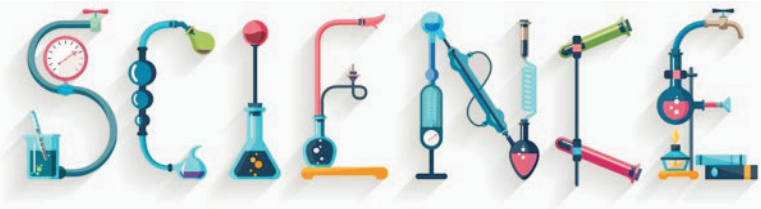
Butter Cakes: Baking Science



BAKING is a science. Many scientific actions occur when making butter cakes. Numerous physical changes and chemical reactions are necessary to prepare the perfect cake. The altitude, humidity level, pan size, and batter depth are all factors associated with baking. Baking a tender, fine-grained butter cake is not accomplished by a trick or by luck—it's science. In this e-unit, you will learn some of the science behind baking, and you'll be one step closer to making the perfect butter cake.

Objective:

Analyze physical changes and chemical reactions that occur in butter cake preparation.

Key Terms:

absorption
caramelization
carbon dioxide (CO_2)
chemical reaction
condensation
conduction
convection
emulsion
endothermic reaction
evaporation
exothermic reaction
gluten
heat transfer
homogeneous mixtures
hydrogenated fats
hydrogenation
hydrolysis
hygroscopic
immiscible
invert sugar
Maillard reaction
osmosis
physical change
radiation
relative humidity (RH)
surface area
trans-fatty acid (trans fat)

The Science Behind Butter Cakes

Baking is a science. Many scientific actions occur when making and baking butter cakes. Numerous physical changes and chemical reactions are necessary to prepare the perfect butter cake. The difference between a chemical reaction and a physical change is compositional.

CHEMICAL REACTIONS AND PHYSICAL CHANGES

This e-unit will discuss the definitions and various situations relating to chemical reactions and physical changes when baking.

Chemical Reactions

A **chemical reaction** is a process that produces a permanent change in the chemical composition and molecular structure of a substance. For example, fresh eggs that are fried cannot become fresh eggs again. The protein in the egg has been permanently changed, and the structural makeup is very different. When batter is heated in an oven, a chemical reaction occurs and new bonds are formed.

Heat creates exothermic and endothermic chemical reactions. For example, baking a cake produces an endothermic reaction that changes sticky batter into a solid cake. An **exothermic reaction** produces heat. An **endothermic reaction** absorbs heat.

- Heat helps leavening agents produce tiny gas bubbles that make the cake light (by rising).
- Heat causes egg proteins to firm, helping to give the cake structure.
- Heat dries cake batter (fats are still able to keep the cake moist).

EXPLORING OUR WORLD...

SCIENCE CONNECTION: The Science of Cake

Ancient Egyptians were the first-known baking scientists. Baking has evolved from a bread-like dough with honey and eggs, to the tender, mouthwatering cakes we have today. Before chemical leavening agents, four eggs might have been beaten for two hours to provide the air to leaven a cake. See the progression of cakes through history, and the science behind cake baking, by reading Andy Connelly's article, "The Science of Cake," on The Guardian (an online news magazine) at https://www.theguardian.com/science/blog/2010/jun/09/science-cake-baking-andy-connelly. Mr. Connelly is a British writer. Notice how cake recipe ingredients and amounts are different from those in the United States.

Basbousa (or namoora) is an Egyptian semolina cake. It is typically served with an almond (or other nut) decoration and, as shown here, a honey syrup. Based on your knowledge of butter cakes, is basbousa a simple cake or a rich, dense cake? Why?

Physical Changes

A **physical change** is the transformation of a substance that does not alter its chemical properties—a phase change. The change can involve a difference in the way the substance displays appearance (color or shape), texture, temperature, or smell, but it usually results in a change of state, such as liquid to solid. Melting, boiling, and freezing are examples how to create a physical phase change. An ice cube that melts is still water, and its chemical properties remain intact. [NOTE: In the physical change described here, the ice cube and warm temperature are the reactants—the ingredients of physical change. The liquid water is the product, or result, of a physical change.]

Absorption

Absorption is the act of one substance (liquid or solid) taking up (soaking up) particles from another substance (gas or liquid) by physical or chemical means.

Hygroscopic

Hygroscopic is a term relating to the ability of a substance to absorb water from its surroundings. Liquid is absorbed into flour. The more water absorbed into flour, the more the batter stretches. This creates more pan flow (ease of the batter filling the pan's shape). Sugars are hygroscopic, including table sugar, honey, brown sugar, and molasses. Sugar attracts water, keeping baked goods moist and soft. [NOTE: The prefix "hygro" relates to humidity. A hygrometer measures humidity, while a hygroscope indicates when humidity is present.]

Gluten

Gluten is an elastic protein found in wheat and cereal flours that gives batter elasticity, strength, and rising ability. Gluten comes from a plant's endosperm (the starchy portion of a grain), and it forms when water is added to the two flour proteins of glutenin and gliadin (found in wheat, barley, or oats). Gluten continues to develop as the butter-cake batter (or other wheat batter) is mixed. Gluten provides chew and density.

Condensation

Condensation is the conversion (a physical change) of a vapor (gas) into a liquid—the reverse of evaporation. When cold batter and dough are placed into a warm oven, moisture (condensation) is produced on the surfaces. This action cools down the crust, and it allows the baked good to rise before the crust hardens. A porous surface on a baked good can be due to over-condensation.

FIGURE 1. The beads of moisture on this soda results from a cold can reacting to a warm environment. This is similar to what happens to butter cake batter when exposed to dry oven heat. If the batter is cold, over-condensation can occur.

Evaporation

Evaporation is the conversion (a physical change) of a liquid into a vapor (gas). The rate of evaporation increases with the rise in temperature. Evaporation is used in many culinary processes to concentrate a solution; such as cooking down pan sauces to thicken and intensify the flavor, simmering tomatoes to release moisture, or thickening a roux.

Emulsions

An **emulsion** is a semi-liquid, stable mixture in which one or more liquids are suspended within another. An emulsion can have two or more **immiscible** (unmixable) ingredients. While emulsions are immiscible, **homogeneous mixtures** are a mix of ingredients that have a uniform composition (the same properties throughout).

Typical emulsions include a liquid suspended in a fat or an oil. (Think of vinegar and oil dressing.) The goal in baking is to form a water-in-fat emulsion. An unstable cake batter emulsion can curdle or weep.

Creaming is a common step in baking and pastry recipes. Typically, room temperature eggs are added one at a time in the creaming method. This slow procedure adds more air to the batter, and the egg yolks act as an emulsifier. They keep the creamed fat and liquids from separating (which makes the batter a homogenous mixture). [NOTE: For more information about emulsions in cake batters, see Sarah Phillips's Craftybaking.com article, "Emulsify," at https://www.craftybaking.com/howto/emulsify.

FIGURE 2. A curdled cake batter is one that coagulates or clots, similar to this cauldron of cottage cheese. Adding a tablespoon or more of flour to a curdled cake batter may reverse the appearance of curdling. This is only necessary when whisking a batter for air leavening. Modern self-rising flours should add enough air bubbles through their leavening process, keeping the cake light. Adding too much flour might make the cake dense and tough.

Heat Transfer

A **heat transfer** is the exchange of thermal energy between two objects, or the physical process of a food absorbing heat from a source. While heating food, molecules absorb energy, vibrate quickly, and bounce off each other. Each collision produces heat, which is transferred to the food. This is the basis of cooking. There are three methods of heat transfer. [NOTE: For more detailed information, read the Biscuit People article, "Heat Transfer for Biscuit Baking," at http://biscuitpeople.com/heat-transfer-for-biscuit-baking/. Their process described for biscuits is the same for butter cakes.]

Radiation

Radiation is the transmission of heat through waves of energy. Microwave and infrared waves are two types of radiation in cooking. Radiant heat is evident when you open a preheated oven, stretch your hand over coals, or get near a boiling pot. Warmed air is transferred to food and cooks it (radiation cooks through indirect contact).

Conduction

Conduction is the passing of heat between solid objects through direct contact. For example, heat is conducted from stovetop burners to pots and pans. Heat is then conducted from the pots and pans to the food. Cake pans transfer heat, by conduction, to batter.

Convection

Convection is the transfer of heat by the circulation of warm air or water. In a convection oven, a fan blows hot air over and around the cake. (In savory cooking, sous-vide is a method of cooking sealed bags of food in a warmed water bath.)

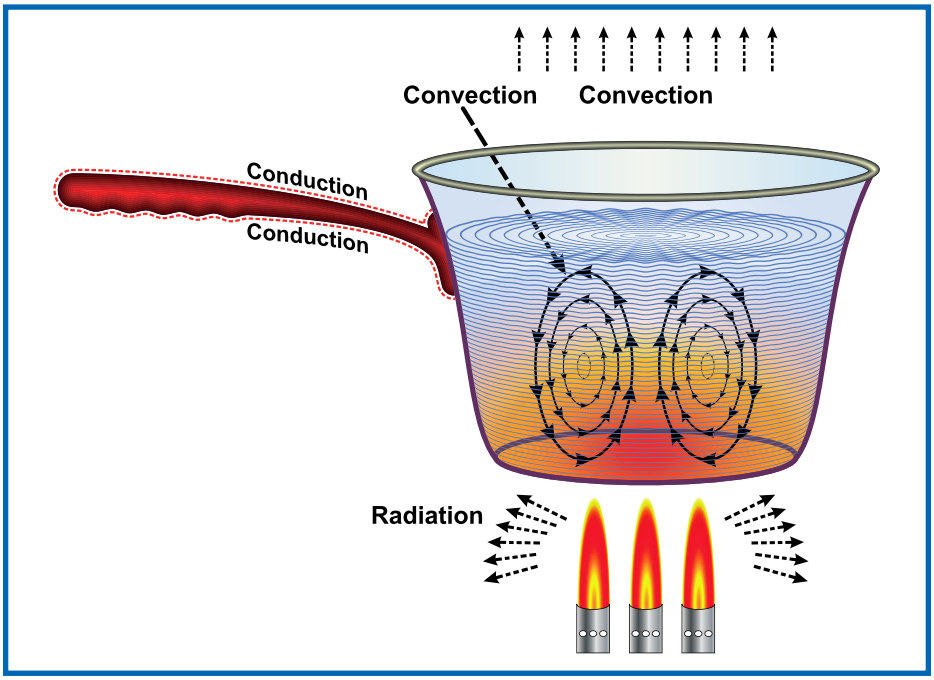


FIGURE 3. A heat transfer is the exchange of thermal energy between two objects, or the physical process of a food absorbing heat from a source. In butter cakes, how does a convection heat transfer happen? How about radiation? What causes conduction? [HINT: Think about what's happening with each specific component during baking: the baking pan, the oven, and the batter.]

Osmosis

Osmosis is the movement of fluid through a semipermeable cell membrane (from a less concentrated substance to a more concentrated one). A solute is the substance that dissolves into a solution (the less concentrated substance). Osmosis occurs in butter cakes, especially

those that contain fruits or vegetables. [NOTE: See simple osmosis and diffusion experiments on the Kitchen Pantry Scientist website at http://kitchenpantryscientist.com/diffusion-and-osmosis-experiments/.]

Fruits and vegetables have semipermeable cell membranes that cause cells to release water when cut. This can cause frozen fruits and cooked fruits to wilt. Fresh fruits are crisper, and release less water.

When sugar is added to freshly cut fruit, the concentration of sucrose is higher around the fruit than inside the fruit cells. Sucrose is too large a molecule to move into the cells of the fruit. Osmosis occurs when the moisture from the fruit moves into the sugar, or when fruit and vegetable slices are mixed with dry ingredients, such as sugar, spices, and flour.

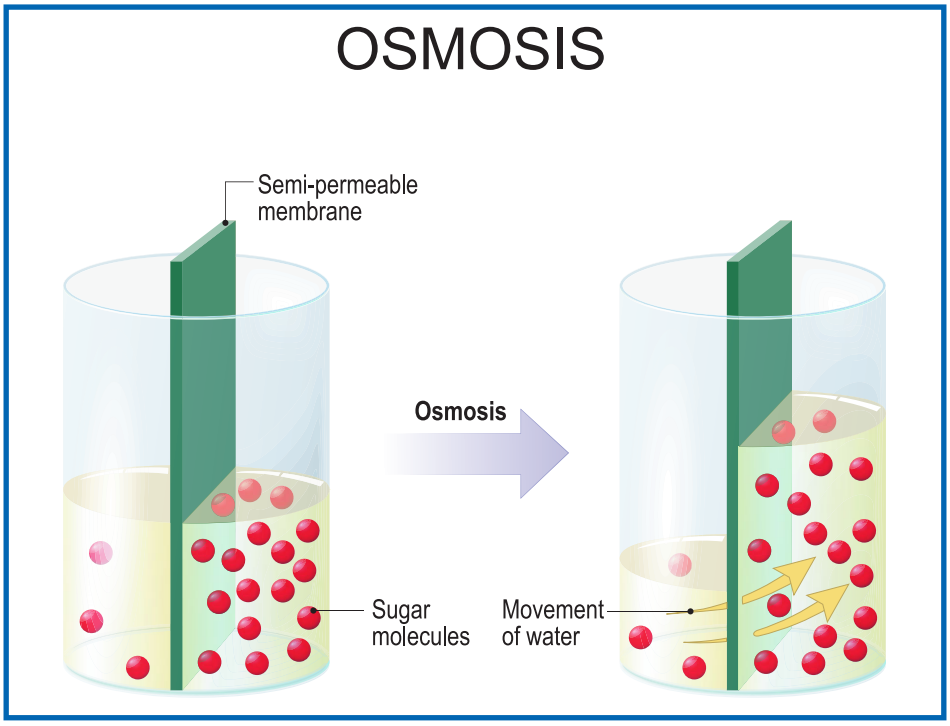


FIGURE 4. When sugar is added to freshly cut fruit, the concentration of sucrose is higher around the fruit than inside the fruit cells. Sucrose is too large a molecule to move into the cells of the fruit. Osmosis occurs when the moisture from the fruit moves into the sugar, or when fruit and vegetable slices are mixed with dry ingredients, such as sugar, spices, and flour.

Caramelization

Caramelization is the oxidization (browning) of sugar, or the natural sugars in fruits and vegetables, in order to get a sweet, nutty, brown sauce or coating. Caramelization is the last chemical reaction to occur during baking. It only occurs when sugars are heated. The flavors of caramelization occur after 356°F is reached. Cakes baked at 350°F have no caramelized flavor, but might have sugars that caramelize. Each sugar type caramelizes at a different temperature.

- Fructose caramelizes at 230°F (110°C).
- Sucrose caramelizes at 320°F (160°C).

FIGURE 5. Caramelization occurs when sugars are heated. These two images show sugar beginning to bubble and then finish the carmelization process. Water has been added to the sugar. As it bubbles, the heat increases and evaporation occurs. The sugar becomes darker and darker (more sugar molecules, fewer water molecules, because of the evaporating water). The longer the caramel liquid cooks, the more concentrated it becomes. The flavors of caramelization occur after 356°F is reached. [TIP: Keep a close eye on sugar while caramelizing. It is a fine line between caramelized sugar or food and a sticky, uneatable goo.]

Baked goods made with honey or fructose develop a darker color, because they begin browning at a lower temperature (honey contains fructose).

Hydrolysis

Hydrolysis is the chemical separation of a compound through the addition of water. For example, adding water to sucrose leaves glucose and fructose. The result of this hydrolysis is an invert sugar. An **invert sugar** is equal parts glucose and fructose (derived from water and sucrose). The creaming method for butter cakes allows time for the hydrolysis of sugar to

FIGURE 6. The creaming method for butter cakes allows time for the hydrolysis of sugar to begin (from being mixed with fat and egg moisture). This is why the dry ingredients are added after the creaming technique is completed. Compare the texture of the individual ingredients in the stand mixer (ready to be creamed) with those that are creamed.

begin (from being mixed with fat and egg moisture). This is why the dry ingredients are added after the creaming technique is completed. Letting sugar-liquid-fat batter set 10 minutes before adding flour ensures the sucrose becomes an invert sugar. [NOTE: Inversion processes can involve the hydrolysis of sucrose with an acid and some heat (used in candy making).]

The Maillard Reaction

The **Maillard reaction** is a chemical effect that occurs when proteins and sugars react and break down under heat. Amino acids and simple sugars rearrange into rings that reflect light and produce a browned appearance (and tantalizing aromas). It is a series of three complex reactions. These reactions occur between amino acids (proteins) and sugars (monosaccharide and some disaccharide sugars that can donate electrons to another chemical) being reduced at higher temperatures. The Maillard reaction (named for the scientist, Louis Camille Maillard) produces different aromas in bread than in standing rib roast or baked fish, because the amino acids and simple sugars differ in those foods. This process is responsible for the browning of a butter cake, as well as its toasted flavor. As the oven, grill, or pan temperatures increase, so does the Maillard reaction. [NOTE: The Food-Info.net website has for more information on complex reactions and Louis Maillard at http://www.food-info.net/uk/colour/maillard.htm.]

FIGURE 7. The Maillard reaction is a chemical effect that occurs when proteins and sugars react and break down under heat. Amino acids and simple sugars rearrange into rings that reflect light and produce a browned appearance (and tantalizing aromas). Notice the color of the cupcakes being piped into their papers and the color after being in the oven.

Carbon Dioxide

Carbon dioxide (CO_2) is a colorless, odorless gas (except in high concentrations), and it is a natural by-product of cellular respiration. Baking soda, baking powder, and yeast are all leavening agents that produce CO_2. (Baking soda and baking powder are two common chemical

leavening agents, while yeast is a living organism.) CO_2 is evident in the leavening of butter cakes and other baked goods.

Baking soda ($NaHCO_3$), or sodium bicarbonate, is a chemical leavening agent that, when heated, produces and releases carbon dioxide using the formula $2NaHCO_3 \rightarrow CO_2 + Na_2CO_3 + H_2O$. (Sodium bicarbonate releases carbon dioxide, sodium carbonate, and water vapor.)

- In a recipe, Sodium bicarbonate needs paired with an acid. If baking soda is used in a recipe without an acid, it will produce a bitter taste and a yellowish color.
- Baking soda is a single-action (reacts only once) chemical leavening agent that reacts when mixed with an acid, such as cream of tartar, buttermilk, molasses, sour cream, yogurt, lemon juice, vinegar, brown sugar, or cocoa. [TIP: When baking a butter cake that uses baking soda, everything must be ready before the liquid is added to the leavening agent (refer back to the section on leavening components).]

Baking powder is a chemical leavening agent that contains baking soda, dry acids, and starch (as filler). It produces more carbon dioxide gas than baking soda. When heated, it produces carbon dioxide using the formula $NaHCO_3 + H^+$(from the acid) $\rightarrow Na^+ + H_2O + CO_2$. (Sodium, water, and CO_2 are all released.) Some butter cake recipes and formulas use both baking soda and baking powder.

FIGURE 8. Carbon dioxide (CO_2) is produced during the chemical leavening of butter cakes. Notice this illustration of one carbon molecule—a carbon atom covalently double bonded to two oxygen atoms. CO_2 is also produced during fermentation (for things like bread, wine, and beer), by fossil fuels (coal, petroleum, or natural gas), and naturally, through breathing in and out.

Hydrogenation

Hydrogenation is the charging or combining of a molecule with hydrogen (H) (a chemical reaction). In baking, hydrogenation helps solidify oils and fats. The benefits include the solidifying of liquid vegetable oils, the absorption of the oxygen in the oil's free fatty acids (converting them to fats that are solid at room temperature), the improvement of the keeping quality of the fats, the ability of oils to stay solid room temperature, and the resistance of fats to break down when exposed to air. Some shortening may have added animal fats, emulsifiers, colorings, and flavorings (butter).

Hydrogenated Fats

Hydrogenated fats are vegetable fats (or oils) that are hardened, or turned into solids, through the hydrogenation process. They provide more volume for baked goods than butter.

- Solid shortenings (like Crisco®) and margarines are hydrogenated.

- Peanut butter can be hydrogenated, or partially hydrogenated. Natural peanut butter is usually partially hydrogenated (oil separates and comes to the top of the jar).

Trans Fat

During hydrogenation, hydrogen is injected into the oil under pressure, turning the liquid oil into a solid fat. In almost all cases of turning oil into a solid fat, some of the oil remains in a state of limbo—neither liquid nor solid—called a **trans-fatty acid (trans fat)**. This type of fat is known to have a particularly unhealthy effect on arterial and heart health. It provides no flavor, cooking, or nutritional benefits.

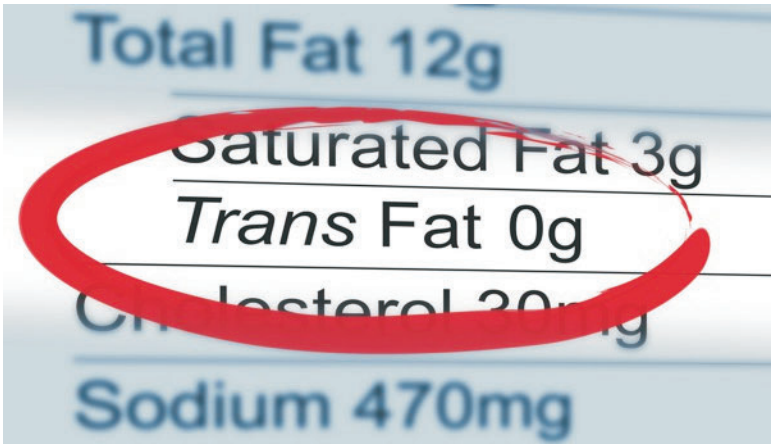


FIGURE 9. Look for zero trans fat on food labels. In baking, a lot of butter and other fats go into delicious creations, but you can still bake responsibly by keeping away from trans fat.

Surface Area

In baking, the **surface area** is the part of a baked product that is directly exposed to the heat—the total uncovered exterior. The surface area of a butter cake determines its baking time. A larger pan has more surface area and, as a result, the cake will bake quicker. On the other hand, if a you fill a smaller, deeper cake pan with the same volume of mix meant for the large pan, the batter will have a smaller surface area, take longer to bake, and, if left at same temperature, would have an undercooked center. As a general rule:

- Two 8 × 2 round pans bake for 30 to 40 minutes.
- One 8 × 8 × 2 square pan bakes for 25 to 30 minutes.
- Cupcakes, with a high ratio of surface area to volume, tend to dry out quickly in the oven. They bake for 14 to 19 minutes.

Batter Depth

Batter depth affects the baking time of all baked goods. As a general rule, Bundt® cakes have more depth than most cakes, and they bake for 40 to 45 minutes.

Oven Temperature

Butter cake oven settings vary by pan type, humidity, and altitude.

- Shiny metal pans bake at 375°F. Shiny metal reflects the heat.
- Dark or nonstick pans bake at 350°F. Dark pans absorb the heat.

- Glass pans traditionally bake at 25°F lower temperatures than shiny or dark pans to prevent over-baking and overbrowning. Glass pans transfer heat more quickly than metal pans.
- Mini cupcakes are baked at a 20°F lower temperature than regular cupcakes to produce a better texture. [NOTE: More information is available in the Lane Cummings article, "How to Adjust the Oven Temperature for Mini Cupcakes," on the Our Everyday Life website at https://oureverydaylife.com/how-to-adjust-the-oven-temperature-for-mini-cupcakes-12368386.html.]

High Altitudes and Humidity

Baking in high altitudes (3,500 to 6,500 feet above sea level) requires an increase in oven temperature by 10°F to 20°F. Baking cakes on a rainy day may have the same effect as a high altitude. **Relative humidity (RH)** is a measure of the moisture in the air. It is the percentage of actual saturation compared to the density of vapor saturation. In other words, the higher the RH percent, the more moisture is available in the surrounding air. Both a high altitude and a high RH result in a lower barometric pressure. Rainy weather is caused by a low-pressure storm system. High elevations have dry, low-pressure air. This lower barometric pressure (thin air) tends to cause cakes to over rise, and then, to deflate. Recipes can be adjusted by decreasing the amount of leavening agent and sugar. Then, liquid and protein (milk, eggs, flour) are increased to strengthen the batter. To experiment with altitude and RH issues, you should follow the directions below.

- Depending on elevation, decrease baking soda and baking powder by ⅛ to ¼ teaspoon. (At 3,000 to 5,000 feet, decrease one teaspoon of soda to ⅞ of a teaspoon. Above 5,000 feet, it would be ¾ of a teaspoon.)
- Increased evaporation also increases the concentration of sugar, which can weaken the structure, so decrease sugar by one to three tablespoons per cup.
- Increase oven temperature by 15°F to 25°F. Use the lower increase when baking delicate or chocolate cakes. Leavening and evaporation move more quickly at higher altitudes, so use a higher temperature. This will set the cake structure before it dries out.
- Decrease baking time by five to eight minutes per every 30 minutes (due to increase in oven temperature).
- Increase liquids by one to two tablespoons at 3,000 feet, and then increase by 1½ teaspoons for each additional 1,000 feet (keeps products from drying out).
- Increase protein in the batter (to trap gas) by adding one to three tablespoons of flour or by adding one egg white. [NOTE: Betty Crocker recommends adding a ¼ cup of all-purpose flour and increasing the water to 1½ cups (from 1¼ cups) in high altitudes. For more information about the affect of rain on baking, read Fred Decker's article, "Does Rain Affect Baking Cakes?," on eHow at http://www.ehow.com/info_12318209_rain-affect-baking-cakes.html.]
- RH should be monitored throughout the baking process: storage, proofing (breads), baking, and cooling.

The Blending Method

The blending method is not only quick, it also has a scientific reasoning behind it. In the blending technique, the dry ingredients are added to the mixer bowl first. Next, the fat is added and mixed. This allows the fat to coat the dry ingredients (including flour) and be absorbed. Wheat flour contains gluten, and gluten stretches and expands when moistened. This can hold the gas produced by the leavening agent. The fat coats the gluten molecules and prevents them from developing this stretchy quality. In the blended method, a baker can beat the mixture as long as necessary and still have a tender, delicate cake.

Cornstarch

Cornstarch can be combined with flour to soften the gluten and create a less chewy, more tender cake. Typically, a ¼ cup of cornstarch would be added for an 8 × 8 pan recipe.

Summary:

Baking is a science. Many scientific actions occur when making butter cakes. Numerous physical changes and chemical reactions are necessary to prepare the perfect butter cake. Understanding concepts, such as convection, radiant heat, and condensation, can aid in your development as a master baker. Finding solutions when baking in humid or high-altitude environments will increase your capabilities in the kitchen. When you know why and how a leavening agent works, you will be able to play with recipes—finding the exact texture and density you were looking for. Now, when recipes fail, you might be able to see where, scientifically, it went wrong. Experiment until you get the right balance of artistic and scientific skills to create the perfect butter cake.

Checking Your Knowledge:

1. Differentiate between a physical change and a chemical reaction.
2. Describe what has happened to the emulsion when a cake batter curdles.
3. Describe the Maillard reaction in butter cakes.
4. How does the surface area of batter in a pan affect baking time?
5. Describe the process of sugar caramelization.

Expanding Your Knowledge:

Processed cakes are often made with trans fats. In a hydrogenated vegetable oil, hydrogen atoms are added to the oil. Hydrogenation makes the oil (originally an unsaturated fat) into a saturated fat. Recent research has found that trans fat raises

bad cholesterol, lowers good cholesterol, and causes hardening of the arteries. Baking your own cakes allows you to know the ingredients used when baking. Most bakers enjoy the original recipes for their favorite butter cake. Others want to find healthier low-fat versions.

Think about cutting smaller serving sizes. This simple action keeps the flavor you like, but it also lowers your calorie and fat intake. Many fat substitutes are also used when you bake. For maximum texture and flavor in a low-fat version, replace half of the fat with applesauce or yogurt. For example, if the recipe calls for a cup of butter, use a ½ cup of applesauce or yogurt and a ½ cup of butter. Mashed bananas are a good replacement for some of the fat in banana-flavored cakes. Fruit purées (especially prune purée) can be substituted for fat in chocolate or spice cakes. Substitute cholesterol-free egg products or egg whites (two per each egg in a recipe) for whole eggs. Whole egg substitutes can save you about 100 calories and 10 grams of fat.

Try the Genius Kitchen website recipe, "Extreme Low-Fat Chocolate Cake," that uses yogurt, applesauce, and egg whites at http://www.geniuskitchen.com/recipe/extreme-low-fat-chocolate-cake-209214. Go to the online magazine, Dessert Professional, and find amazing four-star desserts at https://www.dessertprofessional.com/. Search for heavy fat substitutions. Remember the science you have learned. What if your replacement doesn't aid in leavening, creates too much condensation, or thins your batter? Would cornstarch help? For more information on trans fat, low-fat baking, and more in the world of cakes, see the Web Links below.

Web Links:

Baking Ingredient Science
https://www.thespruce.com/baking-ingredient-science-481226

Healthy Baking Tips and Low-Fat Substitutions
http://www.bettycrocker.com/how-to/tipslibrary/baking-tips/healthy-baking-tips-low-fat-substitutions

Low Fat/Low Cholesterol Guidelines
http://www.medfusion.net/templates/groups/4655/7638/Low%20fat%20Low%20Cholesterol%20Guidelines%2019Dec2011.pdf

Trans Fat
https://www.heart.org/HEARTORG/HealthyLiving/HealthyEating/Nutrition/Trans-Fats_UCM_301120_Article.jsp

Trans Fats: The Facts
https://www.cdc.gov/nutrition/downloads/trans_fat_final.pdf