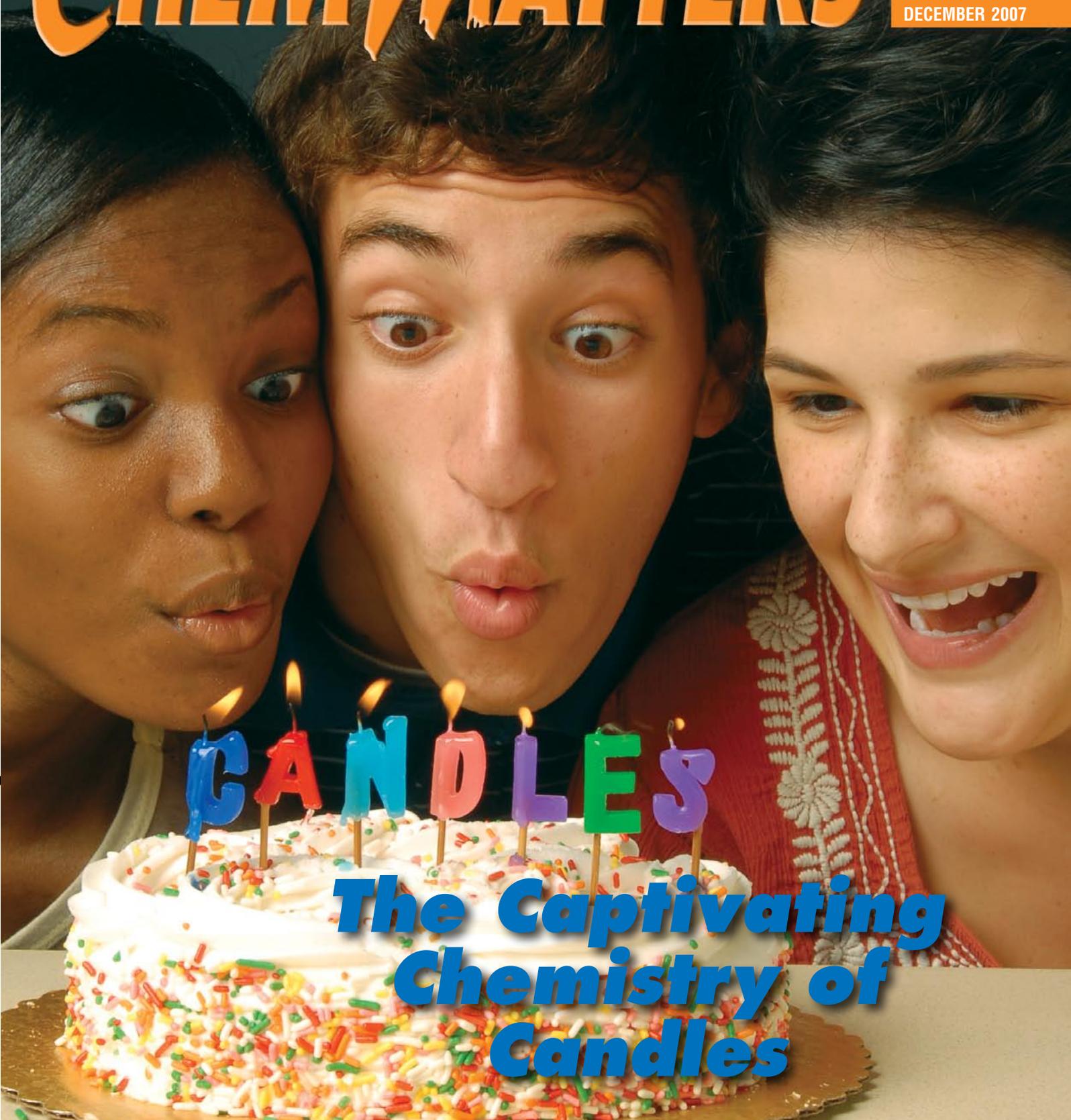


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CHEMISTRY

DECEMBER 2007



The Captivating Chemistry of Candles

From Candles to Cookies to Hydrogen ... Energy at Work



THE CAPTIVATING CHEMISTRY OF CANDLES

Birthdays, holidays, special evenings—all seem better by candlelight. But before electric lights, candles were the dependable source of light for homes.

By Brian Rohrig





Whether you are talking about the most expensive fragrance-enhanced candles or the most basic candles found in emergency supply kits, the components are the same—a source of fuel and a wick. As such, candles have been around for about 5,000 years. Through the ages, candles have been constructed from a variety of materials—beeswax, yak butter, dried fish, and many others. High-quality candles in the 18th and 19th centuries were made from *spermaceti*, an oil extracted from giant cavities in the heads of sperm whales, with yields of up to three tons of fuel from a single 15-meter-long individual! More commonly, candles were made from tallow, or animal fat. While readily available, tallow candles released heavy, odorous smoke—not exactly the stuff of romance.

The fuel

The discovery of paraffin in the mid-1800s revolutionized the making of candles. Paraffin is a by-product of the distillation of petroleum, or crude oil. Today, nearly all candles are made from paraffin. Paraffin refers to a class of hydrocarbons known as *alkanes*, compounds with only carbon-carbon and carbon-hydrogen single bonds. Methane (CH_4), propane (C_3H_8), and octane (C_8H_{18}) are other examples of alkanes. These straight-chain alkanes, like all alkanes, have the general formula $\text{C}_n\text{H}_{2n+2}$, since they consist of a chain of CH_2 groups bonded to each other, and “capped” at each end by a hydrogen atom. Paraffin compounds have more than 20 carbon atoms per molecule.

Paraffin is actually a mixture of several different heavier hydrocarbons. A good average can be represented by the formula $\text{C}_{25}\text{H}_{52}$.

Their large molecular masses make the molecules sluggish, ensuring they exist as solids.

Wax is an even less of an exact term, applied to any substance with a “waxy” feel. Without referring to any specific class of compounds, we ascribe several properties to waxes: they repel water, they are usually less dense than water, they burn, and they may be used as fuel. Wax can be of animal, vegetable, or mineral origin.

The term “paraffin wax” was coined to prevent confusion from other uses of the word paraffin. In Britain, for example, kerosene is referred to as paraffin. Liquid paraffin is commonly used for the fuel used in oil lamps. So “paraffin wax” is the preferred term for the solid hydrocarbon used in candles.

The wick

The wick is generally composed of tightly wound cotton or nylon fibers that make up a sturdy type of twine. All wicks are treated with various flame-retardant solutions in a process known as mordanting. Without mordanting, the wick would be destroyed



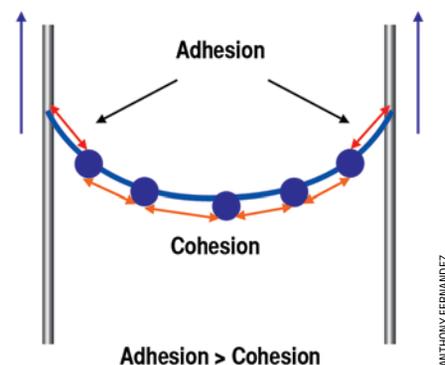
Candle wicks serve as the fuel delivery system for candles.

by the flames. In addition, a variety of substances are employed to make the wick stiff and rigid while supporting a flame. Formerly, candle wicks might contain a lead core to keep them upright. Given concerns about the release of toxic lead vapors, lead cores have been eliminated or substituted with zinc cores if a sturdy wick is required.

The wick is crucial to the proper functioning of the candle, serving as the fuel delivery system. You can think of the wick as the pipeline through which the fuel travels to the surface, making it available for combustion.

Just exactly what happens when a candle is lit? Touched by a flame, the wick quickly conducts heat to the surface of the wax where melting begins. The little pool of molten wax is the key to keeping the candle burning.

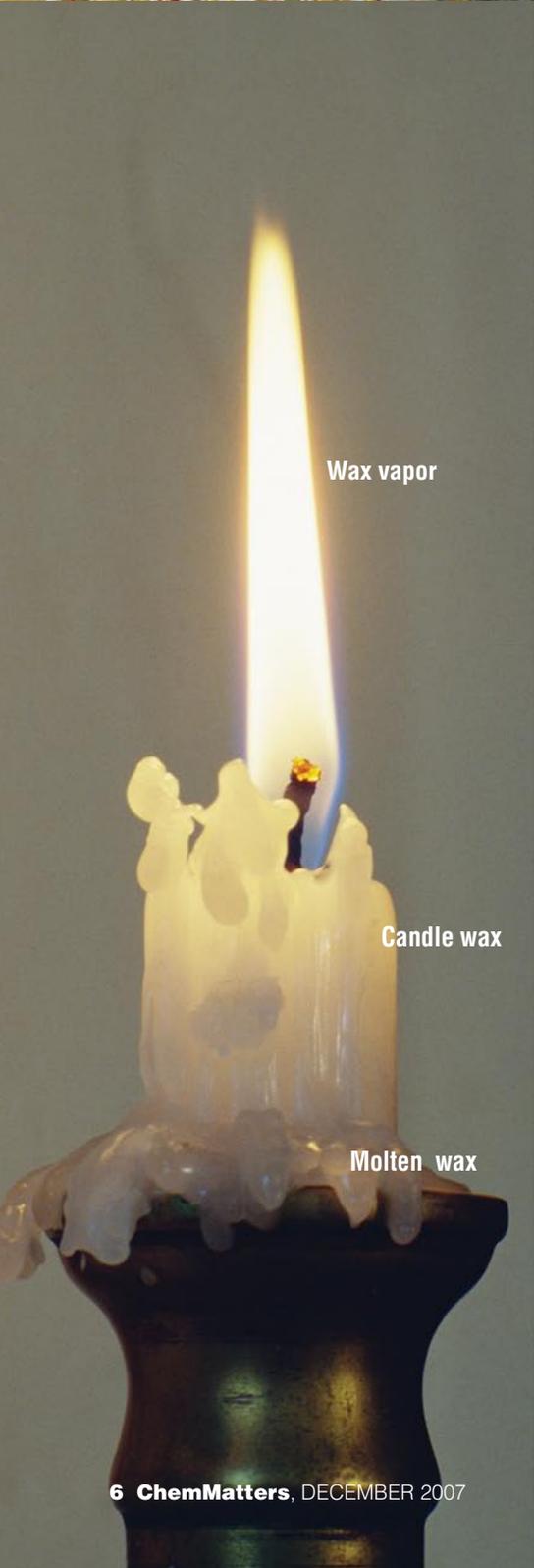
Wax must be in the liquid state to travel upward through the wick and then undergo combustion. Liquid wax travels through the wick by capillary action. Capillary action refers to the ability of a liquid to travel upward through a small tube. This occurs due to the cohesion of the liquid paraffin molecules to



Capillary action occurs due to the cohesion of the wax molecules to each other and their adhesion to the wick fibers.



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Wax vapor

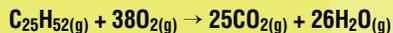
Candle wax

Molten wax

one another and the adhesion of these molecules to the sides of the tube.

Capillary action is the same principle that explains how water travels upward to the tops of trees. In this case water travels through tiny tubes just under the bark called xylem. The absorbency of paper towels is also due to capillary action. Microscopic tubes within the towels facilitate the transport of water through the towel, thereby increasing absorbency.

After the liquid wax travels to the top of the wick through capillary action, it vaporizes upon contact with the burning flame. In fact, wax only burns when it is in the vapor state—never in the solid or liquid phase. Combustion occurs as hot wax vapor combines with oxygen, producing the candle flame. Combustion of hydrocarbons is a rapidly occurring exothermic chemical reaction producing heat and light. The reaction can be summarized by the following equation:



One of the products is easily observed by placing a beaker over a burning candle flame and then quickly removing it. A thin film of water appears on the beaker as water vapor from the combustion reaction condenses onto its cool surface.



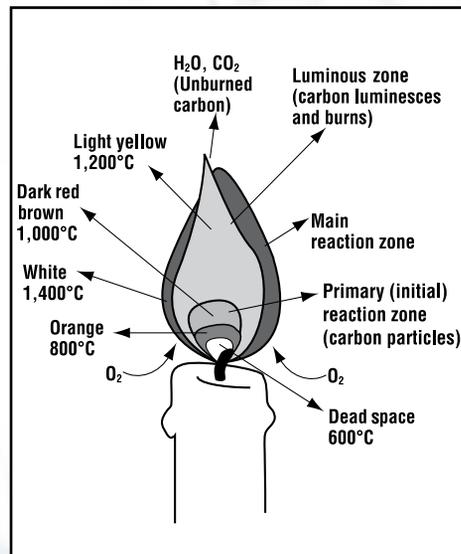
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If you have an oil lamp at home, light it and observe. Liquid oil is carried upward through the wick via capillary action, where it is then burned. A candle works according to the same principle, except the fuel begins as a solid.

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The flame

Look carefully at a burning candle and you'll see three distinct colors within the flame—light yellow, blue, and a darker yellow. Each color represents a distinct zone in which specific chemical reactions are occurring.



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Candle flame reaction zones, emissions, and temperature.

Near the bottom of the flame, you'll see the blue zone in which the combustion of paraffin is nearly complete—yielding only water and carbon dioxide. This region of the flame is termed the main reaction zone. In this cleanest and hottest region of the flame, the wax most efficiently reacts with oxygen—reaching temperatures of around 1400 °C. Gas stoves, propane torches, and Bunsen burners used in chemistry labs always produce blue flames if operated properly.

A blue flame typically exists in the plasma phase. Plasma forms when gas molecules get so hot that they collide with enough violence to break apart individual molecules into ions and charged particles. This assemblage of charged particles is called plasma. Plasma also exists in the sun and in lightning bolts.

Next, notice that the inside of the flame is darker in color than the rest of the flame. This center region—called the dark zone—is the coolest part of the flame. It burns at around 800 °C. With limited oxygen available in this region, unburned wax vapor accumulates. If a glass tube is placed in the center of a candle flame, the end of the tube can be lit. Unburned wax vapors coming from the tube can still

undergo combustion. If a glass tube is placed in any other part of the flame, the vapors exiting the tube will not burn, as unburned wax vapors are not present in sufficient quantity in these other regions.

The largest and most conspicuous part of the flame is the bright yellow luminous zone. Its temperature is intermediate between that of the other two zones, typically around 1200°C. In this region, insufficient heat and oxygen cause incomplete combustion. During incomplete combustion, only a fraction of the paraffin molecules are converted into water and carbon dioxide. As a result, free carbon atoms are released as soot. Hold a watch glass in a candle flame for a few seconds and a layer of black soot will form as these unburned carbon particles collect.

The bright yellow color of the candle flame is due to the incandescence of the unburned carbon particles. Incandescence occurs when a solid substance is heated to the point where it gives off light. It differs from combustion in that incandescence does not involve a chemical change. Incandescence

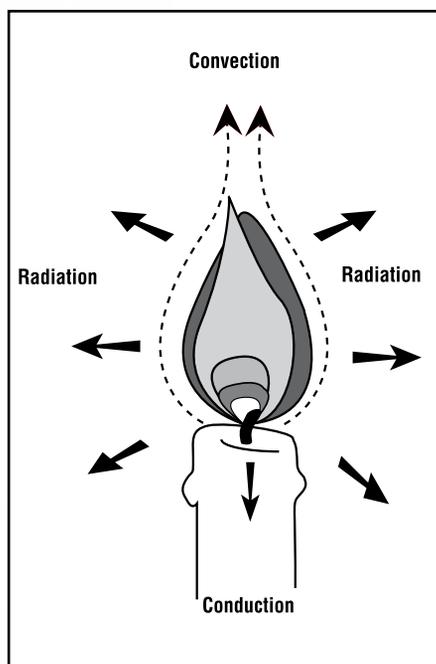


You may be surprised to know that when a candle is blown out, the smoke near the wick can be lit, causing the flame to immediately reignite. This impressive little trick is only possible because the smoke contains unburned wax particles. This invisible wax vapor is what ignites, not the visible smoke particles.

is not burning, but glowing. Similarly, the filament of an incandescent light bulb does not burn, but glows, hence the name.

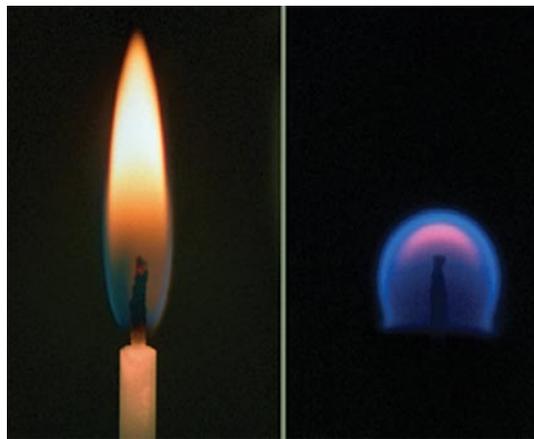
Whenever a breeze causes a candle to flicker, even more smoke is produced. Disrupted by a breeze, the candle burns inefficiently, and more unburned carbon particles—smoke—results. When candles were the primary light sources in homes, the flame was often protected by a glass sleeve, similar to those found on oil lamps today. This glass not only served as a safety measure but it prevented air currents from disrupting the candle flame, producing more soot that discolored walls and ceilings.

The familiar shape of the candle flame, or nearly any flame for that matter, is conical—wider at the bottom and tapering to a



point on top. This characteristic shape is due to convection. Convection occurs as the air around a candle flame is heated. Here, it expands, becoming less dense. Cooler, denser air rushes in from below, pushing up the less dense warmer air to give the flame its shape.

Has this happened to you? You blow out your birthday candles only to have them reignite! These trick birthday candles have some ingenious chemistry behind them. Within the wicks are tiny flecks of magnesium. Magnesium can ignite at temperatures as low as



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Astronauts aboard the space shuttle have conducted experiments with candles in zero gravity. The flames produced were spherical and generally lasted only a minute. Why? There was plenty of oxygen available, but because of a lack of gravity, there was no convection. As a result, CO₂ accumulated around the flame, and, with no convection to carry it away, it quickly smothered the flame. Convection only occurs in the presence of “heavy” air and “lighter” air. At zero gravity, everything weighs the same.

430 °C, so a glowing ember in the wick can ignite this magnesium, which, in turn, reignites the candle.

Today's candles come in a bewildering array of sizes, shapes, colors, and scents. Candle-making can be done easily at home as a rewarding hobby or a money-making venture. As our petroleum reserves become depleted, new fuel sources may become attractive. Already, soy-based candles are becoming increasingly popular.

What will the candles on your cake look like in—say—50 years? With 5,000 years of development behind them, it's still likely that the flame will come with a wick, a fuel, and some fascinating chemistry. ▲

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Brian Rohrig teaches at Jonathan Alder High School in Plain City, OH. His most recent *ChemMatters* article, “Serendipitous Chemistry,” appeared in the October 2007 issue.