FOOD PROCESSING

1. Introduction

Food processing operations can be grouped into three categories: preparation, assembly, and preservation of foods. Preparation processes are used to convert raw plant or animal tissue into edible ingredients. This may include separation of inedible and hazardous components, extraction or concentration of nutrients, flavors, colors, and other useful components, and removal of water. Assembly processes are used to combine and form ingredients into consumer products. Preservation processes are used to prevent the spoilage of foods. Five sources of food spoilage must be addressed in order to deliver fresh, safe foods and ingredients: microbial contamination, including viruses; enzyme activity from enzymes in the food itself and from external enzymes such as from microbial activity; chemical deterioration such as oxidation and nonenzymatic browning; contamination from animals, insects, and parasites; and losses owing to mechanical damage such as bruising. Preservation processes can be used to extend the shelf life of fresh foods, such as produce, or to manufacture products for long-term storage where shelf lives are measured in years. The processing of foods is regulated by federal food laws that cover good manufacturing practices, nutritional content of foods, and food and ingredient standards.

Plants and animals are the primary sources of food. The food processing industry devotes considerable research to the selection and improvement of plants and animals for raw materials. Genetic engineering (qv), as well as conventional breeding methods, are being used to improve the yield, color, flavor, texture, nutrient content, and resistance to diseases, insect loss, and climatic stress. However, product quality can vary owing to weather, soil, growing practices, harvest methods, and postharvest handling. Thus food processing unit operations must be designed to accept raw materials having a wide range of qualities. In addition, provision often must be made for profitable use of by-products and waste streams.

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2. Regulations

Food processing operations are usually regulate'd and mandated by national and international laws, regulations, and standards that define nutritional requirements and the use of certain ingredients, process conditions, and even the composition of some products. Food safety and toxicology regulations include standards for toxic and carcinogenic substances in foods, pathogenic microbes, and physical hazards. Chemical hazards include heavy metals, carcinogens such as aflatoxins and nitrosamines, pesticides and herbicides (qv), and other natural toxicants such as solanin and gossypol. Microbial hazards include *Clostridium botulinum Listeria monocytogenes*, and *Salmonella* sp. Physical hazards include extraneous material such as metal, wood, pits, glass, insect fragments, and rodent hair. Food regulations are covered in the Federal Code of Regulations (1).

3. Process Optimization

A number of food processing unit operations, such as distillation (qv), filtration (qv), and crystallization (qv), are common to the chemical process industry. Mechanical operations such as size reduction (qv), materials handling, and mixing are also similar to those used in chemical processing. Food processing operations can be optimized according to the principles used for other chemical processes if the composition, thermophysical properties, and structure of the food is known. However, the complex chemical composition and physical structures of most foods can make process optimization difficult. Moreover, the quality of a processed product may depend more on consumer sensory responses than on measurable chemical or physical attributes.

Food process optimization measurements may link a single chemical compound such as a vitamin, or a physical change such as viscosity, to process conditions and to consumer acceptance. Retention levels of ascorbic acid [50-81-7], $C_6H_8O_6$, or thiamine can often be used as an indicator of process conditions.

Particular food products have well-developed technologies associated with their preparation, processing, and packaging. Detailed discussions of processing technologies can be found in the general references.

3.1. Theoretical Basis. Food preservation theory has yielded mathematical models for predicting the heating times and temperatures needed to produce foods free of pathogenic or spoilage microbes (2). Mild heat treatments used to inactivate viruses, vegetative pathogenic bacteria such as *Salmonella* sp., and certain yeasts (qv) and molds, are referred to as pasteurization operations. Milk pasteurization treatments at 61.67°C for 30 min or 71.67°C for 15 s are examples.

Spore-forming bacteria are among the most heat-resistant organisms known. For example, a population of 10,000 spores of *Bacillus stearothermophilus* must be held at 121°C for $\sim$16 min to ensure complete inactivation. These spores are found as contaminants in many raw plant and animal ingredients and must be inactivated or prevented from germinating to prevent the spoilage of heat preserved foods. The spore-forming bacteria of greatest public health concern are the several types of *C. botulinum*. Upon germination, *C. botulinum* releases a highly toxic, cyclic, polypeptide, which is among the most potent human toxins known, based on molecular weight. Research since the early 1920s has been directed toward the development of mathematical models to predict the rate of heat inactivation of *C. botulinum* spores as a function of heating time and temperature, and the composition of the suspending media (2). Heat inactivation rates can be influenced by pH, water activity, salts such as nitrates, nitrites, and sodium chloride, and other chemicals. The polypeptide toxin itself can be inactivated by heating at 100°C for 10 min.

Spore germination can be inhibited by antibiotic substances produced by several types of lactic acid-producing bacteria (3). These substances, called bacteriosins, are finding increased use in preventing the growth of gram-positive bacteria. Nisin [1414-45-5], $C_{143}H_{230}N_{42}O_{37}S_7$, a particularly effective bacteriosin against *C. botulinum*, is allowed in processed cheese food. Wider use is expected in the United States (because) as nisin has already been approved for use in many foods in other countries.

Two other broad areas of food preservation have been studied with the objective of developing predictive models. Enzyme inactivation by heat has been subjected to mathematical modeling in a manner similar to microbial inactivation. Chemical deterioration mechanisms have been studied to allow the prediction of shelf life, particularly the shelf life of foods susceptible to nonenzymatic browning and lipid oxidation.

3.2. Water Activity. The rates of chemical reactions as well as microbial and enzyme activities related to food deterioration have been linked to the activity of water (qv) in food. Water activity, at any selected temperature and moisture content can be measured by determining the equilibrium relative humidity surrounding the food. Thus water activity is different from, but related to the moisture content of the food as measured by standard moisture tests (4). A plot of the relation of moisture content and water activity at any temperature is called a moisture-sorption isotherm.

At very low concentrations of water, or in foods held below the freezing point of water, physical conditions may be such that the available water may not be free to react. Under these conditions, the water may be physically immobilized as a glassy or plastic material or it may be bound to proteins (qv) and carbohydrates (qv). The water may diffuse with difficulty and thus may inhibit the diffusion of solutes. Changes in the structure of carbohydrates and proteins from amorphous to crystalline forms, or the reverse, that result from water migration or diffusion, may take place only very slowly.

When water activity is low, foods behave more like rubbery polymers than crystalline structures having defined domains of carbohydrates, lipids, or proteins. Water may be trapped in these rubbery structures and be more or less active than predicted from equilibrium measurements. As foods change temperature the mobility of the water may change. A plot of chemical activity vs temperature yields a curve having distinct discontinuities indicating phase changes in the structure of the food system and possible release or immobilization of water. An important phase change is that from a rubbery or glassy structure to a more crystalline one defined by the glassy point transition temperature. The glassy point transition temperature of a frozen food may be important for long-term storage stability. Similarly, for baked or dried foods stored at room temperature, the glassy point transition temperature may indicate a temperature at which staling, loss of softness, or the development of an undesirable texture may take place. Glassy point transition temperatures and the non-equilibrium analysis of food structures have been studied (5).

4. Preservation of Foods

Preservation operations to reduce or eliminate food spoilage can be grouped into five categories: heat treatments; storage near or below the freezing point of water; dehydration and control of water activity; chemical preservation; and use of mechanical operations such as washing, peeling, filtration, centrifugation, grinding, ultrahigh hydrostatic pressure, and most importantly, (the) packaging. Most food preservation technologies use two or more preservation operations because virtually all processed foods are packaged.

The extension of the useful storage life of plant and animal products beyond a few days at room temperature presents a series of complex biochemical, physical, microbial, and economic challenges. Respiratory enzyme systems and other enzymes in these foods continue to function. Their reaction products can cause off-flavors, darkening, and softening. Microbes contaminating the surface of plants or animals can grow in cell exudates produced by bruises, peeling, or size reduction. Fresh plant and animal tissue can be contaminated by odors, dust, insects, rodents, and microbes. Packaging must be used to protect the food from these contaminants.

4.1. Short-Term Storage. *Controlled Atmosphere.* The composition of the gas atmosphere surrounding certain respiring fruits and vegetables and meat products can influence their rate of quality loss. For example, an atmosphere having only a few percent of oxygen, 12% carbon dioxide, and the remainder nitrogen, can prolong the useful storage life of selected varieties of apples in refrigerated storage. Using this atmosphere, a shelf-life extension from 3–9 or 10 months is possible (6). Studies using refrigerated meat and poultry products have shown that gas mixtures containing 50% oxygen, several percent carbon dioxide, and the remainder nitrogen can extend the useful shelf-life of these products from days to weeks. In this case, the oxygen inhibits the growth of anaerobic spoilage bacteria under refrigerated conditions.

Controlled atmosphere storage, when used for blemish-free products, is an effective preservation method for clean, intact foods, such as fresh apples and pears. Packaging has been developed to take advantage of the respiration processes taking place in fresh foods. Packaged produce can metabolize oxygen and release carbon dioxide. Packaging materials can be designed to allow diffusion of oxygen from the atmosphere into the package and carbon dioxide to the atmosphere to maintain a desirable ratio of these gases in the package. A ratio can be obtained that is sufficient to reduce the respiration rate of the food and inhibit the growth of aerobic microbes. Chemical GAS scavengers can be included in the package to remove undesirable metabolic gases such as ethylene which can influence the rate and course of respiration.

Refrigeration. Foods contaminated with microbes from various unit operations may require additional preservation to ensure a useful shelf life. Refrigeration slows the growth of spoilage microbes. The effectiveness of refrigeration can be improved by combining storage just above freezing with ionizing radiation or chemical preservatives, eg, food acids, sodium benzoate, and nisin; treatment with ultrahigh [$\sim$300–700 MPa (44,000–103,000 psi)] pressure (7); and for liquid foods, filtration or centrifugation to remove microbes. Holding pork at -15°C for up to 30 days can be used to inactivate *Trichina spirales*, the cause of trichinosis. Raw seafood can be frozen to inactivate parasites.

Vacuum packaging has been effective in extending the shelf-life of refrigerated processed meats. The use of a combination of several preservation steps to inhibit spoilage and induce minimal changes in the quality of the fresh food has been likened to establishing a series of hurdles (8). In some cases a very mild heat treatment, such as holding at 60°C for several minutes, helps reduce microbial and possibly insect contamination without extensive damage to the quality of fresh plant or animal tissue.

Heat Treatment. Shellfish taken from sewage-contaminated waters and containing pathogenic virus can be made safe by thorough cooking. Foods contaminated with large numbers of pathogenic microbes, or containing heat-labile toxins, however, are generally unsuitable for human consumption even if heat could be used to render these foods safe. Foods containing heat-stable microbial toxins, but otherwise free of microbes, are particularly hazardous because these may have no detectable signs of spoilage. Canned mushrooms have been implicated in staphylococcal food poisoning (9). Staphylococcal enterotoxin may lose only 90% of its toxicity by heating 19 min at 121°C.

Preservatives. Bakery products represent an important category of minimally processed foods. Bread and other yeast and chemically leavened baked products can lose their fresh quality characteristics within 24 h at room temperature owing to chemical changes brought about by water migration and starch crystallization. This quality loss, evidenced by staling, represents a complex set of changes among the starch, protein, water, and lipid components of the product. Additives such as sodium stearoyl lactylate can inhibit staling in bread for up to several weeks. The potential for the growth of microbes, such as molds, which can tolerate low water activity conditions, can create the need for a hurdle preservation strategy for extending the shelf-life of fresh bread. Propionates as mold inhibitors or packaging in an oxygen-free modified atmosphere can prevent mold growth.

4.2. Long-Term Storage. Inactivation of microbes and enzymes in foods and food ingredients is necessary to ensure a long useful packaged shelf-life. This can be achieved by using one or more preservation operations such as applying heat; using storage temperatures below -18°C; drying to water activities <0.65, ie, an equilibrium relative humidity surrounding the product $<65\%$; and by adding chemical preservatives such as organic acids (acetic or lactic) or table salt. Generally, heat is used to inactivate enzyme activity prior to other preservation treatments. A mild heat treatment to inactivate enzymes in foods prior to freezing, drying, or chemical preservation is known as blanching. A discussion of the methods and equipment for blanching is available (10).

Food processing firms producing heat-preserved, frozen, dehydrated, or chemically preserved foods may be classified by their finished products. Companies may be further grouped based on whether they process raw materials into ingredients, such as in poultry and meat processing plants, or whether they take these ingredients and convert them to ready-to-eat, convenience consumer products.

4.3. Thermal Preservation Technology. The heat preservation of foods can be accomplished by various combinations of heating times and temperatures depending on the number and type of heat-resistant spores present, the composition of the food, and the physical characteristics of the food and package. Physical characteristics of the food such as viscosity, size of particles, size of the package, and starting temperature influence the rate of heat penetration into the slowest heating point in the package.

The inactivation of heat-resistant spores appears to follow first-order kinetics. Thus if the rate of inactivation of a spore population is known at several temperatures, and the rate of heating of the slowest point in a package can be determined or calculated from heat-transfer principles, then the time needed to sterilize the package can be calculated for any external heating condition. Mathematical formulas for calculating times and temperatures needed to heat foods in cylindrical containers to achieve any desired level of microbial inactivation are discussed in Ref. (2). Computer programs are available that can be used in an interactive mode to monitor steam retort operations in real time to adjust for process deviations. Process deviations are changes in the operating conditions of the retort, such as retort steam pressure, or initial conditions of the product to be heat sterilized, such as product temperature. These are changes from values established with the Food and Drug Administration (FDA) as necessary to produce thermally processed foods free of *C. botulinum*.

The establishment of safe thermal processes for preserving food in hermetically sealed containers depends on the slowest heating volume of the container. Heat-treated foods are called commercially sterile. Small numbers of viable, very heat-resistant thermophylic, spoilage causing, spores may be present even after heat treatment. Thermophylic spores do not germinate at normal storage temperatures.

Chemical changes in foods resulting from heating, such as the loss of pigments, flavors, and vitamins, can also be approximated by first-order kinetics. These reaction rates, however, are much less sensitive to temperature change than are the rates of microbial inactivation. The activation energies for chemical changes in foods are often lower by a factor of 5 than the activation energies for the inactivation of spores (11).

If food can be heated quickly to a temperature of 131°C a lethality equivalent to 6 min at 121°C can be accumulated in 36 s. Rapid heating and cooling of liquid foods, such as milk, can be performed in a heat exchanger and is known as high temperature short time processing. HTST processing can yield heat-preserved foods of superior quality because heat induced flavor, color, and nutrient losses are minimized.

Equipment. Equipment and processes for thermal preservation depend on the physical form of the food and its pH. Foods at pH 4.5 or lower can often be sterilized, for commercial purposes, at or near a temperature of 100°C. Commercial sterility for these products means that the product will not spoil owing to microbial growth as long as the pH remains at or <4.5. Hydrogen ion activity (qv) inhibits the germination of *C. botulinum* spores as well as the spores of most other heat-resistant microbes. The spores of *Bacillus coagulans* are an important exception. This microbe is found in tomato products, and these products are often adjusted to a pH 4.0 or lower, or given an additional heat treatment to insure sterility.

Acid foods generally require the simplest equipment for heat preservation. The food can be heated in the range of 100°C and filled hot into suitable containers. The containers are sealed, inverted to sterilize the closure, held at the filling temperature for a short time to ensure that the package is thoroughly heated, and then cooled. Tomato sauces, jellies, fruits, fruit juices (qv), and pickles are routinely preserved in this fashion.

Low acid foods, those having a pH >4.5, require sterilization at temperatures $>100°C$, and thus require treatment in pressure vessels. Heat preservation processes $>100°C$ can be carried out in batch or continuous heat-exchange equipment. Batch retorts are simple pressure vessels in which the packaged food can be exposed to saturated steam (qv), water and air over pressure, water sprays and air over pressure, or mixtures of air and steam. Microwave energy can be used to heat suitable plastic or glass packages. Small cans serve as their own individual pressure vessels and thus can be heated by direct flames, fluidized beds, or electrical resistance heating. Packages containing fluid foods or slurries with particles can be agitated to increase internal heat transfer. Rigid cans may be filled with particulate foods under very high vacuum with very little liquid to promote the formation of a steam atmosphere inside the package during heat treatment. This atmosphere greatly increases internal heat transfer. Low acid foods can be packaged in chambers pressurized above on atmosphere so that water boils at $>121°C$. Under these conditions the heated food can be filled directly in an appropriate package, held for a short time to sterilize the package, and then cooled. Workers and all materials must pass through air locks on entering and leaving. This process has been designed as flash 18 by its developers.

An interesting application of high pressure to heat sterilization used the phenomenon of compressing heating and expansion cooling of water to achieve almost instantaneous heating and cooling of foods packed in plastic packages. Water shows a 3°C increase in temperature for each 100 MPa of compression. Thus compression of moist food with an initial temperature of 98°C to 600 MPa can increase the temperature of the food to 116°C. Decompression reduces the food temperature back to 98°C. An appropriately sized water compression system can achieve the pressure of 600 MPa in a process pressure vessel in 1–2 min. Decompression requires seconds.

Research has shown that combinations of temperatures $>100°C$ with pressure above 600 MPa can sterilize foods, with holding times at pressure of several minutes. This translates to complete sterilization process times of <5 min for any type of low acid packaged food, regardless of piece or packages size. The concept is under development as a practical food sterilization technology.

Batch process equipment has the advantages of low capital investment and flexibility. There is little restriction on the form or size of the package and length of heat treatment. Systems are available having fully automated process cycle controls and materials handling for ease of loading and unloading. Disadvantages of batch equipment are slow cycle times, because the system must be heated and cooled for each process cycle, and higher energy and labor costs. Materials handling costs are also higher. In general, batch heat process systems are useful in food processing operations that produce a mix of products, in a number of package sizes, with a limited numbers of cases required for any product style.

Continuous heat processing equipment can take the form of heat exchangers for pumped foods, or a materials handling system that automatically introduces individual packages into a sealed steam pressure chamber. Equipment for handling individual packages can use either a mechanical valve system, such as rotating pockets, or hydrostatic legs of sufficient height to balance the internal steam pressure of the system. A hydrostatic cooker operating at 121°C with a gauge pressure of 0.1 MPa (14.5 psi) typically uses 20 m tall hydrostatic inlet and outlet legs. This height is needed to provide a safety factor for possible changes in water level during operation.

Packages are placed on carriers affixed to an endless chain, which travels through the system. Package cooling takes place in the decompression leg. Package treatment rates of 1000 containers per minute are possible. Treatment rates of several hundred packages per min are possible using mechanical valve systems.

Foods continuously heat sterilized and cooled in heat exchangers must be filled under aseptic conditions (and filled aseptically) in presterilized packages. Ohmic, microwave, and induction heating allow particulate foods to be heated more rapidly and uniformly than conduction heating by conventional or wiped-surface heat-exchanger technology. The filling of sterilized and cooled product into presterilized packages, under sterile conditions, is referred to as aseptic processing and has several advantages over inpackage sterilization. One advantage is that heating and cooling for sterilization is independent of package size and package composition. Packages ranging from a few cubic centimeters to the size of bulk tank cars can be prepared with equal quality. Products are filled at room temperature. Thus packages can be constructed from plastics having a relatively low softening temperature. These packages can have lower costs and greatly reduced permeability because heat-resistant polymers are not needed. Additionally, a wider range of structures is possible.

Aseptic filling systems can accept a wide range of packages including metal cans and covers sterilized by superheated steam; paper, foil, and plastic laminates sterilized by hot hydrogen peroxide; ionizing radiation sterilized bags; and a variety of plastic and metal containers capable of being sterilized by high pressure steam. A novel aseptic filling system designed for acid foods, such as applesauce and fruit juices, uses hot, food-grade, organic or inorganic acid to produce commercially sterile packages as they enter the sterile filling area. Aseptic filling machines can use filtered air or nitrogen under a slight positive pressure to prevent the entrance of microbes into the sterile filling area where the sterile product is filled and sealed in presterilized packages. A nitrogen or other inert atmosphere is preferred to keep oxygen away from the product when the package is sealed.

Aseptic processing systems have found wide use for packing juices and dairy products for the retail market and for the bulk preservation of tomato paste and fruit slices for use as ingredients. Further information on aseptic processing can be found in the literature (2).

4.4. Freezing Preservation. The rate of loss of color, flavor, texture, and nutrients, the growth of microbes, and the activity of enzymes and other life forms are all functions of temperature. Thus lower storage temperatures prolong the useful life of foods. Below 0°C, the free water in foods starts to form ice crystals. Ice crystal formation is a function of moisture content, solute composition, and storage temperature fluctuation. Supercooling can occur during the freezing process, but it is a transient phenomenon. Foods having high concentrations of solutes can behave as glassy materials in which water may exist in a noncrystalline state at freezing temperatures owing to inhibited diffusion and high soluble solids content. The conditions needed for establishing and maintaining the glassy state in frozen foods is discussed in detail elsewhere (5).

Ice formation is both beneficial and detrimental. Benefits, which include the strengthening of food structures and the removal of free moisture, are often outweighed by deleterious effects that ice crystal formation may have on plant cell walls in fruits and vegetable products preserved by freezing. Ice crystal formation can result in partial dehydration of the tissue surrounding the ice crystal and the freeze concentration of potential reactants. Ice crystals mechanically disrupt cell structures and increase the concentration of cell electrolytes, which can result in the chemical denaturation of proteins. Other quality losses can also occur (12).

Equipment for food freezing is designed to maximize the rate at which foods are cooled to −18°C to ensure as brief a time as possible in the temperature zone of maximum ice crystal formation (12,13). This rapid cooling favors the formation of small ice crystals, which minimize the disruption of cells and may reduce the effects of solute concentration damage. Rapid freezing requires equipment that can deliver large temperature differences and/or high heat-transfer rates. Foods, not packaged, exposed to large temperature differences, and high heat-transfer rates can under go significant moisture loss, as heat and mass transfer coefficients are linked. Freezing equipment should be designed to minimize this moisture loss. Some approaches are outlined in the section in freezing equipment.

Many formulated foods and certain animal products tolerate freezing and thawing well because their structures can accommodate ice crystallization, movement of water, and related changes in solute concentrations. Starches can be modified for freeze–thaw stability against gel breakdown through several freeze–thaw cycles. By contrast, most fruits and vegetables lose significant structural quality on freezing and during storage because their rigid cell structures fail to accommodate to ice crystal formation. Frozen food storage equipment must be designed to minimize temperature fluctuations. It is not practical to store commercial frozen foods at temperatures low enough to ensure complete conversion of all water to ice. Commercial frozen food storage temperatures (−18 to −24°C) represent an economic balance between storage costs measured in time, energy, and capital investment, and desired shelf-life and product quality.

Freezing can also disrupt tissue structures and allow cell contents to become mixed so that undesirable enzyme–substrate reactions can take place at significant rates even at storage temperatures of −18°C. These reactions can generate off-flavors, reduce nutrient concentrations, and cause changes in the structure and appearance of foods. The amount of free liquid or drip found after a freeze–thaw cycle is a good indication of structural damage. Heat treatment (blanching) prior to freezing is used to eliminate enzyme activity. Most enzymes responsible for quality loss in plant materials can be inactivated by exposure to a temperature of 100°C for 1–5 min. Enzymes in heat-sensitive fruits often can be inhibited using sulfur dioxide, sucrose, or combinations of citric acid, table salt, and ascorbic acid, preceded by vacuum removal of air if heat is not used. Specific, nontoxic, enzyme inhibitors have been described in the literature.

Most frozen foods have a useful storage life of 1 year at −18°C. However, foods high in fat such as sausage products may become rancid after 2 weeks in frozen storage if not protected from oxygen by special packaging and antioxidants. The time–temperature tolerances of various frozen foods are discussed in Ref. (14). Moisture migration and loss of moisture through packaging materials or defective seals can occur in frozen foods during storage. The process is similar to freeze–drying and is accelerated if the storage temperature is not constant. The heat-transfer surfaces used to maintain the storage temperature of a frozen storage room must be at a lower temperature than the storage area and frozen foods must be protected by moisture-proof packaging. Storage under varying temperature conditions favors the migration of water in the food from areas of high to areas of low concentration. In addition, foods susceptible to oxidative deterioration must be protected from air by hermetically sealed containers, by coating with an oxygen impermeable coating, or by incorporating an antioxidant in the product. Water glazes have been used to protect fish during frozen storage. Edible barriers are being evaluated to limit the rate of moisture migration (15).

Equipment. Food freezing equipment can be classified by the method and medium of heat transfer used. High velocity air is the most common medium used for direct contact freezing of nonpackaged foods. Typically, foods are loaded on a continuous mesh or perforated belt and passed through air moving upward at 5 m/s at temperatures as low as −40°C. The air is recycled through cooling coils and fans located next to the conveyor and returned through the conveyor. Because cold air has a partial water vapor pressure lower than the warm food, evaporation to the extent of several percent of the weight of the food can occur from the surface. This water vapor condenses on the air-cooling coils, making periodic defrosting necessary. Whereas air is a convenient and safe heat-transfer medium for food freezing, it has several drawbacks including its low heat capacity and poor heat-transfer characteristics. Rapid freezing requires high air velocities and low operating temperatures. For these and other reasons many foods are frozen in equipment using conduction or liquid heat-transfer methods. Capital and energy savings, reduced moisture loss, and elimination of defrosting are some advantages of these methods.

Liquid heat-transfer media for immersion freezing include solutions of edible salts, sugars, alcohols, and esters. These heat-transfer agents offer high heat-transfer rates, reduced pumping costs, and allow operating at higher refrigerant temperatures. Not all foods are suitable for direct immersion in these freezing media. However, irregularly shaped foods such as whole turkeys can be shrink wrapped in plastic and thus can be adapted to immersion freezing.

Conduction freezing between chilled plates is a very cost-effective method of heat removal for products that can be packaged in such geometry so as to fit between refrigerated plates. Packages having a regular geometry, such as a semiinfinite slab, can be loaded automatically between platens through which a refrigerant is circulated. The platens are stacked to provide a large product-holding capacity and thus sufficient contact time to ensure complete freezing. As unfrozen packages are introduced, frozen packages are removed in a continuous fashion. Good conduction heat-transfer conditions are achieved by maintaining pressure on the stack of platens to ensure good contact between the package and heat exchanger surfaces.

Cryogenic freezing equipment uses liquid nitrogen or carbon dioxide snow. These units have the advantage of portability and simplicity and can produce extremely fast freezing rates. The refrigerant can be sprayed directly on the product to ensure rapid heat transfer. Cryogenic freezing produces very high quality products and ensures that little product weight loss occurs. This is important for high unit value foods and ingredients such as meat, poultry, bakery, and seafood products.

The quality of a frozen food may be determined more by the temperature at which it is stored than by the method or rate of freezing. Storage temperatures may fluctuate as products move from manufacturing through distribution channels to the consumer's home freezer. The useful shelf-life of a frozen food may be severely limited by exposure to storage temperatures above −18°C, even for a few hours.

4.5. Dehydration Processing. Dehydration is one of the oldest means of preserving food. Microbes generally do not grow below a minimum water activity of 0.65. Water activity is defined as the equilibrium relative humidity surrounding food in a sealed container at a given temperature, ie, no microbes can grow at a water activity <65% relative humidity at storage temperatures in the range of 0–40°C.

Each food or food ingredient shows a characteristic equilibrium relative humidity at a given moisture content and temperature. Thus as a food is dried and its moisture content is reduced from its fresh value, where water activity is generally 1.0, to lower and lower values, the equilibrium water activity of the food decreases as a complex function of residual moisture. The shape of the equilibrium relative humidity–moisture content curve is set by the chemistry of the food. Foods high in fructose, eg, bind water and thus show lower water activities at high moisture contents. Dried prunes and raisins are examples. Drying can be terminated at any desired moisture content and hence any water activity.

Foods dried to water activities in the range of 0.65–0.85 are often referred to as intermediate moisture foods. These partially dried foods tend to be soft and rehydrate easily. The remaining water acts as a plasticizer. Because molds and yeast may be able to grow in these partially dried products, they must be preserved by heat, vacuum, or modified atmosphere packaging, refrigeration, or chemical means. For example, bakery products can be filled or topped with intermediate moisture content fruit or cheese fillings, which have a microbial stability matching the lower moisture baked pastry portion.

Foods high in sucrose, protein, or starch (qv) tend to bind water less firmly and must be dried to a low moisture content to obtain microbial stability. For example, grain and wheat flour can support mold growth at moisture contents >15% (wet basis) and thus are stored at moisture contents <14%. Stored grains and oil seeds must be kept at a water activity <0.65 because certain molds can release aflatoxins as they grow. Aflatoxins are potent carcinogens.

Fresh plant and animal tissue when dried to a water activity much <0.97 show irreversible disruption of metabolic processes. However, individual metabolic enzymes may retain activity almost to dryness. Foods are usually heat treated (blanched) prior to drying. Some foods, upon drying, are susceptible to rapid nonenzymatic browning owing to high concentrations of reducing sugars, ascorbic acid, and free amino acids (qv). Dry fruits can be treated with sulfur dioxide to prevent nonenzymatic browning. Products susceptible to oxidation and oxidative rancidity such as potato chips, can be treated with antioxidants and inert gas packed to minimize exposure to oxygen. Low temperature storage can further reduce the rate of chemical deterioration. Dehydrated ingredients must have the same water activity when mixed together in a blended product to prevent undesirable moisture migration from high to low water activity ingredients.

Equipment. Continuous hot air driers are used to prepare most of the high quality, dried, piece-form fruits and vegetables produced in the United States. Optimum quality can be achieved by matching the rate of heat input to the food to the rate of moisture release from the food while carefully controlling the product temperature. The bed depth, dry-bulb temperature, relative humidity, air velocity, and direction of air movement through the bed are selected to maintain a wet-bulb temperature, which minimizes product deterioration owing to heat-induced chemical reactions. Typically, continuous belt dryers are staged to provide three or more drying zones into which product is fed to give a very even bed depth. The drying product can be redistributed as a progressively deeper bed in each zone. Each zone is set to operate at a controlled wet- and dry-bulb temperature, up or down air-flow velocity, and bed depth which, optimizes product quality, minimizes energy use, and maximizes product throughput. Excessive heating of the product during any stage of drying reduces product quality; thus food dryers must be designed to provide very uniform drying conditions. The successful operation of a continuous belt drying system depends on establishing a uniform feed rate to the belt to ensure a uniform bed depth. Liquids and pastes are commonly dried in spray, drum, or freeze dryers. Particulate foods can be dried in batch or continuous air-fluidized beds or freeze dryers. Many agricultural commodities are sun-dried when weather conditions at harvest provide low humidity, warm temperatures, and good air circulation.

Rehydration rate and extent of rehydration of a dried food are important quality factors. Instantized dried foods refer to products, which re-hydrate to approximate fresh appearance and eating quality in several minutes in the presence of either hot or cold water. Freeze-dried meats, seafoods, vegetables, and specialty products are particularly useful for instant soups, sauces, meals, and garnishes. Instantized rice, potato, and carrot dice, and other vegetable and cereal products, can be made using puffing guns, centrifugal fluidized beds, or single- or double-screw extruders. These and other drying technologies are covered in the literature (16).

4.6. Chemical Preservation. Food additives (qv) can enhance the effectiveness of food preservation by heat, refrigeration, and drying methods. The addition of a food-grade acid to a low acid food to shift the pH to a value <4.5 allows heat preservation at a temperature of 100°C instead of in the range of 121°C. Antioxidants such as butylated hydroxyanisole [25013-16-5] (BHA) can be added to potato chips to reduce the need for expensive oxygen-impermeable flexible packaging. Sulfur dioxide is used in wine (qv) and in dry fruit and vegetable products to preserve colors and flavors and prevent nonenzymatic browning.

Food can be preserved by fermentation (qv) using selected strains of yeast, lactic acid producing bacteria, or molds. The production of ethanol (qv), lactic and other organic acids, and antimicrobial agents in the food, along with the removal of fermentable sugars, can yield a product having an extended shelf-life. Mild heating of foods, acidified by fermentation and packaged to prevent further contamination, results in a shelf stable product. Cucumber pickles and sauerkraut are examples. The course of the fermentation process can be controlled by the addition of sodium chloride to help provide optimum fermentation conditions for the lactic acid-producing bacteria present on the raw materials at harvest.

Lactic acid-producing bacteria associated with fermented dairy products have been found to produce antibiotic-like compounds called bacteriocins. Concentrations of these natural antibiotics can be added to refrigerated foods in the form of an extract of the fermentation process to help prevent microbial spoilage. Other natural antibiotics are produced by *Penicillium roqueforti*, the mold associated with Roquefort and blue cheese, and by *Propionibacterium* sp., which produce propionic acid and are associated with Swiss-type cheeses (3).

Ionizing radiation is considered to be a chemical preservation method and applications must be cleared by the FDA for use, not only on a product-by-product basis, but also on a dose basis. In the United States, up to 100 Gy (10,000 rad) may be used to inhibit potato sprouting, and up to 500 Gy may be used to kill insects and insect eggs in grain products. Fruit, poultry, and other fresh products can be pasteurized at doses up to 10,000 Gy to inactivate pathogenic bacteria, spoilage microbes, insects and larva, and parasites, and to reduce total microbial counts to extend refrigerated shelf-life. Packaging materials, spices, and medical devices can be sterilized at doses up to 60,000 Gy. The theory and applications of ionizing radiation in food preservation are discussed elsewhere (17). The use of ionizing radiation to preserve a food product requires extensive testing to determine the effect of dose on the flavor and possibly structure of the packaged product. Since the absorbed dose is a function of the thickness of the product, product at the surface of the package may receive more radiation than product in the center.

Foods can be treated with solutions of ozone, chlorine, chlorine dioxide, and other approved agents to reduce surface microbial contamination. The success of the treatment depends on the control of concentration, temperature, exposure time and microbial load.

4.7. Other Technologies. Several technologies for the preservation of foods using a minimum of heat are being explored. The application of ultrahigh pressure to the preservation of foods has been commercialized (7). Ultrahigh hydrostatic pressure is known to inactivate vegetative microbial cells and parasites in foods at a rate proportional to pressure at any temperature. Studies using a wide variety of fresh and processed foods have shown that these foods can be rendered free of vegetative bacteria, parasites, yeasts, and molds by subjecting the foods to hydrostatic pressures in the range of 300–600 MPa (43,000–87,000 psi) for times between 1 min and 1 h, at room temperature. Spores, viruses, and food spoilage enzymes, such as polyphenol oxidase, have been found to be quite resistant to inactivation by pressure at room temperature. However, combinations of pressures and temperatures up to 80–90°C have been used to inactivate spores and enzymes in low acid foods. Pressure resistant viruses are easily inactivated by heat at relatively low temperatures.

Foods having a pH <4.5 can be made commercially sterile using pressures in the range of 400 MPa (58,000 psi) because the germination of most bacterial spores is inhibited. Yeasts and molds are much more susceptible to inactivation by pressure than are vegetative bacterial cells. Pressure appears to disrupt cell membranes and to denature proteins. Foods preserved by ultrahigh pressure processes must be stored at their intended storage temperature for a time sufficient to determine whether microbes can repair pressure damaged cell structures during storage. Inactivation and regeneration rates of pressure treated microbes are strongly influenced by the chemical composition of the media in which they are held.

Equipment for batch ultrahigh pressure preservation of foods has been adapted from units used in the metal and plastic industry for cold or warm isostatic pressing at operating pressures to 1000 MPa (145,000 psi). Operating volumes of several hundred liters are possible at these pressures using wire-wound and multiple layer vessels. Batch chambers operating from 300 to 600 MPa (43,000 to 87,000 psi) may be made from multiple shrink fit cylindrical tubes that can be closed at either end using continuous thread, interrupted thread, pin, or yoke closures. It is possible to treat liquid foods in a semicontinuous manner by pumping them into a series of pressure vessels, which fill and discharge automatically. The treated foods must be stored and filled under aseptic conditions into presterilized packages as with heat-treated aseptically filled foods. High pressure is used commercially to shuck and pasteurized shellfish, and to pasteurize guacamole and other avocado products, hams, fruit juices, and specialty foods.

Capacitance discharge has also been investigated as a means to pasteurize or commercially sterilize foods, which can pass between plates sufficiently close together to allow an electric field of ~25,000 V/cm (18). The field is established preferably as a square-wave pulse of millisecond duration to avoid heating effects. The strong electrical field appears to disrupt or permeable cell membrane structures. The degree of disruption, and hence microbial inactivation, can be related to the number of pulses to which each element of food is subjected. Cell permeability by capacitance discharge can be used to improve the extraction of secondary metabolites from microbes, plant and animal cells, and hence to increase the yield of mechanically pressed fresh fruit and vegetable juices (18). Very high intensity pulses of visible light can be used to pasteurize fruit juices using a minimum of heating in a manner that appears to be similar to capacitance discharge.

4.8. Computer Integrated Manufacturing, Instrumentation, and Controls. Food processing firms are exploring the use of computer integrated manufacturing. However, the diversity of products, the difficulty of measuring meaningful quality attributes on line, and the batch nature of many processes has tended to slow the application of this technology to food processing. However, thermal processing controls have been developed to the point where time and temperature process deviations can be corrected on line. Freezer, dryer, and vacuum evaporator operating conditions can be controlled and optimized using systems already available to the process industry.

An important aspect of food processing, common with other processing industries, is yield of finished product from starting raw materials for any shift and for specific unit operations. Computer integrated manufacturing can start with the measurement of material flows and build upon this information. Instrumentation for the on line measurement of specific food qualities of importance to the consumer such as food flavor, aroma, texture, and microbial content are under development. These quality factors are monitored using statistical quality assurance (qv) procedures using standard sampling plans and control strategies.

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