner
Tongs
Hammer
Test bars of metal, ceramic, and plastic

Experiments

1. Describe the following characteristics for your material:
    - Color
    - Transparency/Opacity/Texture
    - Reflectivity/Luster
2. Wipe the surfaces of the samples with dilute 6.0 M HCl solutions using a cotton swab (etching) and examine with a low power microscope or magnifying glass. Follow safety procedures for using acids.
3. Melt a drop of tin on a glass microscope slide on a hot plate or over a Bunsen burner and examine the surface under a microscope from the glass side.
4. Record observations in data table. You may wish to draw what you see.

Questions

1. Based on your observations, indicate what best describes the materials samples—metallic, opaque, or transparent?
2. Does wiping the surfaces of the samples with 6.0M HCl solution reveal any structure? Describe what you see.
3. Describe the material's **hardness**—how readily is it scratched?
4. Describe the material's **malleability**—can it be deformed by pounding with a hammer?
5. Are there any other physical properties you would like to mention or test (magnetism, porosity, etc.)? How would you devise an experiment to test or observe these properties?
6. Why are some materials shiny (they show metallic luster), opaque, or transparent? Draw a diagram to describe your answer.

II. Mechanical Properties

Safety ◆ Wear safety goggles. At the failure load, some materials may shatter.

Materials

Test bars of metal, ceramic, and plastic
Ring stands (2) and clamps
Weights or sealable containers to be filled with water or sand
Metric ruler with mm spacings
Twine
Pointer with sharp tip (e.g. nail, pin, dissecting needle)

Experiments

1. Perform a three point bend test on your material. Use Figure A below to help you set up the apparatus. Increase the load on the bar until it deforms or breaks.

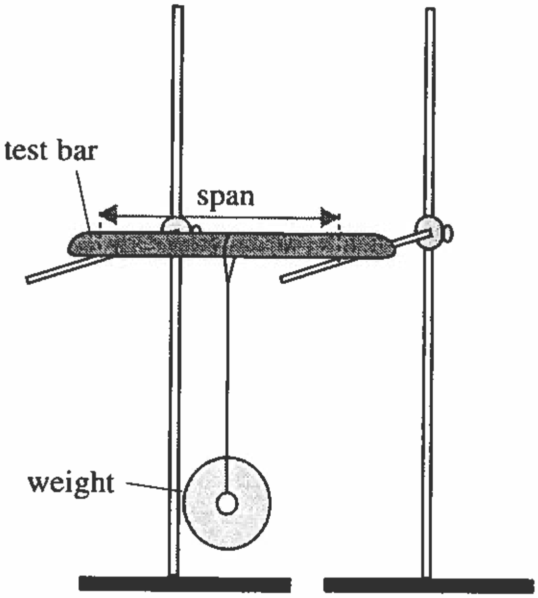
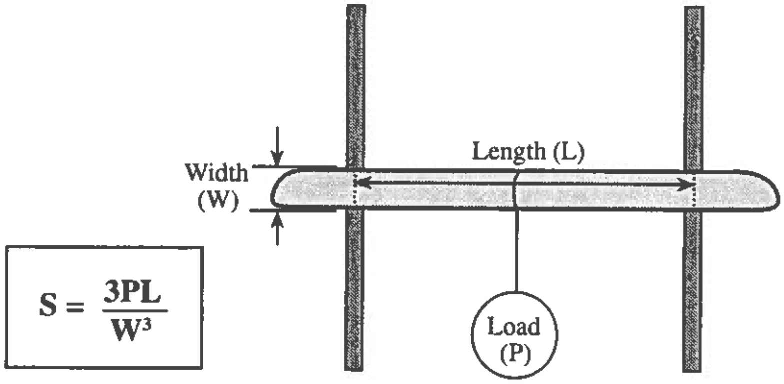


Figure A. Set-up for bend test.

2. Use the maximum load from the previous test to calculate the **strength** of your material as shown below in Figure B. Measure width at the widest point of your test bar. S=strength (kg/cm^2), W=width (cm), P=load (kg), L=span (cm).



$$S = \frac{3PL}{W^3}$$

Figure B. Strength calculation.

3. Perform a **creep test** on a tin bar. Apply a constant load in a three-point bend configuration, as is illustrated in Figure C, sufficient to cause the bar to slowly deform. You can determine the appropriate load from the previous bend test experiment. Observe and record the motion of a pointer attached to the tin bar versus time. Plot deformation versus time. You should see an initial region of gradually decreasing rate of deformation followed by a roughly straight line region of constant **rate** of deformation. The slope of the curve in the linear region is referred to as the **creep rate.** Try different loads and observe the effect on the creep rate. Try chilling the bar with ice water and observe the effect on the creep rate. Try it again with warm water.

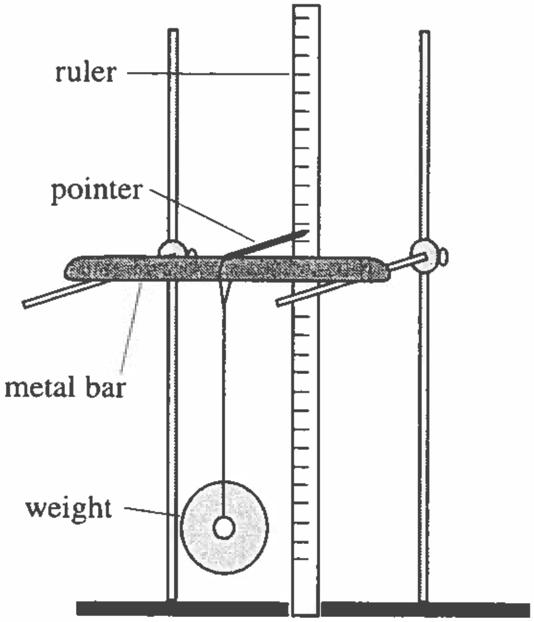


Figure C. Set-up for creep test.

Questions

1. Why are some test bars of the same material weaker than others? (Hint: look for flaws in the fracture surface.)
2. Are some of the materials ductile (deform extensively under load) and some brittle (fracture with little or no deformation)?
3. Is any of the deformation recoverable on removal of the load? Is the recovery instantaneous or time dependent?
4. Describe the characteristics of the mechanical properties of metals, ceramics, and plastics in terms of ductility, brittleness, strength, and ability to recover from deformation.
5. What did you learn from the displacement measurement?
6. Which material is the strongest and which is the weakest?
7. Describe the nature of the creep curve. Is there a “transient” region? A“steady state” region?
8. How is the creep rate affected by load? By temperature?

III. Transport Properties

Safety

◆ Hot wax can burn. Avoid getting it on your skin.

Materials

Test bars of metal, ceramic, and plastic
Multimeter or ohmmeter
Paraffin wax or candles
Hot plate
Ring stand and clamp
Beaker
Disposable glass pipettes

Experiments

1. Measure the **electrical resistance** of the metal, ceramic, and plastic using a multimeter, ohmmeter, or other resistance measuring apparatus, such as an LED conductivity tester. Determine whether your material is an electrical conductor or an electrical insulator. Recall that an electrical conductor has a low electrical resistivity and hence a low electrical resistance and an electrical insulator has a high electrical resistivity and hence a high electrical resistance.

2. Measure the relative **thermal conductance** of your material using the method shown in Figures D and E. First, melt the wax by placing some paraffin in a glass beaker and then placing the beaker on a warm hot plate. Using a glass pipette, pick up some melted wax from the beaker and drop a bead of wax every centimeter on a test bar of each material.

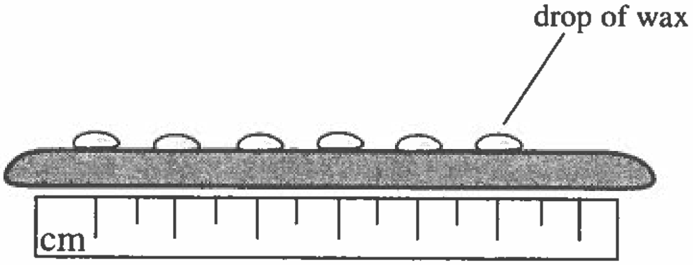


Figure D. Preparation of test bar for thermal conductance testing.

Using the hot plate as a heat source, set up an apparatus like the one in Figure E. The hot plate must be set hot enough to melt at least some of the wax drops, but not so hot that it melts the test bar. In a data table, record the time elapsed for each drop to melt and become clear.

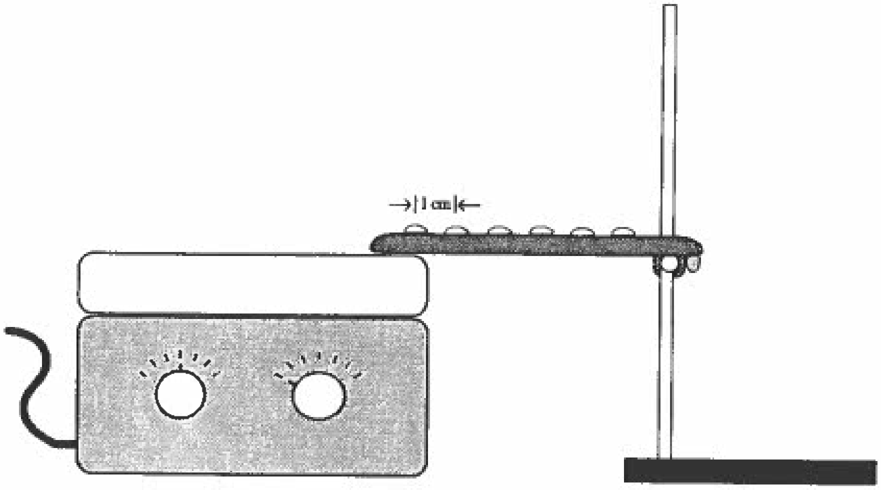


Figure E. Set-up for thermal conductivity testing.

3. Construct a graph of the distance at which the wax drops melt versus time. This will help you to see the difference in thermal conductance of the three materials. Measure each sample for no more than 5 minutes.

Questions

1. Calculate the average rate of heat transfer for each of the materials in cm/sec.
2. By analyzing the graph, determine which material has the highest thermal conductivity and which material has the lowest. Suggest a reason why.
3. Describe the relative thermal and electrical conductivities of metals, ceramics, and plastics.

IV. Density

Safety

- Be careful when working with broken pieces of the test bars. The edges can be quite sharp.

Materials

Graduated cylinder
Balance
Test bar pieces of ceramic
Test bars of metal and plastic
Ruler

Experiment

Measure the mass first and then the volume of your material and calculate the density by using the following formula.

$$\textbf{Density (g/cm}^3\textbf{)} = \frac{\textbf{mass (g)}}{\textbf{volume (cm}^3\textbf{)}}$$

The mass is measured by using a balance and the volume can be measured by displacement, direct volume measurement, or Archimedes principle. Use broken pieces of ceramic from previous experiments to measure density. Do not use your ceramic test bar. Why shouldn't you use your ceramic test bar?

Questions

1. Compare your measured density for tin with the literature value. Discuss the reasons for observed discrepancies, if any.
2. What are some reasons that materials might vary in density? (Consider such factors as atomic weight, atomic bond length or atomic packing, and porosity.)

V. Chemical Properties

Safety

- Wear safety goggles.
- Use caution when handling strong acids and bases. Wear gloves.
- Use caution when handling strong oxidizers and reducers. Wear gloves.

Materials

Test tubes
Test tube rack
Test bar pieces
6.0M HCl
6.0M NaOH
$KMnO_4$ solution, saturated
reducing reagent (optional)

Experiments

1. Reaction with strong acid—place a small piece of material (about the size of a pea) into a small test tube and fill half way with 6 M HCl (hydrochloric acid).
2. Reaction with strong base — place a small piece of material (about the size of a pea) into a small test tube and fill half way with 6 M NaOH (sodium hydroxide).
3. Reaction with strong oxidizing agent — place a small piece of material (about the size of a pea) into a small test tube and fill half way with saturated $KMnO_4$ (potassium permanganate).
4. Reaction with strong reducing agent. Wait two days before recording observation.

Question

Which material is the most reactive? Which is the least reactive?

VI. High Temperature Behavior

Safety

- Perform this experiment in a hood to avoid breathing hazardous fumes and smoke.
- Use care when heating the material in the Bunsen burner. Use tongs to hold the material.

Materials

Test bars of metal, ceramic, and plastic
Bunsen burner
Tongs

Experiment

Observe and record the high temperature behavior of your material in the flame of a Bunsen burner. Perform this experiment in hood or well ventilated area.

Question

Which material is most changed by high temperature? The least changed?

Explorations

Summary and conclusions

- Summarize the characteristics of ceramics, metals, and plastics. How do these characteristics determine the way the three materials are used?
- Name five applications of each type of material from your personal experience and relate the use to the properties you measured [e.g. copper (metal) wire for conducting electricity, wire insulation (plastic), and dishes (ceramic)]. Also consider how materials' properties affect the choice of materials for furniture, pots and pans, stoves, barbeques, silverware, light bulbs, lamps, fans, etc.

Glossary

Alloy

An intimate mixture of two or more metals.

Brittleness

The property of failing with little or no deformation.

Ceramics

Inorganic, non-metallic compounds and mixtures that may be crystalline or noncrystalline (glassy). Ceramics often have high melting temperatures, and are generally brittle and poor conductors of heat and electricity.

Conductor

A material which allows the flow of heat (thermal conductor) and/or the flow of electric charges (electrical conductor).

Creep

The time dependent deformation of a material under constant load. Creep deformation is not recovered after removal of the load.

Density

A measure of the weight per unit volume of a material. Generally expressed as grams per cubic centimeter.

Ductility

The property of deforming without breaking (the opposite of brittleness).

Elastic Deformation

Deformation of a body that is linear with stress or load (Hooke's Law) and that is instantaneously recoverable on removal of the load.

Electrical Conductivity

A measure of the ability of a material to conduct electricity. The inverse of electrical resistivity. Measured in units of 1/(ohm-cm).

Electrical Resistivity

Defined by the relation $\rho = RA/L$, where ρ is the electrical resistivity, R is the electrical resistance, A is the cross-sectional area of the material, and L is the length of the material. Measured in units of ohm-cm.

Grain	A term applied to an individual crystal that makes up the polycrystalline microstructure of a typical metal or ceramic.
Insulator	A material which resists the flow of electric charges (electrical insulator) and/or heat (thermal insulator).
Intrinsic Property	A property which does not depend on the dimensions of a material.
Malleable	The property of metals which allows them to be hammered into thin sheets.
Metallic Luster	Characterized by an opaque, shiny surface with a relatively high reflectance.
Metals	Inorganic materials characterized by the presence of unbound (free) electrons. Metals are reflective, have a metallic luster, and are highly conducting of both heat and electricity. Many metals are malleable and ductile. Examples of metals are tin, copper, aluminum, iron, and steel.
Mold-Release Agent	An agent used to prevent sticking of a formed article in a mold. In this module, petroleum jelly is used where necessary.
Opacity	The light absorbing property of a material.
Phonon	Energy associated with the lattice vibrations of a solid material.
Plastic	Materials that consist essentially of large organic polymers formed into a rigid structure. Examples of plastics include Plexiglas™, polyester clothing, and polyvinyl chloride used in tiles and tubing.

Plastic Deformation

Change in dimensions of an object under load that is not recovered, either instantaneously or slowly with time, when the load is removed.

Polyester

A polymer made by reacting a carboxylic acid with an alcohol.

Polymers

Large molecules made up of many small molecules (monomers) joined in a regular way, generally as long chains or a branched network. Most common polymers are made up of arrays of carbon atoms to which other atoms such as hydrogen, oxygen, and nitrogen are bonded. Silicone polymers are made up of a backbone of silicon atoms in place of the carbon.

Porosity

The amount of void contained within a material.

Reflectivity

The ability of a material to reflect light.

Strain

Deformation of a body in response to an applied load or stress. Expressed in dimensionless units of change in a dimension per unit dimension (e.g. mm per mm).

Strength

The ability of a material to support a load without breaking.

Stress

Force per unit area applied to a body.

Thermal Conductivity

A measure of the ability of a material to conduct heat. Measured in units of watts/(meter-Kelvin).

Thermoplastic

Polymeric material that softens upon heating and hardens when cooled.

Thermoset

Polymeric material that becomes permanently rigid upon curing.

Transparency

The ability of a material to transmit light.

Twinning

A deformation that occurs when the atoms of a crystalline material move along a "twin plane" such that the atoms on either side of the twin plane are in mirror image positions. In tin, twinning can be heard as a crunching sound when the metal is bent back and forth.

Viscoelastic Deformation

Deformation of a body that is recovered in a time-dependent manner on removal of the load.

Additional Resources

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Nagyvary, J. "Music Issue Strikes a Dissonant Chord," *MRS Bulletin,* Volume 20, Number 7, p. 3, 1995.

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World Wide Web Sites

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General Atomics Sciences Education Foundation home page

http://mrsec.wisc.edu/EDETC/Edetc.html
University of Wisconsin-Madison Materials Research and Engineering Center Education and Outreach page

http://vims.ncsu.edu
"Visualizations in Materials Science" (VIMS II): a course from North Carolina State University, Professor John Russ

http://www.rsc.rockwell.com/function/209/
Materials Science Function at Rockwell Science Center

http://tantalum.mit.edu/
MIT Department of Materials Science and Engineering home page

http://www.mrs.org/
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http://www.asm-intl.org/MI/
Metals and Engineered Materials Literature Databases

http://www.materials.drexel.edu/matotm.html
Drexel University Department of Materials Engineering Materials Site of the Month

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Links to Materials Science Sites

http://www.lbl.gov/MicroWorlds/
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The University of Chicago Materials Research and Engineering Center

http://www.nsf.gov/mps/dmr/mrsec.htm
National Science Foundation, Division of Materials Research, Materials Research Science and Engineering Centers

http://www.msc.cornell.edu/education.html
Cornell Center for Materials Research: Educational Outreach

http://web.mit.edu/cmse/www/daycamp.html
CMSE Education and Outreach Minority Science and Engineering Day Camp (MIT)

http://mwm.ms.nwu.edu/
Materials World Modules at Northwestern University

http://www.lbl.gov/MicroWorlds/Contents/MWactivities.html
Teacher's Guide to Microworlds Activities

http://www-dmse.mit.edu/wom/
The World of Materials

http://pmi.princeton.edu/pccm/mrsecs.html
Princeton Center for Complex Materials

http://www.lrsm.upenn.edu/lrsm/sci.html
Univerisity of Pennsylvania Summer Science Academy

Team Bios

Terry D. Gulden, PhD - Team Leader

Dr. Gulden is currently Director of the Advanced Materials Technology Division at General Atomics in San Diego, California, where he is responsible for advanced materials programs. He received his B.S. degree in Ceramic Engineering at the University of Washington, and his MS and Ph.D. degrees in Materials Science at Stanford University. Dr. Gulden also performed two years of Post Doctoral study at the Berkeley Nuclear Laboratory in England, where he was engaged in fundamental research on atomic level defects in materials, employing transmission electron microscopy.

Dr. Gulden is a Fellow of the American Ceramic Society and a Registered Professional Engineer in the State of California. He is the author or co-author of more than 30 technical publications in refereed journals, the co-editor of a special issue of Nuclear Technology, and the holder of two patents. He served for several years on the Board of Directors of the United States Advanced Ceramics Association. He has also served on several Government advisory panels, including the Panel on Beam Technologies convened by the National Materials Advisory Board of the National Academy of Sciences. He is also a member of the Industrial Advisory Board of the Department of Materials Science and Engineering at the University of Washington.

Dr. Gulden has an active interest in science education at the primary and secondary school level. He is a member of the Board of the General Atomics Sciences Education Foundation, and the Team Leader for the "Explorations in Materials Science" Teaching Module. He is also a member of the Board of Trustees of the La Jolla Country Day School, a private K-12 institution.

Holger H. Streckert, PhD - Technical Leader

Dr. Streckert is currently a Sr. Staff Scientist in the Advanced Materials Technology Division at General Atomics in San Diego, California. He received his BS degree in Chemistry at San Diego State University and his Ph.D. in Analytical Chemistry at the University of Wisconsin-Madison. At GA, he is the Program Manager responsible for a number of research and development programs including: the repair of ceramic matrix composites for Air Force applications; the conceptual design study of low activation composite target chamber and components for the National Ignition Facility, a project by the Department of Energy's Office of Inertial Confinement Fusion; the chemical vapor infiltration of thick turbine rotor components for the Air Force; the fabrication of silicon carbide and zirconium carbide rods by chemical vapor deposition for the Knolls Atomic Power Laboratory; the surface treatment of air data sensing probes; and the design and prototyping of composite helicopter windshield wiper components.

Dr. Streckert is a member of the American Ceramic Society and a member of the Handbook Development Committee of the American Society of Nondestructive Testing. He is also a member of the Industrial Advisory Board of the Department of Materials Science at the University of Southern California. He is the author or co-author of more than 30 technical publications in refereed journals and conference proceedings. He holds ten US patents and has several patents pending in the US and Europe.

Dr. Streckert is interested in the advancement of scientific education at the primary and secondary school level. He is active in the General Atomics Education Outreach Program where he contributed to the "Explorations in Materials Science" Teaching Module and he is currently the technical lead for the "Chromatics" Teaching Module under development.

Lawrence Woolf, PhD

Lawrence D. Woolf is manager of the Applied Physics Group in the Advanced Materials Technology Division of General Atomics. He received a Ph.D. in low temperature physics from the University of California, San Diego in 1980 and a BA in physics from Rutgers College in 1975. After a post doctoral appointment at the Exxon Corporate Research Science Laboratory, Woolf joined General Atomics (GA) in 1982. At GA, he has been involved in the development of high temperature ceramic superconducting wire, electromagnetic turbulence control components, nuclear thermionic energy conversion, high temperature electrical insulators, nuclear and solar thermophotovoltaic energy conversion, electronic properties of graphite fibers, and neutron transmutation doping of silicon.

Dr. Woolf is actively involved in education outreach activities at GA for grades K-12. He helped develop the exploration of materials science module and has developed or co-developed modules on light bulbs, color theory, electric energy bills, and the scientific research paper. He developed the *Line of Resistance: Using a Graphite Pencil to Explore the Electrical Properties of Materials and Circuits*, an ICE publication.

He has given over 30 workshops and demonstrations to teachers and students. He is the author of 63 scientific publications and holds 18 patents. He is a member of the American Physical Society, Materials Research Society, Phi Beta Kappa, and Sigma Xi.

Kirk P. Norton

Kirk P. Norton is a Staff Engineer at General Atomics. He has been with GA since earning his Bachelor of Science degree in Chemical Engineering at the University of California, Santa Barbara in 1982.

Mr. Norton has had sixteen years of experience in the design, assembly, startup, and operation of chemical process equipment. He was the lead engineer for the development of a solar-powered reactor for the decomposition of sulfuric acid. His most recent experience has been focused on reactors for chemical vapor deposition on ceramic substrates. Among these is a continuous fiber coater and a low-pressure chemical vapor infiltration reactor for the fabrication of ceramic-ceramic composites.

In addition to work in reactor design, Mr. Norton was the responsible engineer for the installation and start-up of an automated munitions inspection system at Yuma Proving Grounds. This involved robotic handling of live munitions and real-time collection of X-ray imaging. He has developed software that characterizes the behavior of particles in a fluidized bed under given conditions. This software also selects the amounts of different reactant gases for chemical vapor deposition of selected coatings

Roger D. Wynn

Roger Wynn has been a teacher in the Mountain Empire Unified School District for the past 10 years. He received a B.A. in Psychobiology from the University of California, Riverside and a B.S. in Marine Biology from Texas A & M University at Galveston. He holds a Masters License in the U.S. Merchant Marine. Mr. Wynn conducted field research in baboon behavior in Tanzania and co-authored 5 jounal publications on animal behavior.

Subjects Roger teaches include 7th and 8th grade General Science, Computer Science, and High School Chemistry. He currently serves as the Science Department Chairman and as a Science and Technology Mentor teacher. He is active in science and technology programs at General Atomics, San Diego County Office of Education, University of California San Diego, and at the San Diego Supercomputer Center. Mr. Wynn is a California Science Project Leadership fellow interested in science methodology and technology integration in practice.

Danine Ezell, PhD

Danine Ezell has been a science teacher in San Diego City Schools since 1985, teaching general science and biology to students in grades 7-9. Her education background includes a bachelors degree in zoology from Pomona College and a Ph.D. in Zoology from the University of California, Berkeley. She has carried out research in developmental and cellular biology, and has taught at all levels, from 3rd grade through college biology majors. She served as a mentor teacher in San Diego City Schools, and was Coordinator of Bell Junior High's Computer-Mathematics-Science Magnet Program. Currently Dr. Ezell is a science resource teacher for the district.

In addition to her school duties, Danine is actively involved in science education reform efforts at both the national and local levels. She has worked with Project 2061 since 1989, and is the director of the San Diego Project 2061 Center. She also was a member of the content development team for the National Science Education Standards. She continues to be involved in the national effort to implement science standards, and locally is contributing to the improvement of science education through the San Diego Urban Systemic Initiative.

Shauna Brammer

Shauna Brammer has been teaching in the biological sciences for the last eight years at La Jolla High School. She earned a Bachelor of Science Degree in Biology, and a Masters Degree in Education. Ms. Brammer has coached and advised the La Jolla High School Science Olympiad Team and Science Fair students. Shauna was granted an internship from the American Physiological Society, authored curriculum at the state and national level, presented teaching strategies at a number of conferences and workshops, and has been involved in research at Scripps Institute of Oceanography.

Joseph Baron

Joseph Baron has been a teacher with San Diego City Schools since 1973. He is currently teaching chemistry at La Jolla High School. His educational background includes a BS in chemistry, a Certificate in Modern Analytical Chemistry, an MA in Educational Curriculum, course work and research for MS in inorganic chemistry, and a gifted credential. Mr. Baron has written part of a laboratory manual for the Woodrow Wilson Chemistry Institute, co-authored an article in *Science and Children,* "Canned Heat"; units in the "ChemSource", a chemistry resource project; and chapters in the chemistry curriculum guides for San Diego City Schools. He has been involved with the mentor teacher program, internships at a pharmaceutical research laboratory, and Scripps Research Institutes. He has been the chairperson of the American Chemical Society high school program at regional and national conferences, and has presented teaching strategies at numerous conferences at the regional, state, and national level.

About ICE

The Institute for Chemical Education was established in 1983 to provide a center for scientists and science educators to develop and disseminate their ideas for more effective approaches to the teaching of chemistry and science in general. All ICE programs emphasize hands-on science, taught interactively, as a means of helping students develop powers of observation and problem solving. ICE aims to stimulate the scientific curiosity of all students, not just those traditionally well served by our educational system.

At Field Center and Affiliate sites across the country, ICE personnel design and conduct workshops that help teachers overcome some of the common obstacles they face in their efforts to deliver first-rate science education. ICE's programs are structured to involve many individuals and a cross-section of the scientific and educational communitites. ICE also publishes educational materials that help teachers introduce hands-on, interactive activities in their classrooms and laboratories. Some of ICE's programs and educational publications are outlined below.

Outreach

Chem Camps

Middle school students explore the wonders of chemistry through demonstrations and hands-on laboratory experiences. There is also a publication with the same title that details how to organize and operate this type of outreach.

SPICE (Students Participating in Chemical Education)

Volunteers experience the joy of presenting chemistry to school groups and the general public.

Workshops

Super Science Connections

SSC workshops help K-3 teachers integrate language skills, art, mathematics, social studies, etc. into a hands-on science curriculum.

Chemistry and Materials Science

The CMS workshops provide the opportunity for experienced high school chemistry teachers to learn about and teach chemistry from a materials science perspective.

Educational Materials

Solid-State Model Kit

The Model Kit can be used to build different crystalline solid structures in a layer-by-layer manner.

Line of Resistance Kit

The first collaboration between ICE and General Atomics uses a graphite pencil to explore resistance, circuits, and much more!

Topics in Chemistry

A series of monographs providing teachers with background information on everyday topics in chemsitry, such as acid rain and ozone.

Publication 97-005

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