Unit 1: Measurement and Tools of a Chemist

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N.Y. / REGION

8 Violations for School in Wake of Lab Fire

By NINA BERNSTEIN JAN. 8, 2014

Fire Department investigators have cited Beacon High School in Manhattan for eight violations, finding that dangerous chemicals were being stored unsafely and that safety equipment and practices were lacking in at least three rooms. One was the makeshift lab where two students were engulfed in flames last week when a chemistry demonstration went horribly awry.

The department gave the school, which is on the Upper West Side, 10 days to correct some of the violations of fire and building codes, and 30 days for others. But it did not issue a “cease and desist” order, which could have closed the teaching labs, James Long, a Fire Department spokesman, said on Wednesday.

The state Labor Department is also investigating the accident and its context, state officials said, because regulations require safety equipment like chemical fume hoods when teachers handle potentially explosive flammable liquids and toxic chemicals in the workplace. There was none in Room 317, a “science demo room,” where Alonzo Yanes, 16, was badly burned when fumes from the methanol used by a teacher to burn different substances ignited. Alonzo remained in critical condition on Wednesday in the burn unit of NewYork-Presbyterian Hospital/Weill Cornell Medical Center. The other student suffered relatively minor burns.

The Fire Department violations, issued to the principal, Ruth Lacey, also focused on the chemical storage room, Room 331; the school was ordered to immediately reduce the supply of hazardous chemicals to the amounts allowed by law, including no more than 15 gallons of flammable liquids and no more than five pounds of toxic substances. In a formal science laboratory, Room 321, the school was ordered to provide a safety shower and eye wash for decontamination, and to show that a chemical fume hood there was being tested annually for safe ventilation of dangerous fumes.

Devon Puglia, a spokesman for the city Education Department, said it was working closely with the Fire Department to correct the violations as soon as possible.

Science safety experts say that the deficiencies found at Beacon are widespread in American schools, and that accidents that have maimed teachers and students keep happening because of systemic shortcomings.

"I've inspected hundreds of thousands of school laboratories and there are problems everywhere with them," said James A. Kaufman, founder and president of the Laboratory Safety Institute, a national nonprofit educational organization, who has served as an expert witness in personal injury suits in which schools have had to pay millions of dollars for similar accidents. "The kinds of problems that the Fire Department found at the Beacon school are the tip of the iceberg."

Like all but seven states, he noted, New York does not make lab safety education part of the written requirements for science teacher certification, so many teachers are not even aware of the hazards or the safety regulations. Though surveys find that lab accident rates are 10 to 100 times higher in schools than in industry, the scope of the problem has been obscured, he said, because there is no requirement that lab injuries or even fatalities be reported to a central database.

Jonathan Burman, a spokesman for the state Education Department, which certifies science teachers, said safety information was most likely already included in science teachers' coursework. By state law, local districts have sole responsibility for school curriculum, including science experiments, he said.

A federal chemical safety agency last month issued a video warning of the dangers of the same popular demonstration, known as the rainbow or the flame test, that injured the Beacon students. But Mr. Burman said the state's science education officials were not among the 60,000 subscribers who received the warning from the agency, the United States Chemical Safety Board. Asked whether the department had recommendations to make in light of the fire code violations, he wrote:

"We would remind teachers that experiments which utilize flammable or explosive gasses should always be conducted under appropriate fume hoods. We would also remind them of the need to comply with all building and fire codes."

The Metric System, the United States of America, and Scientific Literacy

By Adam Blankenbicker
Posted January 28, 2013

Here's a quick quiz: I weigh 71 kilograms, and am about 1.82 meters tall.

a.) Do you have an idea of about how much I weigh and how tall I am?

b.) Am I taller or shorter than you, and do I weigh more or less than you?

If you don't live in the United States of America, Liberia, or Burma, you most likely can answer both of these questions pretty much without any hesitation. If you do live in one of those three countries, then without the help of a calculator, or a quick search on Google, chances are you would have to think a bit about question "a," and would struggle with question "b."

The issue.

There is a huge disconnect between the science that we do (SI units, commonly interchanged with the *Metric System*) and how we live our daily lives, (U.S. Customary Units, not Imperial Units). Is it possible that people are turned off by science and technology because they don't understand the metric system? And is it possible that this makes us less scientifically literate as a country?

One of my favorite comic strips, Fox Trot, by Bill Amend, consistently brings up math and science humor.

I think the answer is *most definitely*. While U.S. scientists are used to converting units, an ideal scientifically literate society includes artists, public servants, business owners, and waitresses — people who don't have to use the metric system on a regular basis — translating units is one more barrier to understanding the math and science that is used in research.

The only examples that come to my mind where the metric system is in common use in the United States are:

- Miles-per-hour/Kilometers-per-hour speedometers in our vehicles
- A 750ml bottle of wine

- A 1-liter (1,000ml) Nalgene bottle
- The 100 meter dash
- 2 liter soda bottles
- 5k and 10k runs/races
- Most food nutrition labels (How many people actually read those?)

Yet all science is done in the language of SI units. If the goal is for the non-scientific public to be able to engage regularly and enthusiastically with science, wouldn't it make sense for scientists and non-scientists to speak the same language?

To really make SI units and the metric system commonplace in the United States requires more than a little effort on our part. Imagine how many local, state, and federal authorities would be required to change millions of road signs, food packaging, gas station signs and sports fields. And on top of that, does the general public *want* to make the switch?

Some selected history.

The reasons that hold us back from converting range from stubbornness to cost (a 1996 concern in the *Journal of Professional Issues in Engineering and Education Practice*). In 1975, thanks to President Gerald Ford and Congress, the Metric Conversion Act was passed which would have led to the metric system being the preferred system of weights and measures in the United States. This act created the United States Metric Board, which was abolished in 1982, by President Reagan.

From The United States and the Metric System, NIST LC 1136: "The efforts of the Metric Board were largely ignored by the American public, and, in 1981, the Board reported to Congress that it lacked the clear Congressional mandate necessary to bring about national conversion. Due to this apparent ineffectiveness, and in an effort [by President Reagan] to reduce Federal spending, the Metric Board was disestablished in the fall of 1982."

Some readers may be familiar with the "We the People" petition that the White House website hosts. As of this moment, over 35,000 people have digitally signed a petition to make the metric system the official system of weights and measures of the United States. Possibly another act from the federal government is needed to really get things moving again.

A more detailed history can be read here.

Solutions.

Thankfully, the metric system has been taught in schools and this should continue. From my experience, however, it was only as a way to solve given problems. Physics was taught in the metric system, as was chemistry. But when I got to my algebra class, and even in shop class, (a prime opportunity to "feel" what 50 centimeters was), we measured 20 inches (not the same, by the way). I would recommend that all rulers in school should all be inches and centimeters, though I must admit I attended a science teacher workshop and we were given 12 foot tape measurers to take back home.

Should we discourage these words? Image from another blog post about the metric system.

When I learned Spanish, my most effective learning was not being told that café meant coffee — I was given a cup of café and told "este es café," or "this is coffee." We shouldn't miss these tangible opportunities to become friendly with the system.

The next time you go to your doctor's office and they take you height and weight, ask your doctor for the numbers in metric, and you will have that personal connection to some part of the metric system. Do you check the weather online or use online mapping? Change the units to Celsius and meters. These are a few simple changes people can make to become more familiar with the system.

You don't have to look long to find bloggers who are asking why the United States has not yet converted to the metric system. One I found particularly interesting is a blog created in 2012 which focuses on documenting the creation of a documentary about how the United States was *going* to convert to the metric system, but never did. The blog is appropriately named "More than a mile behind." Keep your eyes and ears open for this one.

The world and us.

I have always believed that no matter what language you speak, science and math are the same in any language. If we're not speaking the same scientific language as scientists from other countries (many of whom have made the effort to learn English), we might be isolating ourselves scientifically. So with that, I'll leave you with a clip from The Simpsons.

P.S. Even rocket scientists mess up.

About Adam Blankenbicker

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View all posts by Adam Blankenbicker →

This entry was posted in Uncategorized and tagged metric system, science education, science education research, science literacy, Teaching. Bookmark the permalink

52 Responses to *The Metric System, the United States of America, and Scientific Literacy*

Pingback: *Linda's Series of Fortunate Events* | More Than A Mile Behind: America and the Metric System*

Alain Gaudreau *says:*
July 25, 2013 at 2:27 pm

I still do not understand why Americans have not changed to the Metric system and are still using the Imperial system !!!!! which by the way, as the word Imperial says it, dates back to the British colonnisation and occupation of North America. The Americans kicked out the British but is the only country that still uses the Imperial system; O sorry I forgot about Liberia and Myanmar they also use the Imperial system.
If the only reason that the US resists the Metric system is because it's a French invention well if it was'nt for a French general called Lafayette you would be using the Metric system because you would have remained British subjects and the British are now using the Metric system.
I do not have an explanation why the Americans are still with the Imperial system other than the easiest explanation of refusal of change "WOW" .
My admiration for the USA is severely hampered by that fact!!!
The Eastern Townships of Quebec which was about 50/50 French and English Canadians was the pilot project for the implementation of the metric system in Canada back in 1974. The project led rapidly to the adoption in everyday life of the Metric system in Canada. Meat was sold in grams and Kilograms and gas in liters and we survived happily.
Cant wait for you guys in the US to catch up. Sorry the rest of the planet will not change; the Metric system makes to much sense.

Rating: 0 (from 0 votes)

Reply

Charles E. Winchester, III *says:*
March 29, 2014 at 6:09 pm

"I still do not understand why Americans have not changed to the Metric system and are still using the Imperial system !!!!!"

"The Americans kicked out the British but is the only country that still uses the Imperial system"

As stated in the article: The USA use U.S. Customary Units, not Imperial Units.
U.S. Customary Units are not identical to Imperial Units.

Rating: 0 (from 0 votes)

Reply

testman *says:*
July 24, 2013 at 3:18 am

FYI, it is not 5K or 10K race but 5k or 10k race. Upper K is Kelvin degree of temperature in SI unit. Lower case k is kilo prefix which means thousands.

Metric system is precise ☺

ALso most country talk about "5 thousands meter" race...

Rating: 0 (from 0 votes)

Reply

Adam Blankenbicker *says:*
July 27, 2013 at 1:54 pm

Thanks! Noted and corrected.

Rating: 0 (from 0 votes)

GLASS: More Than Meets the Eye

By Brian Rohrig

A 23-year-old single female is awakened in the middle of the night by an intruder standing over her bed. She screams. The intruder flees in a panic, diving through a closed window. The police are notified immediately. They apprehend a suspect several blocks from the scene. He claims to be innocent, yet the police discover several shards of glass in the suspect's hair and clothing. When these samples are compared to the glass of the broken window, they are discovered to be the exact same type of glass. On the basis of this evidence, the intruder is eventually convicted and sent to jail.

Because acts of violence often involve broken glass, glass is one of the most commonly encountered forms of evidence found at crime scenes. However, many pieces of glass appear identical to the naked eye even though they can differ markedly in their chemical composition.

How do forensic scientists match samples of glass?

Careful observation can reveal subtle but important differences between various types of glass. The forensic chemist may use several methods for determining whether two samples of glass originated from the same source. The first step is to visually examine the glass. Physical properties of the glass are then measured. Subsequent steps involve analysis of the chemical composition and differences in the way it was manufactured.

Physical examination

Some important features to note are edge thickness, color, and the presence of any labels or imprints on the glass. A blacklight lamp may be used to check for repairs as hairline cracks will glow under ultraviolet light. Modern paints will also glow under a blacklight.

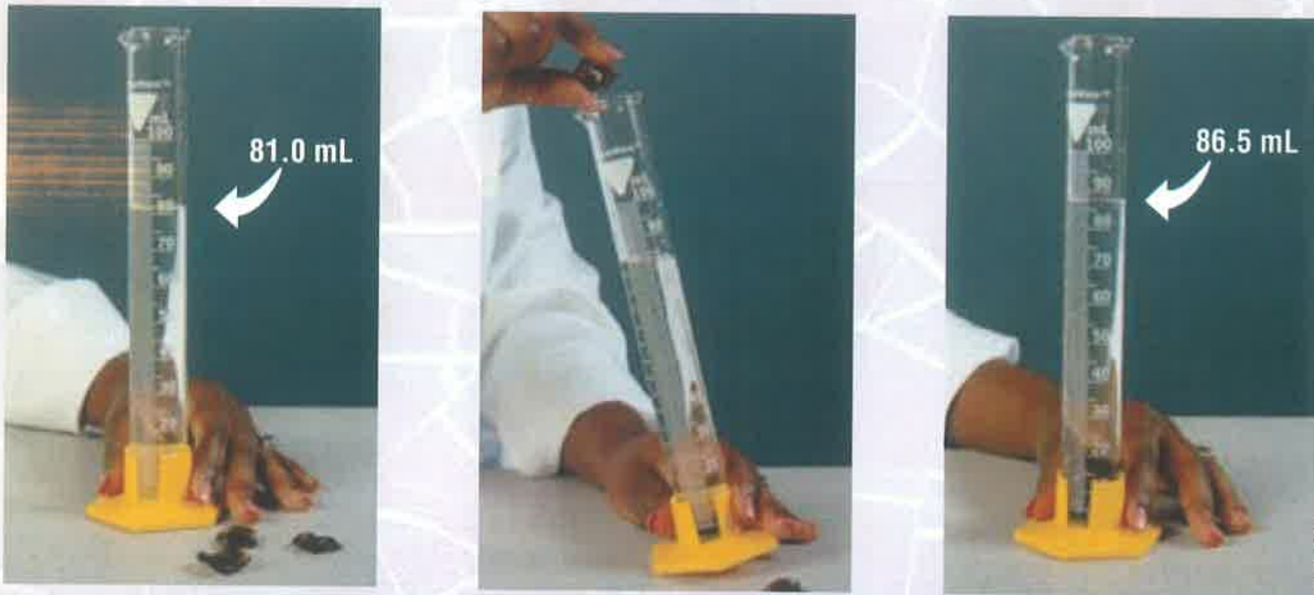
Thickness

Glass thickness is generally a function of its application. Glass from a light bulb is going to be thinner than a pane of window glass. The glass used in a picture frame is generally not subject to gusts of wind, so it will be thinner than glass used in a window. Glass used in a door is generally even thicker, to withstand the forces applied as a result of frequent opening and closing (and sometimes slamming!).

Density

One of the most common methods for matching glass samples is the determination of density. The formula for density is mass/volume, and the density of two pieces of glass will always be the same if they come from the same source, regardless of the size of the two pieces. The formula method for determining density involves measuring the volume of a glass sample of known mass. The volume can be determined by displacing water in a volumetric flask.

Another more accurate method of comparing densities is the flotation method. A sample of glass is dropped into and sinks to the bottom of a liquid containing an exact volume of a dense liquid, such as bromobenzene (d = 1.52 g/mL). Then, a denser liquid, such as bromoform (d = 2.89 g/mL) is added dropwise until the piece of glass rises up from the bottom and attains neutral buoyancy. Neutral buoyancy occurs when an object has the exact



MIKE CIESIELSKI

The formula method for determining density: After finding the mass of an object, measure its volume by water displacement.

JUPITERIMAGES

same density as the surrounding fluid, and neither sinks nor floats but is suspended in one place beneath the surface of the fluid.

The same procedure is then performed with another piece of glass, and if the volume needed to attain neutral buoyancy is the same as for the first sample, then the densities of the two samples are equal. The exact density of each sample can be calculated by using the following formula:

$$d = \frac{X(2.89) + Y(1.52)}{X + Y}$$

X and Y refer to the volumes of the respective liquids, with the numbers in parentheses referring to the densities of each liquid. Any two liquids can be used, as long as they are miscible in one another and have appropriate densities. But when determining the density of glass, liquids with a relatively high density must be used, since glass is always denser than water. The density of a typical piece of single-pane window glass ranges from 2.47 to 2.56 g/mL. If the density of a 1.5-g sample of glass were 2.48 g/mL, what would you predict the density to be for a 3.0-g sample of the same glass? *(Find the answer at the conclusion of this article.)*

Refractive index

Another very accurate method used to compare samples is to determine their index of refraction, or refractive index. Any object that transmits light has its own refractive index, which is a measure of how much the object slows the speed of light. When light passes through any medium, it is slowed down. The denser the medium, the slower the light travels. The refractive index of any substance is a ratio of the velocity of light in a vacuum to the velocity of light in that particular medium. For example, the refractive index for water is 1.33. This means that light travels 1.33 times faster in a vacuum than it does in water. And when light passes from one medium to another one with a different refractive index, refraction (or bending) of the light occurs. This is why objects appear bent or distorted under water.

Every liquid has its own refractive index. If a piece of glass is placed in a liquid with a different refractive index, an outline of the glass is clearly visible—known as the Becke line. However, if a piece of glass is placed in a liquid with the same refractive index, the Becke line will disappear and the glass will seem to disappear. This is because the glass bends light at the same angle as the liquid.

Glycerin has a refractive index of 1.473. If a piece of glass seems to dissapear in glycerin, then it too has a refractive index of 1.473. If two samples of glass have the same refractive index, this does not necessarily prove they are from the same source. But if two samples have different refractive indexes, they are definitely not from the same source. The FBI has a database of refractive index values for approximately 2000 different types of glass, allowing forensic scientists the ability to identify samples. The most common value for the refractive index of glass is 1.5180.

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The beaker on the left contains water and the one on the right, glycerin. Both beakers also contain a glass stirring rod. Because the glass rod and glycerin have the same refractive index, the glass rod in the beaker on the right seems to "disappear."

Chemical composition

If both the density and refractive index of two samples of glass are the same, then the final test will involve sophisticated methods to determine their chemical composition. The difference between types of glass can be due to the chemical composition of the glass itself or differences in how the glass was manufactured. Most glass is made from silicon dioxide (SiO_2), the primary ingredient in sand, which has been heated above its melting point of 1600°C. Various substances are then added, depending on what type of glass is desired.

Different additives can impart different properties to the glass. Sodium carbonate or soda (Na_2CO_3) is added to the silicon dioxide during glassmaking, lowering both its viscosity and melting point. The soda increases the water solubility of SiO_2, making it much easier to fashion into glass. Calcium oxide or lime (CaO) is added next, restoring water insolubility to the mixture. As a result of these two additives, most glass used to make windows or bottles is known as soda-lime glass.

Boron oxide (B_2O_3) is used to make Pyrex glassware. The beakers and test tubes you use in chemistry lab are most likely made from Pyrex, as is the glass used to make auto headlights. Glass made with boron oxide expands and contracts very little when heated and cooled, which is why Pyrex glassware can be heated and then cooled without breaking.

To make eyeglasses, a very sturdy glass is desired, so the additive potassium oxide (K_2O) may be used. This imparts hardness to the glass. Other metallic oxides can give glass a specific color. Copper and cobalt oxides are used to make glass blue, manganese oxides give glass a purple color, and lead-antimony oxide imparts an opaque yellow.

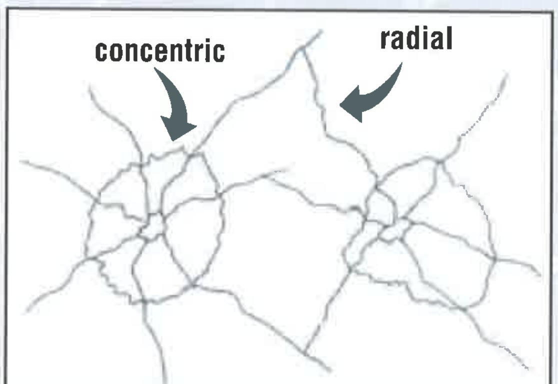
Who fired first?

When a bullet strikes a pane of ordinary window glass, careful observation can reveal several crucial details. First of all, glass has a certain degree of elasticity and will break when this elastic limit is exceeded. This elasticity produces the familiar pattern of concentric and radial fractures that accompany penetration of glass by a projectile. The radial fractures are produced first and always form on the side of the glass opposite to where the

A bullet hole in window glass.

impact originated. Radial fractures look like spider webs that spread outward from the impact hole. Concentric fractures form next, and these lines encircle the bullet hole. Concentric fractures always start on the same side as that of the destructive force.

A radial fracture will always terminate into an existing fracture (see illustration). If there is a second bullet hole in a piece of glass, its radial fractures will always terminate into the cracks from the first bullet hole. The radial cracks from a third bullet will terminate into the radial fractures from the second bullet, and so forth. The sequence of numerous bullet holes can be determined by this method. If the glass is shattered, it may be



The sequence of shots can be determined: the radial fractures of the second hole terminate in those from the first hole.

necessary to reconstruct the broken pieces first. There has been more than one case of a shootout ensuing through the windshield of a car between a police officer and a suspect. By examining the termination lines of the radial fractures from each bullet hole and by comparing the size of the exit and entrance holes of each bullet, it can be determined who fired first.

The direction from which a bullet was fired can be determined by comparing the size of the entrance hole to that of the exit hole. Exit holes are always larger, regardless of the type of material through which a bullet penetrated. Because glass is elastic and bows outward when struck by a bullet, a larger piece of glass will be knocked out on the surface where the bullet is leaving as opposed to the very small hole the bullet makes when it enters.

Because of its elasticity, glass always blows back in the direction the impact originated. Because of the violent tendency of glass to snap back after being stressed, it can blow back glass several meters in the direction from which the shot originated. If a bullet strikes a window from the outside and shatters it, most of the glass will be on the outside. This piece of information can be extremely valuable in determining from which direction a shot was fired.

Was the light on or off?

Here's a bit of information that can be valuable in crime scenes involving a broken incandescent bulb, especially among vehicle collisions. It is easy for someone to drive at night with their lights off while driving down a well-lit street. But suppose you're cruising down the road one night, and bam! You get into an accident with a motorist who did not have his lights on. If it could be proven that the other motorist failed to turn on his headlights, this would be a big boost to your case. But suppose it is his word against yours. By examining the broken filament of a light bulb, it can easily be determined whether the bulb was on or off when it was broken.

Light bulbs do not actually burn, but rather, glow as the tungsten filament becomes very hot due to the resistance that the electrons encounter as they pass through the very narrow wire filament. The definition of incandescence is the property of emitting light as a result of being heated, but not actually burning. The electrons in the filament material absorb energy and jump to higher atomic orbitals (excited state). They then release a photon as they fall back to their original ground state orbital. In a properly functioning light bulb, the glowing filament is inside of the bulb filled with a noble gas such as argon.

But if the filament is glowing when the bulb is broken, it will immediately react with oxygen in the air and break in half. This will form a thick layer of yellowish-white tungsten oxide on the filament due to the reaction of the tungsten with oxygen. If the presence of tungsten oxide on the filament is found, then it can be proven that the bulb was on when the accident occurred. The absence of tungsten oxide on the filament reveals that the bulb was probably off when it was broken.

Solving the crime

Sometimes, a bit of deductive reasoning is all it takes to solve a crime. In 1988, there were dozens of claims by consumers that they had found shards of glass in jars of Gerber baby food. After forensic investigators examined these contaminated jars, they discovered many different types of glass—glass from mirrors, bulbs, and car headlights were all found. If the glass came from the manufacturing plant due to an accident such as a light bulb breaking over the production line, then you would expect to find only one type of glass in the jars, not several. It was therefore concluded that the glass found in the jars of baby food was a result of deliberate tampering.

The field of forensic science provides a fascinating glimpse into how science can be used to solve crimes. A well-trained forensic scientist uses aspects of biology, chemistry, physics, and mathematics to reconstruct what may have happened at a crime scene. Criminals may break society's laws, but they cannot break the laws of nature.

Answer to question:

The 3.0-g sample of glass has the same density as the 1.5-g sample. It might be twice as massive, but then it has twice the volume. Since density is M/V, the density of both pieces would be identical. Remember, density does not depend on the size of the sample!

Disappearing Glass

Here is another cool activity involving glass.

MIKE CIESIELSKI

Materials

approved protective eyewear
paper towels
(2) 10-mL graduated cylinders
1 glass stirring rod
glycerol (about 10 mL)
water (about 10 mL)

Wear your safety goggles during this activity, and do not taste any of the liquids used.

1. Obtain a glass stirring rod from your teacher.
2. Place about 8 mL of glycerol in a 10-mL graduated cylinder and 8 mL of water in another 10-mL graduated cylinder.
3. Put the stirring rod into the graduated cylinder with the water in it.
4. Record your observations.
5. Remove the stirring rod and dry it off with a paper towel.
6. Now place the rod in the graduated cylinder containing the glycerol. What happens?
7. Record your observations.

After discussing this activity with your small group, devise an explanation for what you observed. Be prepared to share this with the class.

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Fisher, D. *Hard Evidence.* Dell: New York, 1995.
Saferstein, R. *Criminalistics: An Introduction to Forensic Science.* Pearson Prentice Hall: Upper Saddle River, NJ, 2004.

INTERNET RESOURCES

Automobile Window Glass—A Design Defect That Should Not Be Overlooked, http://www.auto-law.com/CM/PracticeAreaDescriptions/PracticeAreaDescriptions58.asp.
Bullets Out, None In, http://www.discover.com/issues/nov-03/rd/bullets-out-none-in/.
Different Types of Glass, http://www.diydata.com/materials/glass/glass.htm.
Glass, http://en.wikipedia.org/wiki/Glass.
How does safety glass work?, http://computer.howstuffworks.com/questions508.htm.
Tempered Glass Breakage, http://alumaxbath.com/tech/tgb.htm
What makes glass transparent?, http://science.howstuffworks.com/question404.htm.
What's That Stuff? Glass, http://pubs.acs.org/cen/whatstuff/stuff/8147glass.html.

Brian Rohrig teaches at Jonathan Alder High School in Plain City, OH. His most recent *ChemMatters* article, "The Chemistry of Digital Photography and Printing", appeared in the February 2006 issue.

Forensic Identification of Glass Activity

As the article on glass points out, it is relatively common to find pieces of broken glass associated with crime scenes. Forensic scientists are often asked to determine the origin or prove the identity of various samples of glass shards.

Placing pieces of plastic in isopropanol.

Finding the Density of Glass:

Because the liquids mentioned in the article are not considered safe for routine high school use, here's an alternative method that will demonstrate the same concept.

Before you begin, answer these questions:

1. If you place small bits of plastic in water, will they float or sink? Will they float or sink in rubbing alcohol? What information would you need to know in order to make a prediction?
2. If you used a much larger piece of the same type of plastic, would it affect whether or not it floats in the liquids?
3. If a piece of plastic sinks in a liquid, what does that mean about the density of the plastic relative to the density of the liquid? In terms of the density of plastic relative to the density of the liquid, what does it mean if the plastic floats?

Carefully adding water until the pieces of plastic begin to rise.

Materials

approved protective eyewear
100-mL graduated cylinder
small pieces of plastic from a pen top
100-mL beaker
10-mL graduated cylinder
isopropanol (rubbing alcohol, 70%)
water
balance
dropper pipet

Be sure to wear safety goggles while completing this activity.
Do not taste any of the liquids used in this activity.

Your teacher will provide you with pieces of plastic that have come from ordinary ballpoint pens. Use a balance to determine their mass; record the mass as accurately as possible. Place 50.0 mL of isopropanol in a 100-mL beaker. Add water slowly until the plastic pieces begin to rise. Record the exact amount of water needed to get the plastic pieces to attain neutral bouyancy; that is, they stay suspended about half way to the top of the liquid mixture.

Using the equation from the article, calculate the density of the plastic.

MIKE CIESIELSKI

At this point, the densities of the plastic and the solution are the same.

SUGAR
AN UNUSUAL EXPLOSIVE

By Michael Tinnesand

At 7:15 p.m. on a cool February night in 2008, an explosion rocked an industrial plant that produces sugar near Savannah, Georgia. More explosions followed, with devastating results.

The floors of the Imperial Sugar Company's plant buckled and walls were blown out. The damage caused the electricity to be cut off from most of the plant, making escape and fire suppression difficult.

The fire raged for hours. By morning, the full extent of the devastation was evident. Thirteen people died and 40 were injured. The plant, which is the largest sugar refinery in the United States, was completely destroyed. Investigators on the site quickly discovered the cause of the wreckage and the source of the explosion: sugar.

Most of us are familiar with things that explode, and our thinking usually goes to gunpowder, gasoline, and dynamite. But sugar? How can such a common household food be responsible for leveling an entire sugar refinery and result in so many deaths and injuries?

What do explosions and roasting marshmallows have in common?

All explosions, regardless of their source, are characterized by a large release of energy, the production of gas molecules that expand quickly, and a rapid rate of reaction.

U.S. CHEMICAL SAFETY AND HAZARD INVESTIGATION BOARD

Aftermath of the February 2008 dust explosion and fire at Imperial Sugar refinery in Port Wentworth, Ga.

Burning sugar—chemically known as sucrose ($C_{12}H_{22}O_{11}$)—produces energy almost immediately. Anyone who has roasted a marshmallow—which is mostly made of sugar—over a fire knows the marshmallow ignites and burns like a torch.

This process, called combustion, is described by the following chemical reaction:

$$C_{12}H_{22}O_{11}\text{ (solid)} + 12\ O_2\text{ (gas)} \rightarrow 12\ CO_2\text{ (gas)} + 11\ H_2O\text{ (gas)} + \text{energy}$$

Note that there are 12 moles of gas on the left side of the equation for the combustion of sugar but 23 moles of gas on the right side. This explains the increase in volume typical in explosive reactions. What this chemical reaction does not show, though, is that this volume needs to increase rapidly for an explosion to occur.

So, why doesn't sugar explode or at least light on fire when we eat it? When we eat sugar, the process is different because it happens within cells in our body and is controlled by large molecules called enzymes. In this process, called respiration, sucrose is first digested in the stomach into its component sugars, one of which is glucose ($C_6H_{12}O_6$). Glucose subsequently reacts with oxygen in a series of small steps within our cells.

The process can be summarized according to the following equation:

This reaction occurs at a slower rate and the energy is stored, so no explosion occurs.

The sugar molecules still react with oxygen and produce carbon dioxide and water, but

$$C_6H_{12}O_6\ (solid) + 6\ O_2\ (gas) \rightarrow 6\ CO_2\ (gas) + 6\ H_2O\ (gas) + energy$$

the energy is first captured and then released through many steps.

The explosion at the Imperial Sugar plant is more closely related to the burning marshmallow than the digestion of sugar. The chemical reaction involved is the same, but the speed at which it happens and the fact that many such reactions occur at the same time are what causes an explosion.

Sugar dust explosions

But what is the difference between the slow chemical reaction that results in a ruined marshmallow and the catastrophic destruction of an industrial plant? The answer has to do with factors that affect the rates of chemical reactions. These factors include the nature of the reactants, their physical state (solid, liquid, or gas), the surrounding temperature and pressure, and the amount of surface area—the area of exposed surface of solid or liquid reactants.

In the case of the Imperial Sugar plant explosion, the most important factor is the amount of surface area. A chemical reaction of a solid substance can occur only on its surface (Fig. 1a). For example, when a cut apple is left exposed to air, it soon begins to turn brown. This browning of the apple's surface is a chemical reaction between the molecules at the surface of the apple and oxygen from the air (Fig. 1b).

But the browning occurs only on the exposed cut surface of the apple. If you were to cut the apple again, you would expose fresh apple underneath, and the amount of browning would increase. Oxygen from the air can interact only with surface molecules, so that's the only place where browning can occur.

Another example is what happens when we try to start a campfire. Trying to light a fire with just one big log is ineffective and frustrating. No matter how long a match is held underneath the log, it is not likely to start burning. But if the log is divided with a hatchet into a number of slender sticks, commonly known as kindling, the fire is much easier to start.

Now, imagine taking this process to the extreme. If the log is divided into increasingly smaller slivers, eventually nearly all of the molecules in the wood would be near the surface and available to react. Indeed, finely divided wood dust will not only burn but explode.

More than 200 dust fires and explosions have occurred in U.S. industrial facilities over the past 25 years.

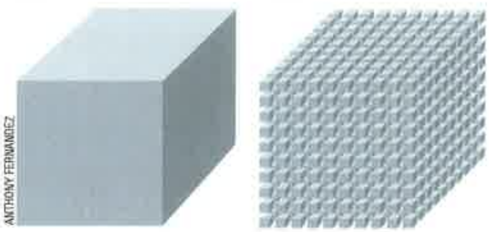

Figure 2. The higher the surface area, the higher the rate of a chemical reaction. If a substance is divided into smaller pieces, the amount of surface area increases. For example, a cube (a) with sides that are 10 cm-long has a total surface area of 10 cm x 10 cm x 6 faces = 600 cm^2. If this same cube is divided into 1,000 small cubes (b), the total surface area becomes: 1 cm x 1 cm x 6 faces x 1,000 cubes = 6,000 cm^2, which is 10 times the surface area of the original cube.

Let's go back to sugar. As raw sugar is refined, it is ground into smaller particles. Sugar particles in granulated sugar range in size from 570 to 635 micrometers—about the thickness of a fingernail. (One micrometer is one-millionth of a meter.) In powdered sugar, the particles are much smaller: Their average size is 60 micrometers.

When a substance is divided into smaller and smaller particles, even though the total amount of the substance remains constant, the number of particles increases, and so does the total surface area that is available to react chemically (Fig. 2). For example, one kilogram of a substance divided into particles of 120 micrometers each has more than 500 square feet of surface area.

As the surface area increases, the number of collisions between the molecules on the surface and the oxygen molecules in the air increases. That's what occurs when dust is dispersed in the air: Each dust particles is surrounded by oxygen molecules, so collisions occur between these dust particle and surrounding oxygen molecules.

In the presence of a spark or a flame, all of these collisions become combustion reactions that occur at a very rapid rate. Lots of heat is released, which quickly causes a very rapid increase in the volume of the gases being formed, creating a shock wave—a series of air waves that move very fast—typical of explosions.

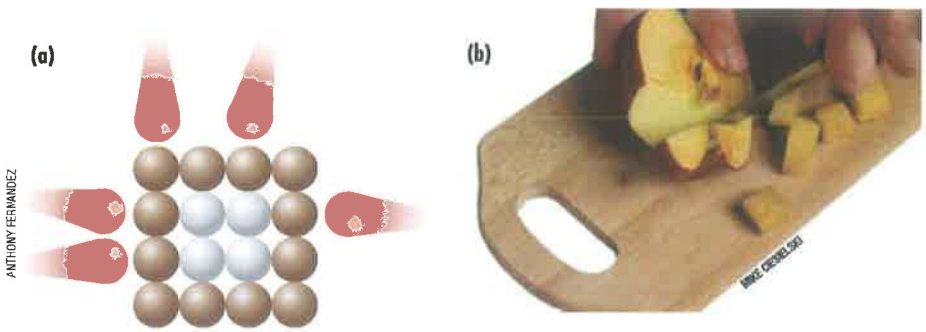

Figure 1. A chemical reaction of a solid substance can occur only on its surface, as shown in these two examples: (a) For a substance made of regularly aligned particles (spheres), only the particles on the surface (brown spheres) interact with other particles (red spheres); (b) In the case of a piece of apple, only the exposed cut surface turns brown after interacting with oxygen molecules in the air. If the apple is cut again, more fresh apple is exposed to the air, and it turns brown as well.

When a substance is divided into particles that are 500 micrometers or less in size—what scientists formally call "dust"—it can easily explode, especially if it is dispersed in the air. This allows every single particle in the dust to potentially react with oxygen in the air. Note that it will still be difficult to ignite a pile of sugar dust. It is not until the dust is suspended in air that it will explode in the presence of a spark.

In industrial processes, as sugar is ground and milled, the smallest particles can float into the air and cause an explosion, unless they are captured by an exhaust system.

This is exactly what happened at the Imperial Sugar plant. The various grinding and refining processes filled the air in the plant with finely divided sugar dust. Exhaust systems were inadequate to keep the dust out of the air. A spark or flame from one of the machines in the plant started the explosions, which quickly spread to other parts of the facility. As the explosions tore the plant apart, sugar dust that had collected on the floor and equipment was tossed into the air and quickly added to the explosions.


U.S. CHEMICAL SAFETY AND HAZARD INVESTIGATION BOARD

Investigators and firemen at the site of the explosion and fire at the Imperial Sugar Refinery in Port Wentworth, Ga.


U.S. CHEMICAL SAFETY AND HAZARD INVESTIGATION BOARD

The U.S. Chemical Safety and Hazard Investigation Board investigated three major industrial explosions involving combustible powders.

Other dust explosions

This type of dust explosion is not just a problem with sugar. Dust from coal, flour, metals, plastics, and wood can all explode under the right conditions. More than 350 such explosions have occurred in the United States during the past 30 years, resulting in more than 130 fatalities and hundreds of injuries. The explosions occurred in 44 states, involving a variety of industries. According to the CBS News television program 60 Minutes, originally broadcast on June 8, 2008, 30,000 U. S. factories are at risk for explosive dust.

Sometimes, finely ground substances can be used to our advantage. In many coal-burning power plants, coal is finely ground before it is blown into the combustion chamber. Once inside, the finely divided coal burns more quickly and more cleanly than lump coal. Also, in automobile engines, liquid gasoline fuel is sprayed into the piston cylinder through fuel injectors that disperse it into a fine mist. Just like coal dust, gasoline burns rapidly, and nearly all of it is consumed in the combustion reaction.

So, why has this dangerous situation been allowed to persist? To some extent, it is because dust is so familiar to us that we are not too concerned about it. We are all familiar with household dust or dust that is carried by the wind. But when dust from high-energy substances, such as sugar, is allowed to accumulate in closed spaces and happens to ignite, it can cause an explosion.

The U.S. Chemical Safety and Hazard Investigation Board (CSB), a federal government agency that investigates industrial chemical accidents, issued a report in 2006 calling dust explosions a "serious hazard." CSB also called on another U.S. government agency, the Occupational Safety and Health Administration (OSHA), to issue safety standards covering all potential sources of industrial dust explosions. OSHA issues and enforces rules called standards to prevent work-related injuries, illnesses, and fatalities.

Late in 2009, OSHA announced that it was planning to propose new standards to determine how to control the amount of dust present at a work site, how to eliminate sources of ignition that could start an explosion, and how to control damage should a catastrophic explosion occur.

Thanks to these new efforts, workplaces that contain large amounts of dust—such as sugar factories and wood workshops—should become safer in the future. But it is equally important that more people realize that dust can become an explosive, so they can find ways to prevent it from becoming hazardous.

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