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.

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

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

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).

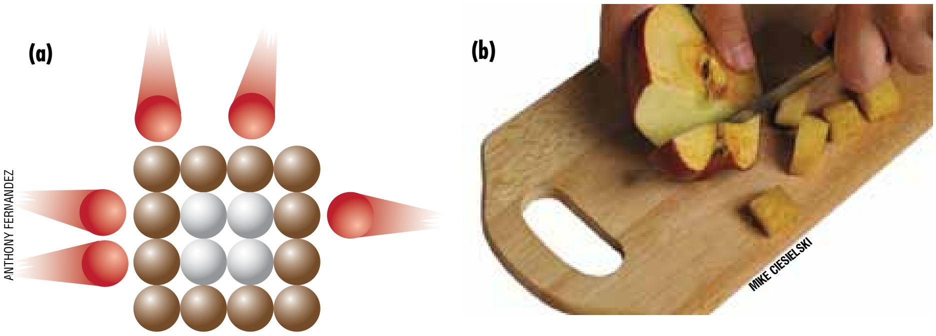

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Figure 1. A chemical reaction of a solid substance can occur only on its surface, as shown in these two examples: (a) For a substance made of regularly aligned particles (spheres), only the particles on the surface (brown spheres) interact with other 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.

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.

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

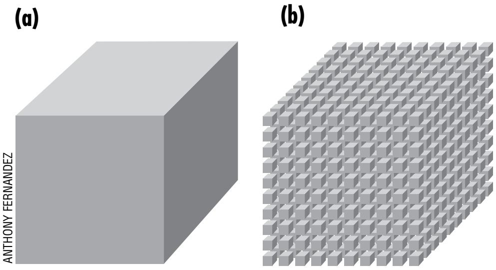

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Figure 2. The higher the surface area, the higher the rate of a chemical reaction. If a substance is divided into smaller pieces, the amount of surface area increases. For example, a cube (a) with sides that are 10 cm-long has a total surface area 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.

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.


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

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.


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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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Michael Tinnesand is a science writer and education consultant who lives in Portland, Ore. His latest *ChemMatters* article, “What Makes Tricks Tick?,” appeared in the October 2010 issue.


MIKE CIESIELSKI